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NOWCASTING AIRCRAFT ICING CONDITIONS USING GOES-DERIVED SATELLITE PRODUCTS

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1. BACKGROUND

Researchers at the NASA Glenn Research Center (GRC) in Cleveland, Ohio have been flying an instrumented DeHavilland Twin Otter into known icing conditions for many years. The data they gather are used by meteorologists to study the atmospheric conditions associated with icing and by aeronautical engineers to develop algorithms to predict ice shapes and their effects on aircraft performance (Miller et al. 1998). Since the winter of 1996-97, meteorologists at the National Center for Atmospheric Research (NCAR) have provided forecasts and nowcasts of icing conditions to the flight engineers and pilots who control these missions. The forecasts, which cover the 1 to 36-h time frame, are first used to determine whether or not icing conditions are likely to be present within the aircraft's range and below the aircraft's ceiling (4600 m). If so, the forecast is used to aid in planning the route and time to fly so that the heaviest icing conditions can be sampled. Nowcasts are provided to the crew during the flight to help direct the aircraft into and maintain exposure to the desired icing conditions (large supercooled liquid water contents [SLWC] and/or supercooled large drops [SLD]). An example of this process will be presented here.

2. NOWCASTING TOOLS

By combining information from a variety of sources a forecaster can infer where the best icing conditions are in space and time and suggest flight locations accordingly.

Basic satellite fields can help the forecasters find areas where supercooled liquid water (SLW) is more likely. For example, sending the plane toward a pocket of subfreezing clouds with relatively warm tops (typically > -13 °C) and relatively high albedo has often resulted in an increase in measured SLWC at cloud top.

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Radar data are used in different ways depending on the situation. For most warm topped clouds the best icing conditions can often be found in areas that are free of radar echoes or in gaps between echoes exceeding ~15 dBZ. Areas with reflectivity above ~15 dBZ in winter clouds are more likely to be dominated by ice crystals, which tend to be associated with low SLWC.

Surface observations of cloud cover and precipitation type can also be very useful. Even a slight lowering (raising) of cloud base can increase (decrease) the SLWC in a moist adiabatic cloud layer. Also, a change in precipitation type may signal an increase or decrease in the expected SLWC for a certain area. For example, if cloud properties remained mostly unchanged, a change from snow to a lack of precipitation at a station could signify that ice crystal production has decreased, allowing more SLW to survive in the cloud.

Other aircraft in the area can provide information on the presence or absence of icing and an indication of its severity through pilot reports (PIREPs). A PIREP of moderate icing in an area that the forecaster is considering directing the aircraft into can increase the confidence that the desired conditions will be found there. Likewise, a negative or trace icing report will decrease the forecaster's confidence in finding icing there.

Recently, NCAR icing forecasters were provided with new satellite tools to aid in both the flight planning and directing of the aircraft in flight. These GOES-derived cloud products were developed by researchers at the NASA Langley Research Center (LaRC). They combine information from basic satellite fields with model data to derive additional information about the microphysical properties of the cloud (Minnis et al. 1995, 2004a, 2004b). The products of most interest to the forecasters are cloud phase, liquid water path, and effective radius. These products have proven to be useful in refining the diagnoses of SLWC, especially near cloud top. A case study showing the use of these products in conjunction with other tools before and during a NASA GRC

Twin Otter icing flight will be presented in the next section.

3. EXAMPLE CASE

On February 16, 2005 the Twin Otter sampled a single layer icing cloud near Cleveland, Ohio. This encounter provided the researchers with light to moderate icing on two separate occasions. The GOES-derived cloud products were a key contributor in helping to get the aircraft into these conditions.

3.1 Setup

Early in the morning, clouds were present over most of Ohio, Michigan, and Indiana. Some of the clouds had fairly cold cloud top temperatures (CTT) near -30 °C, and the radar showed that a large area of precipitation was present (Fig. 1). These features were associated with a cold front that had passed by overnight. All surface stations beneath the cold cloud tops were reporting snow or rain. Since these clouds were likely to be dominated by ice crystals (possibly mixed with some SLW) they were not of interest to the GRC researchers.

