RADAR OBSERVATIONS OF A RARE "TRIPLE" THREE-BODY SCATTER SPIKE

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Abstract

On 1 July 2006, several supercell thunderstorms produced significant hail during the late afternoon and evening across northeast Wisconsin. The hail storms were responsible for over 10.3 million dollars of damage. The most intense storm produced hail up to 4 in. in diameter that damaged over 100 cars and numerous homes in Oconto County, Wisconsin. This storm exhibited a rare, triple three-body scatter spike (TBSS) and a very long, impressive 51 mile TBSS. This paper will diagnose the structure and character of the hail cores responsible for the multiple TBSS using several different tools, illustrating that TBSS are 3-D features that are not confined to a single elevation slice. In addition, the paper will connect the unusually large scattering angle associated with the 51 mile long TBSS to the increased scattered energy responsible for the long TBSS.

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1. Introduction

Since the early days of weather radar, radar operators have noticed a "flare echo" down the radial believed to result from large hail in a thunderstorm (Wilson and Reum 1988). When the radar beam encounters large hailstones with a coating of liquid water, power from the radar is scattered in all directions, some radiating to the ground beneath the scattering volume. Some of the power is then back-scattered from the ground, to the hail core and then scatters back to the radar receiver along the same radial. The resultant triple scattered energy produces a "flare echo" 10-30 km down radial from the highest reflectivities, with reflectivity values ≤ 20 dBZ (Fig. 1; Wilson and Reum 1988; Lemon 1998). Zrnic (1987) describes this "flare echo" as a three-body scatter spike (TBSS) caused by non-Rayleigh radar microwave scattering. "A scatterer whose diameter to wavelength ratio is greater than $1/16^{th}$ of the radar wavelength will cause non-Raleigh or Mie scattering" (Lemon 1998). Although the $1/16^{th}$ condition for the 10 cm wavelength radar only corresponds to a hail diameter around 0.25 inches, significant scattering out of the main beam required to produce the flare echo implies the presence of a large number of hailstones larger than this. The presence of a TBSS signature is therefore a good indicator that a particular thunderstorm contains large hail (Lemon 1998). While the presence of dual TBSS signatures has been observed (Stan-Sion et al. 2007), three distinct TBSS signatures in a single volume scan and elevation angle is a phenomenon that has yet to be documented and is the main motivation for this paper. The terms "flare echo" and TBSS will be used interchangeably throughout this paper.

A supercell on 1 July 2006 produced hail up to 4 in. in diameter (Fig. 2) as it moved across northeast Wisconsin; and exhibited a triple TBSS signature as well as an unusually long single TBSS. In addition to traditional 4-panel elevation displays, graphics generated from the GR2Analyst Edition (GR2AE) software (http://www.grlevelx.com/) was used to examine the radar structure of this supercell. The GR2AE software has the ability to interrogate a storm in a simulated 3-D display, including the capability to filter reflectivities and create an isosurface of a specific reflectivity value.

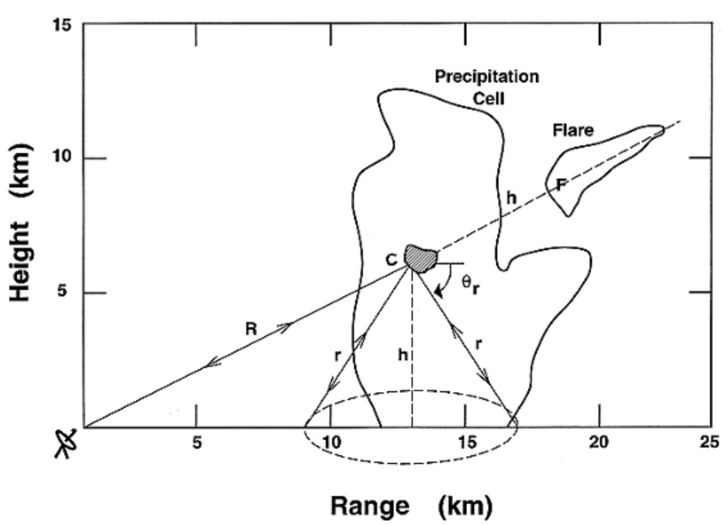

Fig. 1. Shows a schematic of the radar signal path responsible for the three-body scatter spike (flare echo). The dark shading near point C represents the 60+ dBZ reflectivity core responsible for producing the artifact. The outbound radar energy follows path R, and is reflected off the hail core C. Part of this energy is then deflected downward to the ground and back to hail core C along path R, before traveling back to the radar along path R. The deflected energy from the ground causes the radar to "see" hydrometeors along path h, producing the flare echo past point F. From Wilson and Reum (1988), Lemon (1998), and Smallcomb (2008).

Fig. 2(a).

Fig. 2(b).

Fig. 2(a-b). Photos of the hailstones from Oconto Falls, WI on 1 July 2006, courtesy of Jared Alfson, KC9IPS and Kris Ingenthron, KC9KNC.

2. Environment

During the afternoon of 1 July 2006, a pre-frontal surface trough (Fig. 3) and 500 mb shortwave trough (not shown) moved across the western Great Lakes. Surface temperatures in the lower to middle 80s °F and dew points ranging in the middle to upper 60s °F ahead of the trough, resulted in surface-based (SB) CAPE values ranging from 1500 to 2500 J kg^{-1} at 2000 UTC. A RAOB sounding from Green Bay, Wisconsin (GRB) at 1800 UTC and a Tropospheric Airborne Meteorological Data Report (TAMDAR) sounding from Appleton, Wisconsin (ATW) at 1831 UTC (Fig. 4) showed a capping inversion in place (surface-based convective inhibition values of 50 to 100 J kg^{-1}) with steep mid-level lapse rates (700 to 500 mb lapse rates of 7.0 to 8.0° C km^{-1}) and adequate deep-layer shear (0 to 6 km shear values of 20 to 25 m s^{-1}) (Weisman and Klemp 1982) across northeast Wisconsin.

The GRB and ATW soundings (Fig. 4) were modified using the surface temperature (88°F) and dew point (70°F) from Clintonville, Wisconsin (CLI) at 2000 UTC (Fig.3) and yielded surface-based convective inhibition (SB CIN) values of 52 and 83 J kg^{-1} respectively. Although the CLI observation was 33 miles south of the storm when it entered Menominee County, it is the only observation ahead of the trough that is not obscured by cloud cover. The development of deep convection indicated that the weak cap was easily overcome by the lift from the approaching surface trough. Furthermore, the modified GRB sounding yielded 2450 J kg^{-1} of SB CAPE. The high CAPE density and steep lapse rates in the maximum hail growth zone (-10 to -30°C) shown by the GRB sounding were indicative of strong updraft potential, suspending hail stones for an adequate duration to become very large (Knight and Knight 2001).

