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VERIFICATION OF S-POLKA KA BAND RADAR/RADIOMETER LWC AND RES RETRIEVALS WITH GRIDS RETRIEVALS AND AIRCRAFT MEASUREMENTS AND COMPARISON TO GOES ICING PRODUCTS FOR THE WISP04 10-11MARCH EVENT

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1. INTRODUCTION

Recent studies have shown the usefulness of employing a two-channel microwave radiometer and a millimeter wave radar for retrieving liquid water content (LWC) and radar-estimated size (RES) fields (Zhang et al. 2004). This study demonstrates the utility of the supercooled liquid water (SLW) detection method by validating the retrieval results from a case study with in situ and remotely-sensed data.

The current study compares retrieved LWC and RES from the S and K_a-band dual-polarization radar (S-Polka) and GRound-based Icing Detection System (GRIDS) platforms to the airborne in situ probe and to products derived from the Geostationary Earth-Orbiting Satellite (GOES) for the 10-11th of March icing event during the Winter Icing Storms Project 2004 (WISP04). This upslope-induced event produced significant SLW aloft, with little precipitation at the surface.

2. FIELD PROGRAM OVERVIEW

An array of instrumentation platforms were operating from February through early April during WISP04 near Boulder, Colorado. The S-Polka, along with a collocated 2-channel radiometer, was located 21 km southwest of the GRIDS platform. The GRIDS platform consists of the NOAA K_a-band radar and its own collocated 2-channel radiometer. A research aircraft with an LWC probe was flown in the radar domain during periods of winter weather. Icing products derived from the GOES-W, such as liquid water path (LWP), cloud phase, effective particle size and cloud top and base heights, were available.

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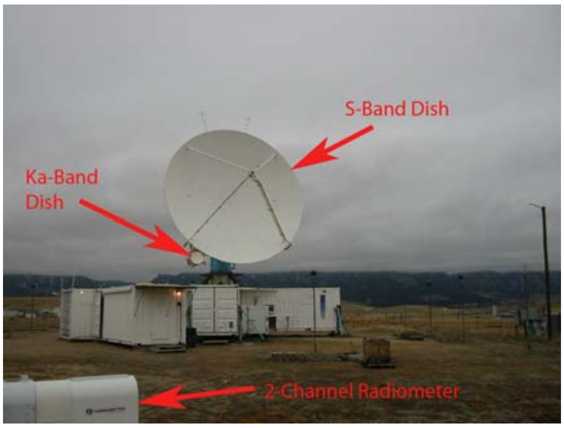

Figure 1: Instrument platforms at the Marshall Mesa site for the WISP04 field program.

3. ALGORITHM OVERVIEW

The algorithm used in this study derives LWC and RES from a single radar frequency and a collocated 2-channel radiometer using: i) the Hitschfeld-Borden (H-B) attenuation correction method, and ii) the constrained-gamma cloud drop size distribution (DSD) model (Zhang et al. 2004). The H-B method uses an attenuation-reflectivity (A and Z, respectively) power law (1) and adjusts its coefficient (2) by path- integrated attenuation (PIA) which is derived from the radiometer.

$$A = \alpha \varepsilon Z^{\beta} \tag{1}$$

Coefficients α=2.45 and β=0.704 were derived for a cloud droplet spectrum (Vivekanandan et al. 1999).

$$\varepsilon = \left(1 - 10^{-\beta PIA/10}\right) / 0.2 \ln \beta \int_0^{\infty} \alpha Z_m^{\beta}(s) ds \tag{2}$$

Using ε, the attenuation-corrected reflectivity is

$$Z(r) = Z_m(r) / \left[1 - 0.2 \ln 10 \varepsilon \beta \int_0^{r} \alpha Z_m^{\beta}(s) ds\right] \tag{3}$$

and thus a value for A can be obtained from (1). LWC (4) and RES (5) can then be calculated.

$$LWC = A/c \quad (4)$$

where c=1.15 dB km^{-1} gm^{-3} for liquid cloud at a temperature of -5°C.

$$RES = \left(Z/LWC/(\pi\rho/6) \right)^{1/3} \quad (5)$$

where ρ is the water density in g m^{-3}. The algorithm process is summarized as:

