4.14 INTEGRATION OF ADVANCED SATELLITE CLOUD PRODUCTS INTO AN ICING NOWCASTING SYSTEM

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1. INTRODUCTION

The presence of supercooled liquid cloud drops can pose a hazard to aircraft operations. Products developed at the National Center for Atmospheric Research (NCAR) and disseminated by the U.S. National Weather Service provide current and short-term forecast estimates of the potential for supercooled liquid water, supercooled large drops, and icing severity. The Current Icing Potential (CIP) and Forecast Icing Potential (FIP) products rely on basic satellite-derived information, including a cloud mask and cloud top temperature estimate, together with multiple other data sources to produce gridded, three-dimensional icing fields (Bernstein et al., 2005). 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. Advanced satellite-derived cloud products developed at the NASA Langley Research Center (LaRC; Minnis et al. 2005) provide more detailed descriptions of cloud properties compared to the basic satellite-derived information currently used in CIP. Several of the LaRC derived fields can be related to CIP icing fields. This paper describes the processes of integrating these advanced cloud products into CIP and understanding the conditions under which satellite-derived cloud products may improve detection of icing conditions and estimation of their severity.

2. THE CURRENT ICING POTENTIAL 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 potential for icing and supercooled large drops to exist 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 potential for icing and for supercooled large drops (SLD) within a given volume. Figure 1 is an example of CIP hourly output; the field shown is icing potential at 825 mb. Routine CIP output is available on the Aviation Digital Data Service web page at: http://adds.aviationweather.noaa.gov.

An experimental version of CIP estimates icing severity. Severity is also represented as a number between 0 and 1 corresponding to icing categories ranging from “trace” to “severe”, and is dependent on liquid water content (LWC) (Politovich et al., 2004). A high-resolution version of CIP is currently in development; this version will be the first to incorporate advanced satellite products.

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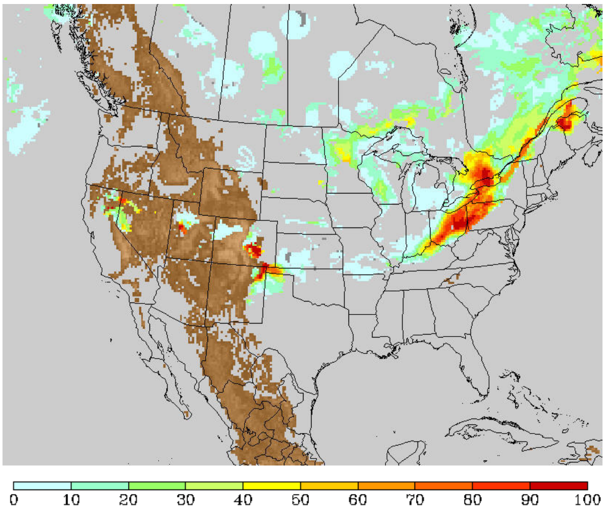

Figure 1: Icing potential at 825 mb at 1600 UTC on February 16, 2005 as estimated by the Current Icing Potential (CIP) algorithm.

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. 1995, 1998).

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 12.0 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.

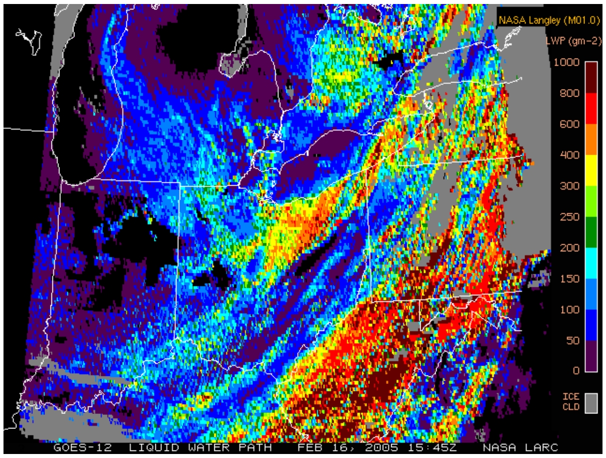

Figure 2: Liquid water path at 1545 UTC on February 16, 2005 as derived from GOES-12 imagery using the Visible Infrared Solar-infrared Split window Technique (VISST).

