

Characterization of Satellite-derived Cloud Products for Application in an Aircraft Icing Prediction System

Julie Haggerty, Scott Landolt, Cory Wolff,
Jennifer Simard, Ben Bernstein
National Center for Atmospheric Research
Boulder, Colorado USA
haggerty@ucar.edu

Patrick Minnis
NASA Langley Research Center
Hampton, Virginia USA

Abstract— Cloud properties as derived from the Geostationary Operational Environmental Satellite (GOES) Imager are evaluated for their ability to detect supercooled liquid clouds that may produce aircraft icing. Assessment methods include point comparisons with in situ measurements and statistical characterization of image uniformity and gradients. Results are consistent with anecdotal evidence that suggests satellite-derived liquid water path and hydrometeor phase are useful for this application.

Keywords—aircraft icing; clouds; remote sensing applications

I. INTRODUCTION

The presence of supercooled liquid drops within a cloud can be hazardous to aircraft operations. In-flight icing may result in loss of lift, reduced airspeed, and, in some cases, loss of control. Research efforts related to in-flight icing have elucidated the meteorological conditions associated with icing events and provide the foundation for icing diagnosis and forecasting techniques. Such techniques rely on a variety of data sources including radar, satellite, and surface observations as well as model predictions to determine probable times and locations of icing conditions. 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 in clouds. Specifically, the NCAR Current Icing Potential (CIP) system combines basic satellite-derived information with multiple other data sources to produce a gridded, three-dimensional, hourly depiction of icing potential and severity [1][2]. Advanced satellite-derived cloud products developed at the NASA Langley Research Center (LaRC) provide a near real time description of cloud micro- and macro-physical properties [3]. Integration of the LaRC cloud products into the CIP system may enhance icing detection in some situations. In support of the integration effort, assessment of satellite product accuracy in various conditions is required to develop methods for optimal use of the products.

Cloud droplet phase (liquid or ice), liquid water path (LWP), and droplet effective radius (R_e) are related to aircraft icing potential [4]. Hence these variables, as estimated over the continental United States by the LaRC algorithms, have the

potential to improve CIP system results. Anecdotal evidence provided by the use of LaRC cloud products as a nowcasting and short-term forecasting tool during icing research 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. Wolff et al. provide examples where the LWP field was used to identify regions with relatively larger supercooled liquid water contents during icing research field programs [5].

In this paper, we begin with forecasters' anecdotal conclusions about the value of the LaRC products for locating areas of probable icing conditions. We translate their qualitative guidance into hypotheses that can be verified statistically and demonstrate methods for testing the hypotheses. The LaRC satellite products are described in Section II, and the data sets used for evaluation of the satellite products are reviewed in Section III. Preliminary results from various data comparisons are presented in Section IV.

II. SATELLITE DERIVED 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 [1] [6].

The LaRC system first classifies each 4-km GOES pixel as clear or cloudy using a complex cloud identification scheme [7]. 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 of the

This work is sponsored by the NASA Advanced Satellite Aviation-weather Products (ASAP) project

LaRC LWP product over the northeastern United States is shown in Figure 1.

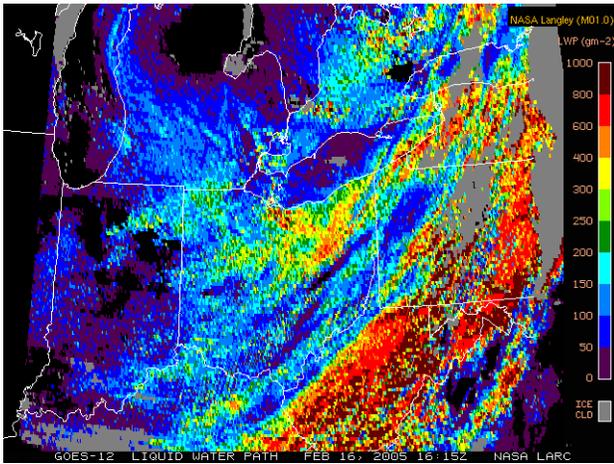


Figure 1. Liquid water path at 1615 UTC on 16 February 2005 as derived from GOES-12 imagery using the Visible Infrared Solar-infrared Split window Technique (VISST).