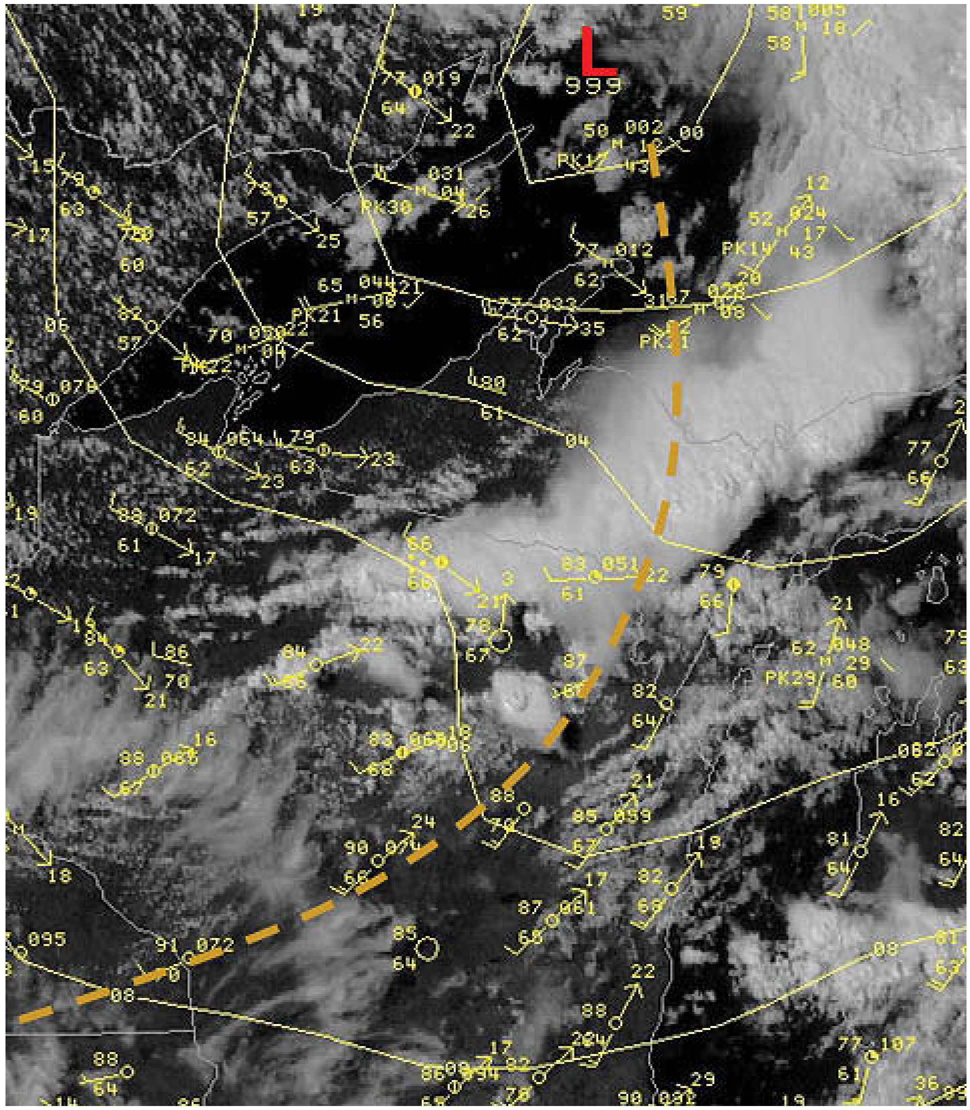

Fig. 3. Visible satellite image from 1 July 2006 at 2000 UTC with an objective analysis of mean sea level pressure (yellow contours, 2 mb intervals) and plotted standard surface observations across the western Great Lakes. The surface low (red) is analyzed over northern Lake Superior with a pre-frontal trough (orange), trailing southward.

3. Radar Observations

A line of thunderstorms entered northeastern Wisconsin shortly after 1800 UTC along the surface trough, while a few isolated storms developed ahead of the main line (Fig. 5). The storm of interest experienced rapid development shortly after 2000 UTC as it entered Menominee County (Fig. 6).

Figure 7 shows a traditional 2-D four panel display. Several TBSS signatures were evident from 2033 to 2102 UTC as the storm moved through Oconto County. The four-panel display at 2054 UTC shows the 0.4, 3.9, 7.9 and 10.0 degree elevation slices (Fig. 7) of the storm, 30 miles north of the GRB radar. At 0.4 degrees a TBSS is already evident. The presence of a TBSS at this elevation angle is atypical, given that the low altitude of the hail core at this slice tends to make the TBSS appear closer to the storm core and masks the feature (Smallcomb 2008). Higher up at 3.9 degrees, there are two TBSS signatures and evidence of two distinct hail cores. At 7.9 degrees, the two TBSS

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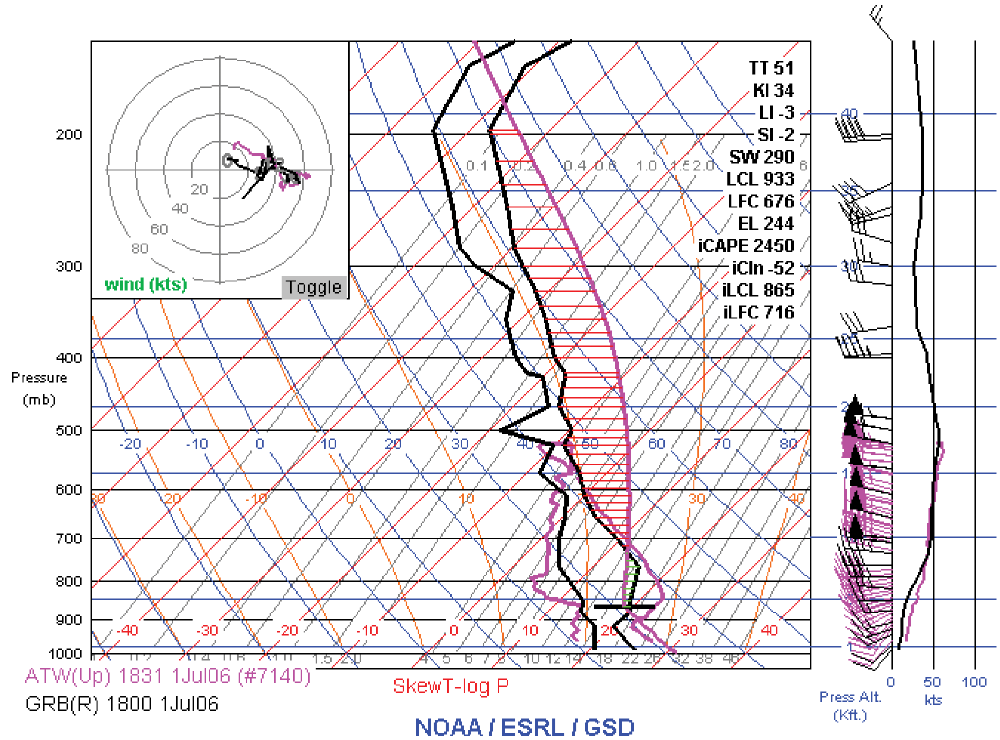

Fig. 4. 1 July 2006 1800 UTC RAOB sounding at Green Bay, WI (GRB; black) and 1831 UTC TAMDAR sounding at Appleton, WI (ATW; pink) showing temperature, dew point, and a modified parcel with a surface temperature of 88° F and surface dew point of 70° F (pink). This modified parcel yields CIN (green hatching) of 52 J kg-1 and SB CAPE (red hatching) of 2450 J kg-1 at GRB with a CIN of 83 J kg-1 and low level SB CAPE of 568 J kg-1 at ATW. Winds at right are in knots. Image courtesy of the ESRL AMDAR website.