Cloud phase, liquid water path, and droplet effective radius as estimated by the LaRC algorithms are expected to be good candidates for improving CIP results. Anecdotal evidence provided by the use of LaRC cloud products as a nowcasting and short-term forecasting tool during icing field programs indicates that these satellite-derived fields are useful for discerning the existence of supercooled liquid water and ice crystals. Cloud top height estimates may also be useful for corroborating the current satellite- and model-derived cloud top heights used in CIP. By examining these products in an operational setting, forecasters have been able to identify situations where specific fields are effective. Wolff et al. (2005) provide examples where the LWP field was used to identify regions with relatively larger supercooled liquid water contents during icing research programs.

4. PRODUCT EVALUATION

Objective assessments of LaRC cloud products and CIP output are being conducted prior to integration. This process establishes baseline CIP performance so that the effect of integrating satellite data can be measured. The evaluation process also establishes the quality of satellite products in various conditions. Results are used to develop logic for combining satellite-derived fields with other data sources used by CIP. Prior comparisons of these products with ground truth measurements are also considered (e.g., Khaiyer et al., 2003; Nguyen et al., 2004; Smith et al., 2002).

Various data sources serve as ground truth for CIP and satellite cloud product assessment. Research aircraft data provide in situ measurements of several of the satellite- and CIP-derived variables, pilot reports (PIREPS) indicate locations of observed icing conditions, and retrievals from surface-based microwave radiometers estimate liquid water path.

The Alliance Icing Research Study (AIRS-II) based in Montreal, Canada and the Winter Icing Storms Project (WISP04) based in Colorado, USA fielded aircraft that collected in situ measurements of cloud macro- and microphysical properties (Isaac et al., 2005). Comparisons between satellite- and aircraft-estimated cloud phase, liquid water path, and cloud top and base heights were made for available cases where supercooled liquid water was observed during the aircraft mission. CIP estimates of cloud top height were also compared with aircraft and satellite data. Shown here are cloud top phase estimates (Figure 3) and cloud top height estimates (Figure 4) for nineteen cases where the aircraft penetrated cloud top. Figure 3 is a scatter plot showing the cloud top phase estimates from satellite versus aircraft measurements. The numbers in parenthesis next to each data point indicate the number of cases with that combination of values. Of thirteen cases where the aircraft detected liquid, ten were classified correctly by satellite. Two liquid cases were erroneously classified as ice by the satellite retrieval algorithm; it is suspected that an overlying cirrus layer observed by the satellite, but not by the aircraft, is responsible for the mis-classification in each of these cases. One liquid case was classified as clear by the satellite; examination of the image shows a broken cloud field. Two cases where the aircraft detected mixed phase clouds were both classified as ice by satellite. Finally, of four cases where the aircraft detected ice phase, the satellite classification was correct three times and incorrect (clear) one time.

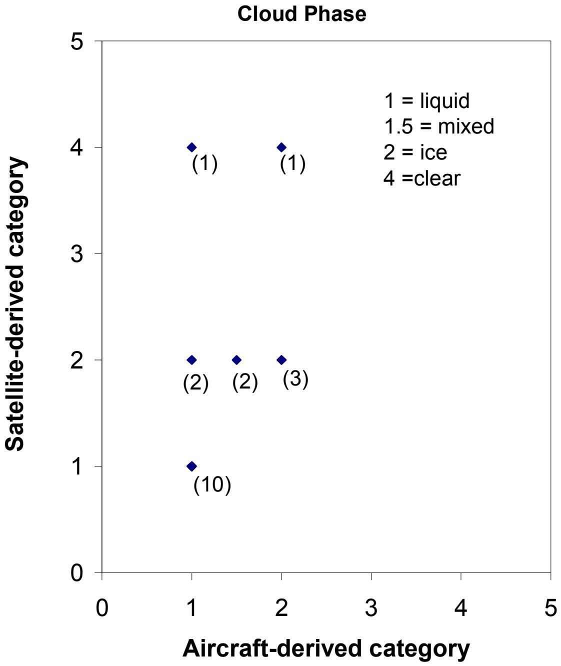

Figure 3: Comparison of cloud drop phase at cloud top as derived from GOES Imager data and research aircraft measurements. Numbers in parenthesis indicate the number of cases with that combination of values.

This set of aircraft cloud-top penetration cases was also compared qualitatively with CIP output. CIP-estimated icing potential (0-1) at aircraft-estimated cloud top height was compared with aircraft-detected cloud phase. A positive icing potential was observed in all but one case where the aircraft observed supercooled liquid. An icing potential of zero was estimated in all cases where aircraft observed ice phase at cloud top.