III. DATA SETS USED FOR EVALUATION

A data set over the Great Lakes region from the winters of 2003-2005, including satellite products, research aircraft data, and surface-based observations has been assembled for evaluating LaRC products in icing conditions. The Alliance Icing Research Study (AIRS-II) based in Montreal, Canada during November 2003 through February 2004 fielded aircraft that collected in situ measurements of cloud macro- and microphysical properties [8]. Surface-based microwave radiometer measurements and radiosonde observations near Montreal also provide data for comparison with satellite products. A second data source is the annual winter icing research flight program conducted by the NASA Glenn Research Center's Twin Otter aircraft. Twin Otter flights in the Cleveland, Ohio region target icing conditions and provide numerous in situ cloud measurements useful for comparison with satellite products [9].

IV. PRODUCT EVALUATION

Evaluation of the NASA LaRC satellite-derived cloud products for application to supercooled liquid water detection began during icing research field campaigns in the 2003-2005 winter seasons. Forecasters employed the satellite products as one source of information for locating regions of probable icing in order to direct research aircraft to those areas [10]. The satellite products were found to be useful for refining the diagnosis of supercooled liquid water, especially near cloud top. Based on their experiences, forecasters developed "rules of thumb" for using the satellite fields effectively. For example, cases with spatially uniform values of cloud hydrometeor phase, liquid water path (LWP), and/or effective radius (R_e) over large areas are usually more reliable than cases with high spatial variability. Gradients in LWP are often found to be qualitatively accurate. Sharp transitions in values are sometimes problematic. Phase determinations are typically

reliable, and high R_e estimates tend to correlate positively with in situ observations of larger drops. Cloud top heights are often over-estimated. These qualitative observations provide direction for more systematic evaluation of the products and for developing logic to integrate the products into the CIP algorithm.

A. Point Comparisons

Numerous comparisons between satellite- and aircraft-estimated cloud phase, liquid water, and cloud heights have been made in this and previous studies for cases where supercooled liquid water was observed during flights (e.g., [11][12][13]). Results show that cloud phase estimates are generally accurate. Data from AIRS-II and NASA Twin Otter flights showed that, of 19 cases where the aircraft penetrated cloud top, satellite-derived phase agreed with aircraft observations in 13 cases. Most of the other cases are explained by the fact that the aircraft did not penetrate an upper level cirrus layer observed by the satellite sensor. Comparisons with both aircraft and radiosonde observations of cloud top height show that the LaRC cloud top height product often overestimates, largely due to the presence of cirrus clouds above the radiosonde profile. The mean radiosonde-derived cloud top height at Montreal during AIRS-II was 3901 m, while the corresponding mean satellite-derived cloud top height was 5023 m. When situations with cirrus clouds are removed, the agreement is much better. Mean cloud top height from radiosonde is 3554 m compared to 3036 m from satellite with a RMS error of 306 m. Liquid water path estimates have previously been shown to compare well with ground-based microwave radiometer retrievals of LWP, particularly at LWP values below about 400 g m^{-2} [14], and this data set is consistent with previous findings. Analysis of the LaRC LWP product and LWP from a ground-based microwave radiometer in AIRS-II gave mean LWP of 263 g m^{-2} and 216 g m^{-2} , respectively.