PIA → ε→ Z(r) → A → LWC → RES

4. 10-11 MARCH EVENT SYNOPTIC OVERVIEW

Figure 2 shows three regional surface analyses from 1800Z 10MAR (top), 0000Z 11MAR (middle) and 0600Z 11MAR (bottom). Starting at 18Z on the 10th, a surface cold front passed east of the Front Range. This produced a significant upslope wind directional component of winds from 45° at the two observing stations closest to the radar sites - FNL (Fort Collins/Loveland) and APA (Denver/Arapahoe). Surface temperatures at this time were 50°F for both sites. As time progresses to 0000Z on 11MAR, the surface front stalls out over the central mountains of Colorado, but strengthening high-pressure axis extending from central Wyoming through the Nebraska panhandle maintains the northeasterly component of the wind along the Front Range. By this time, surface temperatures decrease to 34 and 36°F at FNL and APA , respectively. By 0600Z on 11MAR, the ridge centered east of the Front Range had further strengthened and expanded southeastward. This led to a weak 2 kt surface wind from the south-southeast. Surface pressure rose to 1028.5 mb and the temperature was 30° F for both locations. No precipitation was reported for either of these sites during the time period, but station AFA (Air Force Academy) farther south reported a shower at 0000Z and fog by 0600Z. Figure 3 is a sounding taken from DEN (Denver) at 0000Z on 11MAR. Some differences in the atmospheric structure will exist over the 20+ miles distance separating DEN from the Marshall S-Polka, but this sounding should illustrate the general characteristics and is closest in time and location to our interests. Note that the surface temperature is roughly 34°F, and that the lowest 1km above the surface is not saturated but has a conditionally unstable lapse rate. The 0.7 km thick layer above that is saturated (where the solid blue dewpoint line is collocated with the solid red temperature line), indicating the level where cloud exists. This cloud layer is virtually isothermal. The winds are upslope (from 10 to 60°) from the surface up through the middle of the cloud layer, and increasingly strong from the west (downslope) above. The 1.5 km thick layer above the clouds stays relatively humid (over 80%), before becoming dry and stable above that.

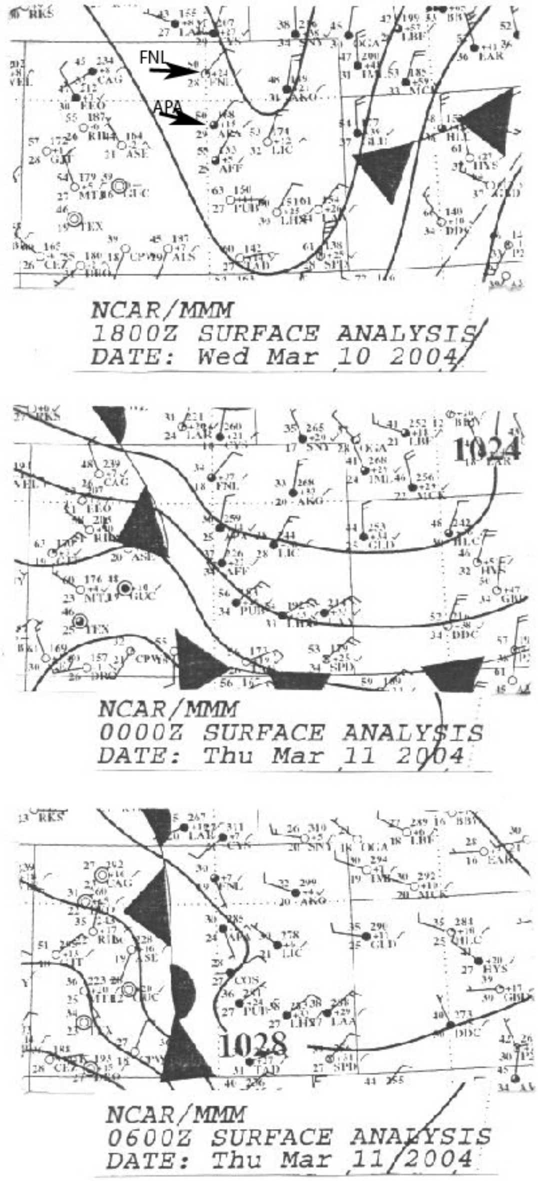

Figure 2: Regional surface analyses from 1800Z on 10MAR (top), 0000Z on 11MAR (middle) and 0600Z on 11MAR (bottom).

