3.13   INTEGRATION OF SATELLITE-DERIVED CLOUD PHASE, CLOUD TOP HEIGHT, AND LIQUID WATER PATH INTO AN OPERATIONAL AIRCRAFT ICING NOWCASTING SYSTEM

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1. INTRODUCTION

Products developed at the National Center for Atmospheric Research (NCAR) and disseminated by the U.S. National Weather Service provide nowcast and short-term forecast estimates of icing probability, severity, and the potential for supercooled large droplets (SLD). The Current Icing Product (CIP) system combines multiple data sources using fuzzy logic methods to produce a gridded, three-dimensional, hourly depiction of icing-related conditions (Bernstein et al., 2005). The CIP algorithms rely on basic satellite-derived information, such as a cloud mask and cloud top temperature estimate, as one source of input data. The goal of the NASA Advanced Satellite Aviation-weather Products (ASAP) program is to devise methods for incorporating more sophisticated satellite products into aviation weather diagnosis and forecast systems. In this component of the ASAP program, the objective is replacement of the satellite module in the CIP system with satellite-derived cloud products developed by the NASA Langley Research Center (LaRC) Cloud and Radiation Research Group. This paper describes the use of the LaRC cloud hydrometeor phase, cloud top height, cloud effective temperature, and liquid water path products to refine estimates of icing parameters.

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2. THE CURRENT ICING PRODUCT SYSTEM

The operational CIP algorithm combines information from satellites, radars, surface observations, lightning sensors, and pilot reports with model forecasts of temperature, humidity, supercooled liquid water, and vertical velocity. Fuzzy logic and decision tree logic are applied to combine up to fifty-six interest fields derived from these data sources into a single fused product. The algorithm generates a three-dimensional hourly diagnosis of the probability of icing and supercooled large drops over the continental United States at 20-km horizontal resolution (McDonough and Bernstein, 1999; Bernstein et al., 2005). Results are presented as numbers between 0 and 1 (or as a percentage) that indicate the probability of icing and for the existence of SLD within a given volume. Figure 1 depicts the process of combining data from surface observations, models, radar, pilot reports, and satellite sensors to arrive at three-dimensional estimates of icing probability and the potential for supercooled large drops (SLD) over the continental United States. Following determination of the cloud structure and classification of conditions into pre-defined meteorological scenarios, fuzzy logic methods and decision-tree techniques are applied to determine the likelihood of icing and SLD at each location, thereby maximizing the strengths of each dataset. Routine CIP output is available on the Aviation Digital Data Service web page at:
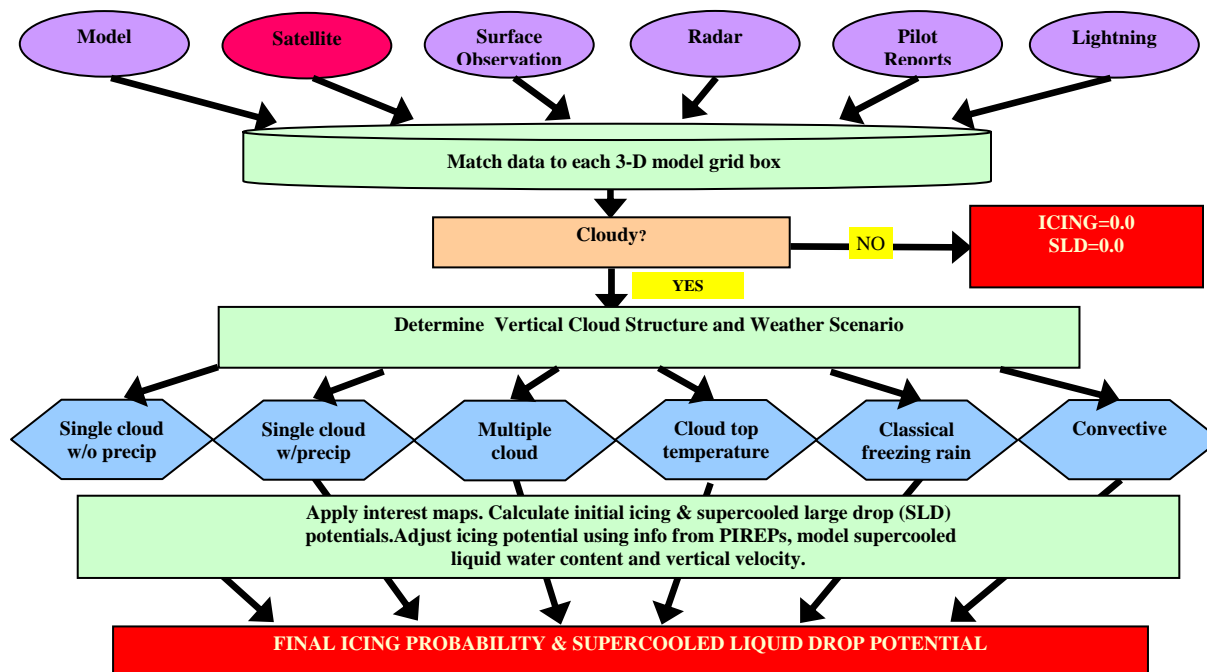
http://adds.aviationweather.noaa.gov.