B. Characterization of Spatial Uniformity

Observations by forecasters suggest that spatially uniform fields convey more reliable information than fields with high spatial variability. This finding is assessed by quantifying the smoothness of each field of interest. A texture parameter is used as a measure of spatial variability for this purpose. Texture is defined as:

$$T_{\text{var}} = \frac{\left(\sum_{j=1}^n \sum_{j=1}^m (\text{var}(i, j) - \text{var}(i-1, j))^2 \right)}{nm}$$

where "var" represents any of the satellite derived variables considered here, and n and m are the number of pixels in each dimension of the domain [15]. Local texture of the satellite-derived phase and LWP products is calculated over an area of 10×10 pixels (160 km^2) centered at each pixel. Figure 2 is a sample phase image from 11 November 2003. In the location where a research aircraft penetrated cloud top, the aircraft observed ice phase cloud particles and the satellite technique indicated liquid phase. Preliminary estimates of texture in this area are relatively high, corresponding with the spatial variability seen in Figure 2. A second case on 30 November

shows significantly lower texture values than in the first case. At the location of the aircraft cloud top penetration on this date, both aircraft measurements and satellite estimates indicated liquid phase.

These preliminary examples demonstrate the method being used to compile statistics on image texture versus product accuracy. The method will be applied to LWP images as well as phase.

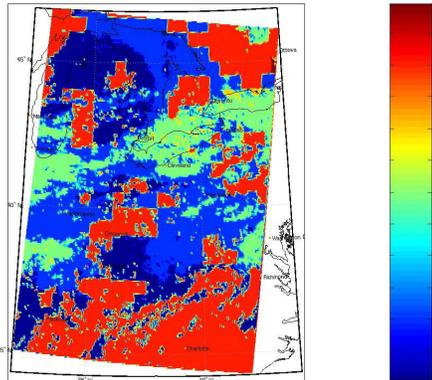


Figure 2. Cloud top phase on 11 November 2003 at 2045 UTC. Red areas represent ice clouds, blue represents liquid, and green represents clear skies.

C. Gradients in Satellite Products

Gradients in satellite-derived fields tend to be qualitatively accurate, according to forecasters who have used the LaRC products for detection of icing conditions. This conclusion is tested by comparing variation along straight and level flight segments with corresponding variables derived from satellite data. Straight and level flight segments are identified by examining variations in heading and altitude. Airborne measurements along these segments are averaged over 4 km for comparison with satellite pixels of similar scale. Direct comparisons between variables measured by the aircraft and derived from satellite radiances are not always possible, since the same variables are not available from both. For example, aircraft instruments measure mean volume diameter (MVD) of cloud droplets, while the LaRC algorithms produce an effective radius (R_e) product to characterize droplet size. Similarly, aircraft sensors provide an in situ measure of supercooled liquid water (SLW) content, while the satellite product gives a vertically integrated liquid water path (LWP). Thus we cannot compare these measurements directly in their current form, but we can compare gradients along the flight tracks.

A sample comparison showing variation along a flight track of the NASA Twin Otter on 16 February 2005 is given in Figure 3. The red line shows satellite-derived hydrometeor phase; a constant value of 1 indicates liquid droplets exclusively in this case. Other satellite-derived variables shown are LWP (solid blue line), and R_e (solid green line). Corresponding aircraft measurements are SLW (dashed blue line) and MVD (dashed green line). Variables are scaled by an

arbitrary factor to simplify comparison. Over the length of this straight and level segment (9 minutes or 32 km), we see a consistent increase in both the aircraft and satellite-derived liquid water variables. The particle size variables also show a slight increase over the length of the flight segment. A second example is shown in Figure 4. Here, the gradients in liquid water and droplet size measurements are not consistent over the length of the flight segment. A probable explanation for the differing results is that the aircraft was flying near cloud top in the first case, but was significantly below cloud top in the second case. Because the LaRC algorithms rely on visible and infrared radiances, the products are most representative of conditions near cloud top. Given the possible vertical variations in liquid water and droplet size through the cloud layer, the conditions encountered by the aircraft in the second case may be significantly different than those at cloud top.

Using this method, we are analyzing all available research aircraft data to compile statistics on the accuracy of spatial gradients in the LaRC LWP, R_e , and phase products. Flight segments near cloud top and within cloud will be separated for the analysis.