Comparisons of aircraft- and satellite-derived cloud top heights for the AIRS-II and WISP04 cases are shown in Figure 4. A similar comparison was performed for CIP- vs. aircraft-derived cloud top heights. The satellite-derived mean cloud top height of 5377 m and the CIP mean cloud top height of 5923 m both overestimate the aircraft-derived mean of 4039 m.

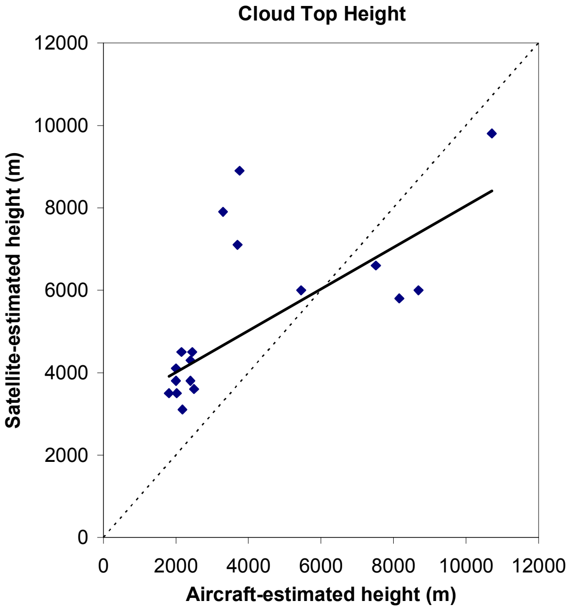

Figure 4: Comparison of cloud top height as derived from GOES Imager data and research aircraft measurements. Solid line is a least squares fit to the data points; dashed line shows 1:1 correspondence.

Estimates of LWP were retrieved from a ground-based microwave radiometer (MWR) during the AIRS-II field program using the method of Liljgren et al. (2001). LWP estimates from the LaRC satellite cloud products and aircraft LWP estimates were compared with the surface radiometer estimates. Half-hourly satellite cloud products were spatially averaged over an area within a 10 km radius of the ground site. Ground-based MWR retrievals were averaged over a one-hour time period centered at the time of the satellite products. Aircraft liquid water content was integrated vertically during ascent or descent through cloud layers in the vicinity to obtain LWP. Cases with primarily liquid clouds according to the phase retrieval were selected; surface meteorological observations were reviewed to eliminate cases with precipitation at the surface.

Figure 5 shows LWP estimates from each source for a case with a single layer, liquid stratus cloud on November 30, 2003. The agreement between the satellite-derived and MWR LWP estimates is quite good in this case, and the aircraft estimate agrees well with the other estimates in one of the two flight segments evaluated. Average LWP's for the entire time period were 239 g m^{-2} for the MWR retrieval, and 264 g m^{-2} for the satellite retrieval with a correlation coefficient of 0.72. In general, agreement between the satellite and MWR LWP retrievals is very good at LWP values below 300 g m^{-2}. Satellite retrievals tend to overestimate LWP at higher values. This result is consistent with previous findings (Khaiyer et al., 2003) from similar comparisons at the Southern Great Plains facility in Oklahoma. The bias at high LWP can be partly attributed to an known overestimation in the particle effective radius for clouds with larger optical depths.

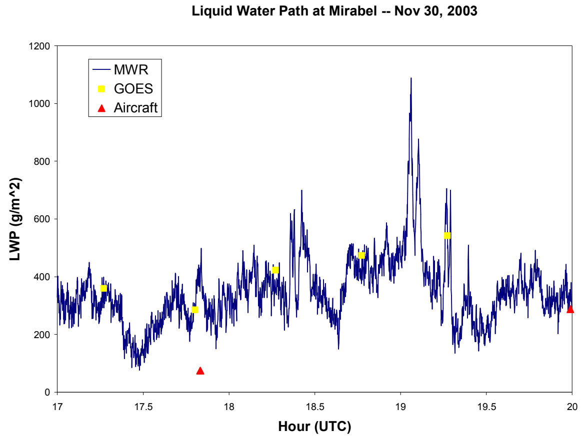

Figure 5: Liquid water path as estimated by a ground-based microwave radiometer (blue line), GOES satellite products (yellow symbols), and research aircraft (red symbols) on November 30, 2003 near Montreal, Canada.

