Lindley, T. T., and L. R. Lemon, 2007: Preliminary observations of weak three-body scatter spikes associated with low-end severe hail. *Electronic J. Severe Storms Meteor.*, 2 (3), 1–15.

Electronic Journal of
SEVERE STORMS METEOROLOGY

Preliminary Observations of Weak Three-Body Scatter Spikes Associated With Low-End Severe Hail

T. TODD LINDLEY
NOAA / NWS, Weather Forecast Office, Lubbock, Texas

LESLIE R. LEMON
Cooperative Institute for Mesoscale Meteorological Studies –
NOAA/NWS, Warning Decision Training Branch, Norman, Oklahoma

(Submitted 6 June 2006, in final form 3 July 2007)

ABSTRACT

The three-body scatter spike (TBSS), an artifact caused by radar microwave scattering associated with large hydrometeors, traditionally has been utilized in the National Weather Service as an operational indicator of destructive hail. Severe weather warning strategies based on the TBSS were derived using a lower-bound reflectivity threshold of 5 dBZ. With recent WSR-88D workstation software and product upgrades, the operational display of very low value reflectivity data to -30 dBZ has allowed meteorologists to observe more subtle, but meaningful, atmospheric targets and artifacts. Since these upgrades, radar-based interrogations of thunderstorms over west Texas and South Dakota (among other places) have revealed weak TBSS signatures characterized by faint radar returns as low as -14 dBZ. A sufficient dataset of weak TBSS cases does not exist currently to support a robust statistical analysis. Preliminary observations, however, indicate that the artifact may occur prior to and during low-end severe hail measuring between 1.9 cm and 2.5 cm in diameter, especially when recognized to emanate from pulse-type convective storms sampled at close range over the Great Plains. These observations suggest that an extension to the current conceptual use of the conventional TBSS model, which associates the traditional signature to a likelihood of "very large hail," should be investigated.

1. Introduction

The three-body scatter spike (TBSS) is a radar microwave scattering artifact occasionally observed in association with severe convection producing large and damaging hail. The signature appears most commonly as a "flare echo" comprised of weak reflectivities that extend down-radial from intense mid level precipitation cores (Fig. 1).

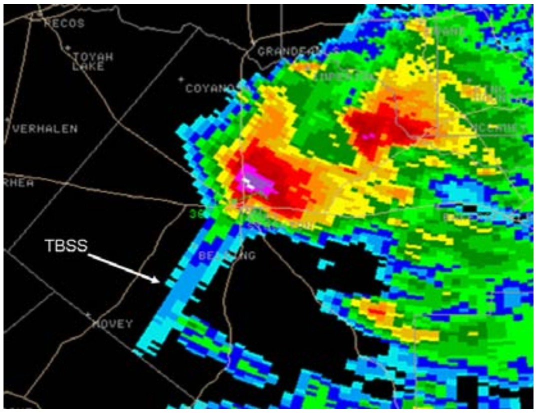


Figure 1: A TBSS example associated with 11 cm hail (NCDC 2002). Radar image at 1.5° elevation from the Midland, Texas, WSR-88D, 0118 UTC 11 May 2002.

Corresponding author address: T. Todd Lindley, National Weather Service, 2579 S. Loop 289 #100
Lubbock, TX 79423.
Email: Todd.Lindley@noaa.gov

Zrnić (1987) concluded that the TBSS signature is an artifact caused by non-Rayleigh, or Mie, scattering from a region of large hydrometeors, most frequently large and wet hailstones. According to Zrnić the process consists of: 1) forward microwave scattering from strongly reflecting hydrometeors to the ground below, 2) backscattering from the ground to the same hydrometeor region aloft, and 3) backscattering to the radar (Fig. 2).

In agreement with Zrnić and as a consequence of Mie scattering, Wilson and Reum (1988) concluded that the TBSS artifact is dependent on radar wavelength, with the occurrence frequency of TBSS decreasing with increasing radar wavelength. Wilson and Reum demonstrated that the signature can be created by large raindrops illuminated with 3 cm (X-band) and 5 cm (C-band) wavelength radars. The artifact, however, only occurs with the use of larger wavelength radars when hydrometeors become sufficiently large to exceed the 1/16 scatterer diameter to radar wavelength ratio that results in Mie scattering (Zrnić 1987). Lemon (1994 and 1998) extended these findings by deriving an operational application and criteria for the signature as observed by 10 cm (S-band) wavelength radars, such as the WSR-88D. This application has been utilized as a deterministic indicator of hail ≥ 2.5 cm in diameter.

Lemon (1998) recommended applicable use of the TBSS in the National Weather Service's (NWS) severe storm warning program. As described above, warning decision making (WDM) methodologies derived from Lemon's study suggest that the recognition of a TBSS is a sufficient, but not a necessary indicator for the impending occurrence of "very large hail" (NOAA WDTB 2004).

Both Lemon's study and current WDM practices in the NWS are based on a minimum reflectivity detection of 5 dBZ. This was the lower-bound reflectivity value viewable by meteorologists interrogating WSR-88D "precipitation mode" data on operational workstations through the turn of this century. Previous studies and diagrams by Wilson and Reum (1986 and 1988), however, showed that TBSS signatures defined by minimum reflectivity contours between -10 dBZ and -5 dBZ were detected with radars of varying wavelengths between 3 cm (X-band) and 10 cm (S-band). Some of these weak TBSSs, observed over Alabama, seldom were associated with surface hail. Lemon acknowledged that lowering the displayable lower-bound reflectivity threshold would increase TBSS frequency, and that the operational importance of such "weak" signatures likely would be altered with potentially smaller scatterers resulting in TBSS artifacts in WSR-88D data.

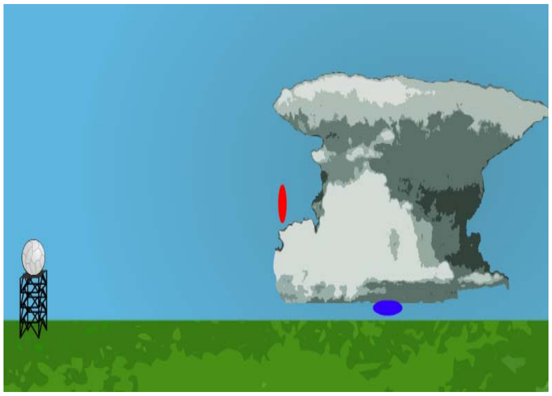


Figure 2: This FLASH animation (NOAA WDTB 2004) serves as a simplistic depiction of the triple reflected microwave scattering that results in the radar detected TBSS. *Click image for animated FLASH graphic (29KB).*

In 2002, the NWS deployed WSR-88D Open Radar Product Generator (ORPG) Build 1.2 and the Advanced Weather Interactive Processing System (AWIPS) Build 5.2.1 (NOAA WDTB 2002). These were the initial software upgrades to support "8-bit" 256 data level radar imagery with displayed reflectivity values ranging from -30 dBZ to 90 dBZ in the operational environment. The inclusion of very weak radar returns, previously filtered out of the WSR-88D dataset because of equipment and bandwidth limitations, has enhanced sampling and allowed NWS meteorologists to detect more subtle meteorological features.