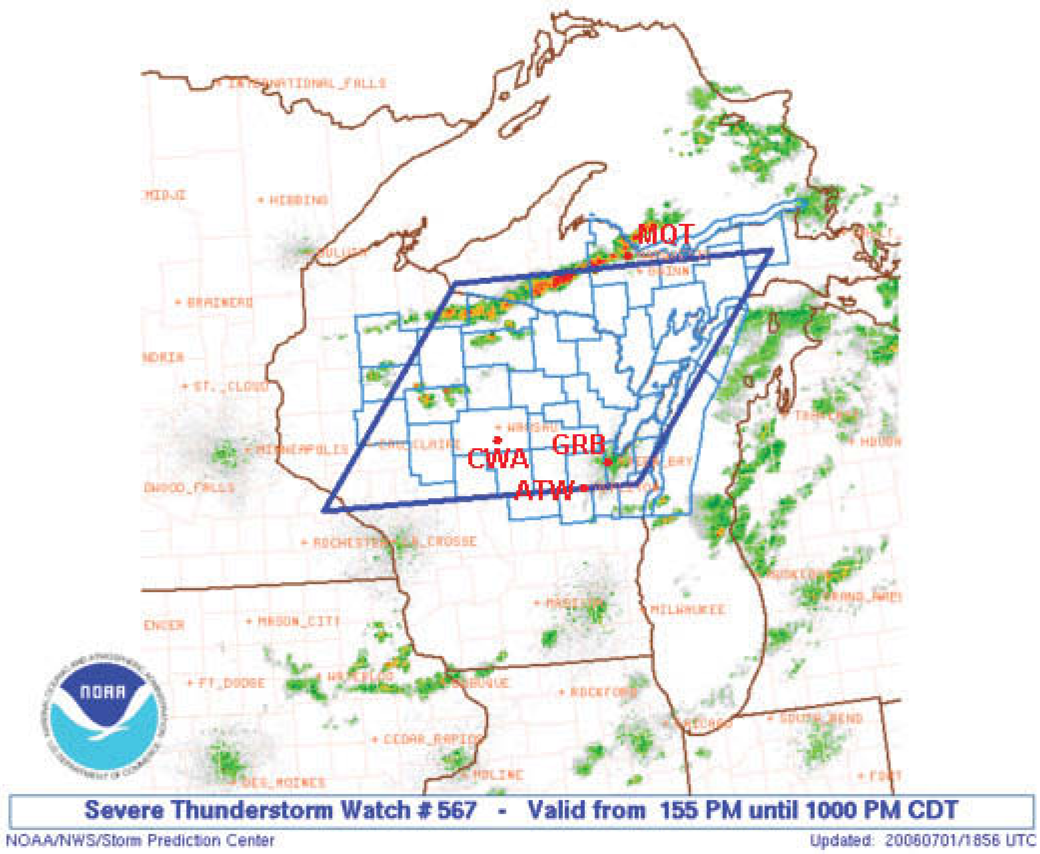

Fig. 5. Composite reflectivity radar image from 1856 UTC 1 July 2006 showing the line of convection entering north-central Wisconsin and Severe Thunderstorm Watch #567 (blue) issued for northern Wisconsin and portions of Upper Michigan. Selected locations (red) Green Bay, WI (GRB), Appleton, WI (ATW), Mosinee, WI (CWA) and Marquette, MI (MQT) are shown on the map for perspective. Image courtesy of the Storm Prediction Center.

