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1. INTRODUCTION

Aircraft icing is one of the most dangerous weather conditions for general aviation. Currently, model forecasts and pilot reports (PIREPS) constitute much of the database available to pilots for assessing the icing conditions in a particular area. Such data are often uncertain or sparsely available. Improvements in the temporal and areal coverage of icing diagnoses and prognoses would mark a substantial enhancement of aircraft safety in regions susceptible to heavy supercooled liquid water clouds. The use of 3.9-µm data from meteorological satellite imagers for diagnosing icing conditions has long been recognized (e.g., Ellrod and Nelson, 1996) but to date, no explicit physically based methods have been implemented. Recent advances in cloud detection and cloud property retrievals using operational satellite imagery open the door for real-time objective applications of those satellite datasets for a variety of weather phenomena. Because aircraft icing is related to cloud macro- and microphysical properties (e.g., Cober et al. 1995), it is logical that the cloud properties from satellite data would be useful for diagnosing icing conditions. This paper describes the a prototype real-time system for detecting aircraft icing from space.

2. DATA AND METHODOLOGY

The datasets used in the retrievals include half-hourly GOES-8, 10, and 12 4-km spectral radiances. The GOES-8 and 10 imagers measure radiances at 0.65, 3.9, 10.8, and 12 µm, while GOES-12 uses a 13.3-µm channel in place of the 12-µm channel. GOES-12 replaced GOES-8 at 75°W in April 2002, while GOES-10 remains at 135°W. Hourly Rapid Update Cycle (RUC) analyses (Benjamin et al., 2004) provide hourly profiles of temperature and humidity at a spatial resolution of 20 km. The profiles are used to assigning height from the retrieved cloud temperature *Tc* and to correct the radiances for atmospheric attenuation. Clear-sky visible (VIS; 0.65 µm) reflectance for each location is derived from the CERES clear-sky albedo map available on a 10' grid (Sun-Mack et al., 1999). Spectral surface emissivity derived from GOES (Smith et al. 1999) and CERES (Chen et al. 2002) data are used with the RUC data to specify the clear-sky radiating temperatures at 3.9, 10.8, and 12-µm. The data are ingested and analyzed within ~15 minutes of the GOES observation.

The visible infrared solar-infrared split-window technique (VISST; Minnis et al., 2001) is used during daytime, defined as the time when the solar zenith angle *SZA* is less than 82°. It matches the observed values with theoretical models of cloud reflectance and emittance (Minnis et al., 1998). At night, the solar-infrared infrared split-window technique (SIST) is used to retrieve all of the cloud properties. The SIST, an improved version of the 3-channel nighttime method (Minnis et al. 1995), uses thermal infrared data only. For each pixel, the methods retrieve *Tc*, cloud height *z* and thickness *h*, phase, optical depth τ, effective droplet radius *re* or effective ice crystal diameter *De*, and LWP or ice water path *IWP*. SLW clouds are those pixels with *Tc* < 273 K and a phase of liquid water. Other properties related to icing include *h*, τ and *LWP*. Recently, a new method was introduced to derive low-level cloud heights because of the difficulty in accurately representing boundary-layer inversions in numerical weather analyses. The new method (Heck et al., 2004) uses a fixed lapse rate that is anchored to the 24-hr running average surface temperature. This new approach minimizes the cloud-top altitude over-estimate that was common for low-level stratus clouds.

Aircraft icing potential depends on many factors, but generally requires supercooled liquid water (SLW), relatively large droplets, and relatively large concentrations of droplets or high liquid water content (LWC). Obviously, *Tc* can be used to discriminate SLW from warm clouds and the concentration of large droplets should be related to *re*. LWC ican be estimated as LWP/*h*. However, since both LWP and *h* depend on τ, only LWP is used here as a surrogate for LWC. Using matched VISST and in situ aircraft data, Smith et al. (2003) found some weak positive dependencies of icing intensity on LWP and *re*, and a weak negative dependency on *Tc*. Using those results as guidelines, a prototype icing classification system was developed to begin the refinement process to arrive at a reliable algorithm for converting real-time cloud properties to icing assessments. The preliminary algorithm is summarized in Table 1. When no clouds are present, no SLW is detectable, the cloud is relatively thin (LWP < 100 g m^{-2}), the retrieved cloud

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Table 1. Prototype icing classification criteria.

