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In Situ Observations of the 21 April 2007 Tulia, Texas Tornado

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ABSTRACT

A localized tornado outbreak occurred across the Texas Panhandle during the afternoon and evening hours of 21 April 2007. One supercell thunderstorm produced an EF2 tornado in the town of Tulia, TX. A mobile mesonet vehicle was struck by the tornado while fortuitously collecting in situ data near the center of the vortex. The instrumentation sufficiently resolved the wind and pressure characteristics, at approximately 2.9 m and 2.6 m respectively above ground level, of the tornado's micro-α scale environment. A maximum wind of 50.4 m s^{-1} and a pressure deficit of 194 hPa were measured, yielding the largest known pressure fall within a tornado. Analysis of the recorded data and instrumentation were conducted; results are presented and discussed.

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1. Introduction

Mobile mesonet (MM) vehicles (Straka et al. 1996) have been utilized by several private individuals and researchers within the past two decades as a means of obtaining surface observations at resolutions not available from existing conventional operational network platforms. Field projects such as Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX; Rasmussen et al. 1994), Severe Thunderstorm Electrification and Precipitation Study (STEPS; Lang et al. 2004), and International H20 Project (IHOP_2002; Weckwerth and Parsons 2006) have demonstrated the usefulness of increased resolution of basic meteorological variables of pressure, wind speed and direction, temperature, and RH for an improved understanding of mesoscale phenomena.

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In addition to MM instrumentation, attempts have been made to place specifically-designed instruments within the paths of tornadoes over the past 25 years to achieve in situ observations for a better understanding of meteorological conditions within the lowest few m of the surface in tornadoes. These devices have been deployed within, and in close proximity to, tornadoes yielding diverse results (Bedard and Ramzy 1983; Bluestein and Golden 1993; Bluestein 1999; Winn et al. 1999; Lee et al. 2004). The relatively short window of opportunity to deploy meteorological instrumentation within a tornado, combined with the challenging environment associated with tornadic storms and field operations, have contributed to the difficulty of obtaining datasets for analysis.

Only a handful of known in situ measurements with large pressure deficits (arbitrarily defined ≥ 40 hPa) from within or close to the center of tornadoes have been

Table 1: Measured Tornado Pressure Deficits ≥ 40 hPa in Chronological Order

Location	*Year*	*P Deficit*	*Measuring Device*	*Reference*
St. Louis, MO	1896	82 hPa	Personal Aneroid Barometer	Baier (1896)
Minneapolis, MN	1904	192 hPa	Personal Aneroid Barometer	Outram (1904)
W. Lafayette, IN	1976	44 hPa	Personal Aneroid Barometer	Agee et al. (1977)
Allison, TX	1995	55 hPa	Turtle Probe	Winn et al. (1999)
Stratford, TX	2003	40 hPa	HITPR Probe	Wurman and Samaras (2004)
Manchester, SD	2003	100 hPa	HITPR Probe	Lee et al. (2004)
Tulia, TX	2007	194 hPa	MM Analog Barometer	Blair et al. (2008), this paper

documented (Table 1). Aneroid barometers were used to measure inadvertent tornado encounters in Saint Louis, MO (1896) and Minneapolis, MN (1904), with maximum pressure deficits of 82 hPa and 192 hPa respectively (Baier 1896; Outram 1904). Unfortunately these readings were taken under stressful conditions and dynamic pressure effects are unknown, leading to an unsubstantiated accuracy of these measurements. Modern research efforts have produced portable instrumentation with the ability to record characteristic properties of tornadoes with improved accuracy and resolution. A probe measured a 55 hPa pressure fall within 660 m from the center of the Allison, TX tornado of 1995 (Winn et al. 1999). Probes in 2003 recorded a 40 hPa depression in the Stratford, TX tornado (Wurman and Samaras 2004) and a 100 hPa pressure deficit near Manchester, SD (Lee et al. 2004). Under investigation in this paper, a MM vehicle utilizing an analog barometer measured a substantial pressure fall of 194 hPa from the environmental station pressure of 882 hPa within the Tulia, TX tornado.

This paper will reveal data collected by a MM vehicle at approximately 2.6 m and 2.9 m above ground level (AGL) within a tornado at Tulia. An overview of the convective event and meteorological environment is provided in Section 2. A description of the MM vehicle and instrumentation is offered in Section 3. Visual observations of the tornado and MM involvement are described in Section 4. In Section 5, wind and pressure data collected from the Tulia tornado are summarized. Section 6 discusses the validity and interpretation of the collected data, in addition to theoretical and observational considerations. The paper concludes with a summary of the results presented in Section 7.

2. Overview

During the late afternoon of 21 April 2007, numerous supercellular storms developed across portions of west Texas and the Texas Panhandle. The storms developed as a high amplitude shortwave trough approached (Fig. 1). The environment was characterized by large 0-6 km layer shear of approximately 25 m s^{-1} magnitude, and modest buoyancy, with 1500 to 2000 J kg^{-1} mixed layer convective available potential energy (MLCAPE) based on a 100 hPa mixed layer. In response to the upper level trough, several surface boundaries across west Texas served as foci for the initiation of deep moist convection and the augmentation of the low level mass and kinematic fields which fostered an environment favorable for tornadogenesis (Fig. 2). Sixteen tornadoes were reported in Storm Data (NOAA 2007), with two distinct families of tornadoes. One cluster of tornadoes occurred along and north of a warm front that was enhanced by differential heating from morning cloud cover over the northern Texas Panhandle. The second cluster occurred east of a dryline and along and south of the aforementioned warm front (Fig. 3). Four of these tornadoes, including the Tulia tornado, were rated as Enhanced Fujita Scale Two (EF2) with maximum nominal wind speeds between 50 m s^{-1} to 60 m s^{-1} (WSEC 2006).

Convective initiation occurred at approximately 2200 UTC over the far western Texas Panhandle. The storm of interest evolved into a supercell between 2200 UTC to 2300 UTC as it moved northeastward from Morton, TX to west of Littlefield, TX. The supercell produced its first significant tornado near Olton, TX around 0000 UTC. The tornado persisted for nearly 40 minutes, obtaining a maximum width of approximately 1,100 m and a damage survey rating of EF2 (NOAA 2007). As the tornado

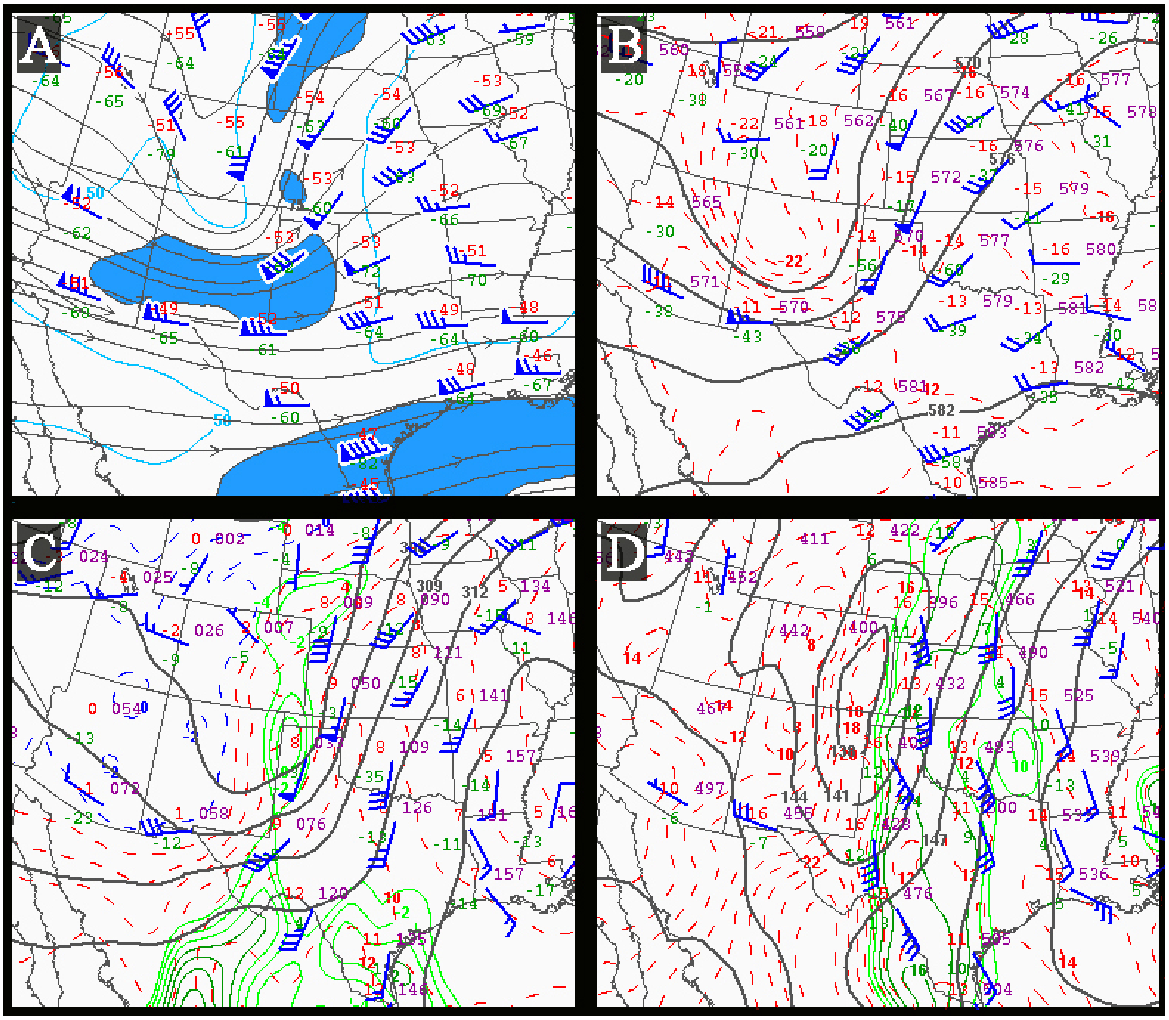

Figure 1: Objective upper air analysis valid 0000 UTC on 22 April 2007 with heights at (a) 250 hPa, (b) 500 hPa, (c) 700 hPa, (d) 850 hPa. Standard station model in abbreviated format; temperature and dewpoint (°C), heights (m) and winds (half barb = 2.5 m s^{-1}, full barb = 5 m s^{-1}, pennant = 25 m s^{-1}). Wind speeds > 37.5 m s^{-1} are shaded in blue (a). Isotherms (dashed) in °C, isodrosotherms (solid green) depicting dewpoint temperatures greater than or equal to 4 °C and 8 °C (d). Image courtesy Storm Prediction Center, 2007.

dissipated, a new mesocyclone developed with another tornado occurring inside the town limits of Tulia at 0054 UTC. A more detailed investigation of the tornado evolution in Tulia is explored in section 4a.