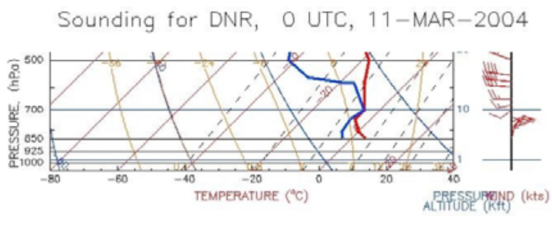

Figure 3: DEN (Denver) sounding from surface through cloud level at 00Z on 11MAR. Temperature (red) and dewpoint temperature (blue) profiles are plotted.

5. RETRIEVAL RESULTS

The GRIDS radar main channel was added with a 10.5 dB bias to avoid saturation of the receiver with its cross-channels in winter weather conditions. This bias was removed for all subsequent calculations. All heights referenced are in Mean Sea Level (MSL). Figure 4 shows a time series of retrieved LWC versus height from GRIDS from 20:02Z on 10Mar through 3:29Z on 11MAR. Values greater than 0.25 gm^{-3} exist below 2.5 km from 22:20 through 23:30 on 10MAR. Values of greater than 0.2 gm^{-3} occur at 3.0 km at 0:50Z and from 1:30 through 2:15Z on 11MAR between 2.3 and 2.7 km. Figure 5 is a similar time series of GRIDS DPOL (depolarization ratio). Relatively large values (more than -30 dB) are associated with non-spherical targets such as ice crystals that preferentially change the polarization ratio signal. Relatively small values (less than -30 dB) are nearly spherical targets such as warm or cold liquid droplets. The region between 2.3 and 2.7 km and between times 1:30 and 2:15Z (shown as red box) have DPOL values of around -35 dB and therefore are indicative of targets that are nearly spherical in nature. Radar reflectivity (dBZ, Figure 6) values in this region are about -5 dBZ, and RES (radar-estimated size, Figure 7) values are 35 to 45 µm. These are in the range of expected values for SLW. The higher LWC values between times 22:20 and 23:30Z on 10MAR have too high of dBZ and RES values to indicate a clean SLD signature. These large values combined with borderline DPOL values of -20 to -25 dB mean there was probably a small number of large ice particles present.

Since the two WISP04 radar platforms each had collocated 2-channel radiometers, it was possible to derive LWC and RES fields from both. The findings were then validated by comparing

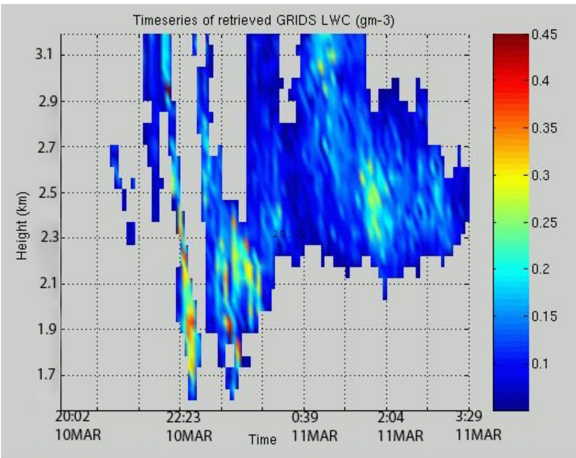

Figure 4: Time series of retrieved LWC (gm^{-3}) versus height from GRIDS from 20:02Z on 10MAR through 3:29Z on 11MAR.

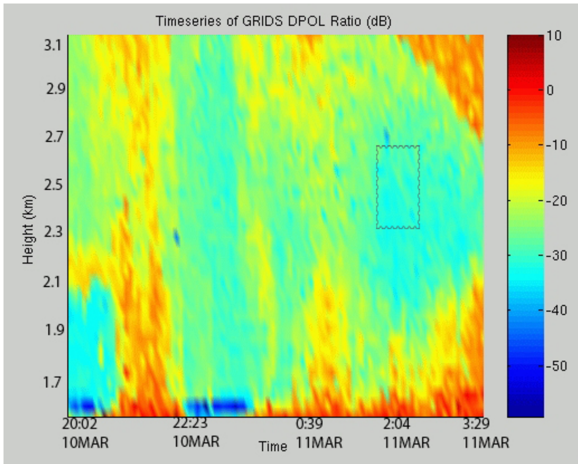

Figure 5: Time series of DPOL (dB) versus height from GRIDS from 20:02Z on 10MAR through 3:29Z on 11MAR.