Statistical verification of the capability for CIP and LaRC cloud products to detect icing conditions using pilot reports of icing incidence as a reference are described by Politovich et al. (2004). The satellite-derived cloud phase product was used for initial evaluation. Both CIP and the LaRC products demonstrated positive skill, with CIP showing a higher probability of detecting observed icing. Refinements to this study are reported in Chapman et al. (2005).

5. INTEGRATION OF ADVANCED SATELLITE PRODUCTS INTO CIP

Validation exercises discussed here and elsewhere support conclusions of the icing research flight forecasters with respect to the utility of the LaRC cloud products for improving identification of regions with supercooled liquid. Preliminary results coupled with forecaster experience suggest that phase estimates are typically accurate, and higher effective radius estimates tend to correlate positively with in situ observations of larger drops. LWP estimates compare well with independent observations, particularly at LWP values below 300 g m^{-2}. Cases where the LaRC cloud products exhibit uniform values of phase, LWP, and effective radius over a large area tend to be more accurate than cases with high spatial variability. While assessment of the LaRC products continues, evidence acquired thus far suggests that there is value in adding these advanced satellite products to the CIP algorithm.

The experimental high-resolution CIP algorithm has been targeted for integration of the satellite products because it can make better use of higher resolution satellite data. This version of CIP features enhanced grid spacing of 5 km or less (compared to 20-km resolution for the operational CIP) and temporal resolution of 15-30 minutes. Satellite data are essential for achieving these improved resolutions. The experimental algorithm is currently applied over the Great Lakes region in the northeastern USA.

The initial attempt to utilize the LaRC cloud products for enhancement of CIP output incorporates the cloud phase and LWP products to adjust the CIP severity index (Politovich et al., 2004) within the uppermost cloud layer. The satellite-derived phase field locates pixels with either liquid or supercooled liquid cloud tops. For those pixels, the retrieved LWP is assumed to represent liquid in the upper cloud layer. An empirical scaling factor is then used to convert LWP into a scaled LWC parameter that can be related to the CIP severity index. The resulting severity value is then compared to the original CIP severity index estimate; if the two estimates are different, the original severity index is adjusted upward or downward by half the difference between the satellite-enhanced severity value and the original value.

The modified CIP algorithm is applied to a case study on February 16, 2005. On this day, an icing research flight was conducted by the NASA Glenn Research Center’s Twin Otter over northern Ohio (Miller et al., 1998). Meteorological conditions at the time of the flight are described by Wolff et al. (2005). At 1500-1600 UTC a non-precipitating, single layer stratus cloud with cloud top temperatures of -10 to -15°C covered the study area. Figure 6 shows the LaRC cloud phase and LWP products for 1545 UTC. The phase product indicates that cloud tops are liquid phase over most of the region. The LWP product shows a swath of locally high LWP across the northern border of Ohio, and another area of high LWP over West Virginia and southwestern Pennsylvania.

The phase and LWP fields were incorporated into CIP as described above. The original and adjusted CIP severity index fields at the Twin Otter flight level are shown in Figure 7. Areas with zero icing potential are masked in brown. The original icing severity ranges from 0.25-0.75 (trace-light to moderate-severe categories), and is output at 20-km spatial resolution corresponding to the primary input data from which it is derived (model output and PIREPS). The lower image in Figure 7 is the icing severity field as modified by the inclusion of satellite-derived LWP. Here, the icing severity index range has been expanded to 0.15-0.85 (trace to heavy), and the spatial resolution is enhanced by the inclusion of satellite data. Significant increases to the icing severity index along the northern Ohio border and at the southeast portion of the icing area correspond to relatively high LWP values in Figure 6 (lower image). The NASA Twin Otter aircraft, operating in northeastern Ohio during this time, reported light to moderate icing, consistent with the severity index values of 0.3-0.6 shown in Figure 7 (lower image). The aircraft also measured LWC values and gradients consistent with satellite-derived LWP (Wolff et al., 2005).

6. FUTURE PLANS

This first attempt at incorporating advanced satellite cloud products into the Current Icing Potential product provides encouraging results. In the February 16, 2005 case study, the addition of phase and LWP fields from satellite data clearly altered the CIP icing severity estimates in a way that is consistent with satellite and research aircraft observations. Integration of the satellite data also made possible the differentiation of severity values on a much finer spatial scale than is possible using the current version of the CIP severity algorithm.