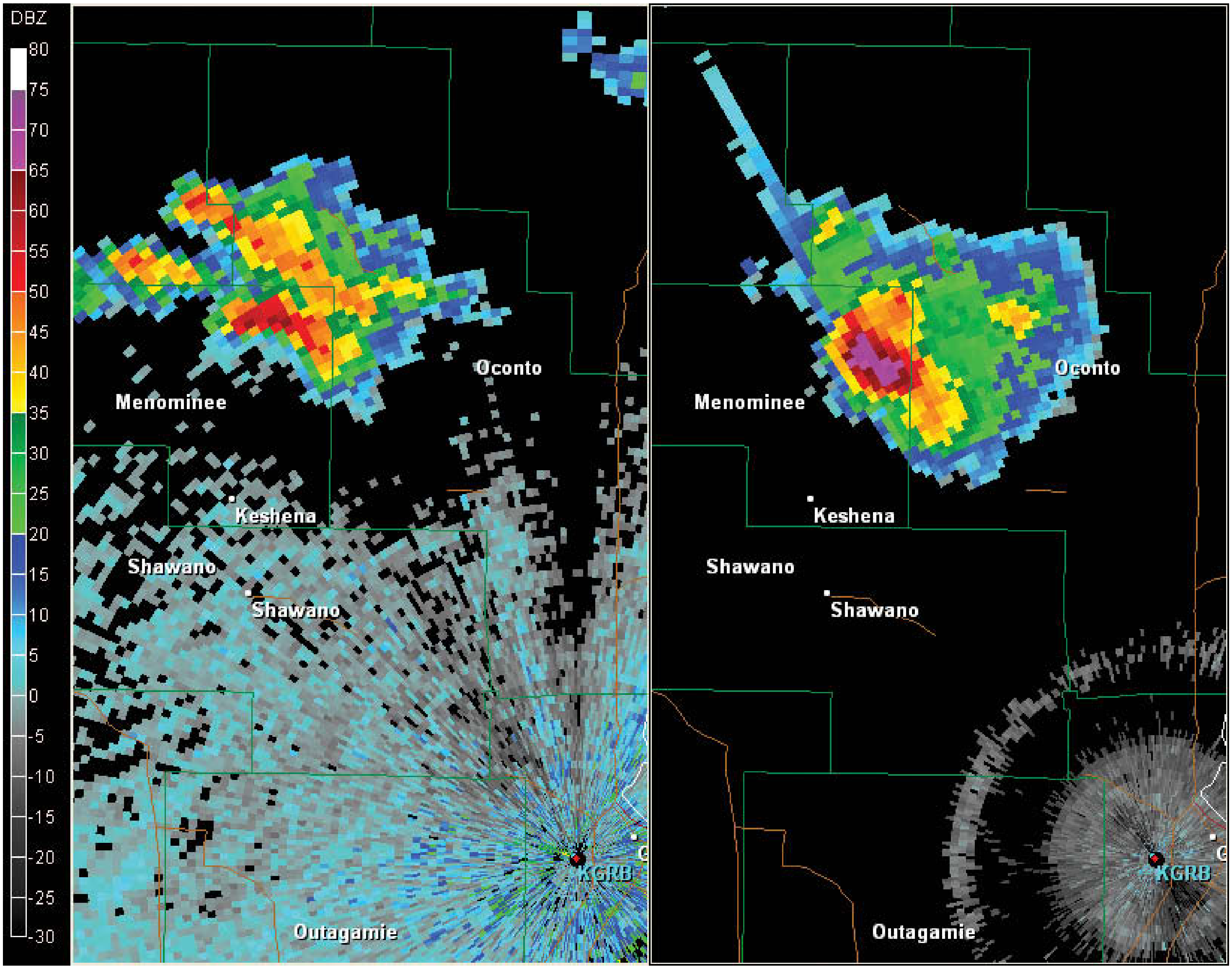

Fig. 6. Reflectivity image from the GRB Doppler radar at 2021 UTC 1 July 2006, showing the 0.4 degree (left) and 6.4 degree (right) elevation slices with the thunderstorm in its initial stages of rapid development over northeastern Menominee County. Although the base reflectivity (left) is not too impressive, the reflectivity values aloft show a hail core producing a TBSS (right). The height of the storm above the ground is approximately 2892 ft. at 0.4 degrees and 26,012 ft. at 6.4 degrees. County names (white), selected cities (white dots), and the KGRB radar (cyan with red dot) are shown on the map for perspective.

signatures related to the previous elevation angle are still evident; however, at this elevation angle there is a third TBSS between the two lower signatures. Finally at 10.0 degrees, the third TBSS is shown by itself. This elevation is the highest angle at which any TBSS signatures are observed.

The GR2AE software offers a different perspective, and allows one to visualize the spikes and reflectivity cores at 2054 UTC. A 3-D -9.0 dBZ isosurface image highlights the three separate TBSS signatures (Fig. 8) evident in the traditional four-panel display. In addition to an isosurface image, the software can filter out reflectivity values to view the core of a storm. Figure 9 shows the same storm with reflectivity values below 58 dBZ filtered out. This filtering highlights the two distinct cores at the lower elevation angles responsible for the dual TBSS at 3.9 degrees. There is also evidence of the third core higher up, which may be responsible for the third TBSS at 10.0 degrees.

4. Warning Decision Making

A severe thunderstorm warning was issued for the rapidly developing storm at 2010 UTC for Menominee and Oconto Counties. Although the storm was not too impressive at 0.4 degrees, the large core aloft and TBSS (Fig. 6) prompted golf ball size and large dangerous hail wording in the follow up Severe Weather Statement at 2018 UTC. Weak rotation, a tight reflectivity gradient, and a pendant shape prompted possible tornado wording

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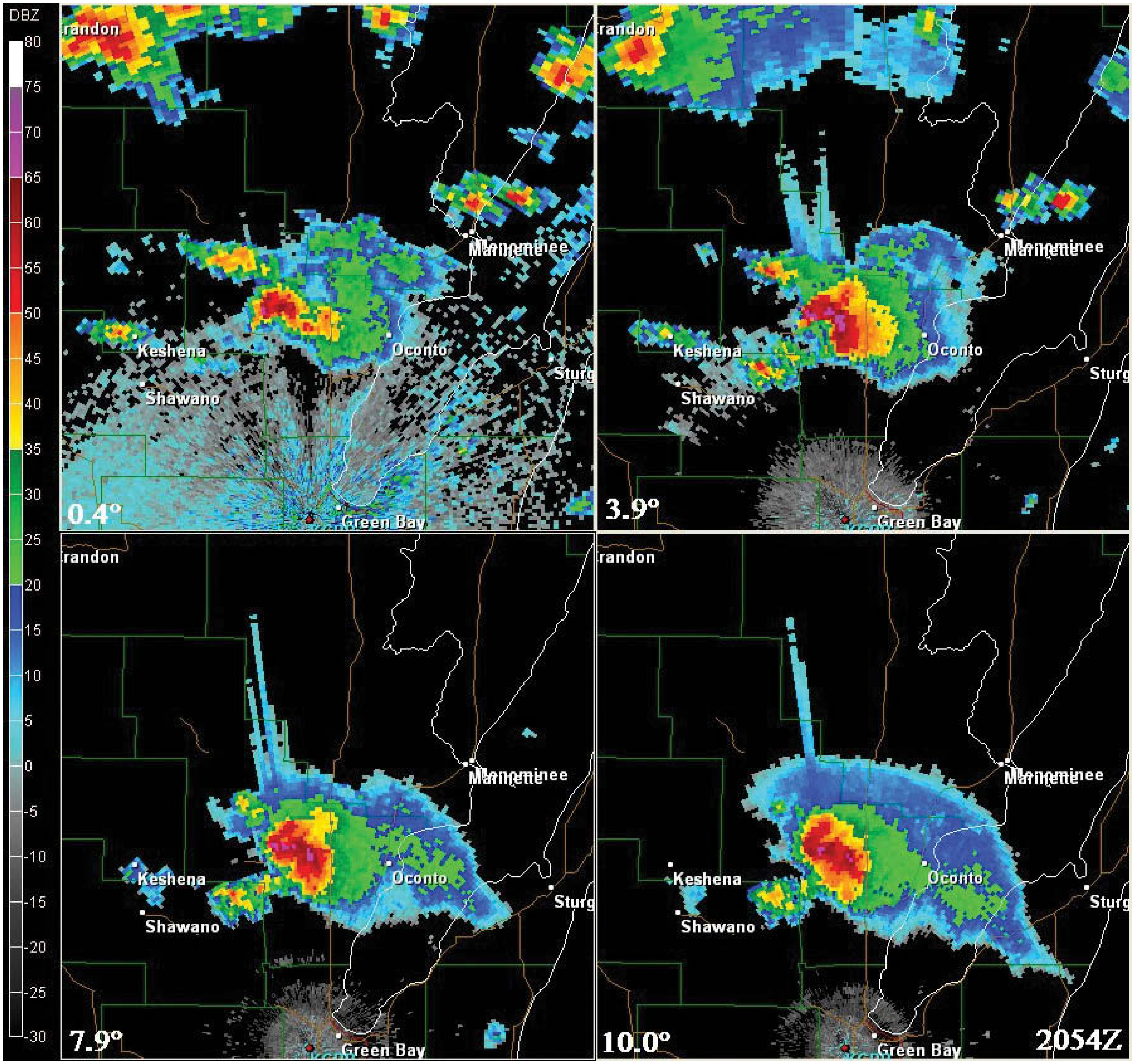

Fig. 7. Traditional 2-D four-panel reflectivity display used by National Weather Service (NWS) meteorologists in the warning decision making process. Image is from the Green Bay, WI (GRB) Doppler radar (denoted by red dot) at 2054 UTC 1 July 2006. Elevation angles in degrees (storm height in feet) displayed clockwise from upper left are 0.4 (1802), 3.9(11,701), 7.9(22,499), and 10.0(27,949). The storm of interest is at the center of each image, located approximately 30 miles north of the GRB Doppler radar.