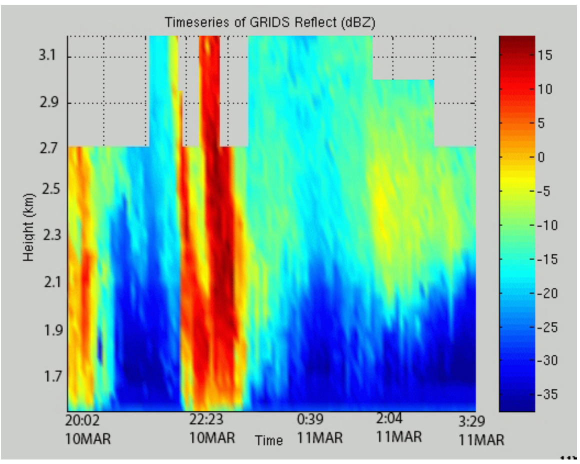

Figure 6: Time series of reflectivity (dBZ) versus height from GRIDS from 20:02Z on 10MAR through 3:29Z on 11MAR.

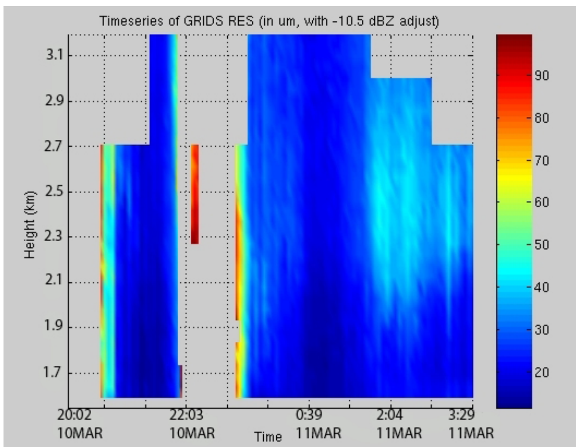

Figure 7: Time series of retrieved RES (µm) versus height from GRIDS from 20:02Z on 10MAR through 3:29Z on 11MAR.

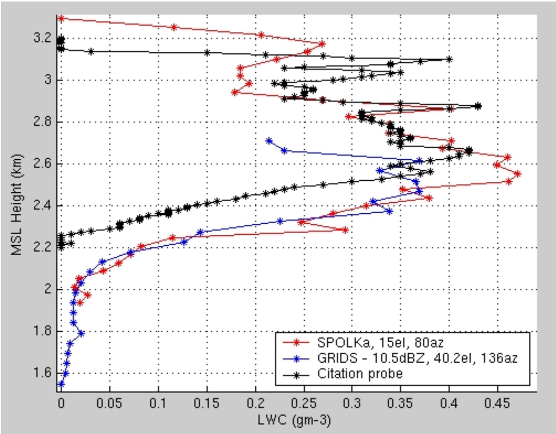

Figure 8: LWC retrieval profile for S-Polka (1:39Z, red), GRIDS (1:39Z, blue) and Citation probe (1:03-1:05Z, black) on 11MAR.

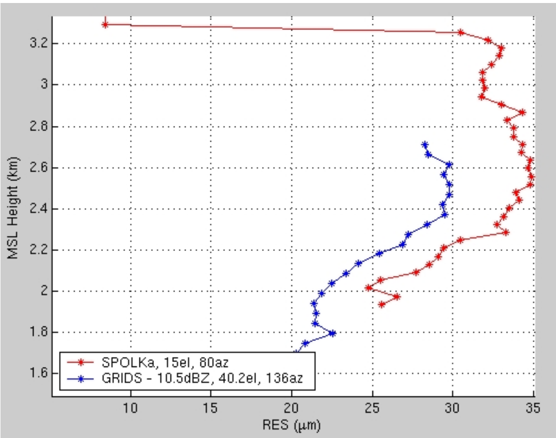

Figure 9: RES retrieval profile for S-Polka (1:39Z, red) and GRIDS (1:39Z, blue) on 11MAR.