3. Instrumentation

The MM vehicle (2006 Nissan Xterra) utilized similar instrument design and layout to that used in VORTEX (Straka et al. 1996) in conjunction with customized and modernized upgrades (Fig. 4). Inherent differences exist with the use of a sport utility vehicle versus a sedan and differences in instrument placement relative to the vehicle, which is discussed further in Section 6. A suite of meteorological instruments and a global positioning sensor were mounted on an aluminum rack and vertical mast fixed to the MM roof between heights of 2 m and 3 m AGL. The outside sensors were routed inside the vehicle to a data logger and laptop computer (Fig. 5).

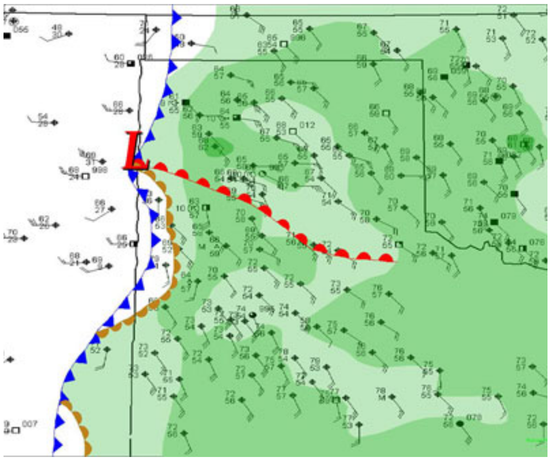

Figure 2: 0000 UTC 22 April 2007 surface map with standard station model used; temperature and dewpoint (°F), and sky conditions. Winds as in Fig. 1. Dryline, cold front, and warm frontal boundaries depicted with conventional symbols. Warm front resolved using Θ_v contours (not shown). Subjectively analyzed dewpoint temperatures ≥ 50 °F shaded (green) every 5 °F. *Click image to enlarge.*

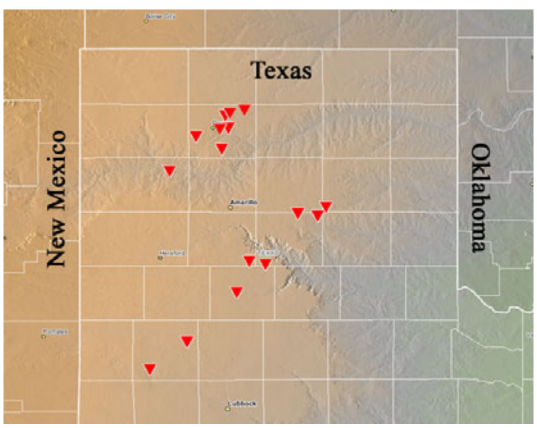

Figure 3: Red triangles denote the starting location of the tornadoes that occurred on 21 April 2007 (NOAA 2007).

MM instrumentation were calibrated during the early months of 2007, prior to any field operations. On days of operation, the sensors and associated data were examined during periods when meteorological conditions were relatively homogeneous. The MM data were monitored for any gross reporting errors, whether systematic or periodic, and analyzed to detect the source of the error. Upon the Tulia tornado encounter, post-event inspection found the

Figure 4: The exterior of the mobile mesonet vehicle: (a) on 24 February 2007, and (b) after being struck by the Tulia tornado on 21 April 2007, sustaining significant damage. Photos by Eric Nguyen.

instruments in good working condition. Section 6 provides additional calibration information and potential measurement errors associated with the instrumentation and MM vehicle. The following subsections detail individual instrument specifications unique to the MM configuration.

a. Data logger, software, GPS

A Campbell Scientific Inc. CR800 data logger recorded instrument readings with a capacity of up to 2 million data points stored with non-volatile flash memory. Analog inputs were measured and digitized into a text format, which was then processed and used in real-time calculations. The software was written with CRBasic, a Campbell Scientific Inc. software package that works in conjunction with the Campbell Scientific Inc. CR data logger series.

A Garmin 16 HVS Global Positioning System (GPS) receiver was utilized to obtain latitude and longitude coordinates for MM position, vehicle speed and heading, and UTC time at a sample rate of 1 Hz. The GPS unit contained a built-in wide area augmentation system demodulator for improved accuracy and performance. When the vehicle was stationary, the last GPS heading was used in substitution of a flux-gate compass to minimize potential errors from radio frequency (RF) interference from UHF radio traffic that may result in the loss of data or incorrect positioning. GPS derived vehicle speed and heading inaccuracies were less than 0.05 m s^{-1} and 1^{o} respectively.

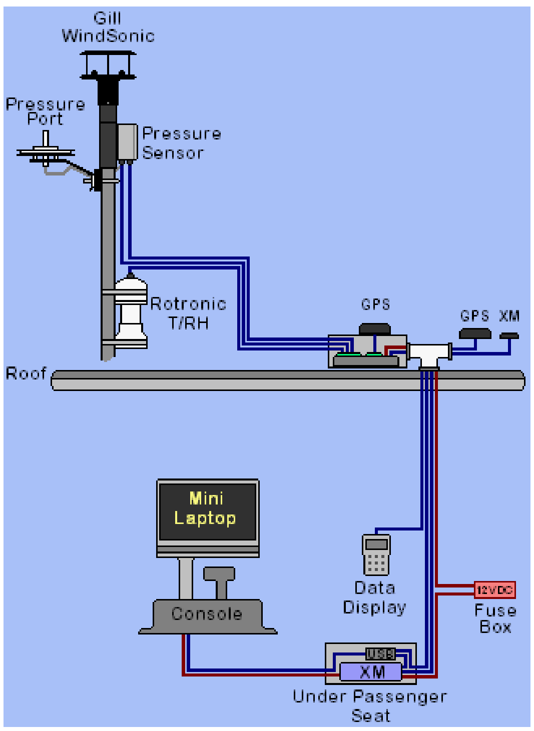

Figure 5: Schematic of the wiring diagram, location of the microcomputer, and the various instrument components associated with the mobile mesonet vehicle. Diagram by Eric Nguyen.

b. Wind speed and direction

A Gill WindSonic anemometer was mounted atop an aluminum mast, situated 2.9 m AGL. The instrument sampled at a rate of 40 Hz, which was then averaged over a 1 s period. The anemometer was capable of measuring instantaneous wind speeds up to 60 m s^{-1}. Speed and direction accuracy of the sensor specified by the manufacturer was within 3% and 3^{o} respectively. Turbulence from the vehicle was minimized due to the placement of the anemometer, although Section 6 reviews measurement errors specific to the MM configuration. Measured wind speed and direction, along with GPS vehicle heading and speed, were used to obtain an estimate of the true wind speed and direction utilizing simple vector calculations.

c. Pressure

Atmospheric pressure was measured at a height of 2.6 m AGL, using a Vaisala PTB101B analog barometer with a silicon capacitive sensor inside a PVC enclosure. To best prevent dynamic pressure error (e.g. error caused by wind, especially wind induced by vehicle motion), an R.M. Young static pressure head was mounted at the front of the instrument rack with a tube installed directly to the pressure sensor. It was discovered that measurement errors from dynamic pressure affects of the vehicle can arise under strong wind flow, and this is further discussed in Section 6. The instrument sampled at a 1 Hz rate with an achievable range of 600 hPa to 1060 hPa. Factory specified uncertainties of the sensor were less than 0.5 hPa with a 0^{o} wind angle of attack on the static pressure head. Fig. 6 displays a close view of the top of the instrument mast, housing the pressure and wind sensors.

d. Temperature, RH

An aspirated water and radiation shield mounted 2.2 m AGL housed the temperature and RH sensor. The shield was constructed of white schedule 40 PVC, designed to minimize solar radiation and evaporative cooling errors. A 7.6 cm diameter fan was mounted inside the enclosure to ensure a constant aspiration of air, efficiently minimizing the enclosure from artificially warming in an environment of strong solar radiation.

Temperature and RH were measured using a Rotronic HygroClip S3 platinum resistance temperature detector and Rotronic capacitive chip mounted in the protective enclosure surrounded by a thin filter. This filter was necessary to protect the capacitive chip from dust or other foreign objects that could lead to the potential of measurement inaccuracies. This configuration slowed the response time of the

Figure 6: Top of the instrument mast containing the Gill WindSonic anemometer, Vaisala pressure sensor (inside enclosure), and R.M. Young static pressure head. Photo by Eric Nguyen.

RH and temperature measurements to values of 10 s and 30 s respectively, which in this specific case was insufficient to permit detailed analysis of the tornado micro-alpha scale environment.

4. Visual observations and MM involvement

a. Tornado evolution

The supercell moved northeastward at approximately 17 m s^{-1} through Tulia, TX, beginning around 0040 UTC. Fig. 7 depicts the rapid evolution of the low-level updraft region from 0052 UTC to 0055 UTC. A well-defined clear slot, indicating the rear-flank downdraft (RFD), was in the process of encircling the rotating updraft. Cascading downward motion was observed within the cloud elements immediately along the outskirts of the rain-free base. In advance of the updraft, it is speculated that outflow from the forward-flank precipitation core provided rain-cooled air aiding in scud cloud development. A rotating wall cloud quickly evolved just south of Tulia by 0053 UTC.

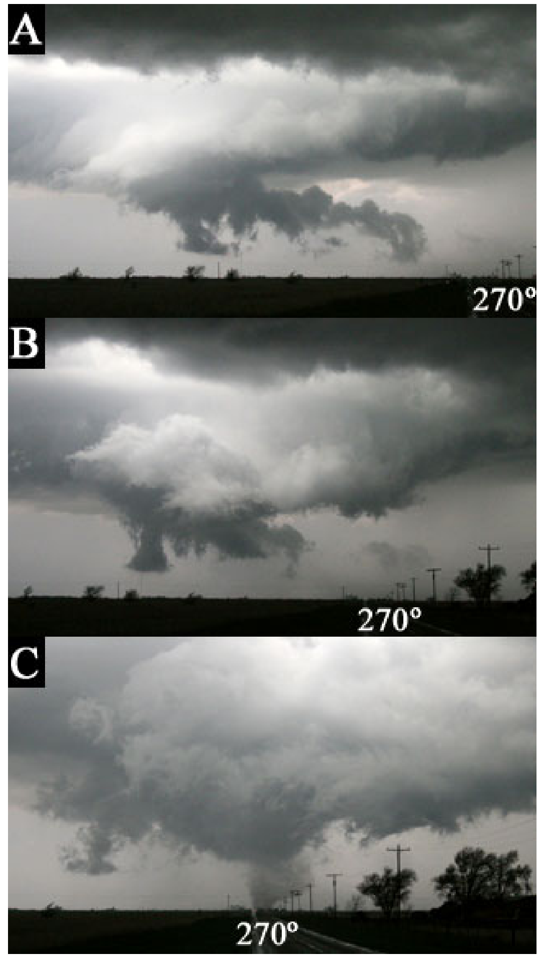

Figure 7: The sequence of photos shows the rapid evolution of the low-level updraft region within a 200 s period [times approximate: (a) 0052 UTC, (b) 0053 UTC, and (c) 0055 UTC]. Photographer location was 3.2 km east of Tulia along Ranch Road 1318. A reference angle of 270^{o} (looking west) is provided. Photos by Dustin Wilcox.