Validation of the satellite products continues as additional sources of verification data become available. This work provides a knowledge base that describes the accuracy of the various cloud products in specific meteorological conditions. Using this knowledge base, guidelines for integrating the LaRC satellite-derived cloud products into CIP under a variety of conditions will be developed and tested.

The high-resolution CIP, which will be the first version of the product to include advanced satellite products, is scheduled for experimental mode in 2007. It will become operational in 2009, leaving ample time for thorough testing of satellite product integration methods. Advanced satellite products may also be included as an upgrade to the operational 20-km CIP.

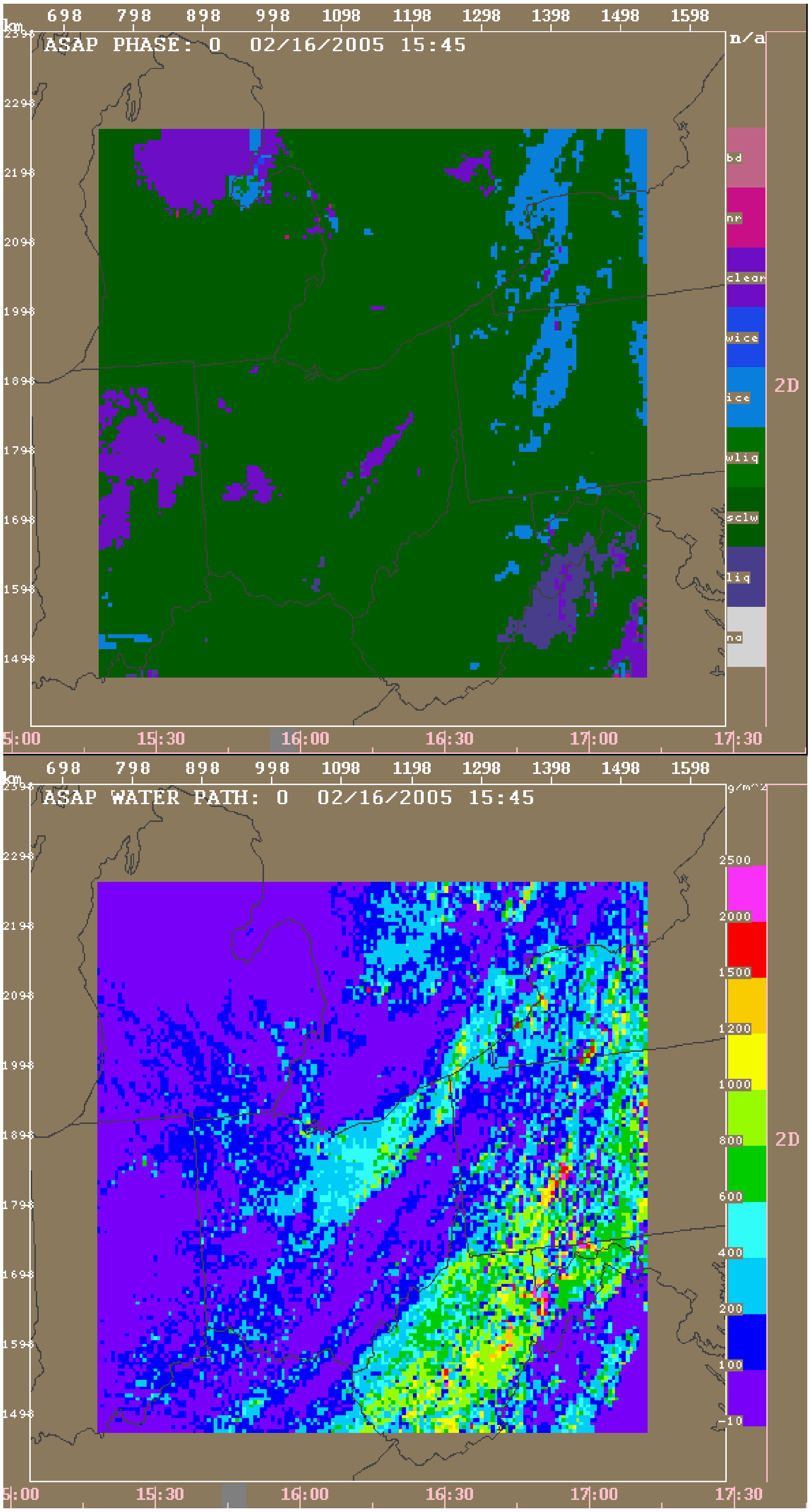

Figure 6: Cloud drop phase (upper image) and liquid water path (lower image) at 1545 UTC on February 16, 2005 as derived from GOES-12 Imager data using the NASA LaRC VISST algorithm.