In the wake of the cold-topped, precipitating clouds was a non-precipitating stratocumulus cloud layer that was more likely to be dominated by SLW, rather than ice crystals. Cold advection behind the 850 mb front was producing boundary layer capped convection. In the past these types of clouds have provided the GRC researchers with icing cases of moderate to high values of SLWC and mostly small drops, depending on the layer depth (Bernstein et al. 2004). The 1200 UTC sounding from Detroit, MI (DTX; Fig. 2) showed a somewhat shallow stratocumulus cloud layer from 900 mb to 860 mb with a CTT of -8 °C, as well as some of the higher, -30 °C clouds. There were some PIREPs of light to moderate icing over southeast Michigan in the lowest layer around this time.

The GOES-derived satellite products could not be used to aid in the forecast during the early morning hours because they require good illumination by sunlight. On this day, the products became useful using satellite data from 1415 UTC. Images of the derived products were typically available to forecasters ~20 minutes after their valid time. At the daily briefing (1200 UTC) standard weather data were used to determine the approach of promising icing conditions. It was decided that the Twin Otter would delay takeoff until the non-precipitating, warm-topped clouds were just upstream of Cleveland, allowing for more time to sample the more promising icing conditions close to the aircraft base.

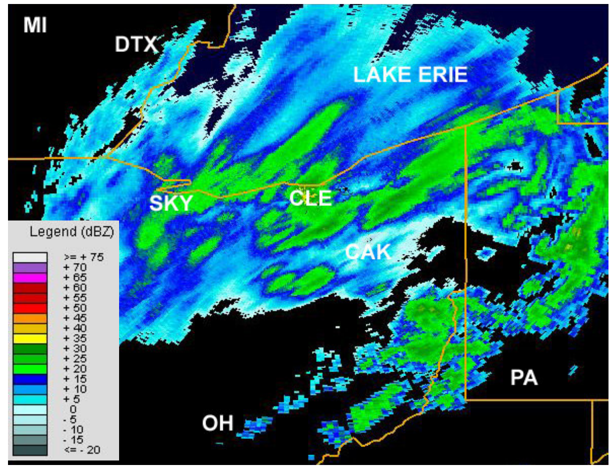

Figure 1. Radar reflectivity image from CLE at 1204 UTC on February 16, 2005.

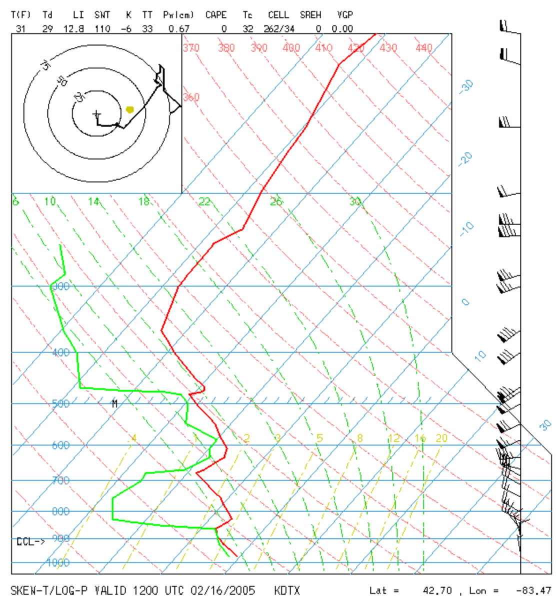

Figure 2. 1200 UTC sounding from Detroit (KDTX) on February 16, 2005 showing an icing cloud between 900 and 860 mb.