The first visible signs of a tornado were noted at approximately 0054 UTC within the industrial section of western Tulia near State Highway 87, with an initial diameter of less than 50 m. In the first 30 s, the tornado obtained a maximum damage path width less than 100 m and was characterized visually as a single-cell vortex (E. Nguyen and A. Magliocco 2007, personal communications). Condensation occasionally made contact between the wall cloud base and the debris-filled surface vortex. As the tornado evolved, the width of the damage track expanded to approximately 200 m. Subsidiary vortices within the circulation first were observed by the MM occupants after the tornado moved north of the vehicle (Fig. 8). This movie shows the tornado approximately 10 s after passing the MM. Multiple vortices can be identified within the circulation. EF1 to EF2 damage resulted at a local automotive dealership and an ALCO supermarket respectively during this clip. The tornado proceeded through town towards the north with a similar forward speed as the parent supercell at approximately 17 m s^{-1}. By 0057 UTC, the surface circulation broadened to a maximum diameter in excess of 200 m and visually appeared less-organized. Video evidence suggested the dissipation of the tornado at approximately 0059 UTC after a 5.5 km path length.

Figure 8: Video clip from inside the MM vehicle post-tornado at 0055 UTC. The tornado is located near the intersection of NW 6th Street and Highway 87, approximately 200 m north of the MM. Video by Amos Magliocco. *Click image to play and enlarge.*

b. MM transit

At 0050 UTC, the MM vehicle was in the process of repositioning relative to the updraft region to obtain improved visual observations by flanking the supercell to the northeast. The quickest route dictated by the existing road network utilized State Highway 87 north through Tulia to Ranch Road 1318 eastbound. The vehicle initially was located on the southern periphery of the updraft base and the favored faster road option took the MM underneath the updraft base to reposition. This navigational strategy contained an inherently greater risk of severe weather-related dangers simply due to the close proximity of the storm where the preferred region of severe weather is typically found (Doswell 1985). While the MM occupants were aware of the potential dangers, the updraft base appeared fairly benign to the observers when the route was chosen (E. Nguyen 2007, personal communication).

At 0053 UTC, the vehicle entered the far southern town limits of Tulia near the intersection of Highway 86 and Highway 87. At approximately 0054:40 UTC, the visible tornado developed just west of Highway 87, in between Broadway Avenue and NW 2nd Street. The MM was northbound on Highway 87, situated within 100 m to the north of the initial central vortex position. Strong surface inflow into the vortex prevented the MM from maneuvering away from the approaching tornado. The vehicle was forced off the road and came to rest at the Leja Tire Company near the corner of Highway 87 and NW 4th Street, only seconds prior to the arrival of the tornado. Upon post-discussion with the MM occupants, it was concluded that rapid tornadogenesis combined with limited depth perception resulted in the unexpected tornadic encounter.

5. Data

The analysis of the collected MM data will focus on a two-minute period from 0053:55 UTC to 0055:55 UTC. The midpoint of the dataset is approximately the time the vehicle was struck by the tornado. Likewise, the midpoint differentiates the first half of the dataset, when the MM was in motion, from the second half when the vehicle was stationary.

a. Wind speed and direction

The wind speed and direction at 2.9 m AGL recorded by the MM is displayed in Fig. 9. Wind speed and direction encountered while the MM was in motion just before the tornado encounter is plotted in Fig. 10. At the beginning of the sample set, the wind encountered was southwesterly (237^{o}), which was followed by a 15 s gradual backing of the wind to a south-southeast (160^{o}) direction. This duration of backing winds can be partially attributed to the position of the MM with time relative to the surface cyclonic circulation pattern. Wind speed increased from 11 m s^{-1} to 21 m s^{-1} as the wind backed. As the MM moved north within closer proximity to the developing tornado cyclone, the surface winds responded by a continued backing.

South-southeasterly surface winds averaging approximately 13 m s^{-1} persisted for an additional 30 s as the vehicle continued northbound through Tulia. A small increase of wind speed and direction variability was noted as the vehicle drove through the industrial region of Tulia. The MM moved underneath to slightly north of the developing tornadic region by approximately 0054:35 UTC, moments before the tornado became visible.

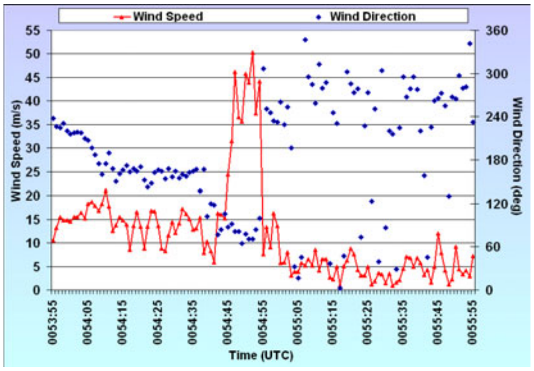

Figure 9: Wind speed (red, m s^{-1}) and direction (blue, azimuthal degrees) at 2.9 m AGL during a 120 s sample period (0053:55 to 0055:55 UTC). *Click image to enlarge.*

Figure 10: Mobile mesonet vehicle and tornado locations with time through western Tulia. Exact position of MM plotted in 1 s increments. Yellow wind barbs (winds as in Fig. 1) signify the measured wind by the MM at 2.9 m AGL. Red triangles represent approximate location of tornado at indicated approximate times (UTC). Background image by Google Earth. *Click image to enlarge.*

When the visible tornado formed around 0054:40 UTC, the MM was within 100 m north of the estimated central vortex position. Wind direction abruptly responded with a change from south-southeasterly (160°) to easterly (90°) during the course of a few seconds. Wind speed increased following the backing wind direction, with a 3 s rise from 15 m s^{-1} to 46 m s^{-1}. Encountering these severe winds, the MM vehicle was pushed off the road and came to rest, facing a near-westerly orientation. It is worth noting that these winds were measured in advance of the visible debris cloud.

As the tornado approached and eventually struck the vehicle, wind speeds remained > 35 m s^{-1} with a maximum 1-s wind of 50.4 m s^{-1}. Relatively consistent east-northeast winds began to veer as the vortex overtook the MM. At 0054:55 UTC, an abrupt change in wind direction from 99° to 306°, along with a sudden decrease in wind speed from 44.2 m s^{-1} to 7.9 m s^{-1} was measured. It is speculated this rapid transition may identify the near-center region of the vortex, and this concept is further explored in Section 6.

The GPS position of the MM vehicle spontaneously changed from 274 ° to 0.4 ° shortly after the tornado passage, and persisted through the remainder of the dataset. This type of error is common in instances when vehicle position is stationary and a fluxgate compass is not utilized by a MM. With the erroneous position yielding an 86° wind direction error, a correctional method to obtain the ambient wind was applied to the measurements beginning at 0054:57 UTC. Video taken from inside the MM following the tornado served to validate the augmented wind measurements.

Wind direction immediately following the tornado was consistently west-southwesterly in direction. Wind speeds along the southern periphery of the tornado were considerably less than the measured wind on the northern side. This likely may be an artifact of the surrounding surface obstructions around the MM, which is discussed in Section 6. The obstructions also contributed to a larger variability of the wind direction within the final 50 s of the dataset relative to the pre-tornado portion.

b. Pressure

The atmospheric pressure at 2.6 m AGL recorded by the MM is presented in Fig. 11. The overall behavior of the pressure trace is characterized by a gradual decrease in pressure, followed by an abrupt depression indicating the passage of the tornado, with readings returning to nearly identical values that were found initially. The pressure environment, sampled at one minute prior and one minute post tornadic encounter, reveals a fairly uniform and consistent value of approximately 882 hPa. This value effectively serves as the basis for the initial environmental atmospheric pressure (referred to as P_i hereafter) when applied to the collected dataset to examine pressure deficits.

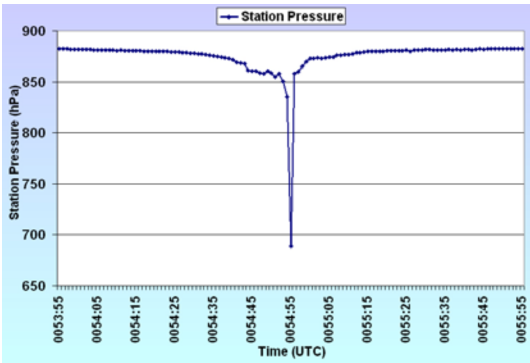

Figure 11: Station pressure (hPa) trace at 2.6 m AGL during a 120 s sample period (0053:55 to 0055:55 UTC). *Click image to enlarge.*

A 10 m increase in elevation occurred during the sample period while the MM was in motion. This increase in elevation over roughly a 60 s period generated approximately a total pressure fall of 1 hPa using standard atmospheric estimates. The differential elevation was considered negligible in relation to the analysis of the pressure values and trace structure.

The first 30 s of the pressure series is characterized by a relatively gradual decrease on the order of 0.1 hPa s^{-1}. The pressure fall rate increased to 1 hPa s^{-1} just before the first visible signs of a tornado were present around 0054:40 UTC. Pressure decreased by 6 hPa within 1 s at 0054:44 UTC before falling by another 3 hPa throughout the next 8 s. This period of near-constant low pressures (858 hPa to 861 hPa) prior to the tornado passage can be partially attributed to the MM vehicle holding a similar position relative to the tornado, as both features were nearly parallel in motion. As inflow winds inhibited the vehicle's forward progress, the MM came to rest and was struck by the tornado. The vortex region is identified by the 3 s downward spike of significant pressure falls. This duration of pressure drops is reasonable when considering the approximated vortex diameter of 60 m and translational speed of 17 m s^{-1}. Pressure values recorded within the approximated 3 s tornado duration were 850.2 hPa, 835.7 hPa, and 688.4 hPa (P_i 33 hPa, 47 hPa, and 194 hPa). Directly following the tornado passage, the pressure returned to the pressure value found prior to the tornado of 858 hPa. Pressure steadily increased by 15 hPa within the following 4 s before transitioning to a gradual increase in pressure, eventually returning to 882 hPa. Fig. 12 depicts the relationship between the measured wind speed and direction at 2.9 m AGL and the station pressure deficit at 2.6 m AGL derived from P*i*. A 14 s time period of 20 hPa deficits or greater was measured, partially attributed to the mobile vehicle paralleling the tornado cyclone region. The minimum pressure deficit recorded within the approximated 3 s tornado passage was 194 hPa.