Value	criteria			icing intensity
0	clear or water cloud w/ Tc > 272 K or LWP < 100 gm^{-2} or ice cloud with τ < 8)			none
1	ice cloud with τ > 8			unknown
	re (μm)	LWP (gm^{-2})	Tc (K)	
2	> 11	> 100	< 272	low
3	> 11	> 200	< 272	mid
4	> 11	> 300	< 272	high
5	> 9	> 400	< 272	low
6	> 9	> 500	< 272	mid
7	> 11	> 300	< 253	high
8	> 9	> 400	< 253	high

is classified as optically thin ice, or the results do not satisfy any of the other criteria, then the algorithm returns a classification of no icing. If the cloud is determined to be an optically thick ice cloud, then it is assumed that the icing is unknown because the upper ice cloud may or may not hide a lower-level SLW cloud. The remaining classifications are various icing categories. These classes will be used until enough statistical data from PIREPS and field programs can be gathered to verify or to alter this classification system.

3. RESULTS

3.1 Continental United States (CONUS)

The cloud property and icing methodology is currently being applied in near-real time to GOES-10 data between 25°N and 50°N and 100°W and 130°W and to GOES-12 data between 25°N and 50°N from 65°W to 100°W. The results are derived separately and stitched together. Figure 1 shows an example of the CONUS results for GOES-10/12 imagery taken at 1915 UTC, 15 March 2004. The colder high clouds over the central and northwestern CONUS are classified as indeterminate or unknown because they are optically thick. The cirrus clouds over Arizona and New Mexico and Minnesota and Wisconsin are ignored and given the no icing classification. The low clouds over the southeastern CONUS are too warm to contain SLW. Icing is primarily diagnosed over western Washington, Nebraska, Missouri, Tennessee, North Carolina, North Dakota, Colorado, and eastern Canada. In the last area, the cloud deck is inhomogeneous so that the pixels diagnosed to contain icing conditions are scattered in space and in intensity. Some of the pixels, like those near the tail of

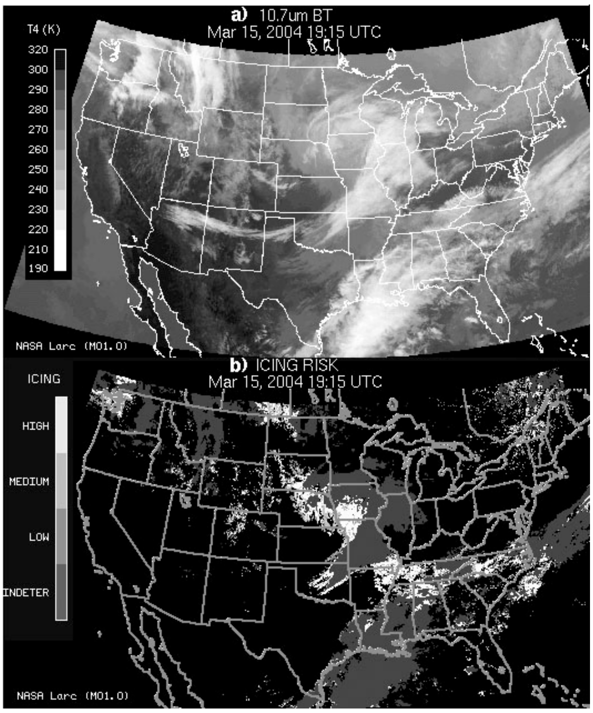

Fig. 1. Cloud and icing data for 1915 UTC, 15 March 2004. (a) Stitched GOES-10/12 infrared brightness temperature images. (b) Icing categories.

cirrus shield in Oklahoma, are probably misclassified because a thin cirrus over a low cloud can produce radiances similar to those from a SLW cloud. This confusion factor needs further scrutiny.

3.2 Field programs

The most important parameters for air safety are the horizontal locations of icing intensity and the range of altitudes where it is expected to occur. In these products, the cloud top and base altitudes are provided. The uncertainties in those altitudes are being determined through various validation studies. In early studies, Smith et al. (2000) verified that, when overlying cirrus clouds were absent, the VISST retrieved SLW in 98% of the PIREPS reports of positive icing.

Since then the VISST cloud products have been used to support both formal and informal field projects designed to study icing using in situ and ground-based instrumentation. In turn, the measurements yield valuable validation data for the remote sensing products. The VISST SLW identification was further validated with comparisons to cloud top penetrations by NASA Glenn Research Center's Twin Otter (hereafter, NGTO; see Smith et al., 2002). Later NGTO flights during 2003 successfully used the VISST results in real time to guide them to areas of icing confirming the general relationships used to establish the icing criteria. Microphysical data from NGTO flights have become available, facilitating objective assessment of the satellite observations.