3.2 Preflight

At 1400 UTC the trailing edge of the precipitation was nearing Cleveland (CLE) from the west. PIREPs of moderate icing were still being made within the cloud layer in southeast Michigan. It was decided that the Twin Otter would fly west toward Sandusky (SKY) and sample the stratocumulus cloud that was

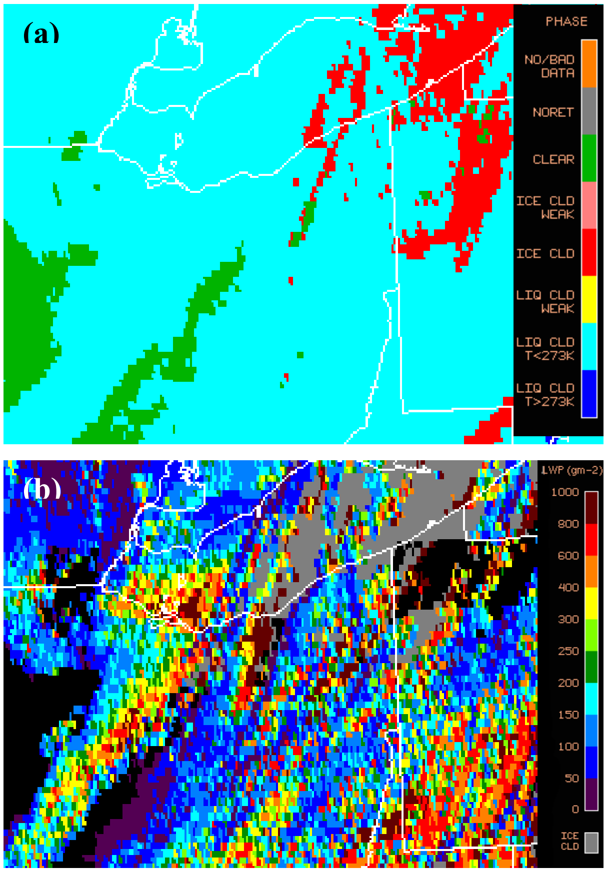

Figure 3. NASA Langley GOES-derived cloud products showing (a) cloud phase and (b) liquid water path over the Ohio domain for 1415 UTC on February 16, 2005.

producing icing as it approached CLE from the northwest.

While the crew prepared for take off, the first daytime images from the GOES-derived products became available. Almost all of the clouds across the region were diagnosed to have supercooled liquid at their tops (light blue; Fig. 3a). There were some ice clouds (red) over portions of Lake Erie and northwestern Pennsylvania, matching the cooler tops of the upper cloud shield (Fig. 4b). The area covered by the ice clouds differs from the area covered by the radar echo and snow reports at the surface (Fig. 5), which means that some snow was falling out of clouds that were diagnosed to contain SLW at the tops. This is not uncommon, and is often an indication of mixed phase conditions. Of particular interest to the forecaster was the liquid water path (LWP) product (Fig. 3b). This product provides an integrated liquid water path through the cloud and, in practice, has been found to relate to the liquid water content that may be expected near cloud