Since the 8-bit data became operationally available, close range radar-based observations of convective storms producing low-end severe hail (defined here as hail between 1.9 cm and 2.5 cm), indicate that weak reflectivity (less than the previous lower-bound reflectivity of 5 dBZ) TBSS signatures are detectable using the WSR-88D. The weak TBSS most frequently has been observed prior to surface hail fall measuring less than 2.5 cm in diameter within pulse-type severe storms, as defined Burgess and Lemon (1990).

This paper will present animated WSR-88D imagery depicting five storms exhibiting weak TBSSs. The evolution of two such storms will be detailed, showing the initial weak TBSS signatures as hail cores develop aloft, and then tracking the core's descent prior to the occurrence of low-end severe hail. Possible contamination of radial velocity-derived products within the weak

TBSS, and the potential use of spectrum width data in identifying this subtle artifact will be discussed. Lastly, radar, ground-truth information, and photographic imagery of a sixth artifact-bearing storm will be used to illustrate the convective mode associated with a particular weak TBSS hail event.

Based on these observations, the authors suggest that the weak TBSS may have operational utility as a close range (within 75 km) indicator of hail measuring 2.5 cm in diameter or less. A more exhaustive study, however, consisting of additional weak TBSS cases and statistical analyses is required to confirm such correlation. Instead this paper is intended to document preliminary observations of weak TBSS occurrences for the benefit of operational forecasters involved in the WDM process. Conditions in which the weak TBSS may be observed in association with more organized and significant severe storms also will be briefly discussed.

2. Observed weak TBSS cases

Radar analyses of five low-end severe thunderstorms bearing weak TBSSs over west Texas and South Dakota are provided in the form of animated four-panel reflectivity data. Additionally, the appearance of the weak TBSS in 8-bit data is contrasted to the lack of conventional three-body scattering in 4-bit data, or when the lower-bound reflectivity is 5 dBZ, for each case. Data for these cases are presented in Table 1 as Fig. 3 through Fig. 12. During these events, weak TBSSs were recognized prior to and during surface hail fall measuring 2.5 cm in diameter or less. During one event, hail also was accompanied by damaging thunderstorm winds.

All of the storms examined here occurred within 75 km of the respective WSR-88Ds; Midland, Texas (KMAF), Lubbock, Texas (KLBB), and Rapid City, South Dakota (KUDX). The weak TBSS artifacts emanated from hail-bearing precipitation cores at heights between 1200 m and 8200 m [all heights above ground level (AGL) and rounded to the nearest 100 m given ambiguity from radar beamwidth and other assumptions]. The storms of interest exhibited well-defined weak TBSS signatures and were well-observed by trained storm spotters.

The evolution of two weak TBSS events from the above dataset is detailed in the following individual case studies.

a. Detailed examination of the 4 July 2005 weak TBSS case

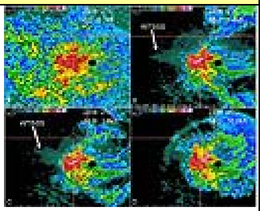
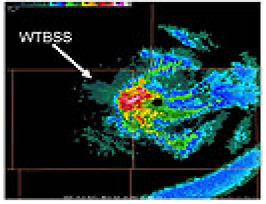
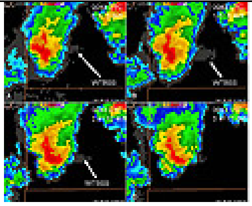
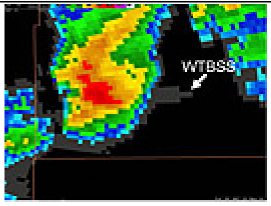
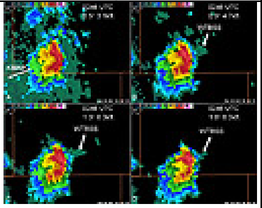
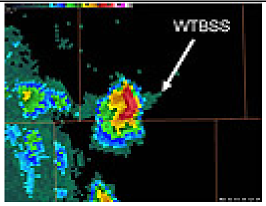
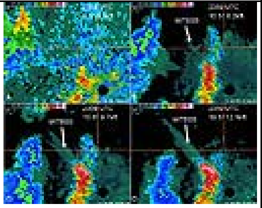
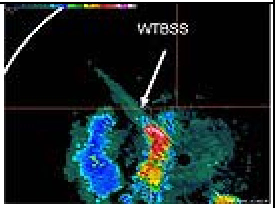
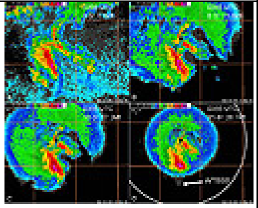
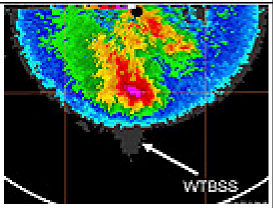
A severe thunderstorm affected Howard County, Texas, during the early hours of 4 July 2005. The KMAF four-panel reflectivity imagery of this storm is depicted in Fig. 7. A weak TBSS initially was recognized in the 0.9° and 1.3° (1500 m and 1800 m) elevation scans at 0241 UTC (Fig. 7 panels B and C). Reflectivity values contained within the weak TBSS ranged from -3.5 dBZ to 3.5 dBZ, and the artifact emanated from a core characterized by maximum reflectivity values of 62 dBZ. These maximum core reflectivities are comparable to those observed in association with conventional TBSS artifacts downrange of 63 dBZ or greater core echoes, as noted by Lemon (1998).

In the 0246 UTC volume scan, the maximum reflectivity of the storm's core maintained near constant height and intensity (61 dBZ at 1800 m) relative to the previous scan. The weak TBSS, however, became more apparent through a deeper layer. The artifact was recognized in the 0.9° through 1.8° (1500 m through 2400 m) elevation slices (Fig. 7 panels B, C, and D). Reflectivity values within the weak TBSS ranged from -1.5 dBZ to 4.5 dBZ.