Figure 1: : Diagram showing the Current Icing Product (CIP) system which uses multiple sources of data as input and combines them using fuzzy logic methods and decision tree technology to produce estimates of icing probability and the potential for supercooled large drops.

3. SATELLITE CLOUD PRODUCTS

The cloud products under evaluation for inclusion in CIP are derived from the Geostationary Operational Environmental Satellite (GOES). The GOES Imager has channels in the visible, near-infrared, and thermal infrared portions of the spectrum. NASA LaRC algorithms are applied to half-hourly GOES-10 (Western U.S.) and GOES-12 (Eastern U.S.) Imager data. The Visible Infrared Solar-infrared Split-window Technique (VISST) is used during daytime hours. The Solar-infrared Split-window Technique (SIST) uses a subset of the Imager channels to derive products at night (Minnis et al., 2005).

The LaRC system first classifies each 4-km GOES pixel as clear or cloudy using a complex cloud identification scheme (Trepte et al. 1999). VISST/SIST thresholds are then applied to each cloud pixel to determine phase, optical depth, effective particle size, effective temperature, effective height, and ice or liquid water path. These parameters are used to estimate cloud-top and base altitudes and temperatures. The analyses utilize the 0.65, 3.9, 10.8, and 13.3 µm GOES imager channels during daytime hours and the latter three channels at night. An example showing the derived liquid water path over the northeastern United States is shown in Figure 2.

Based on results of multiple validation studies performed on the LaRC cloud products in meteorological conditions associated with icing (Wolff et al., 2005; Haggerty et al., 2005; Khaiyer et al., 2003; Smith et al., 2002; Black et al., 2007), specific fields have been targeted as likely to provide useful information about the location of supercooled liquid clouds. Black et al. (2008) describe an objective verification process that classifies meteorological conditions into one of the CIP-defined scenarios and compares the satellite products to PIREPS. Using results of these studies, methods for integrating specific products into an experimental version of CIP have been developed.
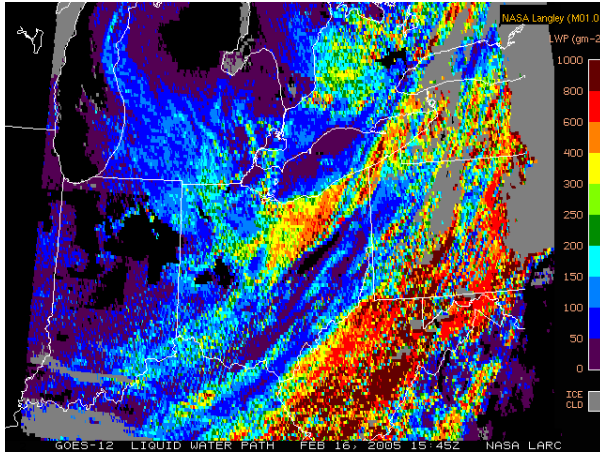
Figure 2: Liquid water path at 1545 UTC on February 16, 2005 as derived from GOES-12 imagery using the Visible Infrared Solar-infrared Split window Technique (VISST).