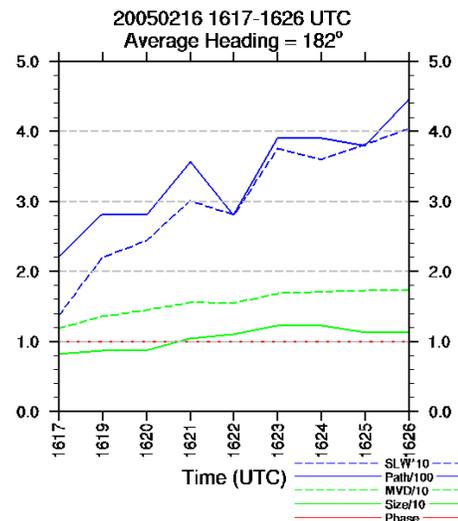


Figure 3. Trends in aircraft and satellite-derived variables over a straight and level flight segment in northern Ohio on 16 February 2005. Supercooled liquid from aircraft sensors (dashed blue line) is compared to liquid water path derived from satellite sensors (solid blue line). Mean volume diameter from the aircraft (dashed green line) is compared to effective radius derived from satellite sensors (solid green line). Phase as derived from the satellite algorithms has a constant value of one, indicating liquid (red line).

REFERENCES

- [1] Bernstein, B., F. McDonough, M. Politovich, B. Brown, T. Ratvasky, D. Miller, C. Wolff, and G. Cuning, 2005: Current Icing Potential (CIP): Algorithm description and comparison with aircraft observations. *J. Appl. Meteorol.*, 44, 969-986.
- [2] Bernstein, B.C., F. McDonough, C.A. Wolff, M.K. Politovich, G. Cuning, S. Mueller and S. Zednik, 2006: The new CIP icing severity product. 12th Conf. on Aviation, Range and Aerospace Meteorology, Atlanta GA, 29 Jan - 2 Feb, Amer. Meteor. Soc., Boston. Preprint available on CD-rom.
- [3] Minnis, P., L. Nguyen, R. Palikonda, P. Heck, Q. Trepte, D. Phan, M. Khaiyer, W. Smith, Jr., J. Murray, M. Haeffelin, 2005: Near real-time satellite cloud products for nowcasting applications. WWRP Symposium on Nowcasting and Very Short Range Forecasting, Toulouse, France, 5-9 September.
- [4] McDonough, F. and B. Bernstein, 1999: Combining satellite, radar and surface observations with model data to create a better aircraft icing diagnosis. Proc. AMS 8th Conference on Aviation, Range and Aerospace Meteorology, Dallas, Texas, USA, 10-15 January, 467-471.
- [5] Wolff, C., B. Bernstein, and F. McDonough, 2005: Nowcasting aircraft icing conditions using GOES-derived satellite products. WWRP Symposium on Nowcasting and Very Short Range Forecasting, Toulouse, France, 5-9 September.
- [6] Minnis, P., D. Garber, D. Young, R. Arduini, and Y. Takano, 1998: Parameterization of reflectance and effective emittance for satellite remote sensing of cloud properties. *J. Atmos. Sci.*, 55, 3313-3339.
- [7] Trepte, Q., Y. Chen, S. Sun-Mack, P. Minnis, D. Young, B. Baum, and P. Heck, 1999: Scene identification for the CERES cloud analysis subsystem. Proc. AMS 10th Conf. Atmos. Rad., Madison, WI, 28 June - 2 July, 169-172.
- [8] Isaac, G. et al., 2005: First results from the Alliance Icing Research Study II. Proc. 43rd AIAA Aerospace Sciences Meeting, Reno, Nevada, USA, 11-13 January.
- [9] Miller, D., T. Ratvasky, B. Bernstein, F. McDonough, and J.W. Strapp, 1998: NASA/FAA/NCAR supercooled large droplet icing flight research: summary of winter 96-97 flight operations. Proc. 36th AIAA Aerospace Science Meeting and Exhibit, Reno, Nevada, USA.
- [10] Bernstein, B.C., C.A. Wolff and P. Minnis, 2006: Practical application of NASA-Langley Advanced Satellite Products to in-flight icing nowcasts. AIAA-2006-XXXX. 44th Aerospace Science Meeting and Exhibit, Reno, NV, 9-12 January. American Institute of Aeronautics and Astronautics, Washington, D.C., 20pp.
- [11] Politovich, M., P. Minnis, D. Johnson, C. Wolff, M. Chapman, P. Heck, and J. Haggerty, 2004: Benchmarking in-flight icing detection products for future upgrades. Proc. AMS 11th Conference on Aviation, Range, and Aerospace Meteorology, Hyannis, Massachusetts, USA, 4-8 October.
- [12] Nguyen, L., P. Minnis, D. Spangenberg, M. Nordeen, R. Palikonda, M. Khaiyer, I. Gultepe, and A. Reehorst, 2004. Comparison of satellite and aircraft measurements of cloud microphysical properties in icing conditions during ATREC/AIRS-II. 11th Conference on Aviation, Range and Aerospace Meteorology, Hyannis MA, 11-14 October, Amer. Meteor. Soc., Boston. Available on CD from the AMS.
- [13] Smith, W.L., Jr., P. Minnis, B. Bernstein, F. McDonough, and M. Khaiyer, 2002: Comparison of super-cooled liquid water cloud properties derived from satellite and aircraft measurements. 10th Conference on Aviation, Range and Aerospace Meteorology, Portland, OR, 13-16 May.
- [14] Khaiyer, M., P. Minnis, B. Lin, W. Smith, Jr. and A. Rapp, 2003: Validation of satellite-derived liquid water paths using ARM SGP microwave radiometers. Proc. 13th ARM Science Team Meeting, Broomfield, CO, March 31 - April 4.
- [15] Kessinger, C., S. Ellis, and J. Van Andel, 2003: The radar echo classifier: A fuzzy logic algorithm for the WSR-88D. Preprints, 3rd Conference on Artificial Applications to the Environmental Science, Amer. Meteorol. Soc., 9-13 February 2003, Long Beach, CA.