By 0251 UTC, radar revealed a slight decrease in intensity. A weak TBSS was only recognizable in the 0.9° (1500 m) elevation slice (Fig. 7 panel A). Reflectivity values within the artifact ranged from -2 dBZ to 5 dBZ. The weak TBSS signature emanated from a maximum reflectivity core of 57 dBZ. Maximum reflectivities within the weak TBSS-bearing core were notably less than those traditionally observed with TBSS. At the time of this volume scan, 2.25 cm hail was reported in the community of Elbow (NCDC 2005a).

In this example, the initial conclusive evidence of a weak TBSS was recognizable at least ten minutes before surface hail fall was observed. A simple comparison using the 0241 UTC 1.3° (1800 m) elevation slice demonstrates the enhanced ability to detect three-body scatter signatures in 8-bit data against the legacy 4-bit data with a 5 dBZ lower-bound reflectivity (Fig. 8). In this instance, the weak TBSS was most pronounced with reflectivity values as low as -3.5 dBZ; therefore, no identifiable TBSS is present when the lowest value reflectivity data displayed is 5 dBZ.

Table 1: Animated and static reflectivity data showing five examples of weak TBSS (WTBSS)-bearing storms associated with low-end severe hail are presented in Fig. 3 through Fig. 12, including comparisons of 4-bit and 8-bit data. Severe weather reports, sampling range to the artifact-producing reflectivity core, and WSR-88D radar are indicated. *Click on the image thumbnails to view full-resolution images and to access the animated case presentations. * Severe weather reports per NOAA/NCDC Storm Data (NCDC 2003, NCDC 2004, NCDC 2005a, NCDC 2005b, and NCDC 2006).*

Examples of Weak TBSSs Associated With Low-End Severe Hail				
Event Date	Animated Four-Panel Reflectivity	4-bit vs. 8-bit / TBSS vs. Weak TBSS Comparisons	Severe Weather*	WSR-88D (Range)
31 May- 1 June 2003	 Figure 3	 Figure 4	2.25 cm hail & $36\ \mathrm{m\ s^{-1}}$ winds	KMAF (11 km)
22 May 2004	 Figure 5	 Figure 6	2.5 cm hail	KUDX (72 km)
4 July 2005	 Figure 7	 Figure 8	2.25 cm hail	KMAF (61 km)
12-13 August 2005	 Figure 9	 Figure 10	2.25 cm hail	KMAF (16 km)
31 May 2006	 Figure 11	 Figure 12	2.25 cm hail	KLBB (29 km)

b. *Detailed examination of the 12-13 August 2005 weak TBSS case*

The brief life cycle of a pulse-type severe storm occurred over northwestern Midland County, Texas, around 0000 UTC 13 August 2005. This storm exhibited a dramatic weak TBSS that was sampled at close range by the KMAF 88D.

Rapid convective intensification is seen in the 19.7° (3000 m) elevation slice (Fig. 9 panel D) after 2350 UTC. A 64 dBZ elevated core and weak TBSS characterized by flare reflectivities ranging from -14 dBZ to -3 dBZ is identified initially at 2355 UTC. By 2359 UTC, the weak TBSS became very pronounced in the 10.5°, 15.6° and 19.7° (1800 m, 3000 m, and 3700 m) elevation cuts (Fig. 9 panels B, C, and D). A substantial portion of the storm's vertical extent [heights above the 19.7° (3700 m) slice] was not sampled due to the storm's proximity to the KMAF 88D. It is likely that the hydrometeors producing the artifact originated in a hail growth layer above this level, where sufficiently cold temperatures existed to support hail formation. The 0004 UTC scan sampled the hail core as it descended through the lower portion of the storm. Reflectivities above 3000 m decreased, and evidence of a weak TBSS aloft disappeared (Fig. 9 panels C and D). Maximum reflectivities below 3000 m continued to increase as the core descended through the storm's low levels, and the weak TBSS persisted at the 10.5° (2100 m) elevation height (Fig. 9 panel B) with artifact reflectivities ranging from -13 dBZ to 4 dBZ and maximum reflectivities within the core increasing to more than 65 dBZ.

By 0009 UTC, 65 dBZ reflectivities had descended to the 0.5° elevation (near-surface). At this time, marginal to low-end severe hail was falling. When hail fall ceased, 0.6 cm to 2.25 cm hail covered the ground (NCDC 2005b).

As in the previous case, a comparison of reflectivity data at a specific elevation cut and time is used to emphasize the dramatic difference between three-body scattering represented by the legacy 4-bit imagery and that observed with 8-bit products (Fig. 10). Examination of the 2359 UTC 19.5° (3700 m) elevation slice using 8-bit data clearly depicted three-body scattering in the form of a weak TBSS. Flare reflectivity ranging from -11 dBZ to 2 dBZ extended down-radial a distance of 30 km from a 70 dBZ elevated core. Little evidence of three-body scattering is observed using the 5 dBZ lower-bound reflectivity threshold of 4-bit data for the same elevation slice and time, and the use of TBSS would not have been possible in the WDM process. By using 8-bit reflectivity data, however, the initial weak TBSS could be conclusively identified at least ten minutes prior to surface hail fall.

The potential utility of the weak TBSS signature is restricted with increasing range from the radar. This limitation is due to the radar's decreased ability to detect weak reflectivity values at range through power loss by attenuation, absorption, averaging across the widening beamwidth, and a decreasing signal to noise ratio with increasing distance. The range-limiting attributes of the weak TBSS can be demonstrated in this case by using data from the neighboring San Angelo, Texas, WSR-88D (KSJT).

A comparison of the KMAF 2359 UTC reflectivity at 19.7° (3700 m) with the KSJT 0.5° (3400 m) reflectivity at 2357 and 0003 UTC shows dramatic differences in three-body scattering. Sampling distances were 16 km and 195 km from the KMAF and the KSJT radars respectively. No conclusive evidence of three-body scattering is identifiable in the KSJT imagery (Fig. 13 panel A and B), with only subtle hints of "flaring" present. In fact, the 0003 UTC 8-bit reflectivity image from KSJT (Fig. 13 panel B) is comparable to the 19.5° (3700 m) legacy 4-bit image from KMAF at 2359 UTC (Fig. 13 panel D) due to the power losses previously discussed, and neither TBSS nor weak TBSS could be used with confidence in the WDM process when sampled from the range and azimuth of the KSJT 88D.

c. *Photographic observation of a weak TBSS-bearing storm and weak TBSS velocity contamination*

During the 4 July 2005 severe weather episode, a second weak TBSS-bearing storm was observed within 15 km of the KMAF 88D. An off-duty NWS meteorologist provided photographic documentation of the storm and ground-truth verification of observed hail sizes.