4. INTEGRATION METHODOLOGY

CIP algorithms apply fuzzy logic methods and decision-tree techniques to determine the likelihood of icing and SLD at each location. The fuzzy logic scheme employs interest maps for each data set to quantify the value (on a scale from 0 to 1) of a given variable in specified meteorological conditions. Thus, new interest maps are developed and/or existing interest maps are refined to incorporate new information provided by the LaRC satellite cloud products. This paper describes efforts to incorporate, via fuzzy logic methods, the LaRC cloud mask, hydrometeor phase, cloud top height, and cloud effective temperature to refine estimates of the CIP icing probability field.

4.1 *Cloud Mask and Hydrometeor Phase*

In the experimental version of CIP, the existing GOES-based cloud masking technique is replaced with a new cloud screening method that uses the LaRC hydrometeor phase product together with various thresholds. Each CIP gridpoint (20 km resolution) is mapped to 16 GOES-LaRC product pixels (5 km resolution). If more than 40% of the phase product pixels contain clouds, then the CIP

gridpoint is classified as cloudy. At this point in the algorithm, additional calculations are made for subsequent use in relating icing probability to cloud top temperature. Cloud pixels are sorted from cold to warm using the LaRC Cloud Effective Temperature (T_e) product; 25th, 50th, and 75th percentiles of T_e values are calculated. The fraction of liquid phase pixels within each T_e bin is also calculated.

The current cloud top temperature (CTT) interest map is also revised using this information from the LaRC phase product. The original CTT map was based on the statistical probability that ice or liquid would be associated with a certain cloud top temperature. A new variable, the percent of liquid pixels associated with the cloud top temperature, is now being used in the algorithm. Addition of the observed cloud phase to the statistical CTT map modifies the algorithm's level of interest in icing. The new equation for cloud top phase interest is:

newCTT_interest = (0.5 * CTTmap) + (0.5 * % liquid phase)

Thus if a cold cloud top has liquid hydrometeors according to the LaRC phase product, the interest in icing is increased. Conversely, if a warm cloud top shows ice phase at cloud top, the interest in icing will be reduced.

4.2 *Cloud Top Height and Effective Temperature*

Cloud top height estimates in the current operational version of CIP combine model-derived temperature profiles with GOES brightness temperature measurements at cloud top. The method (hereafter referred to as "CIP CTZ") assumes cloud top height is at the level where model temperature is equal to the coldest 10.7 μm brightness temperature among the cloudy pixels, as depicted in Figure 3 (see blue circle in figure). In actuality, the model sounding is frequently too warm, and the actual cloud top is not accurately identified. Instead, the cloud top is placed above the actual cloud top height in this situation.

Such errors in this method are especially large for low-level boundary layer clouds.
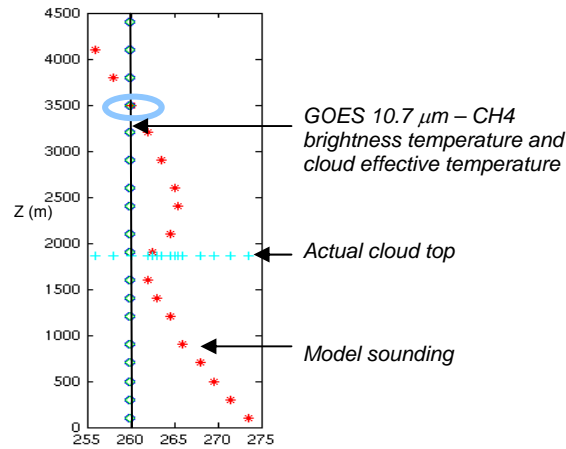

Figure 3: Example showing use of model temperature soundings and GOES brightness temperature in the existing CIP method (CIP-CTZ) for cloud top height estimation.