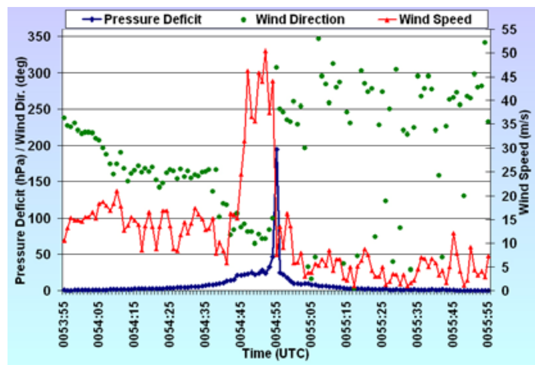

Figure 12: Combination of wind speed (red line, m s^{-1}) and direction (green dot, azimuthal degrees) at 2.9 m AGL and station pressure deficit (blue line, hPa) at 2.6 m AGL during a 120 s sample period (0053:55 to 0055:55 UTC). *Click image to enlarge.*

6. Discussion

A limited collection of in situ measurements containing large pressure falls has been obtained within tornadoes. The Tulia event provides an opportunity to investigate some meteorological characteristics near the center of a tornado. With such a significant minimum pressure recorded by the MM, a great amount of focus was concentrated on investigating the data and any potential measurement errors. The instrument accuracy, capability, and external variables leading to potential biases were examined during the post-event analysis. Velocity data and site characterization were explored further. Additionally, a brief review of theoretical and observational considerations that may increase pressure deficits at the surface was examined.

a. Validity and interpretation of the data

The MM pressure trace is similar in comparison to other tornado pressure traces with a U or V-shaped downward spike identifying the tornado region (Winn et al. 1999; Samaras and Lee 2004; Lee et al. 2004; Wurman and Samaras 2004). Dissimilarities between traces could be attributed to several variables: the sampling rate of instrumentation, instrument location relative to the vortex, the diameter of the vortex, the translational speed of the tornado, vortex intensity, and the parent vortex structure (e.g. single versus multiple vortex and their associated differences between achievable pressure deficits and radial pressure gradients). Varying combinations of these variables will have an effect on the specific shape and acquirable detail in each pressure trace.

In this case of the collected MM data, the symmetry of the pressure trace was compromised due to the vehicle in motion prior to the tornado impact. The trace likely would have been more symmetrical if the measuring device would have been stationary during the entire sample period. As the tornado moved across the MM, an abrupt depression in pressure was recorded during a 3 s duration. This 3 s "spike" of minima pressure can be attributed partially to the 1 Hz sampling rate of the analog barometer coincident with the relatively quick translational speed and small diameter of the vortex.

After the event, Vaisala Inc. conducted independent third-party testing to investigate the quality of measurements and performance of the Vaisala PTB101B analog barometer utilized by the MM. The PTB101B was inspected and calibrated against a Vaisala PTB220 factory-working standard. The PTB220 was calibrated against a Ruska 2465 pressure balance traceable to the National Institute of Standards and Technology at Vaisala Measurement Standards Laboratory. Vaisala Measurement Standards Laboratory has been accredited by the Finnish Accreditation System according to ISO/IEC 17025 standard (Vaisala 2007, Calibration Certificate). Vaisala certified the PTB101B pressure sensor accurate within operational factory specifications during an 8-point pressure calibration within the operating range of 600 hPa to 1060 hPa. Calibration results can be found in Table 2.

Table 2: Post-tornadic Vaisala calibration results on the PTB101B analog barometer. Ambient conditions consisted of a temperature at 23.2 °C, RH of 14%, and pressure of 1027 hPa. Uncertainty is ± 0.15 hPa.

Reference Pressure (hPa)	*Observed Pressure (hPa)*	*Difference In Pressure (hPa)*
619.9	620.3	+0.4
699.8	700.0	+0.2
799.9	799.8	-0.1
850.0	849.7	-0.3
899.9	899.4	-0.5
950.0	949.4	-0.6
1000.0	999.5	-0.5
1060.1	1059.7	-0.4

The Vaisala PTB101B analog barometer is capable of measuring rapid pressure changes within very short periods of time within its operating range of 600 hPa to 1060 hPa. The response time of the instrument to obtain an accurate pressure reading is 300 ms. With a 0.3 s response time, the instrument should respond accurately to fluctuations within a 1 s sampling period. Therefore, the quick change in pressure associated with the tornado passage recorded by the analog barometer is well within the realm of measurability.

Post-event inspection found the overwhelming majority of tornado-related damage to the MM body. Rear and side windows were destroyed with the front windshield heavily damaged. The most significant imprint, presumably from lofted debris, was located on the rear trunk-hatch (eastward-facing surface area). Instrumentation and the associated mast were thoroughly examined post-tornado for any external damage that might indicate a debris impact (Fig. 13). The results were negative with the exception of very small scratches to portions of the instrument mast and sonic anemometer base. It was not known whether these blemishes existed prior to the tornado.

The sensitivity of external forces, such as flying debris, on the analog barometer PVC enclosure was considered. Given the excellent condition of the instrumentation and mast after the tornado, it is speculated only small debris with minimal momentum potentially would have affected the sensors and enclosure. Furthermore, it is believed this would have been insufficient to account for sizeable fluctuations in pressure. Wind speed at the time of the pressure minimum dropped to 7.6 m s^{-1}, which is inadequate to generate an accelerated force resulting in large measurement errors. The potential of a debris-induced pressure fall is negated further when considering an impact substantial enough to flex the barometer's diaphragm will only show itself in the sensor output within the amount of time that the diaphragm remains flexed, or is still vibrating from the strike. This is expected to be only a few ms of true vibration from the initial impulse. Assuming a dampening wave, only the first one or two vibrations would result in the diaphragm significantly deviated from the ambient pressure, further narrowing the window of potential sensor output error.

Figure 13: Different angles display the instrument mast and sensors post-tornado. The instrumentation was cleaned externally to remove soil impurities. Photos by Bob Fritchie.

Free fall tests, sinusoidal vibration tests, and digitally-controlled random vibration tests were conducted by Vaisala Inc. on an analog barometer utilizing the same Barocap sensor and module as the PTB101B (Vaisala Inc. Environmental Tests, TR220029 2006; TR220030 2006; TR220094 2006). The free fall test subjected the barometer to 6 drops from heights of 0.5 m and 1m. Instrument drift was the main concern with this specific test and results showed less than a 0.3 hPa change in pressure. Random and sinusoidal vibrations oriented in three Cartesian coordinates (X, Y, Z) for 30 minutes were examined for varying levels and severities. The pressure changed less than 0.1 hPa during the test and showed no spikes in the trace.

The R. M. Young Company utilized the University of Michigan Aerospace Department wind tunnel facility to evaluate the performance of the static pressure head under a variety of angles of air flow and wind speed. Similarly, Vaisala Inc. tested the SPH10 static pressure head with the Laboratory of Aerodynamics at the Helsinki University of Technology in Finland. The results were comparable with static pressure errors occurring under certain conditions. Wind speeds < 20 m s^{-1} with a 0^{o} angle of attack typically resulted in -0.1 hPa inaccuracies. As the angle of wind flow and wind speed was increased, larger deviations from the static pressure occurred. For instance, wind speeds of 30 m s^{-1} with a 40^{o} angle of attack yielded pressure error measurements up to 2 hPa. Additionally, the location of the PVC pressure enclosure and mast relative to the static head may have resulted in small measurement errors when the flow angle was parallel to the instrumentation. It is believed this measurement error to be relatively infrequent in occurrence.

A field test was conducted to investigate any errors associated with dynamic effects from the vehicle streamline and varying wind angles (0^{o}, 20^{o}, 40^{o}) potentially encountered by the static pressure head (Fig. 14). A vehicle was repeatedly driven along a road with a negligible change in elevation (less than 1 m) and where the ambient wind speed was less than 3 m s^{-1}. City-driving speeds (< 20 m s^{-1}) were found to have < 1 hPa error with each tested wind angle. Much stronger wind speeds on the order of 40 m s^{-1} resulted in increasing error. Deviations from the true pressure at wind angles of 0 ^{o}, 20 ^{o}, and 40 ^{o} at 40 m s^{-1} were -3.2 hPa, -3.3 hPa, and -3.4 hPa respectively. Assuming streamline modification over different source angles is on a similar order of magnitude as those seen head-on, dynamic effects at tornadic speeds (40 m s^{-1} or greater) from the rear or rear quarter-panels of a vehicle may result in potential pressure drops ≥ 3 hPa.

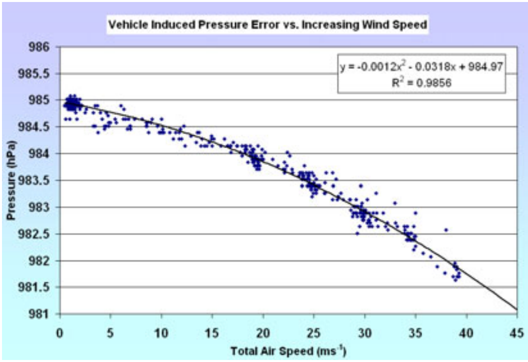

Figure 14: Pressure data collected from closed-road testing performed on the MM platform showing the deviation of the ambient pressure (984.97 hPa) with increasing wind speed (no offset to the static pressure head). The errors due to dynamic pressure effects from airflow over the vehicle are clearly seen and are well described (R^2=0.9856) with a second order polynomial. *Click image to enlarge.*

Wind data were examined to determine whether obstructions from mud or debris on the transducers affected the performance of the Gill WindSonic. If the transducers are covered by an obstruction, then the sensor digital data string produces a 2 digit error code indicating the type of signal failure. When this error code occurs using a fixed field format, wind direction and speed readings are replaced by 999 readings. Therefore if a signal becomes compromised, wind direction and speed would output 999^o and 999 m s^{-1} respectively. Fig. 15 illustrates the wind measurement error during partial and total obstructions from mud to a Gill WindSonic. A clear correlation is established between an obstructed (erroneous readings) versus an unobstructed (valid readings) transducer. In the case of the Tulia tornado, wind readings were reliable and unaffected by mud or other debris.

Testing the sonic anemometer with the MM configuration yielded 4-8% measurement inaccuracies for wind speeds > 30 m s^{-1} from the front of the vehicle. Potential measurement errors from other wind trajectories relative to the vehicle are unknown. Abrupt vehicle accelerations or decelerations from high velocities typically result in brief inaccuracies from a lag in GPS position. No errors of this sort were found within the dataset.