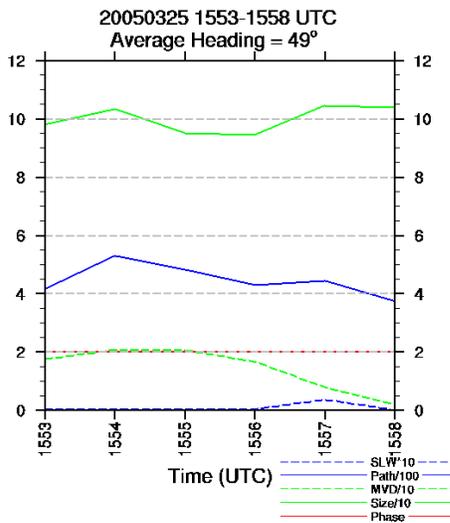


Figure 4. As in Figure 2, except for 25 March 2005.

V. DISCUSSION

Point comparisons between the satellite products of interest and coincident aircraft and ground-based measurements conducted thus far confirm anecdotal guidance we received from forecasters. Phase estimates from the satellite algorithms appear to be reliable and cloud top height estimates often disagree with radiosonde and aircraft measurements due to the presence of cirrus clouds. LWP estimates are consistent with available surface-based measurements.

A method for quantifying the spatial variability of a satellite-derived field using a texture parameter has been demonstrated. Compilation of statistics to understand the relationship between texture and accuracy is ongoing. Spatial gradients in satellite-derived fields are also being examined using in situ data from straight and level aircraft segments.

Synthesis of these results will provide a better understanding of the uncertainties inherent in the satellite cloud products under a variety of relevant meteorological conditions. Using this information, the value of satellite-derived phase, LWP, R_c , and cloud top height for detection of potential icing conditions can be objectively estimated. These findings provide guidance for developing methods to combine this new data source with other CIP input data.

ACKNOWLEDGMENT

This project is supported by the NASA Applied Sciences Program and the NASA Aviation Safety and Security Program through the NASA Advanced Satellite Aviation-weather Products (ASAP) project. NCAR is sponsored by the National Science Foundation.