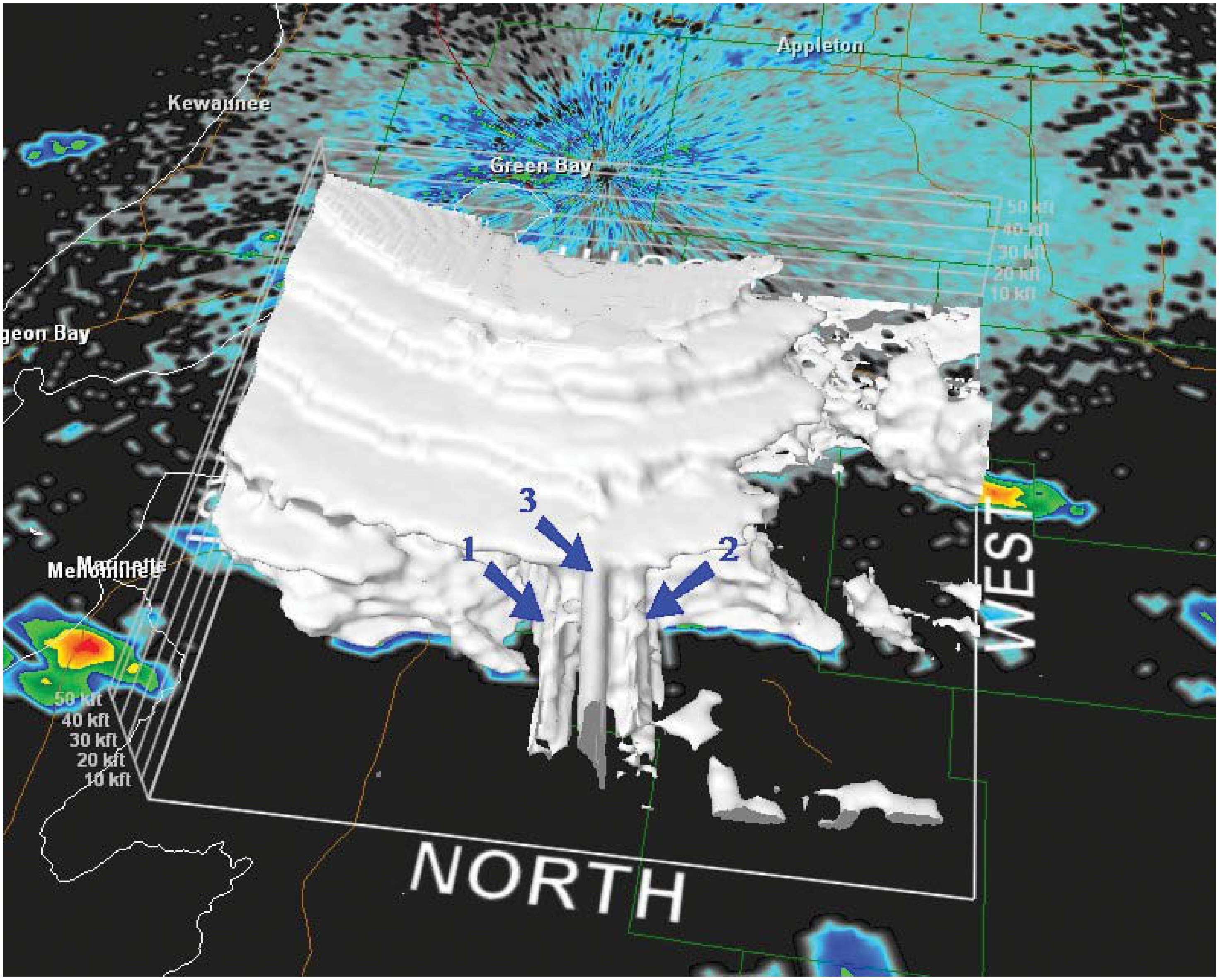

Fig. 8. 3-D -9.0 dBZ isosurface image (from GR2AE) showing the three separate TBSS signatures (denoted by the blue arrows) seen in Oconto County at 2054 UTC 1 July 2006. Perspective is looking southward toward the radar and down at the storm.

as well as highlighting this as a dangerous storm in another follow up statement issued at 2024 UTC. As the storm moved farther into Oconto County, another Severe Thunderstorm Warning was issued at 2055 UTC. The storm maintained its pendant shape (Fig. 7); however, the rotation within this pendant was broad and unorganized (Fig. 10), and there were no wind reports that accompanied the hail reports. These factors led to holding off on issuing tornado warnings, as severe thunderstorm warnings with heightened wording seemed appropriate. It is interesting to note at this time that the TBSS caused anomalously high storm-relative velocity values of 92 knots down radial at 3.9 degrees (Fig. 10), which has been shown to occur with large hail cores (Smallcomb 2008). Despite the contaminated storm-relative velocity values, they occurred far enough down-radial to have little impact on the warning decision making process. Timely spotter reports of 2 and 3 inch hail with this storm (Fig. 2) were highlighted in follow up statements at 2105 and 2117 UTC respectively. Subsequent spotter reports would come in with hail sizes all the way up to 4 inches.

5. Discussion

TBSS signatures in this case were much longer than what the physics would suggest (Wilson and Reum 1988). The longest TBSS from this case (Fig. 11) was 51 miles long produced by a 76 dBZ hail core. For a typical TBSS signature and the triple reflection, there needs to be 25.5 miles between the hail core and the ground to explain the length of the TBSS. Referring to Fig. 1, the distance "h" (height of the hail core above the ground) is 23,535 ft AGL for the Oconto County storm. The hypotenuse of the right triangle "r" would necessarily be 25.5 miles or 134,636 ft to explain the total length of the TBSS. To calculate the scattering angle Θr we use trigonometry where

$$\Theta r = \arccos(23{,}535\ \text{ft}/134{,}636\ \text{ft}) = 79.1\ \text{degrees.} \quad (1)$$

While a scattering angle that large is unlikely, it is not impossible, making this case very unique. (P. Schlatter 2009, personal communication).

A 51 mile long TBSS (Fig. 11) has yet to be documented, and is more than 2.5 times the length of a "typical" TBSS of 18.6 miles from Lemon's study (1998). Although recent improvements to radar data on operational systems, specifically increasing data resolution from 4-bit (16 levels) to 8-bit (256 levels), have led to increased TBSS frequency and length due to a lower-bound reflectivity threshold (Lindley and Lemon 2007), the Oconto County TBSS still measured 48.5 miles using the lower resolution 4-bit data. While the reasons for such a long TBSS are unknown, the unusually large scattering angle of 79.1 degrees meant that the scattered energy interacted with the ground at a very small angle, 10.9 degrees, creating a very large cross sectional area of the ground with which the scattered energy interacted (Fig. 12). This large cross sectional area, the small angle with which the hail-scattered energy hit the ground, and the high reflectivity values in the hail core meant more energy was being scattered in all directions, leading to a long and strong TBSS (P. Schlatter 2009, personal communication). There are a number of unknowns regarding this case, and certainly more research that can be done regarding the unusually long TBSS with the July 1 storm.