KMAF reflectivity from 0150 UTC 4 July 2005 (Fig. 14 panels A and B) depicts weak TBSSs within the 4300 m to 5000 m layer in association with a thunderstorm over northern

Midland County, Texas. A careful analysis of the data reveals three discernible weak three-body scatter signatures resulting from individual updrafts and associated hail cores within the small multicell storm. The weak TBSSs are more apparent in analysis of the corresponding artifact-contaminated relative motion (SRM) data (Fig. 14 panels C and D) where in-bound velocities are enhanced along the TBSS-bearing radials.

The strong in-bound SRM velocities (-32 m s^{-1}) within the weak TBSS immediately down-radial from the maximum reflectivity core are significant. Wilson and Reum (1986 and 1988) recognized that enhanced in-bound Doppler velocities between roughly -20 m s^{-1} and -40 m s^{-1} are common within TBSSs. Additionally, Lemon (1998) noted that Doppler velocity patterns associated with three-body scatter generally are characterized by broad noise-like spectra and contamination, and that the data are unreliable because they result from a complex compilation of radial velocities and hydrometeor vertical motions, with each range gate representing an infinite number of target contributions. Artifact velocity contamination associated with the conventional TBSS has been known to obscure useful storm related velocity signatures such as mesocyclones (Smallcomb 2006). It is unknown if velocity and/or SRM contamination caused by the weak TBSS would be sufficient to obscure meaningful storm features. Such contamination, however, was noted with at least four of the six cases presented here.

Spectrum width data have been shown to be useful for identifying obscure TBSSs, owing to the very large values of spectrum width associated with three-body scatter (Lemon 1998). In this case, high values of spectrum width (9 m s^{-1} to 15 m s^{-1}) were observed within the weak TBSS, as evidenced by the 15.6° spectrum width at 0150 UTC (Fig. 15). Therefore, as with traditional TBSS signatures, spectrum width should be used to help identify subtle or obscured weak TBSSs.

Near the time of the radar observed weak TBSSs, numerous reports indicated that the storm produced 2.25 cm hail between 0144 and 0156 UTC over the north side of Midland, with a single report of 2.5 cm hail also received. It is noteworthy that an outlying report of 4.5 cm hail was received during the storm, and was documented in *Storm Data* (NCDC 2005a).

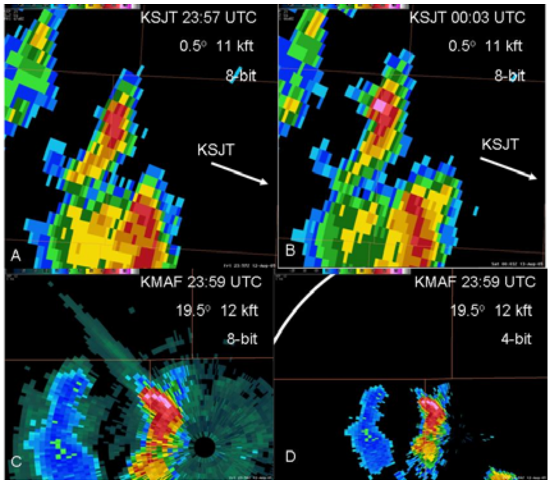


Figure 13: A comparison of three-body scattering at similar heights and times from the nearby KMAF 88D and more distant KSJT 88D. Four-panel format:
A = KSJT 0.5° 8-bit (3400 m AGL) at 2357 UTC,
B = KSJT 0.5° 8-bit (3400 m AGL) at 0003 UTC,
C = KMAF 8-bit 19.5° (3700 m AGL) at 2359 UTC, and
D = KMAF 4-bit 19.5° (3700 m AGL) at 2359 UTC.

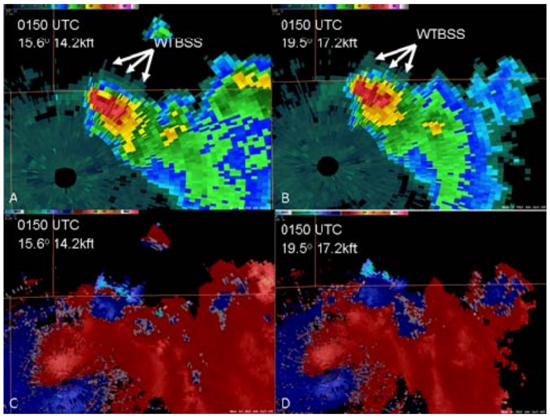


Figure 14: Reflectivity and corresponding SRM four-panel showing a weak TBSS (WTBSS)-bearing storm from the KMAF 88D over Midland, Texas, on 4 July 2005 at 0150 UTC. Four-panel format:
A = 15.6° (4300 m AGL) Z,
B = 19.5° (5000 m AGL) Z,
C = 15.6° (4300 m AGL) SRM, and
D = 19.5° (5000 m AGL) SRM.

Given excellent sampling of the hail core over an urban area by trained spotters, including corroborated reports by many reliable Skywarn spotters, the media, the public, and off-duty NWS meteorologists, that indicated smaller hailstone sizes, the 4.5 cm hail report is suspect and unrepresentative. NWS meteorologists, that indicated smaller hailstone sizes, the 4.5 cm hail report is suspect and unrepresentative.

An NWS meteorologist photographed the storm (Fig. 16) minutes before traveling through one of the hail cores. The view in the photo is looking in a westerly direction toward the storm's updraft at approximately 0150 UTC, and shows a small updraft base with little visible precipitation. The visual appearance of this weak TBSS-bearing storm, combined with data presented in this study, and the authors' experience suggest that the weak TBSS may have more operational utility in the interrogation of low-end severe multicell and/or pulse-type thunderstorms than the traditional TBSS artifact. Traditional TBSSs, in contrast, are frequently associated with more intense and long-lived storms that produce very large hail and destructive winds (Lemon 1998).

3. Conclusions and observational implications

Detailed radar-based interrogations of five low-end severe storms over west Texas and South Dakota have revealed weak three-body scatter signatures characterized by reflectivity values as low as -14 dBZ. A sixth case illustrating weak three-body scatter was correlated to a photograph of the artifact-bearing storm. This storm (as did others) additionally displayed radar-based anomalies in spectrum width and velocity-derived products. Spectrum width has been used to identify subtle and obscure three-body scattering artifacts.

Well-developed weak TBSS signatures were observed to emanate from hail-bearing precipitation cores with reflectivities greater than 56 dBZ. The weak TBSSs occurred in association with storms that produced hail measuring 2.5 cm in diameter or less. All of the observed cases occurred within 75 km of the KMAF, KLBB, and KUDX radar sites, and the utility of such weak signatures is range-limited. The actual range limitation can be established only in practice, but was shown to be less than 195 km for the 12-13 August 2005 storm near Midland, which also was sampled by the neighboring KSJT 88D.