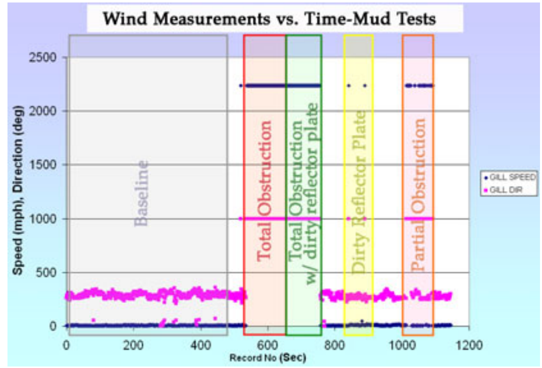

Figure 15: Wind measurements showing affects from mud obstructing the Gill WindSonic transducers. Mud was placed manually onto the transducers and reflecting plate with varying degrees of coverage and combinations. *Click image to enlarge.*

It is impractical to precisely define the true center position of the vortex in the absence of other remote sensing equipment, such as high-resolution mobile Doppler radar. However, the available meteorological data recorded from the tornado passage combined with the MM position relative to the narrow damage swath yields considerable confidence the center of the vortex passed very near the MM location. Fig. 16 plots measured wind speed and pressure with time, utilizing the minimum pressure as the center point.

The recorded pressure minimum occurred simultaneously to an abrupt change in wind direction (99^o to 306^o) and speed (44.2 m s^{-1} to 7.9 m s^{-1}). It is speculated the measurement at 0054:55 UTC was obtained near the center of the vortex; inside the radius of maximum tangential wind. Mobile Doppler radar observations of tornadoes and dust devils have shown a low-reflectivity "eye" defining the vortex center formed by the centrifuging of scatterers (Bluestein and Pazmany 2000; Wurman and Gill 2000; Wurman and Alexander 2005; Bluestein et al. 2004; Tanamachi et al. 2007). The aforementioned investigations have also shown a substantial reduction of wind speed within the center of tornadoes; essentially a "relative calm" compared to the ring of intense wind surrounding the center. This wind structure is similar to the Rankine combined vortex model, where the interior core flow increases with an increasing radius, from zero to a maximum

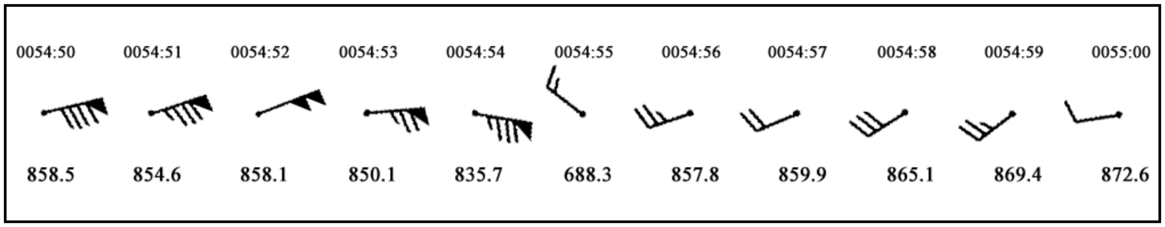

Figure 16: Time series plot of the measured wind speed (winds as in Fig. 1) at 2.9 m AGL and pressure (hPa) at 2.6 m AGL from 0054:50 to 0055:00 UTC.

velocity value. The measurements obtained from the Tulia tornado are suggestive to similar findings from mobile Doppler radar datasets with regards to a large reduction in wind velocity near the center of circulation. It is believed the vortex center would have been inherently small considering the width of damage was less than 100 m at the MM site. However, with the extraordinary pressure minimum recorded combined with the abrupt fall in wind speed, it is plausible the instrumentation resolved wind and pressure characteristics near the center of the vortex. A higher sampling rate of the instrumentation would have likely remedied some of the uncertainty regarding the position of the vortex center relative to the MM.

Measured wind along the southern periphery of the departing tornado showed a notable reduction in speed compared to the northern portion of the vortex. A review of the site characterization around the MM vehicle reveals obstructions that contributed to the lower wind speeds measured (Fig. 17). A nearly overturned 18-wheel tractor-trailer approximately 2 m from the instrument mast served as a large barrier within the 180^o–300^o directions post-tornado passage. The tilted semi-truck height was approximately 1 m taller than the sonic anemometer. The remnants of the Leja Tire Company building (300^o to 350^o) averaged 2 m AGL, owing to minimal wind interference. The remaining coordinates within close proximity to the MM were unobstructed. West-southwesterly (228^o to 260^o range, 7 s) wind speed immediately following the vortex center passage is speculated to have been dampened severely by the tractor-trailer obstruction. Additionally, an axisymmetric wind profile within and around the Tulia tornado may not have been present. Asymmetric velocity structures within tornadoes have been observed in the past using high-resolution Doppler velocity data (Wurman and Gill 2000; Wurman and Alexander 2005).

Figure 17: Aerial images of the tornado damage within the industrial region of Tulia. The yellow arrows denote the location of the MM vehicle. View is looking to the east (a), west (b). Highway 87 serves as a north-south reference. Photos by NOAA/NWS Lubbock, Darrin Davis and Zane Price. *Click image to enlarge.*

Furthermore, the quick translational motion of the tornado away from the vehicle also may have contributed to a lower ambient wind speed south of the vortex.

The wind flow over the tractor-trailer also permits the possibility of pressure measurement errors within the lee-side of the obstruction from dynamic pressure effects. With the wind trajectory over the semi-truck only after the approximated vortex center passed the MM, a minimal degree of pressure falls owing to the obstruction may have been realized by the instrumentation post-tornado.

b. Theoretical and observational considerations

With the difficulty of physically measuring a tornado, laboratory experiments and numerical simulations of the phenomenon afford insight into the characteristics within the lowest few m of the surface. The lowest pressures in tornadoes are believed to occur with a single-celled vortex structure at the surface capped by a vortex breakdown aloft (Davies-Jones 1973; Snow et al. 1980; Pauley et al. 1982; Church and Snow 1985; Fiedler and Rotunno 1986; Lewellen et al. 1997). This configuration effectively identifies a transitional region from a laminar supercritical vortex near the surface to a subcritical vortex comprising turbulent flow aloft (Fiedler and Rotunno 1986). Simulations have shown the lowest pressures obtainable within a tornado typically occur approximately 30 m AGL, with deficits from the ambient pressure well in excess of 100 hPa in the near-surface layer (Lewellen et al. 1997). Following a vortex breakdown, an abrupt expansion in vortex diameter at the surface materializes with rapidly increasing pressures. A two-celled vortex structure and central downdraft aloft descend to the surface, indicating an evolving multi-vortex configuration.

Recent studies have suggested the sensitivity to changes in the near-surface inflow layer may play a critical function in triggering vortex structure evolution that may ultimately lead to significant additional intensification, labeled corner flow collapse (Lewellen and Lewellen 2002). Impeding the inflow through a variety of conditions may result in rapid low-level vortex intensification, and similarly, the ability to achieve very large pressure deficits at the surface for a short period of time (Xia et al. 2003; Lewellen and Lewellen, 2007a, 2007b). While this is an attractive concept to explain large pressure drops within tornadoes, the transient nature of these pressure deficits results in a low probability of resolving them. Additionally, it is unclear how to discriminate between "normal" pressures within a tornado versus a vortex undergoing near-surface intensification with only a single stationary recording device.

The analysis of vortex structure evolution through visual observations is difficult due to condensation typically concealing important features (Fiedler and Rotunno 1986). However, tornadoes without full condensation funnels, but accompanied by dirt and debris, can offer better opportunities to discern vortex characteristics (Hoecker 1960; Golden and Purcell 1977). As discussed in Section 4a, visual evidence initially depicted the Tulia tornado as a compact single-cell vortex prior to affecting the MM. Shortly after the tornado departed the vehicle, multiple vortices were observed within the circulation with an expanding vortex diameter (Fig. 18). The visual evolution of the tornado mirrored some characteristics believed to be conducive for significant pressure deficits at the surface. However, it is not known whether a vortex evolution as previously described assisted in the large pressure minima recorded.

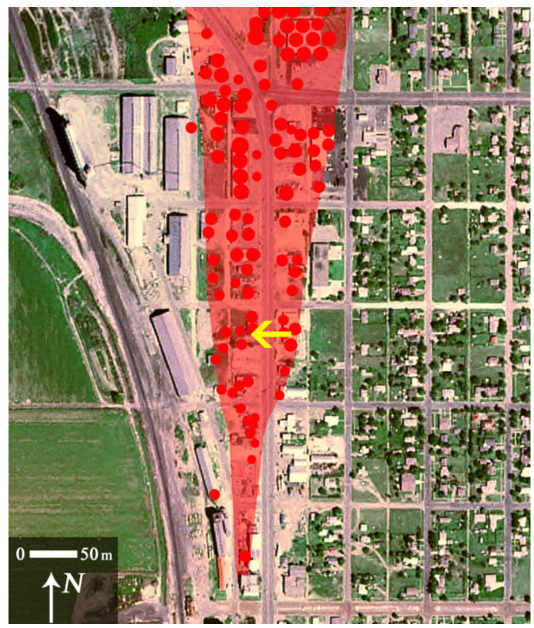

Figure 18: Aerial image of the western sections of Tulia. The red shading represents the approximate damage track of the tornado derived from aerial and ground-based surveys. Red dots indicate locations of visible damage. The yellow arrow denotes the location of the MM vehicle. The tornado translated to the north, or from bottom to top on the image. *Click image to enlarge.*

The MM measured pressure ~2 m higher than the average height of instrumentally-fitted, ground-based probes of less than 1 m AGL. While this differential distance may appear trivial, it is hypothesized the vertical distance above the surface may be of some consequence to the potential pressure minima values achievable. Lewellen et al. (1997) showed average minimum pressure values at ground-level to be underestimated by as much as 80% compared to the lowest minimum pressure at 27 m AGL. While the vertical pressure profile in the Tulia tornado is unknown, it is reasonable to consider the elevated nature of the MM instrumentation above the surface may have contributed to greater minima pressure values acquired.

Meteorologists from the National Weather Service in Lubbock, TX, Texas Tech University, and engineers from private and governmental agencies conducted a ground-based damage survey in Tulia on 22 April 2007. The surveyors found several EF2 damage indicators along the tornado track (*Storm Data*, NOAA 2007). These included damage to a large metal building and local retail shop within close proximity to the MM, an ALCO supermarket, and several manufactured homes and one-story residences. The surveyors determined maximum 3 s wind gusts at 10 m AGL were between 55 m s^{-1} to 60 m s^{-1}.

The peak wind gust measured by the MM at 2.9 m AGL was 50.4 m s^{-1} with a maximum 3 s wind speed of 46.7 m s^{-1}. The conversion from 2 m to 10 m to obtain a mean profile of wind over a specific duration has been conducted in hurricane measurements using a logarithmic wind profile, which incorporates surface roughness characterization and assumed neutral stability (Wieringa 1993; Powell et al. 1996). In the case of the Tulia tornado, it is unknown whether standardization to the wind field with height could be applied, especially in the absence of in situ thermodynamic data and the relatively short duration of the event itself. It is probable that wind speeds extrapolated from 2.9 m to 10 m would yield higher wind speeds.