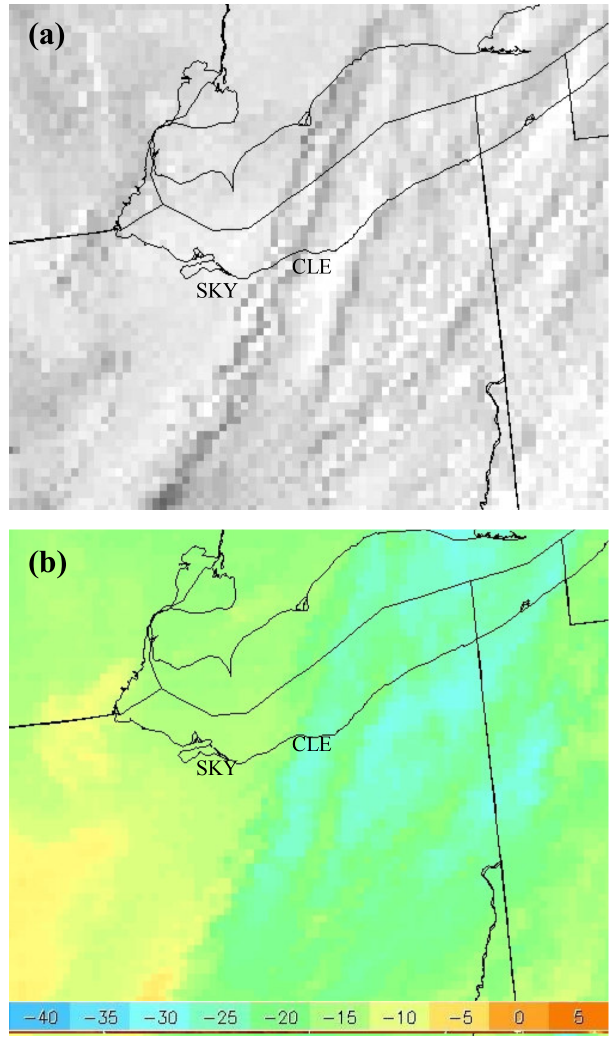

Figure 4. (a) Visible and (b) infrared satellite images from February 16, 2005 at 1415 UTC. Temperatures are in Celsius. The icing cloud is near SKY with a CTT of -10 to -15 °C.

top. At 1415 UTC there was a maximum in LWP evident near SKY, along the Lake Erie coast. The forecaster decided to suggest that the Twin Otter sample the clouds in that area. Comparing the LWP image to the visible and infrared images from the same time (Fig. 4) shows the added value of the extra details provided by the GOES-derived products. Clouds with warm tops and relatively high albedo, like those around SKY, have produced good icing encounters (high SLWC) for the researchers in the past. In this case high LWP values were also associated with these conditions, giving the forecaster extra confidence in the prognosis.

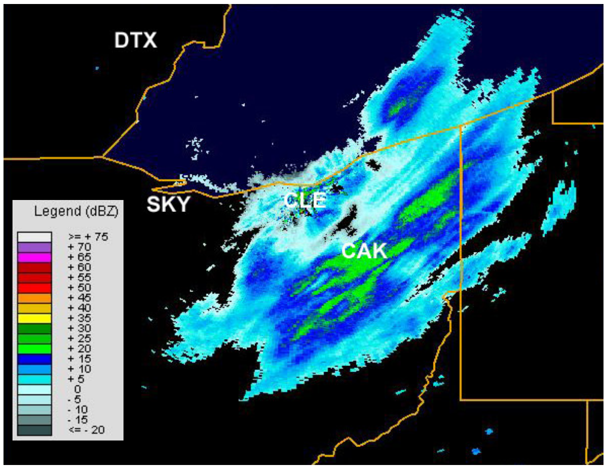

Figure 5. Radar reflectivity image from CLE at 1411 UTC on February 16, 2005.

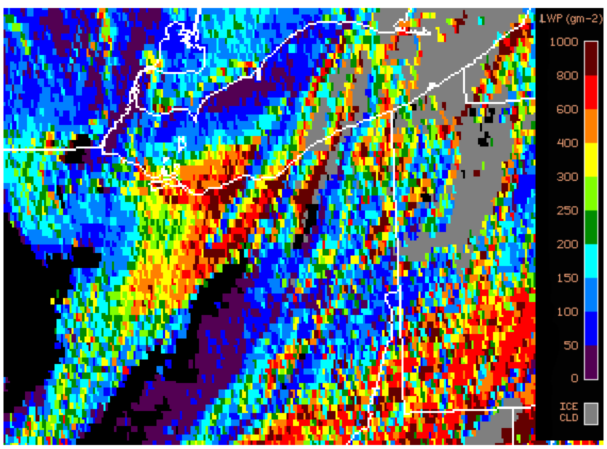

Figure 6. Liquid water path product for 1445 UTC on February 16, 2005.

3.3 Flight Observations

The Twin Otter took off at 1509 UTC. During the flight the crew is in constant contact with the forecaster via a satellite telephone. This allows the crew to provide feedback to the forecaster about the conditions being encountered and the forecaster to suggest changes in flight track or altitude to keep the plane in the desired icing conditions. Since the LWP max was still evident at 1445 UTC (Fig. 6) the flight crew was notified of its presence, and they decided to remain on their original course and sample it.