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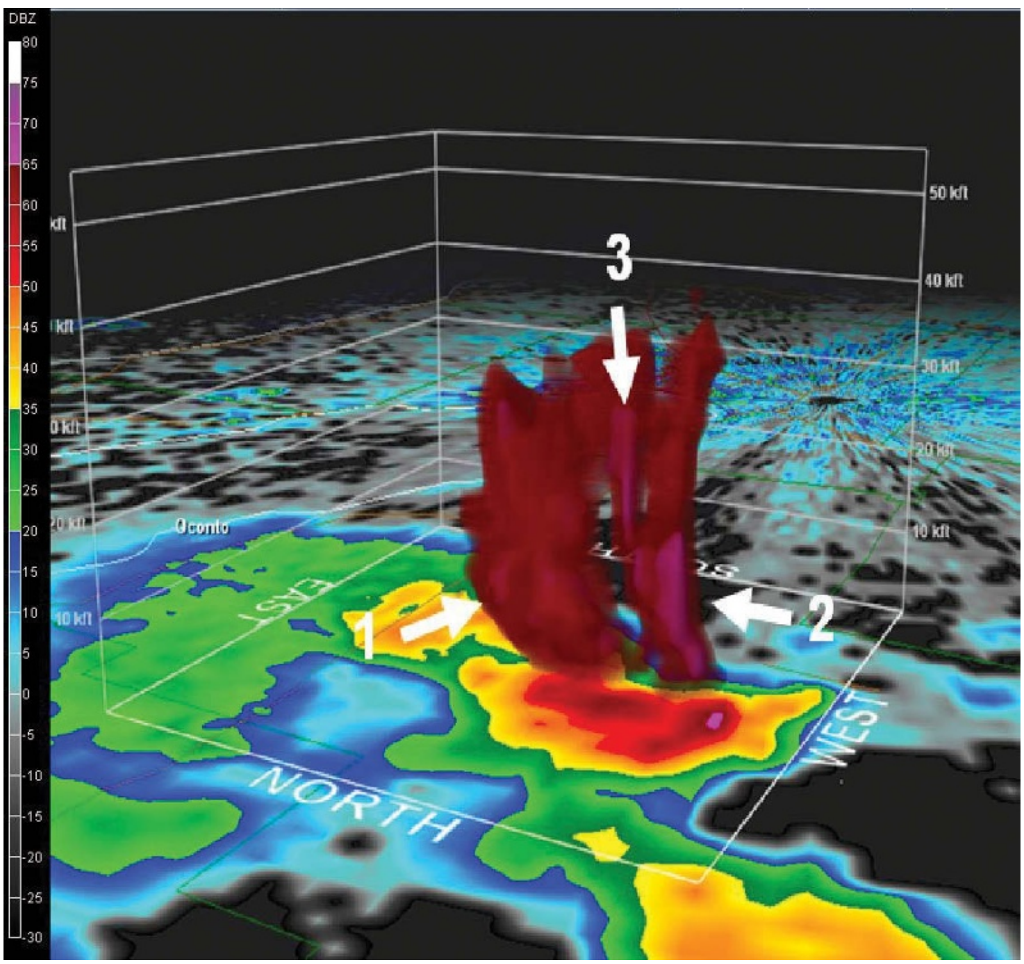


Fig. 9. 3-D reflectivity image from 2054 UTC 1 July 2006 showing the two separate cores at the lower levels and the core at the higher elevation angle responsible for the three TBSS signatures shown in Fig. 8. The image was taken from the GR2AE with all data below 58 dBZ filtered out of the Oconto County storm. Perspective is looking southeastward toward the radar.

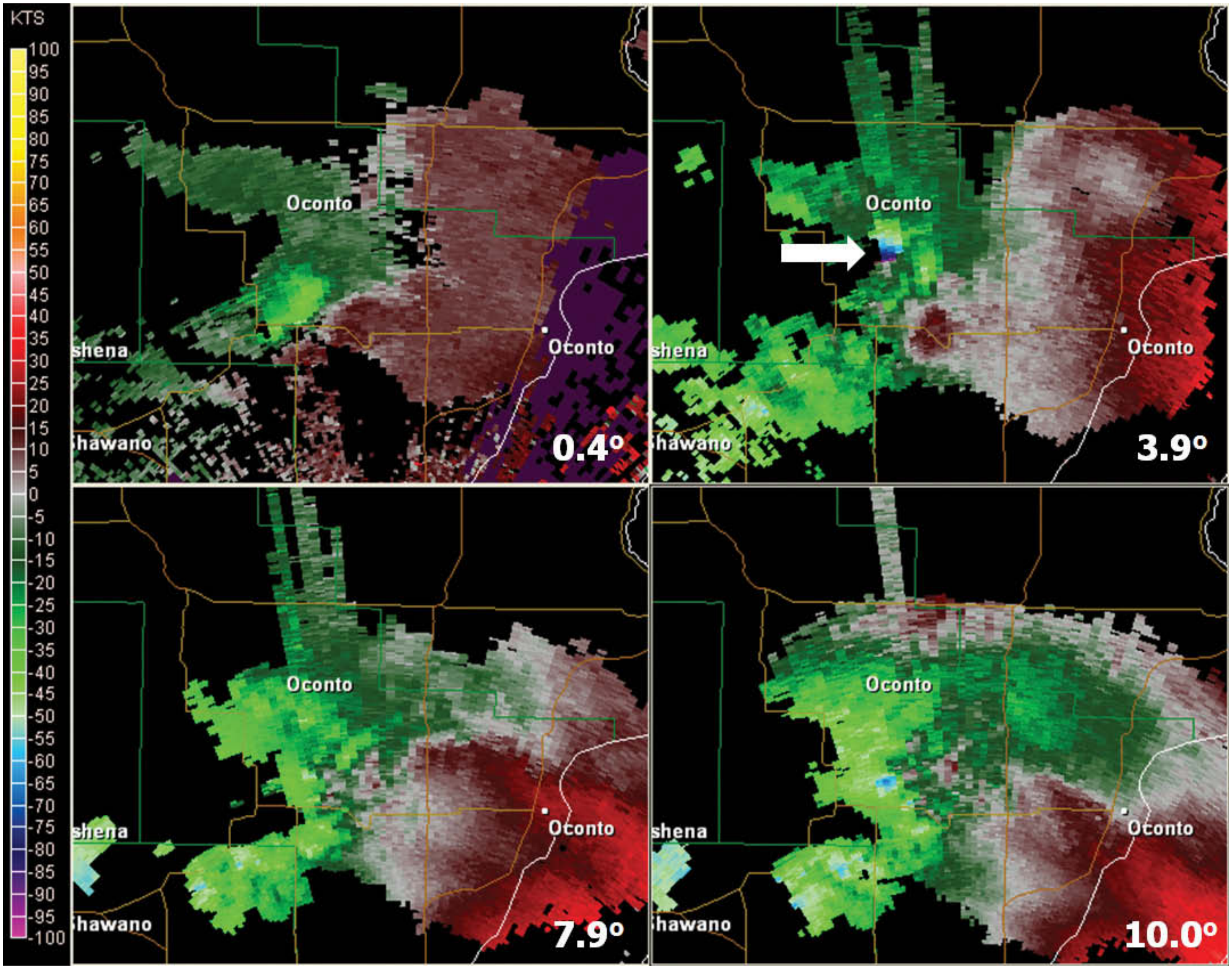
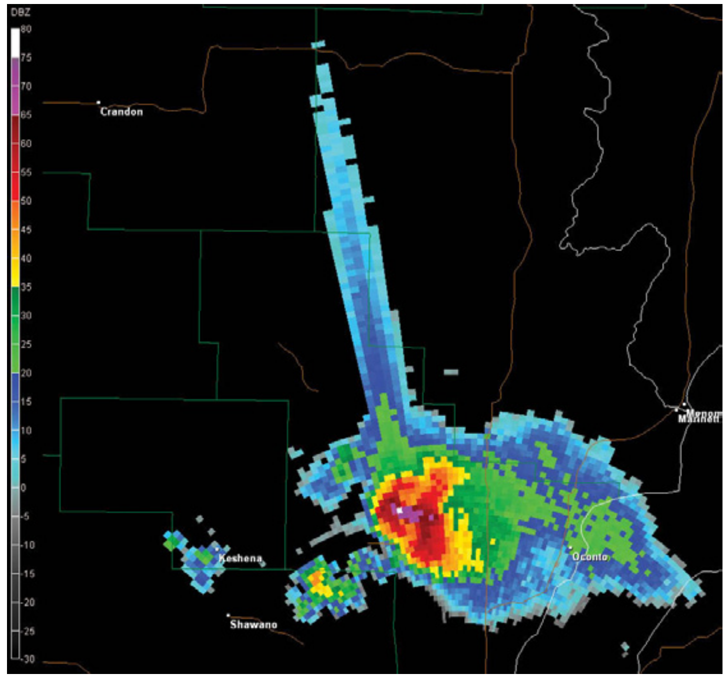