The LaRC cloud top height product (ASAP CTZ) also uses a temperature matching scheme that employs vertical profiles from models, and hence suffers from the same weaknesses as the CIP CTZ method. A hybrid of these schemes, referred to as the Combined CIP CTZ (CCZ) method, blends the LaRC cloud top height and T_e products together with model profiles. The CCZ method applies fuzzy logic based on knowledge that cloud tops are often found in a sounding where:

- Relative humidity (RH) decreases to less than 100%
- An inversion in equivalent potential temperature (θ_e) exists
- Vertical velocity changes sign from positive to negative
- Wind shear is present
- GOES brightness temperature matches model profile temperature

Based on these guidelines, fuzzy logic membership functions are created for each pertinent variable including: 1) Model temperature – T_e(25th percentile); RH; d(RH)/dz; d(θ_e)/dz; d(total model condensate)/dz. Following the CIP paradigm, interest maps are then developed to quantify the value of each variable in specific conditions. Figure 4 shows the interest map for [Model temperature – T_e] which characterizes the interest (on a scale from 0 to 1) as a function of the temperature difference. Weighted values derived from each interest map are combined to arrive at the new cloud top height estimate.
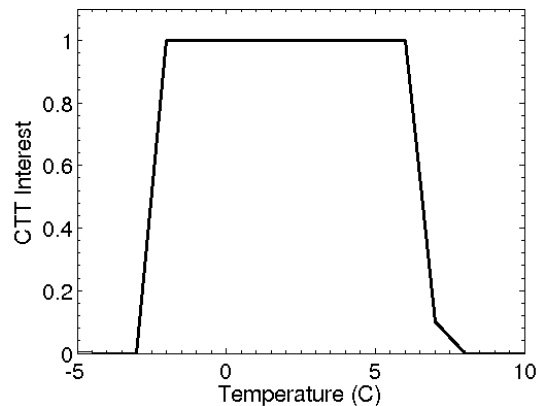

Figure 4: Interest map for [Model temperature – T_e]. This function quantifies the level of interest for purposes of detecting icing conditions in observations with a given difference in the model temperature and the satellite-derived effective temperature.

Each of the three cloud top height estimate methods (i.e., CIP CTZ, ASAP CTZ, and the new CCZ) have been evaluated using a set of 769 daytime pilot reports which give observed cloud top height (TOP-REPs). Differences between calculated cloud top height and PIREP estimated cloud top height for each of the three methods are shown in Figure 5. The tendency for CIP algorithms to overestimate cloud top height is reduced significantly by the hybrid CCZ method. This result could yield significant improvement to the CIP icing probability field by reducing the estimated volume of icing in the gridspace.
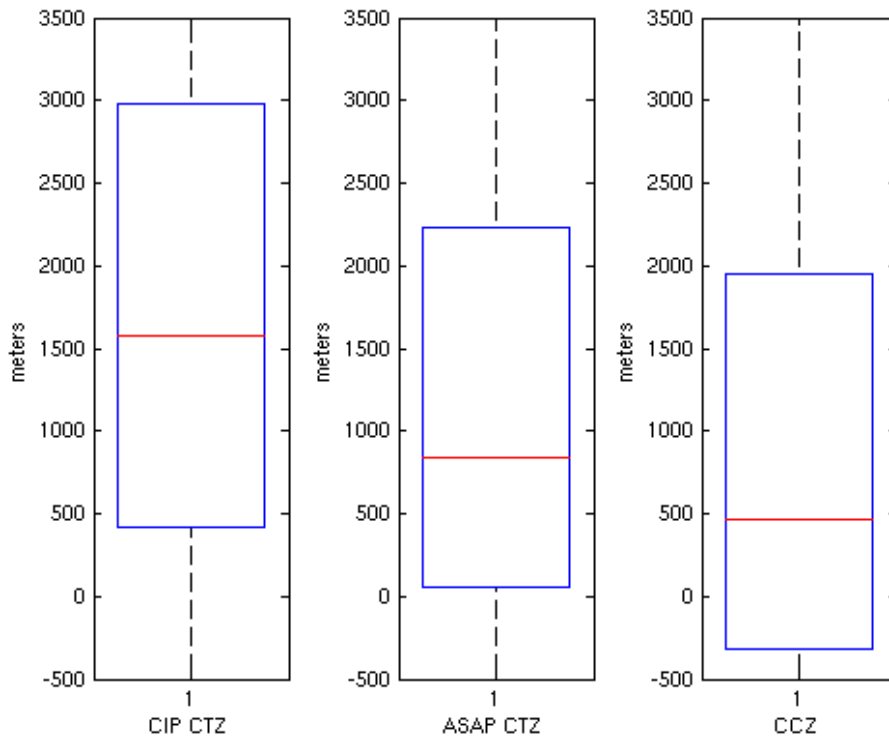
Figure 5: The differences (calculated cloud top height minus PIREP measured cloud top) in the three cloud top schemes for the 769 daytime TOP-REPs. The red line denotes the median error while the box encloses the 25th – 75th percentiles of the errors.