The first icing encounter lasted from 1509 UTC to 1542 UTC (Fig. 7). SLWC of 0.2 to 0.4 g/m^3 with some peaks of 0.5 g/m^3 (Fig. 8) was

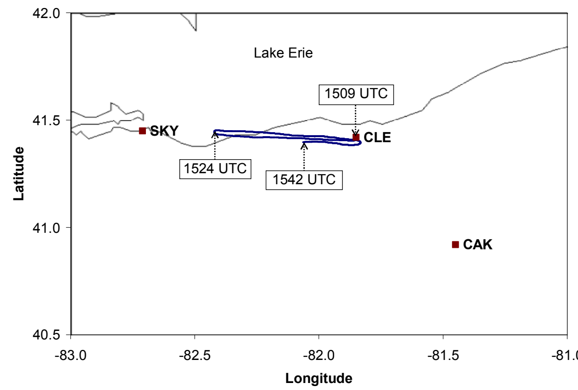

Figure 7. Track of the Twin Otter during the first icing encounter. Arrows mark the starting (1509 UTC) and ending (1542 UTC) points of the encounter.

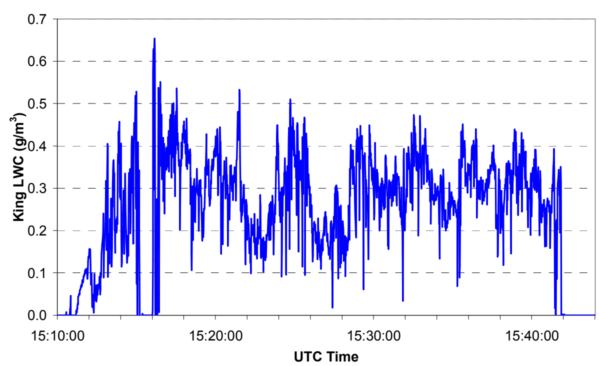

Figure 8. Trace of SLWC from the King probe during the first icing encounter.

found near cloud top (1650 m) at a temperature of -8 °C.

The SLWC decreased to around 0.2 g/m^3 as they flew westward across the shoreline, beyond the LWP maximum (see Fig. 9). They turned back toward the east at 1524 UTC, reentering the northwest portion of the LWP maximum. SLWC values recovered to 0.25 to 0.4 g/m^3. As expected, only small drops were observed within this boundary-layer-rooted, capped convection cloud. The median volumetric diameter (MVD) from the forward scattering spectrometer probe (FSSP) was ~15 μm for this portion of the flight. This correlates well with the effective radius (REFF) product (Fig. 10), which diagnosed mostly small particles (11 to 15 μm) along the track of the first encounter. After calling in a PIREP of light to moderate icing the Twin Otter performed some tests above cloud top (between 1800 and 2100 m) while flying westward to SKY. Following the tests, they deiced the aircraft and descended back into the cloud tops at 1553 UTC to begin a second ice accretion.

While the aircraft performed its tests the latest products available to the forecaster (1515 UTC; Fig. 9) indicated that the LWP maximum had shifted to the south of CLE, so it was suggested that the Twin Otter go in that direction. Icing conditions were encountered again upon reentering cloud top at 1553 UTC. Though the clouds were found at the same altitude and temperature as the first encounter, the SLWC was only 0.1 g/m^3 near SKY (Figs. 11 and 12). The SLWC increased slowly as the aircraft flew to the southeast. However, the SLWC, while rising steadily, was not as high as the first encounter, so the crew requested a new flight track. The forecaster suggested a turn to the northeast (perpendicular to the flow) to attempt to get back into higher SLWC by allowing the better conditions to catch up to the aircraft. Once they turned in this direction (at 1609 UTC) the SLWC increased again (to near 0.3 g/m^3). As the Twin Otter approached Lake Erie the SLWC decreased dramatically, matching the LWP gradient shown near the shoreline (Fig. 13). The aircraft was then turned southward, back toward the LWP maximum, at 1617 UTC. After this turn the SLWC values increased and the Twin Otter was able to remain in SLWC > 0.3 g/m^3 for the remainder of the encounter. Upon returning the CLE to land, the aircraft had to again enter clouds with relatively low LWP diagnosed. Correspondingly low SLWC was observed by the Twin Otter (not shown).