While the preliminary dataset herein does not represent a statistically large sample size, these observations may suggest that the weak TBSS signature commonly indicates low-end severe hail measuring less than or equal to 2.5 cm in diameter. Recognition of the artifact may have operational utility in the integrated WDM process, especially as related to pulse-type thunderstorms over the Great Plains.

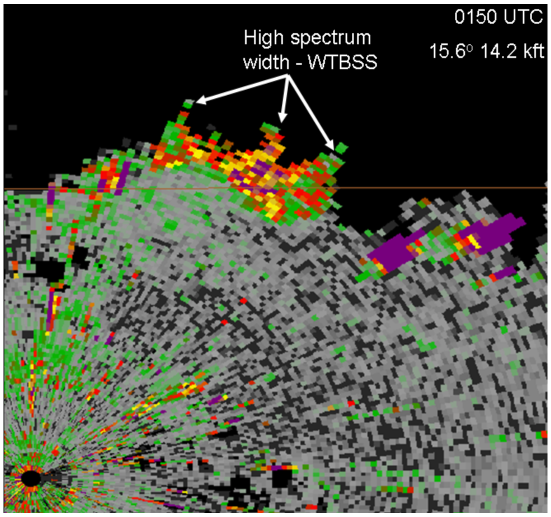


Figure 15: High values of spectrum width observed within weak TBSS (WTBSS) at 15.6° (4300 m) during the 4 July 2005 0150 UTC KMAF volume scan.

Figure 16: The view looking west toward a weak TBSS-bearing storm over Midland, Texas, at 0150 UTC 4 July 2005. Photo by Cody Lindsey.

It is noted that similar signatures observed with 3 cm (X-band) and 5 cm (C-band) wavelength radars over Alabama had no correlation to surface hail fall (Wilson and Reum 1988). An addition to the current conceptual models relating three-body scatter artifacts to particularly large and destructive hail should be investigated for possible inclusion of weak signatures associated with relatively lower-end severe weather threats.

The weak TBSS signature also may be observed during the early development and initial hail-growth stages of more organized severe storms. Such storms may quickly evolve to present a more significant threat of large hail. Additionally, organized severe storms that exist in a particularly dry environment may contain large hail stones that have a relatively dry exterior with little or no liquid water coating. Less reflective than the more common water coated hail stones attributed to traditional TBSS artifacts, these hydrometeors may be associated with weak TBSS. Bunkers (2006) noted a weak TBSS-bearing supercell thunderstorm that resulted in 7.0 cm hail in a deeply dry atmosphere over South Dakota (Fig. 17) on 20 July 2005. Forecasters using the weak TBSS signature operationally should maintain high levels of situational awareness with regard to the ambient near-storm environment; and should monitor for continued storm intensification that may result in a traditional TBSS or other indicators, such as convective mode, that represent an increased severe weather threat.

In addition, severe and sometimes extreme downburst winds commonly are associated with storms displaying traditional TBSS signatures (Wilson and Reum 1986 and Lemon 1998). Damaging winds estimated up to 36 m s^{-1} and 2.25 cm hail accompanied the weak TBSS-bearing storm near Midland, Texas, on 31 May 2003 (Fig. 3). Only one out of six cases presented here was accompanied by severe surface gusts. Therefore, the limited weak TBSS dataset does not indicate a corresponding relationship between the weak TBSS and destructive winds at the ground. Since downbursts are commonly associated with storms producing even small hail, however, forecasters independently should assess the near-storm environment for the potential of damaging surface winds with weak TBSS-exhibiting storms.

Future research will need to focus on expanding the weak TBSS dataset with cases associated with differing convective modes and ground-truth verification. Although the authors suggest that diagnosis of the weak TBSS may be operationally useful for detecting low-end severe hail in pulse-type convection over the Great Plains, and that an addition to the current TBSS model should be investigated, a more thorough statistical analysis is clearly required before operational warning practices are modified. As well, cases from other geographical regions both throughout the U.S. and internationally should be included in a more vigorous dataset. Moreover, because of the common use of 5 cm (C-band) wavelength weather radars by the media and by international weather services, the authors welcome corresponding studies using those radar systems. In order to extend this study, extensive and accurate ground-truth information is essential to the proper analysis of candidate storms accompanied by similar weak TBSS signatures.

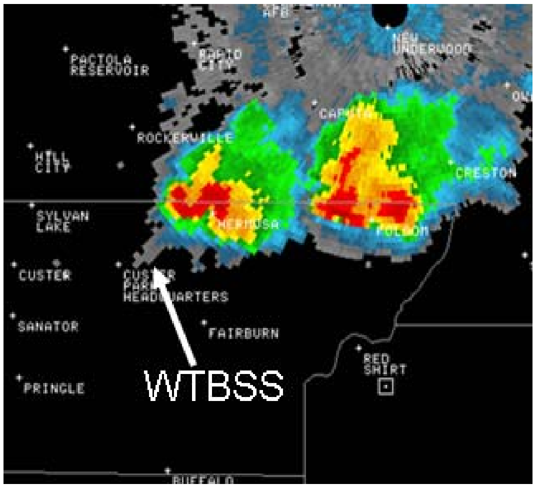


Figure 17: A supercell thunderstorm in a notably dry airmass over South Dakota accompanied by weak TBSS (WTBSS) and 7.0 cm size hail on 20 July 2005 (NCDC 2005a).

Acknowledgments: The authors would like to extend their gratitude to the reviewers and all of those who assisted in the completion of this paper and the research presented herein. This includes: Rebecca Gould, Greg Jackson, Greg Murdoch, and Pat Vesper of the NWS Forecast Office in Midland, Texas, Steve Cobb, Gary Skwira, John Holsenbeck, and Justin Weaver of the NWS Forecast Office in Lubbock, Texas, and Jeffrey Cupo of the NWS Forecast Office in San Juan, Puerto Rico, for their technical and editorial assistance. Cody Lindsey, also of the NWS Forecast Office in Midland, Texas, provided photographic documentation and ground-truth verification of the 4 July 2005 Midland event, and Matthew Bunkers of the NWS Forecast Office in Rapid City, South Dakota, provided case data and correspondence. NWS Warning Decision Training Branch meteorologists Elizabeth Quoetone and Paul Schlatter additionally provided correspondence, technical and editorial information. Sharon Tarbet assisted in the editorial process.

REFERENCES

Bunkers, M. J., 2006: An update on TBSSs and relatively moist environments. NOAA/NWS local training study, National Weather Service Forecast Office, Rapid City, SD, [Available online at: http://www.srh.noaa.gov/lub/science/research/TBSS-moisture.ppt EJSSM copy: http://www.ejssm.org/ojs/public/vol2-3/TBSS-moisture.ppt]

Burgess, D. W., and L. R. Lemon, 1990: Severe thunderstorm detection by radar. *Radar in Meteorology*, D. Atlas, Ed., Amer. Meteor. Soc., Boston, MA, 619-647.