5. VERIFICATION

Using the experimental version of CIP that now includes the LaRC cloud mask, cloud hydrometeor phase, cloud effective temperature, and cloud top height products, the CIP icing probability field is compared to the operational version of CIP. A data set covering daytime cases for six weeks during the winter of 2005 was used. Estimated cloud top height, icing volumes, and probability of detection (POD) using PIREPS of icing were compared for the operational CIP versus the experimental CIP.

Figure 6 shows cloud top height as estimated by the operational CIP (left panel) and the experimental CIP (right panel) on 19 January 2005 at 1800 UTC. Considering a post-cold-frontal area centered on Ohio, where research aircraft measurements are available, a reduction in cloud top height on the order of several hundred meters is produced by the CCZ method in the experimental CIP. Coincident aircraft measurements and local radiosonde profiles are in better agreement with the new estimate.

The corresponding icing probability field at 650 mb is shown in Figure 7. The area centered on Ohio contains icing probabilities as high as 90% according to the operational CIP (left panel). Due to the verified reduction in cloud top height produced by the experimental CIP, the area of high icing probability is significantly reduced (right panel). Independent data sources including research aircraft data and radiosonde data confirm that the reduction in cloud top height and icing volume better represents the actual situation.
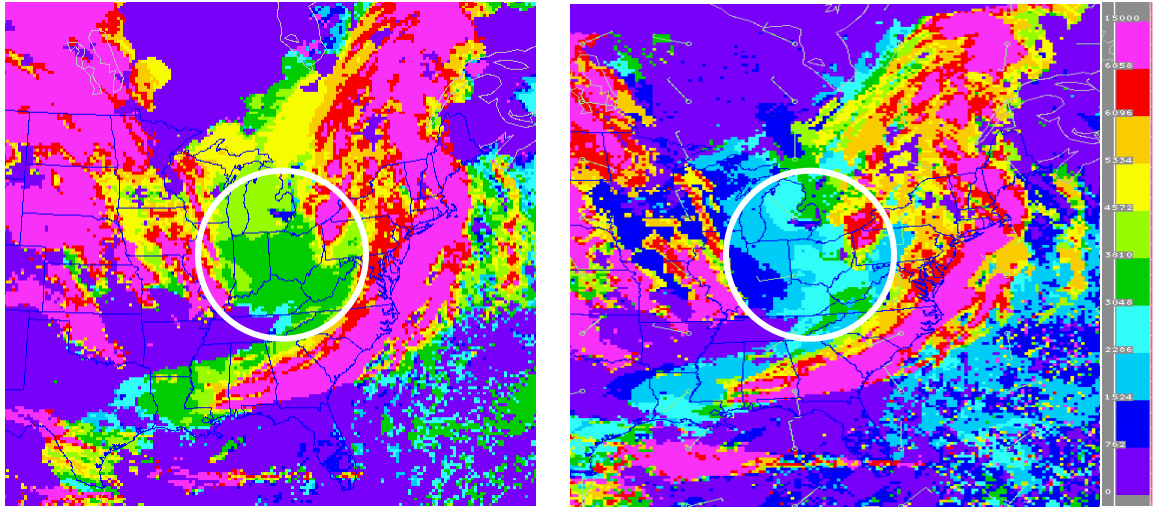
Figure 6: Cloud top height generated by the CIP-CTZ method in the operational version of CIP (left panel) and by the new CCZ method in the experimental version of CIP (right panel) on 19 January 2005 at 1800 UTC.
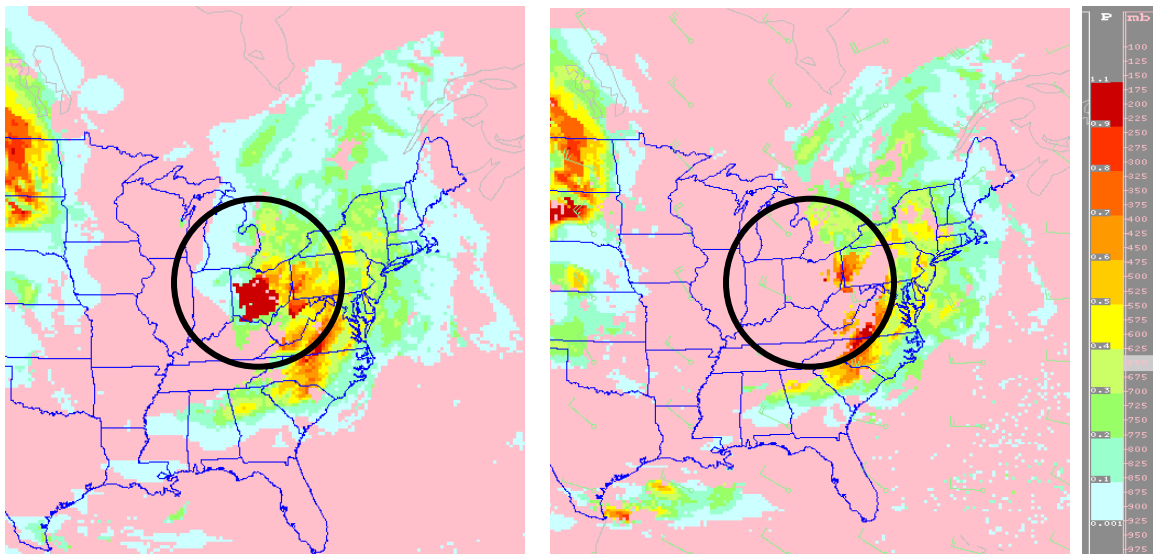