7. Summary

A mobile mesonet vehicle equipped with a suite of meteorological sensors encountered a strong tornado within the town limits of Tulia, TX, on 21 April 2007. Instrumentation measured the wind and pressure characteristics at 2.9 m and 2.6 m AGL respectively of the tornado. The data were recorded at a 1 Hz rate, which was a limitation in resolving fine details of a fast-moving and relatively small diameter vortex. Maximum wind speed measured was 50.4 m s^{-1} with a 3 s peak wind of 46.7 m s^{-1}. The minimum recorded station pressure was 688 hPa, yielding a 194 hPa deficit from the environmental pressure. This is the largest known pressure fall measured within a tornado to date.

The instrumentation was calibrated and examined for potential inaccuracies. It was found that pressure measurement errors can arise under specific circumstances contributed mainly to the MM design. These potential inaccuracies are small relative to the magnitude of the recorded minimum pressure. Through the use of visual observations, collected wind and pressure data, and surveyed damage track, it is believed the center of the Tulia tornado passed very near the MM instrumentation. Wind data were compromised within the southern periphery due to surrounding obstructions restricting wind flow. While the MM vehicle sustained substantial damage from the tornado, the sonic anemometer and analog barometer remained operational during the entire event.

Laboratory experiments and numerical simulations suggest that minimum pressure values during the life cycle of a tornado exist near the time of a vortex breakdown approaching the surface (Davies-Jones 1973; Pauley et al. 1982; Church and Snow 1985; Fiedler and Rotunno 1986; Lewellen et al. 1997). Corner flow collapse and the associated low-level vortex intensification also can explain large pressure falls within tornadoes at the surface (Lewellen and Lewellen 2007a, 2007b). It is unknown whether such processes can account for the extreme measured pressure deficit in Tulia, and it remains to be seen whether or not a pressure fall of this magnitude can be duplicated in subsequent tornado intercepts. It is hoped future investigations, through direct observations in the field or numerical simulations, will explore the maximum achievable pressure falls in tornadoes near the surface. Additional observations will be necessary to determine whether pressure deficits in tornadoes on the order of ~200 hPa are anomalies, transient in nature, or more common than previously believed.

ACKNOWLEDGMENTS

The authors wish to acknowledge the late Eric Michael Nguyen for making this paper possible. Eric's innovative passion to sample the atmosphere provided the platform to investigate this unlikely tornadic encounter. Eric greatly assisted the authors by performing post-event quality-assurance tests on all meteorological equipment, providing instrument specifications, and recounting essential eye-witness documentation. Above all, he provided unparalleled inspiration, support, and interest towards the authors' research efforts.

The authors extend appreciation to Amos Magliocco, who also served as an important eye-witness reciting critical details of the event, providing high-resolution video, and proofreading previous drafts. The authors also like to thank the reviewers and those who aided in the research presented herein. This includes: Bob Fritchie, School of Meteorology, University of Oklahoma; Dr. David Lewellen, Dept. of Mechanical and Aerospace Engineering, West Virginia University; Jeff Snyder, School of Meteorology, University of Oklahoma; Dustin Wilcox, photographs; National Weather Service Forecast Offices in Lubbock, TX and Amarillo, TX; and the authors respective weather forecast offices of the National Weather Service in Topeka, KS; Pleasant Hill, MO; and Goodland, KS.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Erik N. Rasmussen):

Initial Review:

Recommendation: Revisions Required

General and Substantive Comments:

My general comment regarding this manuscript is that the authors have done a lot of work, and can make this paper into a good contribution to the literature. I think the contribution would be this: the authors bring to light dynamics issues that control the low-level pressure deficit, and the authors present a some evidence that ought to motivate additional observations (can we duplicate this extreme pressure deficit?). *[Tangential discussion omitted.]*

This table summarizes my evaluation of this study. Specific comments follow the table.

Criterion	**Satisfied**	**Deficient, but can be remedied**	**Deficient; *cannot* be remedied by modifying the paper**	**Deficient, *not known* if it can be remedied by modifying the paper**
1. Does the paper fit within the stated scope of the journal?	X			
2. Does the paper 1) identify a gap in scientific knowledge that requires further examination; 2) repeat another study to verify its findings; or 3) add new knowledge to the overall body of scientific understanding?	X			
3 Is the paper free of errors in logic?	X			
4. Do the conclusions follow from the evidence?		X		
5. Are alternative explanations explored as appropriate?		X		
6. Is uncertainty quantified?				X
7. Is previous work and current understanding represented correctly?		X		
8. Is information conveyed clearly enough to be understood by the typical reader?		X		

Detailed explanation of ratings, enumerated as above.

1. The paper is well-suited topically for inclusion in EJSSM.

2. The paper suggests that more research is needed regarding the dynamics of observed tornadoes, and hence it identifies a gap in knowledge and satisfies this criterion. It does not, and I believe can not (because of limitations in the observations) add new knowledge, and I urge the authors to try to change the tone/emphasis of the paper to one of highlighting some intriguing observations that require more research, as opposed to providing a concrete explanation of the observations in hand.

3. I cannot point out any particularly troubling errors in logic. There are small errors here and there as noted in the comments in the manuscript. But, of more significance, see #4 and #5 below.

4. The problem here is that the conclusions are not put forth definitively. To a great degree, it is left as an exercise to the reader to "conclude what you will." This is unsatisfactory. The writer needs to state clearly the conclusions, and let the reader decide if they agree. In particular, I think the authors were trying to tell this story:

   - we measured a ~200 mb pressure fall.
   - we believe our measurements.
   - here is how that sort of fall can happen in the atmosphere.
   - here is why we believe it happened at Tulia.

   If indeed that is the story and conclusion, then I would say the conclusion does not follow from the evidence. Here is how I would revise the story to remedy this deficiency: I would say that we have an interesting set of observations. Absent local dynamic effects (structures, sensor mounting, etc.) and assuming that the sensor really did function correctly, this is by far the largest pressure fall ever measured in a tornado. (That's a really BIG story, by the way. It's very annoying that the authors did not point out how extreme this event was.) I would then say that, given the extreme nature of the observation, it is worthwhile discussing the body of knowledge regarding pressure falls in a tornado. I would do a little more work to try to tie the theoretical pressure falls with what might be expected in Tulia. One could use CAPE, one could form a relationship using wind speed estimates derived from damage, etc. It ought to be possible to get to the point where you could say the observed fall is plausible, or that it is improbable or highly improbable, etc. My conclusion would be simple: if these observations are to be trusted, they point us in the direction of much further research into tornado dynamics and pressure distribution through the lowest few tens of meters. And, not to put too fine a point on it…but I would say that many more observations are required before we can conclude that 200 mb falls are possible near the ground in tornadoes.

5. See #4. Prominent alternative hypotheses include inaccuracy in the measurements, pressure deficit induced by nearby elements of the observing system, by structures, etc. (I know the overturned semi was discussed… that is good. But it is discussed as an aside, and it the reader should be very aware that this is an alternative explanation for the low pressure readings.)

Agree with the philosophy on items 4 and 5. The second draft of the paper puts forth the conclusions more prominently and a larger effort was undertaken to reevaluate the potential errors and biases of the instrumentation.

6. This potentially very problematic. In the first two paragraphs of Section 3, the authors contend that the mobile mesonet system conforms to the standard of the NSSL mobile mesonet. However, the authors need to provide evidence for that claim. For example, the NSSL mobile mesonet wind instrument placement was based on wind tunnel smoke visualizations provided by the manufacturer of the sedans that demonstrated that the wind instruments were above the vehicle slip-stream. I tend to doubt if this was the case with the Nissan XTerra, being a "blockier" vehicle. An NSSL mobile mesonet instrument is compared, typically on every mission day, with a set of thousands of observations from similar systems operating in the same environment. This sort of frequent comparison to a standard is the only way to detect instrument bias, which can drift around with time.

It should have been clarified that the MM was physically designed similar to the overall instrument layout to that of other MM vehicles, but not necessarily the specific error bars associated with a NSSL MM. Inherent differences exist with the use of different vehicle types and instrumentation placement, and these are described further in Sections 3 and 6.

The authors state that the instruments were calibrated at the start of the 2007 season. What was the method of calibration? It is unfortunate, but these sorts of questions are more relevant with a personal, "hobby" observing system than they might be with a more formally associated and maintained observing system. I suppose the same questions ought to be asked regarding all observing systems. We really need to know the uncertainty.

A third party calibrated the PTB101B during the winter months. Additionally, the MM was driven to a local Oklahoma mesonet site to monitor any deviations between the two operating systems. (This source was personal communications with Eric Nguyen. Technically, I have no material means to prove or disprove this was conducted, but I'm positive his word was good. The calibration conducted following the Tulia event by Vaisala (which is available) showed the analog barometer in excellent working condition, lending confidence to the reliability of pressure measurements during the 2007 season.)

How is it established that in instrument is "within factory specified tolerance"?

My intuition tells me that the placement of the pressure port is very problematic in this mobile mesonet design. It is in the immediate proximity of some sort of electronics box in the mast which would have caused a significant disturbance to the flow with associated pressure increase/decrease depending on the flow angle.

The authors state that "Turbulence associated with the vehicle in motion was determined to be negligible given the sensors' location in proximity to the front of the vehicle, height AGL, and prior field experimentation". Can the authors provide data to justify this claim? I would have thought there would be data or a citation here. I will give the authors the benefit of the doubt that the data do exist, and will be presented in any revision. If this is just a fabricated claim to lend validity to the paper, I would urge the authors to never use this tactic in a formal publication again. We're here to learn about the atmosphere together, and candor is essential.

Significant revisions were performed on several sections, especially Section 6, to include several tests and discussion of the reviewer's concerns. The initial draft provided a limited explanation of instrument biases and uncertainty, and this was remedied within the second version. Eric Nguyen passed away before completing a robust quantification of the vehicle-instrument relationship. We continued the process of testing instrumentation and MM configuration during the winter months of 2007. Eric had believed vehicle effects were negligible on the instrument platform, but never rigorously tested the potential effects at higher wind speeds. Such statements were removed upon further testing in the new draft.

I think the authors have made several unsupportable claims here in order to make credible their subsequent discussion and conclusions. If this is the case, the paper is not lost. At this stage in the growth of our knowledge, just about any/all direct observations of tornadoes are interesting and worth pondering. I believe it is perfectly valid, and necessary, to state how the instruments were calibrated. It is also acceptable to state that the effects of the vehicle form on the wind and pressure are unknown (the alternative is to get the vehicle and instruments to some sort of test site, perhaps at TTU, instrument the bejeebers out of it, and find measure the errors in wind vector and pressure under various flow angles and speeds). It is much more problematic, but still acceptable, to state that the pressure sensor response to a rapid depressurization/compression is not well established. Here it would be more feasible to get the pressure sensor to a lab and perform this sort of test, but that still does not isolate the possible effects of the vehicle, nearby obstacles, etc. on the pressure measurements.