Lemon, L. R., 1994: Recognition of the "three-body scatter spike" as a large hail signature. Postprints, *The First WSR-88D Users Conf.*, Norman, OK, WSR-88D Operational Support Facility, 373-388.

Lemon, L. R., 1998: The radar "three-body scatter spike": An operational large-hail signature. *Wea. and Forecasting*, **13**, 327-340.

NCDC, 2002: *Storm Data*. Vol. 44, No. 5, 379 pp. [Available online at: http://www.ncdc.noaa.gov/oa/climate/sd/]

NCDC, 2003: *Storm Data*. Vol. 45, No. 5, 433 pp. [Available online at: http://www.ncdc.noaa.gov/oa/climate/sd/]

NCDC, 2004: *Storm Data*. Vol. 46, No. 5, 474 pp. [Available online at: http://www.ncdc.noaa.gov/oa/climate/sd/]

NCDC, 2005a: *Storm Data*. Vol. 47, No. 7, 320, 349 pp. [Available online at: http://www.ncdc.noaa.gov/oa/climate/sd/]

NCDC, 2005b: *Storm Data*. Vol. 47, No. 8, 271 pp. [Available online at: http://www.ncdc.noaa.gov/oa/climate/sd/]

NCDC, 2006: *Storm Data*. Vol. 48, No. 5, 371 pp. [Available online at: http://www.ncdc.noaa.gov/oa/climate/sd/]

NOAA WDTB, 2002: ORPG Build 1.2 Training. [Available online at http://www.wdtb.noaa.gov/buildTraining/RPG1_2/]

NOAA WDTB, 2004: ICSvr 3-V-A: Three body scatter spike. AWOC Storm Interrogation Severe Track notes, Lesson 20 [Available online at: http://www.wdtb.noaa.gov/courses/awoc/documentation/screen/Supplemental_Lessons/ICSvr3-V-A_TBSS.pdf EJSSM copy: http://www.ejssm.org/ojs/public/vol2-3/ICSvr3-V-A_TBSS.pdf]

Smallcomb, C., 2006: Hail spike impacts on Doppler radial velocity data during several recent lower Ohio Valley convective events. *23rd Conf. on Severe Local Storms*. St. Louis, MO, Amer. Meteor. Soc., P9.2. [Available online at: http://ams.confex.com/ams/23SLS/techprogram/paper_115422.htm]

Wilson, J. W., and D. Reum, 1986: The hail spike: reflectivity and velocity signature. Preprints, *23rd Conf. on Radar Meteorology*. Snowmass, CO, Amer. Meteor. Soc., 62-65.

Wilson, J. W., and D. Reum, 1988: The flare echo: reflectivity and velocity signature. *J. Atmos and Oceanic Technol.*, **5**, 197-205.

Zrnić, D. S., 1987: Three-body scattering produces precipitation signature of special diagnostic value. *Radio Sci.*, **22**, 76-86.

REVIEWER COMMENTS

REVIEWER COMMENTS

[Authors’ responses in *blue italics*.]

REVIEWER A (James G. LaDue):

Initial Review:

Recommendation: Accept with Minor Revisions

Synopsis: This paper extends the discussion by Lemon (1998) on the operational uses of diagnosing the Three Body Scatter Spike (TBSS) as new 8 bit displays of radar reflectivity allow NWS forecasters to view less reflective versions of these features than what was operationally available during Lemon’s work. The authors examine several multicell thunderstorm cases where a Weak TBSS signature (WTBSS) is associated with marginally severe hail. The authors then make a recommendation that a WTBSS should be diagnosed to help forecasters anticipate hail smaller than 2.5cm in ordinary (nonsupercell) convective events. This study is more of an informal treatment on the diagnosis of WTBSSs and not a statistical study of its performance as a precursor signature to severe wind and/or hail. I believe this format is valuable in that it introduces a concept that is new. However it is not intended to be a substantive quantitative treatment of the signature and its usefulness.

Otherwise, I believe the paper is well written and organized. It should prove to be valuable contribution to anyone responsible for issuing severe thunderstorm warnings.

Major substantive comments:

I am concerned that the authors are making warning recommendations based on just 4 to 6 cases. Starting in the abstract and continuing onward, the authors make a recommendation that the existence of a WTBSS implies a warning forecaster should consider a warning for marginally severe hail and/or wind (assumption that marginal hail is 1.9 to 2.5 cm and winds 25 to 33 m/s). However, there is an insufficient number of cases and a lack of statistical analysis to warrant such suggestions. The authors admit in various places in the paper that the number of cases precludes making conclusions about such things as the association of high winds with a WTBSS and whether or not a WTBSS is associated with a supercell. In fact, the authors show a WTBSS with a supercell producing significant (>2.5cm) hail. I am willing to hypothesize that WTBSSs are more frequent than TBSSs for all storm types. Perhaps more WTBSSs are associated with marginally severe hail than true TBSSs but without the data, it’ll be hard for me to know. As an aside, Lemon (1998) also did not provide a strong statistical analysis of TBSSs and their association with severe hail and/or wind. I suggest that if guidelines and suggestions are to be made then a statistically significant number of cases be analyzed. Otherwise, the authors should refrain from making suggestions.

[Minor comments omitted...]

General Reply

The emphasis of the paper has been shifted to concentrate on introducing the WTBSS into the literature through the use of the presented cases, and to acknowledge that these are “preliminary observations”. In addition, the authors worked to increase the number of cases and their geographic diversity. The dataset remains small, however, so suggestions concerning operational WDM practices were either removed or stated with disclaimers concerning the need for statistical analysis. As an example, the section of the abstract referenced above was edited...

The authors believe that some inference to the possible utility of the WTBSS should remain. Thus the suggestion that an addition to the TBSS conceptual model should be investigated is retained.

Portions of the paper's introduction also were modified to address this concern...

Please see comments regarding WTBSS storm type and associated wind threats addressed elsewhere within our post revision responses…

REVIEWER B (James Johnson):

Initial Review:

Recommendation: Accept with Major Revisions

Summary: This paper is fairly clear and concise. It is an easy read and develops each point fairly well. The authors, drawing from one's earlier work, present a case for defining the weak reflectivity three-body scatter spike (WTBSS) and for using it in the operational warning decision process for low end severe hail and for downburst winds in near proximity to the radar. There appear to be a few problems however based on the citations provided. The authors effectively use available modern technology to enhance their presentation through graphical animations in keeping with EJSSM's desire to encourage more innovative methods of presentation. They are to be complimented on that. On a technical level this paper is excellent for an initial submission and the authors are commended for their quality of writing. From their acknowledgments, they clearly make good use of available assistance with the overall quality of the manuscript. There are, however, some issues of substance and organization in the paper which are addressed below. I hope the authors will re-work the manuscript somewhat to alleviate these concerns. This should easily make it worthy of publication in the EJSSM.