Figure 7: Icing probability at 650mb according to the operational CIP (left panel) and the experimental CIP (right panel) on 19 January 2005 at 1800 UTC.

Statistics for the entire 6-week data set show that 67% of the experimental CIP cases had less icing volume than the operational CIP. Overall, icing volume was reduced by 4.2% in the experimental CIP. By limiting the comparison to locations where both the operational and experimental versions agreed on the presence or absence of clouds, the number of cases with reduced icing volume was 83%. The overall icing volume was reduced from 9% in the operational CIP to 8.4% of the model domain in the experimental version.

CIP comparisons with PIREPs reflect the reduction in icing volume. The experimental CIP gives a higher probability of detecting "no" PIREPS compared to the operational version, and a lower probability of detecting "yes" PIREPS. Further analysis of a larger data set is required to ascertain whether the modifications consistently improve icing probability estimates. However, the operational CIP is known to over-estimate the cloud top height at low altitudes and thereby over-predict the volume containing icing, so the reduction in cloud top height obtained by the new algorithm is expected to improve results.

6. Future Plans

Verification of the experimental CIP with a larger data set is required to asses its suitability for operational implementation. The experimental CIP system is currently being modified to run in near-real-time with LaRC cloud products, so statistics will be compiled for the 2008 winter season. Case studies that will elucidate the effect of the LaRC products on CIP output in specific situations will also be conducted.

Further integration of the LaRC products is anticipated. The LWP, IWP, and optical depth fields appear to have positive correlation with icing severity observations (Black et al., 2008), and hence will be integrated into the CIP icing severity product. The possibility of using the phase and effective radius products for detection of supercooled large droplets aloft will also be investigated. Any new products from the LaRC Cloud and Radiation Research Group will also be considered for use in CIP, e.g., a multi-layer cloud product described by Minnis et al. (2008).

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