Fig. 10. Display is as in Fig. 7 except showing storm-relative velocity. Rotation in the storm was broad and unorganized; the TBSS caused anomalously high storm-relative velocity values of 92 knots at 3.9 degrees denoted by the white arrow (upper right).

Fig. 11 (to right). Reflectivity image from the GRB Doppler radar at 2049 UTC 1 July 2006 showing the 7.9 degree elevation slice. This image highlights the very large hail core 23,535 ft. (4.5 miles) above ground and 31.5 miles from the radar in Oconto County, WI. The reflectivity associated with the hail core was 76 dBZ, and had a 51 mile long TBSS emanating from it.



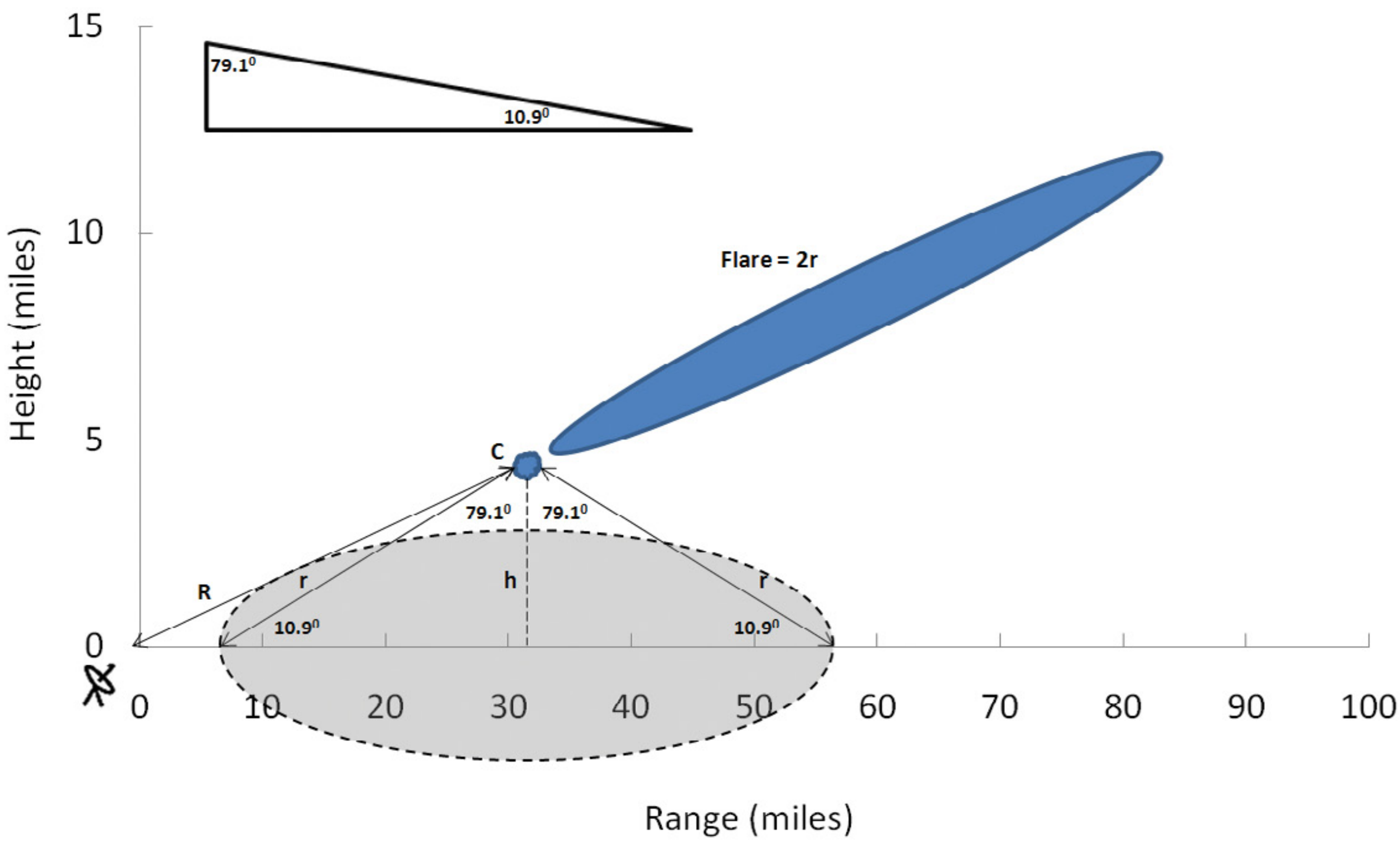


Fig. 12. Using the TBSS conceptual diagram (Fig. 1), the very long TBSS from the Oconto County storm (Fig. 11) is calculated. Blue shading near point C represents the 76 dBZ core responsible for producing the TBSS. Outbound radar energy follows path R (31.5 miles) and is then reflected off the hail core C. Part of this energy is returned downward along path r (25.5 miles), where it is deflected off the ground in a cross sectional area denoted by the dark shaded oval, before traveling back to the hail core C, and then back to the radar along path R. The deflected energy from the ground causes the radar to "see" hydrometeors along path h (23,535 ft or 4.5 miles) which causes the 2r long Flare (51 miles). The scattering angle of 79.1 degrees and angle of the reflected energy that hits the ground (10.9 degrees) are not drawn to scale due to the exceptionally long range in the conceptual diagram. The inset in the upper left shows a right triangle with the actual angles used in the cross section.