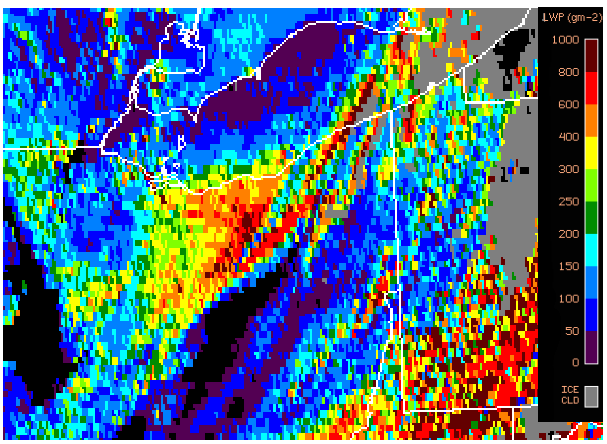

Figure 9. Liquid water path product for 1515 UTC on February 16, 2005.

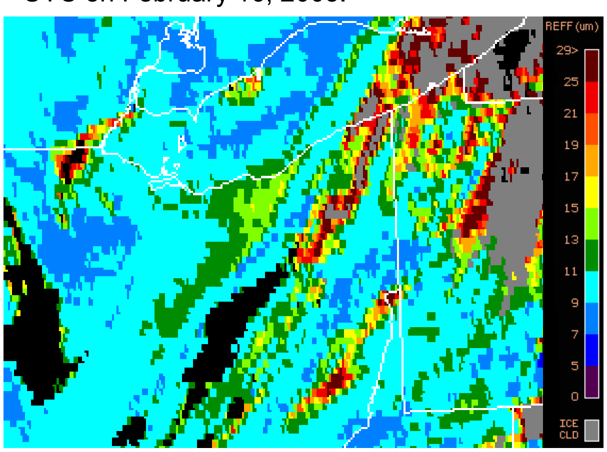

Figure 10. Effective radius (µm) for liquid diagnosed clouds on February 16, 2005 at 1515 UTC.

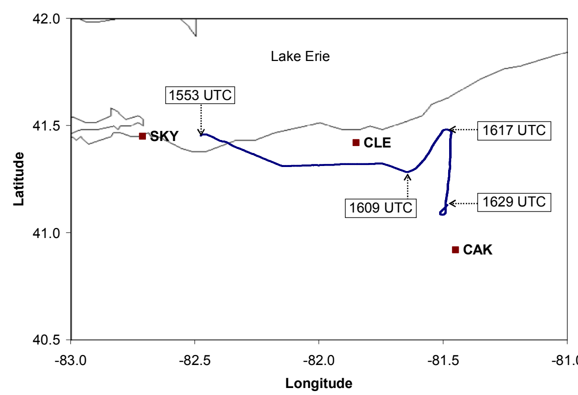

Figure 11. As in Fig. 7, but for the second icing encounter from 1553 UTC to 1629 UTC.

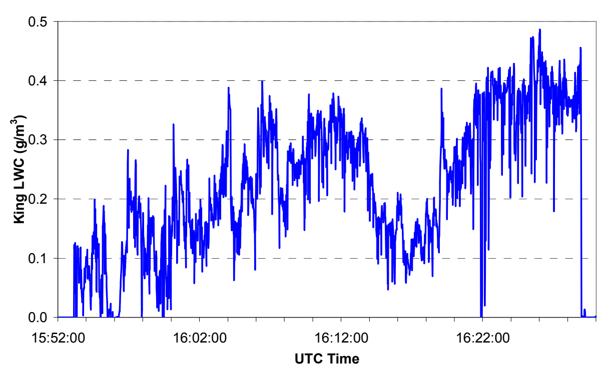

Figure 12. As in Fig. 8, but for the second icing encounter.