values at collocated gates. Figure 8 shows the results of slant-profile (along beam) retrieval of LWC for the S-Polka (red) and GRIDS (blue) radars at 1:39Z on 11MAR and the Citation LWC probe at 1:03 to 1:05Z (black). The Citation was on its initial climb from takeoff and was within 15 km of both radar platforms. The plot of RES for the same times is shown in Figure 9 . These plots show a mean LWC of 0.3 gm^{-3} and a RES of 37 μm in the cloud layer for both radars. Both radars show similar mean value profiles. The Citation transition layer is 0.1-0.2 km higher than that of GRIDS and S-Polka retrievals, which may be due to the aircraft sampling a sub-cloud layer which is more representative of the upslope environment further from the foothills than the radars are sampling. Both the S-Polka and the Citation LWC probe have values of LWC falling off to near zero at 3.2 km. The GRIDS radar retrieval ends at 2.7 km because above that level the signal-to-noise ratio becomes too low.

6. COMPARISON TO GOES ICING PRODUCTS

The GOES icing products were compared to the S-Polka and GRIDS retrievals discussed in the previous section. Figure 10 is a time series from GOES (magenta) and GRIDS (blue) of derived LWP in gm^{-2} from 22:00Z on 10MAR to 3:30Z on 11MAR. The values for GOES were calculated by averaging all the values from the 4 km wide pixels along the

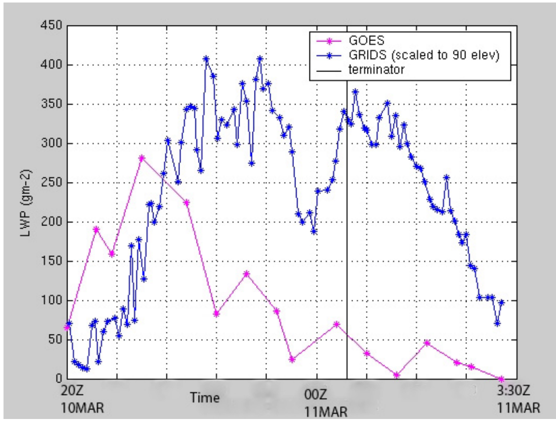

Figure 10: Time series of LWP (in gm^{-2}) derived from GRIDS (blue) and GOES (magenta) from 20Z on 10MAR through 3:30Z on 11MAR.

direction the GRIDS system was scanning (136 degrees azimuth in this case) out to 20km range. The GRIDS LWP is derived from the GRIDS 2-channel radiometer. This product is what is used to scale the dBZ-LWC power law relation. The GRIDS LWP retrieval was scaled to 90^{o} elevation to account for the increased path length the GRIDS beam has at 40.2 degrees elevation. The black line indicates the terminator time, or time of sunset at the radar sites. The GOES LWP product closely matches the GRIDS retrieval's rise from 50 to 300 gm^{-2}, but after 23:00Z on the 10th, GOES LWP rapidly falls back to around 50 gm^{-2} for the remainder of the event. The GOES product's low sun angles before sunset and transition from VISST to SISST methodology (Minnis et al. 2004) at the terminator both contribute to the failure of GOES to detect the LWP levels detected by GRIDS. It seems that the cold, SLW-laden 0.5 km thick clouds which top out at 3 km in MSL height are not well detected by the GOES algorithm. For this reason, we will omit the comparison of the GOES icing products at around 1:39Z on the 11th, which was previously determined to have the 'cleanest' SLW signature.

Figure 11 shows GOES icing products from 22:15Z on 10MAR during the time previously determined to have significant SLW but mixed with some larger ice crystals. The S-Polka site is labeled in the center of the range rings, and the GRIDS