Issues of Substance:

Discussion:

Citation of Wilson and Reum (1988); "The Flare Echo: Reflectivity and Velocity Signature" is an excellent reference in support of the authors' case in that it supports the weak reflectivity artifact in association with smaller hail sizes as observed in Colorado by the CP-2 and CP-4 radars and reported in the PROFS, CIP, PRESTORM, and MAYPOLE project data sets.

Wilson and Reum (1988) (hereafter W&R) also examined data from storms in Alabama (MIST) using the same two radars but with somewhat different findings. In the Alabama data sets, these artifacts were more common than in the Colorado storms but were very seldom associated with surface hail. Furthermore, the artifacts in the Alabama data were generally weaker than those in the Colorado data and were never observed below 1 km. Finally, 2 of the Colorado storms which displayed the artifact produced no hail.

Unfortunately, W&R do not break down their data for all cases by dBZ so we do not know how many of the artifacts occurred for reflectivities less than +5 dBZ though they do provide a striking example from an Alabama storm (their Fig. 7) where this occurred and no hail was observed. This example was from the CP-4 radar, a radar of shorter 5cm wavelength which W&R (and Zrnić) found more likely to identify the feature due to the wavelength dependency.

Working Points:

1) From W&R, the reflectivity spikes are not always associated with hail. The same is apparently true for at least some of the weak reflectivity spikes. While this somewhat weakens the authors' position, it must be addressed as a caveat. That is to say, use of the artifact as a low end severe hail discriminator has at least some limitations which the authors need to address.

It is true that not all three-body scatter artifacts are associated with surface hail. As the reviewer correctly noted, this was previously demonstrated by W&R when working with storms that mainly occurred over the southeastern U.S. It is logical that this would indeed be the case with the WTBSS as well. Several operational meteorologists, in casual conversation with the primary author, have described experiences interrogating TBSS-bearing storms over the plains that did not produce hail. In practice, the primary author has not personally observed a storm, at least in the southern Plains, that exhibited TBSS without some surface hail fall given favorably located observers and diligent verification efforts.

We have modified the text to emphasize that these observations occurred over the Plains. The previous mention of W&R's study also was elaborated upon, so that the non-hail TBSS cases were more notably acknowledged.

The first Great Plains qualification was made in the abstract. Additional references to the possible geographical limitations were similarly added at appropriate locations within the text.

The discussion concerning W&R's results with non-hail associated TBSSs also was emphasized to be obtained using 5 cm radars, and that was contrasted to Lemon's previous work on the TBSS that derived operational guidelines for recognizing the artifact with 10 cm 88Ds.

2) The authors contend that the signature should also lead operational forecasters to consider warnings for possible downbursts. The introduction briefly mentions the possibility of using the weak reflectivity spike to identify severe downburst winds but little other supporting material appears until one reaches the conclusions.

This suggestion was based on previous work regarding traditional TBSSs by Lemon 1998 and W&R. Suggestions here, and those by Reviewer A, prompted the authors to revisit this subject. Given that severe winds were only observed with one out of the six total cases presented, it was deemed that this section should be re-written to indicate uncertainty in correlating damaging winds/microbursts to WTBSSs. The authors recommend that warning decisions for severe winds should be determined based on other near-storm environmental factors, not solely on the presence of a WTBSS. [Modified conclusions quoted....]

Other references to damaging winds/microbursts with respect to the WTBSS were removed throughout the paper. Please read our response to a similar point in Review A.

Zrnić's (1987) derivation of a proposed flare velocity equation may allow the authors to further develop their case for using the feature as a downburst warning decision discriminator.

Given the above, this was not investigated further. However, this could be the topic of future work.

In the case studies section, the first sentence mentions strong in-bound velocities within the weak reflectivity spike in that case study. What is the significance of this? Were downburst winds associated in this case? If not, the sentence does not support the authors' case other than to demonstrate that high radial velocities are seen within the weak reflectivity spike.

In this paragraph the authors observe that the velocity patterns generally seen with the weak reflectivity spike are noisy and contaminated per Lemon 1998. This seems in contrast to Zrnić's 1987 work on a flare velocity equation. If so, this contention needs to be supported in more detail.

In fact, Section 2b, paragraph 8 is somehow disjointed from the case study it follows. It might work better to combine all these references to Doppler velocities within the artifact in the Introduction section where the points raised could be expanded on and the difficulties identified above resolved.

All references to velocity-derived contamination of the WTBSS artifact were consolidated into Section 2c. In fact, the subject became a primary topic of this section per these suggestions and the suggestions noted in Review A. To answer the reviewer's question, the case study in Section 2b was not associated with *downburst winds. Instead the strong in-bound velocities were displayed to increase visibility of the obscure WTBSS artifact. This application of the SRM data was revisited during the revision process, and we have elaborated in Section 2c. Please also refer a similar response to Review A.*

3) Some discussion of the height of the weak reflectivity spike in the two cases presented would also be useful. W&R found there to be a difference in its height between the Colorado and Alabama storms. Might this be due to the geographical location of the storms? The two cases presented are in a geographical location somewhat climatologically similar to that of the Colorado storms thus the authors need to address the possibility that their technique may not be applicable everywhere.

The height of the WTBSS-exhibiting cores, in the five cases currently presented, ranged from 4 to 27kft AGL. This information is provided for each radar image included within the case-loop animations. In addition, [Section 2 modified accordingly]…

The height of the source region for the WTBSS seemed to be dictated by the specific sampling time within the storm's life cycle and the storm's distance from the radar per the limitations provided by such close proximity range. A detailed discussion of this was not provided.

The geographical scope of these observations is noted in detail at other locations within the text, as indicated in responses elsewhere. Since the emphasis of the paper is to document these preliminary observations, the authors do not suggest that the WTBSS has the same operational utility for all geographic areas. Instead, the need to expand the dataset with cases from other geographical regions is now acknowledged in the conclusions.

[Minor comments omitted...]

Second Review:

While the authors have provided a rework of the manuscript and are to be commended for their consideration and application of the reviewers' suggestions to date, a fairly significant problem still exists. The change of focus to be more in line with a collection of preliminary case studies of low end TBSS signatures associated with high Plains hailstorms is a welcome adjustment.