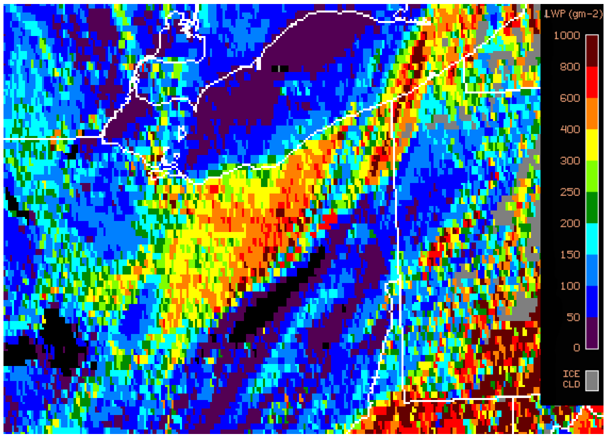

Figure 13. Liquid water path product for 1545 UTC on February 16, 2005.

4. DISCUSSION

This case demonstrates how useful the NASA Langley GOES-derived cloud products can be for nowcasting purposes. These products allowed the forecaster to more precisely identify locations where SLWC might be maximized and suggest that the aircraft sample clouds in those locations. While basic satellite fields such as albedo have proven helpful for this purpose in the past, the NASA-Langley products provide more precise information about the expected liquid water content and possibly drop size. On this day, the products helped identify a particularly promising patch of icing, allowing the Twin Otter to make the most of both its icing encounters.

Using standard observations, the original flight plan was devised and the aircraft was to fly west of CLE. This decision was later supported by the LWP product that became available after the briefing. The decision to fly to the southeast for the second encounter was made using both the GOES-derived cloud products and basic satellite fields. Around the time the Twin Otter was finishing the first icing encounter (1545 UTC) an area of clouds with a fairly consistent CTT was evident over the flight area (Fig. 14b). Visible imagery indicated that it was breaking up and becoming thin north and west of SKY (Fig. 14a). These clouds also had lower albedo, which correlated with the lower LWP values in this area (Fig. 13). The CTT near SKY was slightly warmer than that of the clouds near CLE. Surface observations from the area showed little variation in cloud coverage. The radar still indicated the presence of some very light echoes around CLE

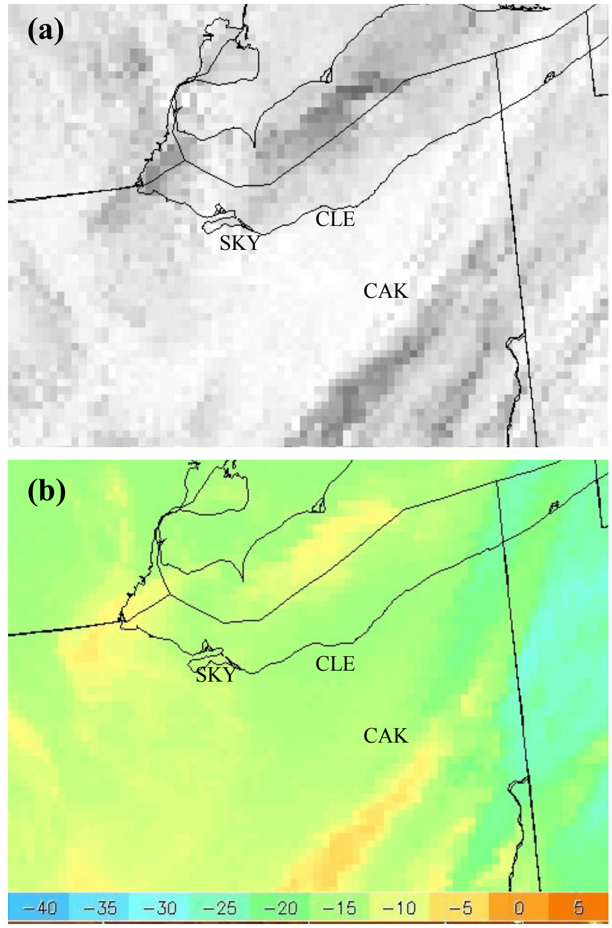

Figure 14. (a) Visible and (b) infrared satellite image for 1545 UTC on February 16, 2005. Temperatures are in Celsius.