Conclusions

Supercell thunderstorms produced large hail during the late afternoon and early evening hours (Fig. 13) with one supercell producing hail up to 4 in. in diameter as it moved through Oconto County. This supercell exhibited a rare triple TBSS with three separate hail cores evident in plan-view and isosurface analysis, and produced an unusually long, impressive 51 mile TBSS, indicative of large hailstones with a coating of liquid water. This unusually long TBSS signature produced a scattering angle of 79.1 degrees, requiring giant hail, high quantities of that large hail, and an unusually large size of the hail core in the radial direction, which is confirmed by the 76 dBZ reflectivity values in the hail core (Fig. 11). This unusually high scattering angle means the scattered energy hits the ground at a very low angle, 10.9 degrees, and hits a large cross sectional area of the ground (Fig. 12). The high scattering angle and high dBZ values in the hail core led to more energy being back scattered to the radar, leading to a long and strong TBSS.

3-D visualization software GR2AE was very helpful in diagnosing the structure and character of the individual hail cores and their associated hail spikes. In particular, it was shown that TBSS signatures are 3-D features that are not confined to just a single elevation slice. 3-D visualization software can aid in identifying individual hail cores and their associated TBSS signatures, something that could be exceptionally useful in the warning decision making process when determining which cores contain the largest hail.

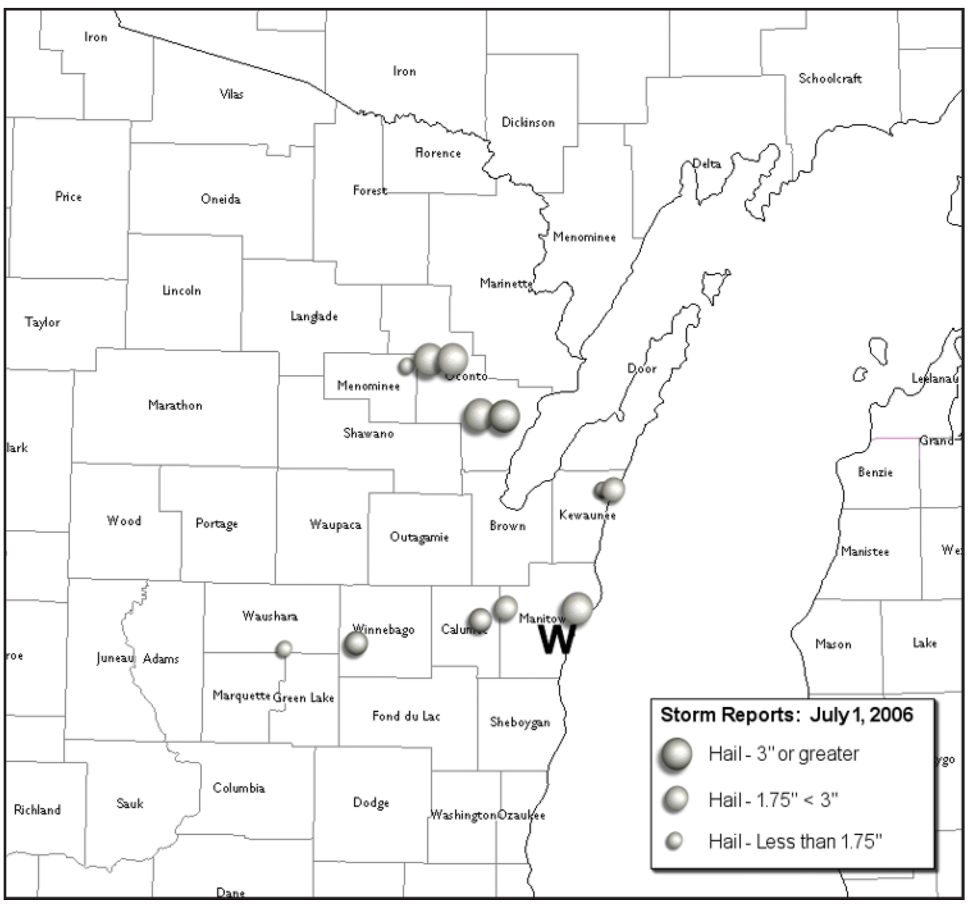


Fig. 13. Reports of large hail (inches), and one severe wind report (denoted by W) across northeastern Wisconsin on 1 July 2006. Image courtesy of Jeff Last, WCM NWS Green Bay, WI.

Author

Phillip G. Kurimski is a Senior Forecaster with the NOAA/National Weather Service Forecast Office in Detroit/Pontiac, Michigan. Phil researched this case while he was stationed as a Forecaster with the NOAA/National Weather Service Forecast Office in Green Bay, Wisconsin and was the Warning Decision Maker during this event. Phil received his B.S. in Meteorology from the State University of New York, Brockport in 1997, and his M.S. in Geosciences from the University of Wisconsin at Milwaukee in 1999.

Acknowledgments

The author would like to express his sincere gratitude to Paul Schlatter, of the NWS Warning Decision Training Branch (WDTB), for his assistance in putting this event in historical context by providing comments and references on the TBSS. Paul also provided useful comments and suggestions on this manuscript. The author would also like to acknowledge Gene Brusky and Jeff Last, SOO and WCM respectively, from the NWS Green Bay office, for their help with the initial research and assistance in putting together presentations and posters for several conferences on this storm. The author would like to thank Rich Mamrosh, Senior Forecaster NWS Green Bay; Dr. Patrick Market, of the University of Missouri at Columbia; Dan Miller, SOO NWS Duluth; and Dr. Greg Mann, SOO NWS Detroit/Pontiac for providing useful comments and suggestions on this manuscript. Leslie R. Lemon, WDTB/CIMMS, offered possible explanations regarding the unusually long TBSS. The author would like to thank James W. Wilson at NCAR for giving permission to reprint Fig. 2 from Wilson and Reum 1988, which is used in this paper (Fig. 1) as well as Jared Alfson, KC9IPS and Kris Ingenthron, KC9KNC for giving permission to print the pictures of the large hailstones used in this paper (Fig. 2).

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