I am willing to recommend acceptance of this case study for publication with the proviso that the authors make one more change in the substance of the work as discussed and suggested below. If the authors and the Editor agree on this change, I do not need to see another draft.

Comments on focus and originality:

The fifth paragraph, while greatly improved from the original still has problem with the citation of Wilson and Reum (1988). As I tried to point out (perhaps unsuccessfully) in the initial review, Wilson and Reum never actually claim to have evaluated any reflectivity lower than +5 dBz in their text or tabular data. However, they do indicate in several of their figures that the TBSS artifact was bounded by areas of reflectivity as low as -10 dBZ. Please consider mentioning that you made use of their figures to arrive at the value of -10 dBZ value cited.

Given the above, I still have some nagging questions concerning the originality of this work. Clearly in 1988 Wilson and Reum had already identified the fact that the TBSS signature exists downscale in the reflectivity data. The fact that National Weather Service WSR-88D radars have only recently been able to display this information to the warning meteorologist does not make it new.

What we apparently have here is a continuum in the TBSS reflectivity (and possibly velocity?) fields which, when it is associated with hail, shows a correlation to the size of the hail stones. Considering this, the author's general response comment identifying, "the need for discriminating WTBSSs from traditional TBSSs…" is worrisome.

Neither Wilson and Reum's data nor the author's case studies build a case for separation of the weak TBSS from the TBSS and thus a new nomenclature. Instead they seem to indicate that the reflectivity range of a TBSS extends downward for smaller hail stones. Software or hardware changes in the radar which now allow the operational meteorologist to "see" these lower values, however significant that may be operationally, do not constitute support for a new acronym either in the literature or in the operational environment.

In order to alleviate this problem I suggest the acronym "WTBSS" be replaced with the term "weak TBSS" indicating that the signature in question is merely a downward extension of the latter and not a new entity.

REVIEWER C (Kevin Scharfenberg):

Initial Review:

Recommendation: Accept with Minor Revisions

The manuscript is well-written and an important extension of Lemon (1998) to WSR-88D data with improved display capabilities and greater sensitivity. Although not the primary target audience, the authors are encouraged to read through the paper from the perspective of meteorologists not associated with NWS warning decision making. I recommend the manuscript be accepted with minor revisions and would be happy to take another look before publication at the editor's discretion. Thank you for the opportunity to review this paper for EJSSM.

[Minor comments omitted...]

Descriptors of hail and wind such as "low-end", "severe", "marginal(ly)", "high-end", etc., appear throughout the paper but are rarely adequately defined. This is important for reader understanding, particularly for the readers not associated or familiar with NWS warning decision making.

Good point. All descriptors have now been defined at least once in the text. The descriptor of most importance here is "low-end" severe, which is defined as hail between 1.9 cm and 2.5 cm. "Very large" hail is now defined in the text as greater than 2.5 cm. We have removed "marginal", and "high-end" is used in a relative context.

[Section 1] The physical reason for the association of large hail with a TBSS is well-covered here. It might be worth a sentence or two explicitly mentioning why damaging winds might be associated with a TBSS (rather than just asserting it).

Per recommendations from the other reviewers, most references to severe winds have been removed from the text. A paragraph on the topic remains in the conclusion, just to indicate that only 1/6 of the cases presented here were associated with severe winds, and that a correlation between the WTBSS and severe winds can not be made.

This [weak TBSS, Section 2a] signature was very subtle. Can you tell the readers how you were able distinguish it from other weak reflectivity signatures often found along the fringes of weather echoes?

The issue of recognizing subtle WTBSSs is also addressed in the revised Section 2c where the use of SRM and SW are discussed.

[Section 2] It could be speculated that the higher-power signal would contribute the most to the velocities, but probably not appropriate here. It would be an interesting discussion. On the other hand, it might be worth mentioning that a WTBSS could easily be masked by higher-power returns that happen to be downrange of the radar from the core (e.g., biological scatterers, stratiform rain, or different storm cores).

Again, this has become a major topic of Section 2c.

I'm not convinced how the authors are going about "labeling" these storms. Is it the one picture and a few radar images determining what "type" of storm label being given the Midland event? Only a few radar images from the other storms to say they are "pulse type" or "multicell"? The authors are encouraged to be more specific about how these storms are being classified "pulse" or "multicell" (with definitions and/or references upon first use of the term). With proper references it can probably be done with a sentence or two for each case.

Rather than using "may," "tend to," "often," etc., be specific and move these overall comments to the conclusions section. For example, "...while 3 of the 4 cases examined by Lemon (1998) showed TBSS associated with supercell thunderstorms, we have discussed the observation of WTBSS associated with X multicell storms and Y 'pulse type' storms..."

In the revised text, we have tried to keep "labeling" to a minimum. Of course, these preliminary WTBSS observations show that the artifact appears to have been useful (at least in the majority of these cases) for ordinary, non-supercell, storms. In fact, in a few of the cases presented, the entire life cycle of the storm is seen in the animations. Thus it's difficult to describe the storms in any other manner than "pulse-type", which is now referenced with definitions. The reference to "multicell" stated to be used in the description of a storm displaying multiple updrafts/cores.

The revised paper should read with more specificity. In the conclusions section, results of the observations were quantified when appropriate.

Many WFOs also have access to C-band (TDWR) radars. The authors mentioned (via reference) the possibility of WTBSS caused by large drops in C-band radar displays, and this has been observed on TDWR displays. Readers should focus on these results as being from S-band radar high-data-resolution displays and modulate the findings for lower-resolution displays and/or radars with different wavelengths.

Good point. We have tried to clearly differentiate this in the introduction and in the conclusion.

Second Review:

The authors have improved the manuscript by being more reserved about making broad conclusions based on a small sample size about the association of the WTBSS with hail and the resulting WDM suggestions. Also the lingo problems (such as “marginally severe hail”) have been largely fixed.

The sample size itself is still too small to make statistically significant conclusions, and the authors have stated such. I went back to look at Lemon (1998), which this manuscript attempts to update with newly available data, and the original paper also did not have enough cases to form broad statistical conclusions. This manuscript appears to be offered in a similar manner.

The question remains whether this is relevant to EJSSM as an article, or perhaps as a technical note instead. On one hand, there isn’t anything particularly earth-shattering here scientifically. However, it is important in the sense of following up and adding to Lemon (1998) with newly-available data. Either as an article or note, this should generate some interest and discussion on the operational side which hopefully makes up a good chunk of the EJSSM readership. Pending the decision of the editor regarding relevance, the manuscript is well-written enough such that if the minor comments below are addressed, I will not need to see the manuscript again before publication.

[Minor comments omitted...]