See above.

However, if the uncertainties are honestly unquantifiable, then the authors will be forced to scale back their discussion and make it clear that they can only speculate as to the dynamics of the tornado because the data are not conclusive. This is not a bad thing. The authors should ask themselves: do we want the readers to believe that we have proven that ~200 mb pressure falls occur in some tornadoes at the ~2.5 m level?

Now, in addition to the unquantified uncertainty in the measurements, a similar problem arises in Sec. 4a. There are many comments related to the tornado size and structure. Are these the observations of one of the authors? How were the observations documented in real time? Were the observations developed based on video or photographic sources? Was photogrammetry performed? These are relatively minor issues, since the section is more of a narrative of the tornado life cycle. So a sentence or two will suffice to clarify these points.

The second version contains these clarifications.

I chose the "not known" box above because if the authors decide that they want to convince the readers that the ~200 mb deficit really occurred, they will have to do a lot of convincing regarding the uncertainty. If, on the other hand, they want the readers to believe that 200 mb might have occurred, and there are plausible explanations for how this could occur, then the level of quantification of uncertainty can be more relaxed.

7. The authors have done a good job surveying the body of relevant tornado literature. Please note the comments in the manuscript. Any issues here simply relate to clarity of expression.

8. I recommend the authors consider the many style and grammar issues noted in the attached manuscript. In general terms, the authors sometimes add unnecessary phrases that complicate their sentences. Also in general terms, the use of non-quantitative adverbs and adjectives is discouraged, and figure captions are for describing the figure nomenclature, etc., not for drawing inferences, conclusions, etc. The term "impact" is a poor or downright incorrect word choice most of the time.

Grammatical suggestions by the reviewer were accepted within the second version of the paper.

[Minor comments omitted...]

Second review:

This paper has been improved greatly since the first round of reviews, and I commend the authors. I am especially impressed with the detailed analysis of uncertainty and instrument performance. Well done!

In my opinion, the authors have established the case for the large pressure fall with enough certainty. It is now up to others to demonstrate how this measurement could be dubious, or somehow outside the realm of the physically possible. That's the kind of debate and refinement of ideas that good journals should foster.

There are a few issues in the marked-up PDF that I strongly encourage the authors to consider. However, I see no major issues left to address before publication.

This table summarizes my evaluation of this study. Specific comments follow the table. [Editor's Note: Please see PDF version for specific comments.]

Criterion	**Satisfied**	**Deficient, but can be remedied**	**Deficient; *cannot* be remedied by modifying the paper**	**Deficient, *not known* if it can be remedied by modifying the paper**
1. Does the paper fit within the stated scope of the journal?	X			
2. Does the paper 1) identify a gap in scientific knowledge that requires further examination; 2) repeat another study to verify its findings; or 3) add new knowledge to the overall body of scientific understanding?	X			
3 Is the paper free of errors in logic?	X			
4. Do the conclusions follow from the evidence?	X			
5. Are alternative explanations explored as appropriate?	X			
6. Is uncertainty quantified?	X			
7. Is previous work and current understanding represented correctly?	X			
8. Is information conveyed clearly enough to be understood by the typical reader?	X			

REVIEWER B (Paul M. Markowski):

Initial Review:

Reviewer recommendation: Acceptable with major revisions

General Comments:

I believe the observations reported herein are probably publication-worthy owing to their rarity, but I believe that the paper must undergo significant improvements prior to publication. For starters, I'm skeptical of the error bars of the measurement. The text cites a factory-specified inaccuracy of 0.5 mb, but does this apply even at extreme pressures like that encountered by the MM? The effects of the vehicle on the pressure reading are claimed to be insignificant for typical vehicle speeds, but is it known what impact the vehicle can have on the surrounding pressure field when winds move over the vehicle at 50 m/s? Also, we do not know exactly where in the tornado the observations were obtained. Contrary to what is claimed, I do not see how it can be known for sure that the wind observations penetrated the tornado's core (defined as the region inside of the radius of maximum wind) without overlaying mobile Doppler radar observations. Are the authors surmising that the observations were likely very close to the tornado's center simply because the pressure drop is so extreme? If so, this assumption should be stated.

Another weakness of the paper is the authors' attempt to relate their observations to some of the latest ideas about tornado intensification (e.g., those of Lewellen et al.). Basically what we have here is one data point showing an extremely large pressure deficit, with the authors claiming that they are likely observing a sudden vortex intensification associated with corner flow collapse (CFC) like that found in Lewellen et al.'s simulations. The authors need to be more forthright in saying that (even if the error bars on p' are relatively small) they have just one extreme pressure observation, the observation is from an unknown location in the tornado (it cannot be known whether the observation is from within the tornado's core or not--all that is known is that the observation is from within the tornado's damage swath), and that many of the key tornado characteristics related to CFC (swirl ratio, core radius, etc.) are unknown, yet despite of all of these uncertainties, they believe that they may have caught a snapshot of the vortex intensification process described by Lewellen et al.

I recommend that the authors collaborate with a tornado dynamics expert. Such collaboration could help them address the issues I've raised above, as well as improve the discussion in section 6, which has a number of problems. For example, the authors seem confused between the swirl ratio of the vortex as a whole versus the corner flow swirl ratio (they do not distinguish between the two, yet based on context, they refer to each at different locations in the paper). They also seem confused at the difference between laboratory and numerical simulations (numerical simulations are cited as laboratory experiments), and have a misunderstanding of how turbulence is generated (friction does not generate turbulence; in the TKE equation, molecular viscosity is a TKE sink--shear generates turbulence, and vertical shear can be enhanced by surface drag, but as written, the authors' explanation is problematic). The authors also fail to note that the extreme pressure drops in the Lewellen et al. simulations last for only a few seconds [e.g., see Fig. 9a of Lewellen and Lewellen 2007a--the big pressure drop lasts for t/ts ~ 0.05, which corresponds to just a few seconds for ts ~ 100 s (see their appendix B, subsection c)]. Do the authors herein claim that they just happened to sample one of these transient extreme pressure minima at precisely the right place and instant? It's certainly possible, but the authors don't really convey just how unlikely such an observation might be. A related question is whether the observed pressure minima indicates anything at all about corner flow collapse and sudden vortex intensification--could such an extreme pressure drop be observed in an intense vortex independent of the corner flow processes studied by Lewellen et al.? The authors conclude that "several forms of evidence substantiate the MM was impacted near an optimal structural timeframe to achieve large pressure deficits at the surface". This is an unjustifiably strong statement based on the fact that we have only a single observation of an extreme pressure minimum, we don't know for sure how accurate the observation was in such extreme conditions, we don't know the structure of the tornado (was there a vortex breakdown or not, and if so where was it?), we don't know exactly where in the tornado the observation was obtained (was it near the axis, near the radius of maximum wind, in the corner region, etc.?), and we don't know if the tornado might have had pressure deficits this large independent of complex corner flow dynamics.

Finally, the overall technical quality of the paper can be improved greatly. At times I found the writing style to get in the way of my evaluation of the science. In many places it seems as though the authors are attempting to use more scientific-sounding terms, but they instead have changed the meaning of what they really want to be saying. For example, the term "kinematic" is used in many places instead of what I believe should just be "wind speed/direction". To me, if one says that "kinematic observations" of the tornado were obtained, then one has obtained measurements of divergence, vorticity, deformation, swirl ratio, etc. Another example is the repeated use of "translate" when referring to the supercell motion, rather than just "move". Supercell motion consists of translation and propagation. To me, "translation" is not a synonym for "motion", but rather the contribution to the overall motion that results from advection by the ambient wind. An "interaction" between the tornado and MM also is mentioned in a few places, when I think that the authors merely intend to say that the tornado struck the MM rather than imply that the MM and tornado had some sort of "reciprocal influence" (per Webster's Dictionary). Other examples are indicated in the annotated electronic copy of the manuscript that I'm also providing.

Significant revision on Section 6 improved the focus on the collected MM data. A greater emphasis was placed on investigating the data through several tests and methods for potential measurement errors. Instrument accuracy, capability, and external variables leading to potential biases were examined and discussed. The theoretical portion was economized to better address material relevant to the dataset. The majority of concerns and grammatical suggestions by Reviewer B were integrated within the second draft of the paper.

[Minor comments omitted...]

Second Review:

Reviewer recommendation: Acceptable

General Comments: The revised manuscript looks much better to me.

[Minor comments omitted...]

REVIEWER C (Tim Samaras):

Initial Review:

Recommendation: Revisions Required.

Background (Major Comments):

1. To date most of the reviewer's in-situ pressure measurements, sampled at 10 samples per second, had a pressure deficit duration exceeding one second. All measurements had more than one rapid fluctuation (Lee 2004, Wurman and Samaras 2004). The extraordinary measurement that Eric collected was sampled for only one second, indicating a dynamic response limited by the recorder sample rate.

The Tulia, TX tornado contained large pressure deficits exceeding one second. The deficits before the extraordinary fall were 33 hPa and 47 hPa, which are also in the upper spectrum of known pressure deficits in tornadoes. Certainly a sampling rate greater than 1 Hz would have produced improved resolution not available with the existing MM settings.

This pressure deficit is equal to a near instantaneous pressure spike of 2.8 PSI in one second. Such a pressure change on their eardrums would have been incredibly painful -- even damaging -- for Eric and Amos to experience (Dr. Timothy Walilko, blast injury expert, personal communications). Neither one of the participants commented about a 1 Hz 'pop' (personal communications).

While neither occupant recalled a specific 1 Hz "pop", both occupants did comment (personal and public communications) on a painful "ear-popping" experience as the tornado overtook the vehicle. It is not believed any of the occupants suffered any barotrauma. Eric Nguyen was quoted in the Amarillo Globe-News stating "It caught us by surprise, my ears popped and the debris was flying." Amos Magliocco posted

"We accelerated, our ears popping, but the inflow jet tugged us off the road" immediately after the event on a public storm chasing forum. Upon post-discussion with the occupants, the duration and magnitude of the ear-popping is unknown, although it was described as "painful." Generally, we would discourage the use of personal accounts from trauma-struck individuals as a credible scientific means to validate or invalidate recorded data.

Also unclear is the actual frequency response/alias filter of the transducer, as this information is not published in the specifications after a brief search.

The response of the PTB101B analog barometer is included in Section 6a.

2. A good indicator of a failure mechanism is that of the wind speed/direction recording from the sonic anemometer, which failed at the exact point of the maximum pressure deficit.

The second version of the paper includes the full wind data set for the 120 s period. Initially, wind direction following the tornado failed to match video from inside the MM and was manually omitted. It was speculated mud or debris on the sonic transducers could have been responsible. However, this would have produced erroneous wind readings (999°/m s^{-1}) and a two-digit error code, which did not occur. It was later discovered the GPS position of the stationary MM vehicle spontaneously changed shortly after the tornado passage. With the erroneous position yielding an 86° wind direction error, a correctional method was applied to the measurements. Video served to validate the augmented wind measurements. Therefore, no failure mechanism of the instrumentation existed.