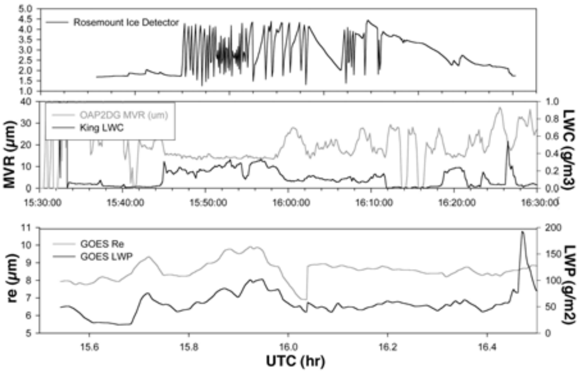

Fig. 3. Comparison of NGTO in situ and GOES-8 VISST data over Lake Erie, 5 March 1998, 1530 –1630 UTC.

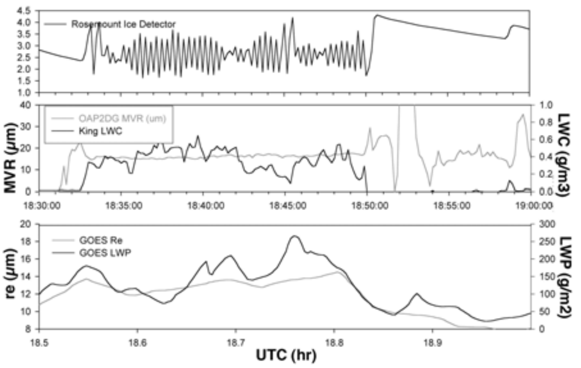

Fig. 4. Same as Fig. 3, except for 1830 –1900 UTC.

Figures 3 and 4 show closely matched NGTO and VISST parameters measured over northern Ohio and Lake Erie by NGTO flights during 5 March 1998. The top panel in each figure is a plot of the Rosemont ice detector signal. It indicates ice accumulation when the response varies rapidly. Thus, icing occurs between 1546 and 1602 UTC (Fig. 3) and between 1832 and 1850 UTC (Fig. 4). The mean volume droplet radius (MVR) ranges between 16 and 22 µm during the first episode while LWC varies from 0.2 to 0.3 gm^{-2}. The corresponding range in r_e is 8.5 – 10 µm and LWP rises from 50 to 100 gm^{-2}. The later flight (Fig. 4) produces much clearer correspondence between the satellite and NGTO data. During the icing event, the MVR is steady at 18 µm while r_e ranges from 12 to 14 µm. The LWP and LWC values are elevated above 100 gm^{-2} and 0.3 gm^{-3}, respectively. The largest values of LWP appear to be coincident with the lower amplitude variations during each icing episode. The satellite data during both events are at or just below the icing threshold levels in Table 1 suggesting that the LWP and r_e thresholds should be reduced.

More recently, data were taken at Montreal from the surface while aircraft flew over the site and over other areas in southern Canada as part of the second Alliance Icing Research Study (AIRS-II) and the Atlantic THORpex Regional Campaign (ATReC) during November and December 2003. The VISST products were generated throughout the experiment

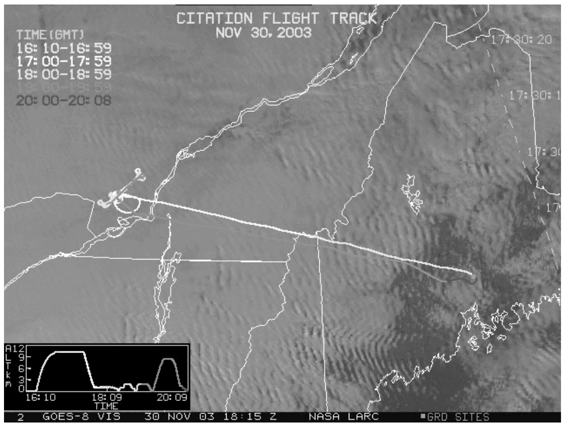

Fig. 5. Flight track of University of North Dakota Citation during icing flight, 1800 UTC, 30 November 2003.

using GOES-12, NOAA-16 Advanced Very High Resolution Radiometer (AVHRR), and *Terra* and *Aqua* Moderate Resolution Imaging Spectraradiometer (MODIS) data to provide a variety of views and resolutions to better understand the retrievals, provide support for the experiments, and validate the remote sensing methodologies. The various datasets are unprecedented for studying icing conditions.