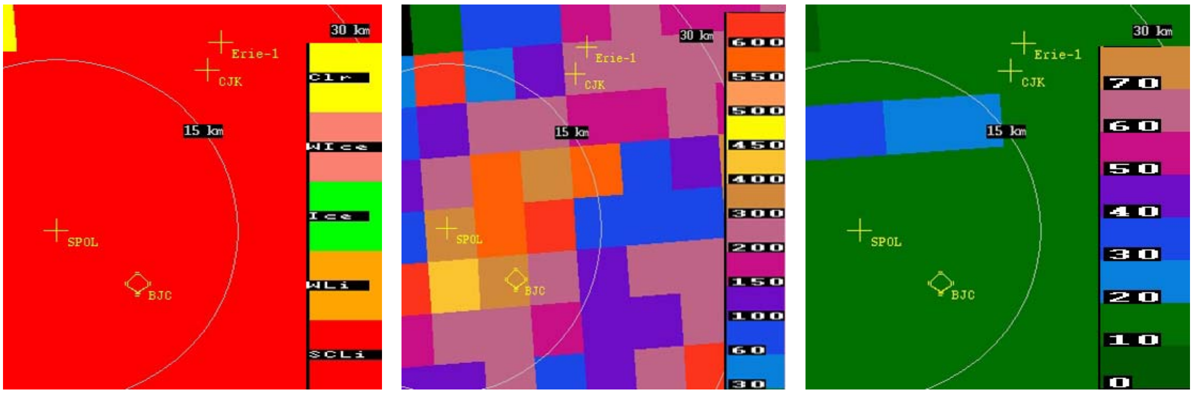

Figure 11: GOES icing products within the radar domain from 22:15Z on 10MAR: water phase (left), LWP (middle, gm^{-2}) and particle size (right, µm).

radar site is labeled as 'Erie-1' at 39^{o} azimuth and 21 km distance from the S-Polka. The left plot in Figure 11 illustrates cloud top water phase. All of the pixels in the scene correspond to SLD. The middle plot in Figure 11 is a similar plot of the LWP product. GOES LWP values along the GRIDS beam range from 100 to 400 gm^{-2}, with a mean of 225 gm^{-2}. GRIDS indicated a value of around 280 gm^{-2} at the same time. The right plot in Figure 11 shows the effective particle size to consistently be between 10 and 20 µm along the GRIDS scan direction. GOES determined the cloud-top height (not shown) to be between 3 and 4 km, and the base (not shown) to be between 2 and 3 km. The radar profiles of RES show a cloud top height of about 3.2 km and a cloud base of 2.2 to 2.4 km. The skew-T plot shown in Figure 3 from station DEN corresponds more closely to the radar retrievals.

7. SUMMARY

The upslope-induced stratiform cloud deck on the 10-11 March, 2004 had a strong supercooled liquid water signature and relatively high LWC, as evidenced by the airborne probe and radar retrievals. The cleanest SLW signal during the duration of the event occurred around 1:39Z on 11MAR. The GRIDS DPOL ratio was small (~ -35dB) and reflectivity was about -5 dBZ, both considered within the range of expected values for SLW. The retrieved slant profiles of S-Polka and GRIDS LWC as well as airborne in situ LWC reached a maximum of between 0.3 and 0.4 gm^{-3} within the cloud deck. Maximum retrieved RES for S-Polka and GRIDS within the cloud deck were between 30 and 35 µm. As found in previous studies which employed the radar/radiometer retrieval method, the method appears to result in an accurate representation of the atmospheric LWC and RES profile. Retrieved S-Polka derived fields were verified by comparison to GRIDS derived fields as well as the airborne in situ probe data.

GOES cloud top and base MSL heights were good compared to radar/radiometer retrievals and radiosonde profiles for this upslope cloud event. An effective particle size of between 10 and 20 µm was determined by GOES for most of the event. Effective particle size is not a similar quantity to RES, so no direct comparison is possible. The qualitative Phase field was very accurate compared to the Citation flight log (not shown) before 22:30Z on the 10$^{th.}$ The GOES LWP field matched up quantitatively well to the GRIDS LWP derived from its collocated 2-channel microwave radiometer from 20:00 to 22:30Z on 10MAR, but vastly under detected LWP from 22:30Z on the 10th through the end of the event at 3:30Z on the 11th. This may be partially due to the terminator passage through the field program region at around 0:45 on the 11th. The GOES icing algorithms are based on a determination of optical depth from the visible channels. The quality of this method inevitably deteriorates as sun elevation angle decreases near sunset. Also, the GOES algorithms are switched to infrared-based detection after local sunset. Accurate detection of low topped, low depth upslope cloud decks along the Front Range becomes very difficult. This is evidenced by the fact that the GOES icing products mostly detected clear conditions with zero LWP at its 1:45Z 11MAR time, the time determined by this study to have the cleanest SLW signature.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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