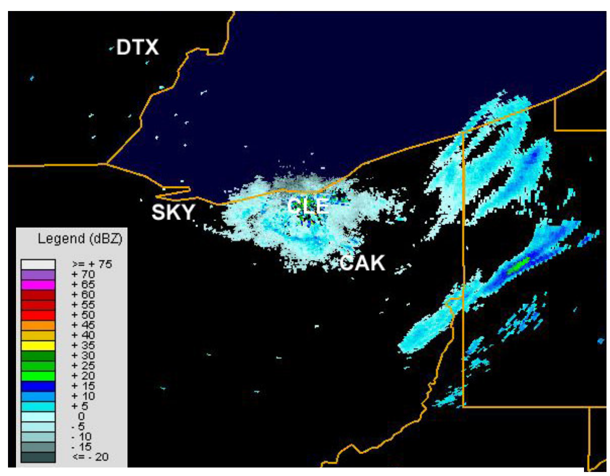

Figure 15. Radar reflectivity image from CLE at 1546 UTC on February 16, 2005.

(Fig. 15) and light snow was being reported at CLE and Canton-Akron (CAK). Without the GOES-derived satellite products it is likely that the forecaster would have suggested a flight path to the south or southeast of SKY based on the visible imagery showing brighter clouds there. But, the combination of the visible imagery and the LWP product showed that the clouds to the southeast likely contained higher amounts of SLW. There is no way of knowing for sure that good icing conditions would not have been found around SKY had they remained there, but the initial descent back into these clouds revealed relatively low water contents.

For this case, the forecaster's confidence and success was enhanced thanks to the use of the GOES-derived products, since some of the more traditional tools (radar, surface observations, and infrared temperature) gave a somewhat contradictory signal. This may not always be the case. Like any other product, the usefulness of the derived GOES fields fluctuates day by day, and the forecaster must gain a feel for cases when certain products are going to help more than others.

Some of the GOES-derived cloud products are planned to be incorporated into the Current Icing Potential (CIP; Bernstein et al. 2005, Haggerty et al. 2005) algorithm developed at NCAR. Through examination of these products in an operational setting, the forecasters have been able to identify situations where the fields are more and less effective. This knowledge will be useful for determining which fields should be integrated into CIP and the best way to combine them with the other input fields for the best icing diagnosis.

5. REFERENCES

Bernstein, B.C., F. McDonough, C.A. Wolff, M.K. Politovich, R.M. Rasmussen, and S.G. Cober, 2004: Diagnosis of supercooled large drop conditions using cloud water content and drop concentration. *Proc. 11th Conf. on Aviation, Range and Aerospace Meteorology*, Hyannis, MA, 4-8 October.

Bernstein, B.C., F. McDonough, M.K. Politovich, B.G. Brown, T.P. Ratvasky, D.R. Miller, C.A. Wolff, and G. Cunning, 2005: Current icing potential (CIP): Algorithm description and comparison with aircraft observations. *J. Applied Met*. In press.

Haggerty, J., G. Cunning, M. Chapman, D. Johnson, M. Politovich, C. Wolff, P. Minnis, and R. Palikonda, 2005: Integration of advanced satellite cloud products into an icing nowcasting system. WWRP Symposium on Nowcasting and Very Short Range Forecasting, Toulouse, France, 5-9 September.

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. *36th Aerospace Science Meeting and Exhibit*, AIAA 98-0557, Reno NV, American Institute of Aeronautics and Astronautics, 20 pp.

Minnis, P., et al., 1995: Cloud Optical Property Retrieval (Subsystem 4.3). "Clouds and the Earth's Radiant Energy System (CIRES) Algorithm Theoretical Basis Document, Volume III: Cloud Analyses and Radiance Inversions (Subsystem 4)", *NASA RP 1376 Vol. 3*, pp.135-176.

Minnis P., W. L. Smith, Jr., L. Nguyen, M. M. Khaiyer, D. A. Spangenberg, P. W. Heck, R. Palikonda, B. C. Bernstein, and F. McDonough, 2004a: A real-time satellite based icing detection system. *Proc. 14th Intl. Conf. Clouds and Precipitation*, Bologna, Italy, 18-23 July.

Minnis P., et al., 2004b: Real-time cloud, radiation, and aircraft icing parameters from GOES over the USA. *Proc. 13th Conf. on Satellite Oceanography and Meteorology*, Norfolk, VA, 20-24 September.

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