An example of one of the icing flights is shown in Fig. 5 for 30 November 2003 when the University of North Dakota Citation flew from Bangor, Maine to the Montreal site. It performed several spirals through the clouds, reporting two decks with one top at 2.2 km and the other at 1.2 km. The 0.3-km-thick upper layer was producing light-to-moderate rime ice and had greater LWC and larger MVR than the lower cloud. The satellite retrievals from GOES-10 (Fig. 6) show clouds between 2 and 4 km in the vicinity of Montreal around 1800 UTC when the Citation was passing over the site. These altitudes are around 1 km higher than the reported cloud tops and are near the uncertainty limit of the VISST retrievals (Heck et al., 2004). Multiple inversions in many of these cases exacerbate estima-

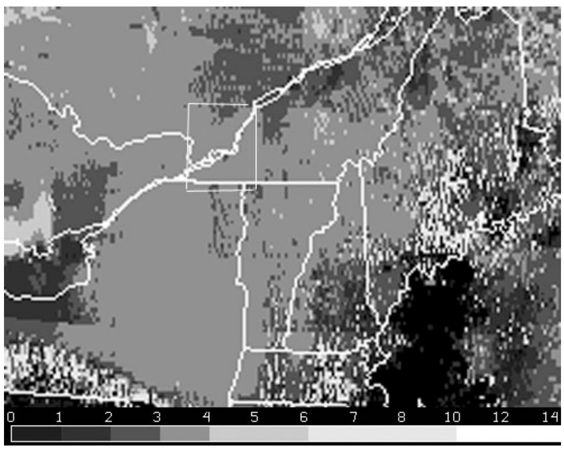

Fig. 6. Cloud-top altitude in km from VISST at 1800 UTC, 30 November 2003. Box encompasses aircraft in situ flight tracks.

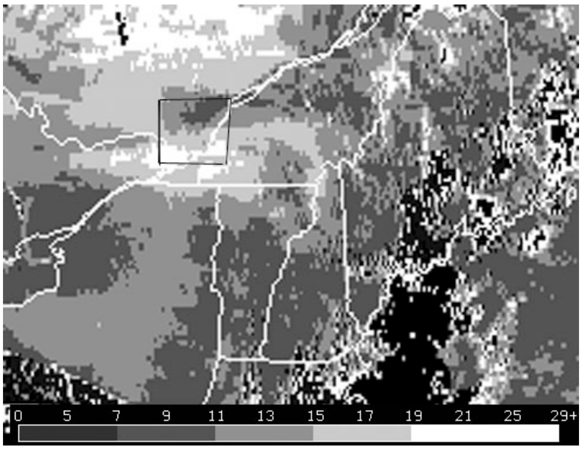

Fig. 7. Same as Fig. 6, except for r_e in µm.

tion of cloud height from *Tc*. Despite the height errors, the VISST retrieved larger droplets (Fig. 7) for the higher cloud compared to values of r_e < 11 µm for the lower cloud, a result consistent with the initial reports from the Citation. The classification algorithm yields moderate to heavy icing for the upper clouds and light to moderate icing for the lower clouds within the vicinity of the site. Most of the area within the domain in Fig. 7 was diagnosed with moderate to heavy icing mainly because of very high values of LWP.

4. CONCLUDING REMARKS

A prototype, physically based method for real time detection of icing conditions has been developed and implemented over the continental United States and southern Canada. The results, currently available on the World Wide Web at http://www-pm.larc.nasa.gov/icing/icing.html, are just one part of a comprehensive aircraft icing program being developed by NASA, NOAA, and the FAA. Ultimately, the results will be combined with PIREPS, model forecasts, and other data to provide a near-real time optimized characterization of icing conditions for pilots and flight controllers.

The methodology is promising, but more refinements are needed to address the uncertainties and outstanding issues. The most glaring problems include the determination of more reliable thresholds, more objective definitions of intensity, mulitlayer misclassifications, height errors, and nocturnal retrievals. Many of these will be addressed using the available in situ and surface datasets to define the "cloud truth" conditions objectively and adjusting the algorithms using the relevant sounding and satellite data. The results presented here are just the beginning of efforts to exploit the valuable datasets from field programs like ATReC and AIRS-II.

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