Based on Eric and Amos' account (personal communications), the failure was likely due to the impact of debris and mud on the sensor.

This was never determined by the MM occupants and likewise no account would have been created. Instead, this was the initial conclusion of the authors, which was incorrect. See above.

On page 5, Fig. 7 of the review-in-process paper, there is a picture of the anemometer showing the pressure head and the actual sensor mounted to the mast. By the very nature of these pressure sensors, they are VERY sensitive to ANY type of external acceleration stimuli - such as debris impacting the sensor housing. It is possible that the debris itself that impacted the anemometer also caused acceleration on the pressure sensor and mast, thus providing a signal inconsistent with a pressure deficit.

With the lack of external impact marks on the sensor housing, the capability of the sensor measuring rapid pressure changes within a short period of time, and deceleration in wind speed at the time of the pressure minimum, it seems unlikely this would be the cause for an artificial spike in the pressure trace. This, along with other suggested recommendations, is discussed further in Section 6a.

It is recommended that an independent laboratory should perform the following tests on the pressure transducer:

1. Measure the mechanical frequency response of the pressure transducer
2. Measure the external acceleration stimulus errors of the pressure transducer.

The reviewer recommends the following methodologies for testing:

1. Provide a pressure step function to the transducer, and record the output on a high speed digitizer. Perform an FFT on the data to determine mechanical/electrical frequency response.
2. Mount an accelerometer on the transducer that is mounted on a similar mast, and provide 'acceleration' that would closely match wind-driven debris/mud and record the result.

See above.

Second Review:

Recommendation: Revisions Required.

The recent revision has improved significantly. The authors have addressed areas of concern where the reviewer had some questions and concerns regarding the claimed 194 hPa pressure deficit. One of the concerns was the mechanical stimulus that could have created the pressure deficit. The authors discussed (p. 11) some of the free-fall/sinusoidal tests that Vaisala had performed with a different model, but contained the same Barocap sensor. The tests involved vibration and drop tests at .5 and 1 m height.

Referring to Figure 12 on page 9, the authors show a graph that plots the pressure deficit, wind speed, and wind direction. At ~54:45 UTC the wind speed dramatically increases over a period of 3 s to values of 45-52 m s^{-1}. Then, at approximately 54:55 UTC the graph shows the pressure drop to a 194 hPa pressure deficit. At this exact same point, the wind speed drops from a value of 43 m s^{-1} back down to an average of 7-10 m s^{-1} in 1 s. At this same exact point, the wind direction becomes highly erratic suggesting possible turbulent flow.

Overall, this is a correct summary. It is believed the turbulent flow measured on the southern periphery of the vortex can be strongly attributed to the semi truck obstruction. This is described in detail on p. 8 and pp. 12-13.

On page 7 a description mentioned "Strong surface inflow into the vortex prevented the MM from maneuvering away from the approaching tornado". One would have to assume that the vehicle is being exposed to the measured wind speed beginning at 54:45 UTC for the wind 'strong enough' to draw the vehicle into the vortex. At this point, based on the measured pressure deficit of ~25 hPa, the MM was likely close/in the tornado core flow region. It is believed that the MM was still in motion at this time during maximum wind based on the wind speed measurements and the MM being 'pulled' into the vortex. It is not possible for the MM to draw the vehicle into the vortex before 54:45 UTC, as the wind speed was only 10-20 m s^{-1} from 53:55 UTC (beginning of the graph) to 45:45 UTC.

This is partially correct, but requires necessary clarification. The MM began to veer off the road when first encountering 30+ m s^{-1} easterly wind speeds at 0054:46 UTC. The MM came to rest at approximately 0054:53 UTC. The 194 hPa pressure deficit was recorded at 0054:55 UTC, approximately 2-3 s after the vehicle became stationary. It is noteworthy to mention the MM encountered up to 44 m s^{-1} wind speeds while stationary and before the minimum pressure recording. (FWIW: The last sentence was confusing and the times appear incorrect. I assume 'inflow' was to be in place of MM?)

Again, on page 7, the description goes on to say that "The vehicle was forced off the road and came to rest at the Leja Tire Company near the corner of Highway 87 and NW 4th Street, only seconds prior to the arrival of the tornado.

This is correct; see the data and comments written above.

Based on Amos Magliocco's personal accounting (http://www.cycloneroad.com/2007april21.htm) of this event, his words compared to the authors are as follows:

> "The pressure drop caused our ears to pop and the engine struggled with a ferocious east-northeast wind. The windows blew out except the front glass and wind rushed into the cabin. The tornado dragged our SUV to the left, toward an old tire shop on the western side of State Road 86. The rush of air was deafening. It was impossible to speak or be heard. I focused on what I believed at the time was Eric's choice to drive us toward this building. Not a bad idea, I thought, use the structure as the barest form of protection since it was clear we wouldn't escape. In reality, Eric was jamming the brake while the tornado pulled us to the west. We accelerated toward the building and I hoped the collision didn't kill us before the tornado had a chance to take its own shot. Then came the first in a series of fortunate turns when instead of hitting the corner of the building (which would have exploded the air bags) we crashed into a pile of old tires, softening our impact dramatically."

It is worthy to acknowledge Amos's account following where the reviewer left off. It is misleading to omit that the vortex struck the MM occupants soon following the vehicle becoming stationary.

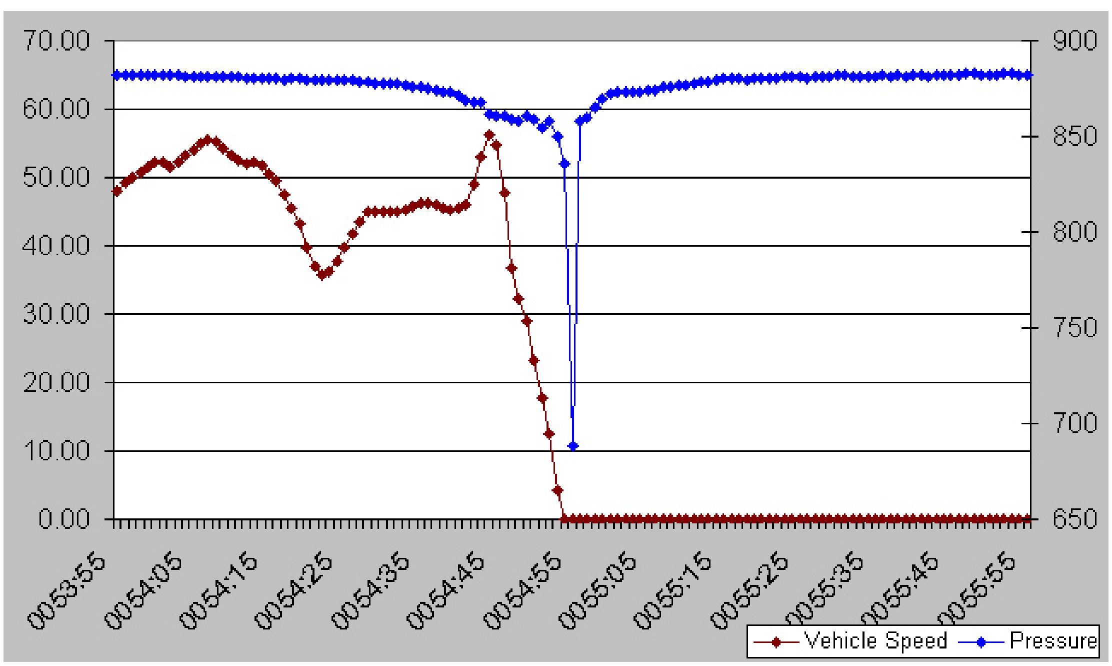
> *"Things went downhill from there. The worst of the vortex hit with a fury of debris and violent noise. We shut our eyes tight and huddled in the center of the truck, ducking as low as possible to avoid missiles through the open windows. We wouldn't have been able to duck so low if the airbags had deployed. The circulation smelled like fresh cut grass. The machine-gun sequence of crashing and crunching sounded like a circus tent coming apart in a gale, metallic echoes and the whip and snap of roofing material and wooden splinters against the doors."*

Based on Amos' account, it appears that the occupants were worried about 'crashing' into the building; they 'crashed' into a pile of old tires. It is the reviewer's theory that it was at the point of impact that the MM recorded the apparent 194 hPa pressure deficit. This would explain the erratic behavior of the wind direction and the notable drop of wind speed by being sheltered by the semi trailer and other structures shown on page 4.

This hypothesis is mainly incorrect. The MM occupants' initial concern of 'crashing' into a building is true. However, it is misleading to characterize the MM deceleration as a "crash." Instead the vehicle came to a relatively gradual stop in the proximity of a pile of tires, perhaps bumping into a few tires at a trivial velocity. Additionally as mentioned above, the MM vehicle was stationary a couple seconds prior to the 194 hPa pressure recording. See below for additional related information.

On page 4, the authors describe the data logger, software, and GPS instrumentation. The paper describes a Garmin 16 HVS system that provides vehicle lat/lon coordinates, vehicle speed and heading at a rate of 1 Hz. The reviewer believes that this missing information in the paper would provide substantiation that the vehicle was likely in motion during the highest wind speed, and instantly came to rest at the exact moment of the maximum apparent pressure deficit. It would be helpful to provide a plot of vehicle speed vs. time based on the GPS information.

It is believed the reviewer would benefit from a graph of GPS vehicle speed and recorded pressure versus time. This graph is attached below (units in mph and hPa). While the reviewer's hypothesis is appreciated, it does not correlate to the recorded data. The MM vehicle was stationary a couple seconds prior to the 194 hPa pressure recording. Additionally, the vehicle decelerated from 54 mph to stationary over the course of 8 seconds, which does not constitute a significant deceleration.



It is theorized by the reviewer that the 'pressure deficit' was caused by the acceleration of the pressure sensor during the impact of the MM against the tires discussed both in the paper and in Magliocco's personal accounting. Although the author shows some of the qualification tests of the pressure sensor, it is believed that the tests would be inconclusive to dismiss the impact deceleration of the actual PT101B sensor under different deceleration values. Using the GPS data, one could roughly calculate the deceleration of the vehicle to see of the reviewer's theory is correct.

Again, 'impact' and 'crash' are highly misleading adjectives to describe the deceleration to stationary of the MM vehicle in support of this hypothesis. See above for author response to the reviewer's hypothesis.

The reviewer also wishes to closely work with the authors off-line (if they wish to do so) to conduct a similar deceleration test using the exact pressure sensor.

This is something that can be discussed and entertained informally off-line, separate from the current paper at hand.

[Editor's Note: This is a perfectly acceptable and reasonable approach. We encourage this sort of cooperation among scientists and will be glad to host any such results in the area devoted to EJSSM's post-publication comments.]