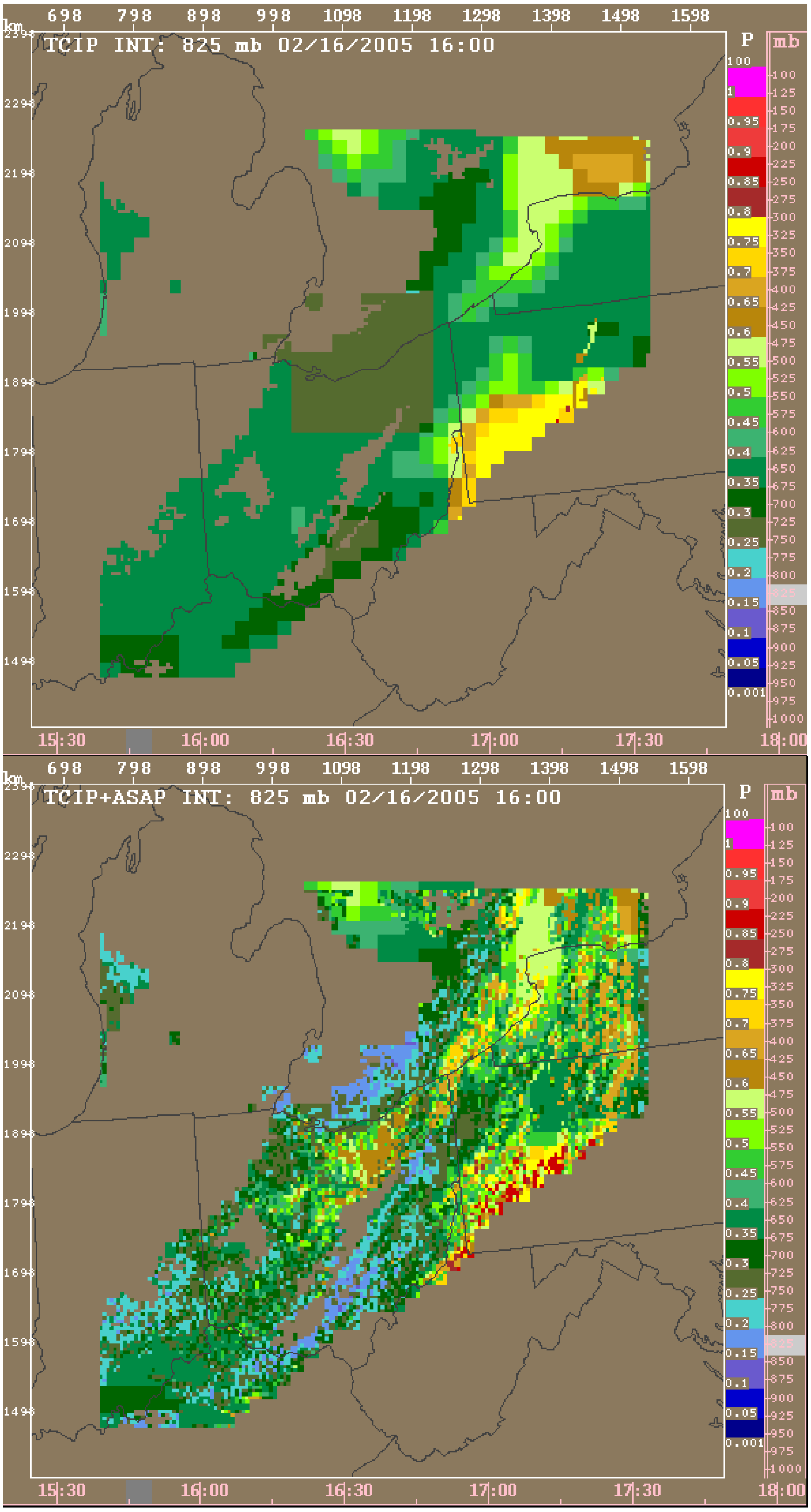

Figure 7: Icing severity index at 1600 UTC on February 16, 2005 as derived by the Current Icing Potential without satellite cloud products (upper image) and with satellite cloud products (lower image).

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