19.4 UPDATED MOBILE RADAR CLIMATOLOGY OF SUPERCELL TORNADO STRUCTURES AND DYNAMICS

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1. INTRODUCTION

High-resolution mobile radar observations of supercell tornadoes have been collected by the Doppler On Wheels (DOWs) platform between 1995 and present. The result of this ongoing effort is a large observational database spanning over 150 separate supercell tornadoes with a typical data resolution of O(50 m X 50 m X 50 m), updates every O(60 s) and measurements within 20 m of the surface (Wurman et al. 1997; Wurman 1999, 2001).

Stemming from this database is a multi-tiered effort to characterize the structure and dynamics of the high wind speed environments in and near supercell tornadoes. To this end, a suite of algorithms is applied to the radar tornado observations for quality assurance along with detection, tracking and extraction of kinematic attributes.

The integration of observations across tornado cases in the database is providing an estimate of observed tornado size and intensity distributions that differ significantly from the damage surveyed distributions. Vertical structure of the tornadoes is examined to characterize differences between near-surface tornado wind speeds and those associated with the larger scale mesocyclonic flow aloft often observed by operational radars. The evolution of angular momentum and vorticity near the surface in many of the tornado cases is also providing some insight into possible modes of scale contraction for tornadogenesis and failure.

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2. DATA

The DOWs have collected observations in and near supercell tornadoes from 1995 through 2008 including the fields of Doppler velocity, received power, normalized coherent power, radar reflectivity, coherent reflectivity and spectral width (Wurman et al. 1997).

A typical observation is a four-second quasi-horizontal scan through a tornado vortex. To date there have been over 10000 DOW observations of supercell tornadoes comprising over 150 individual tornadoes.

Data used for this study include DOW supercell tornado observations from 1995-2003 comprising about 5000 individual observations of 69 different mesocyclone-associated tornadoes. These tornado observations are all at ranges of less than 30 km from the radar. When focusing on the typical sub-cloud layer below about 500 m above ground level (AGL) the number of DOW tornado observations is reduced to about half of the total number, namely about 2500 observations.

DOWs have been fielded in project Radar Observations of Tornadoes And Thunderstorms Experiment (ROTATE) nearly every year since project Verification of Rotation in Tornadoes EXperiment (VORTEX) in 1995, usually between mid-April and mid-June (Wurman 1999, Rasmussen et al. 1994). The greatest frequency of DOW supercell tornado intercepts occurs during the last week of May and the first two weeks of June (Fig. 1).

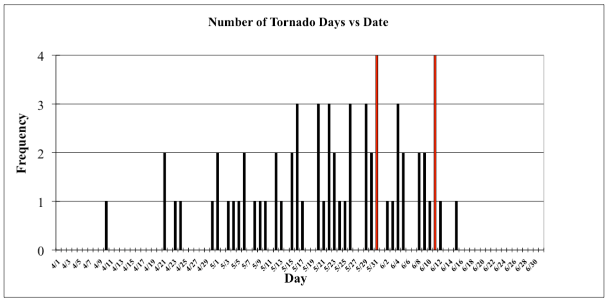

Fig. 1. Number of DOW-observed tornado days per date during projects VORTEX and ROTATE from 1995-2008 showing peak frequency in late May and early June (red).

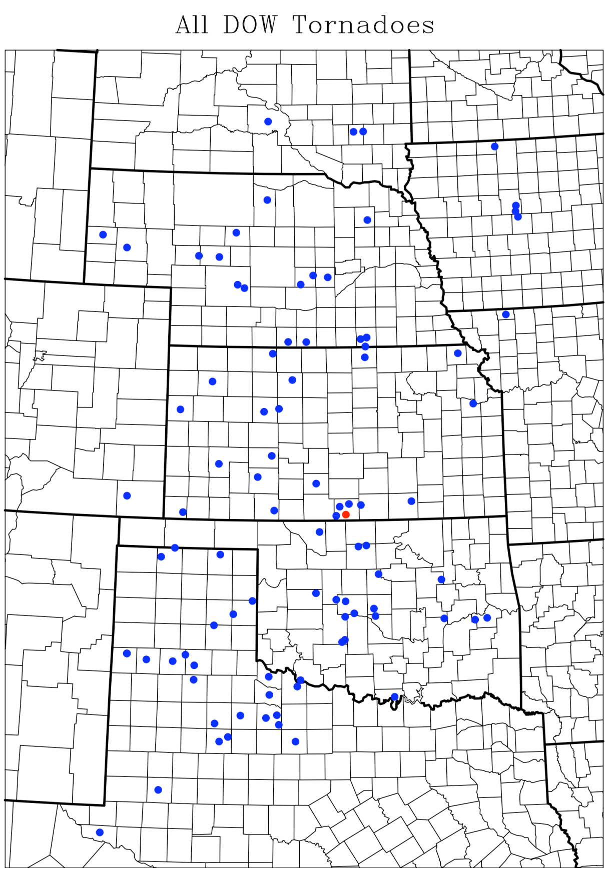

Fig. 2. Location of DOW-observed tornadoes during projects VORTEX and ROTATE from 1995-2005 (blue) and overall averaged location (red).

The ROTATE domain of operations was initially confined to the southern plains of the United States in Oklahoma and adjacent portions of Texas and Kansas. The operations domain was broadened after 1997 to include the remainder of the plains from North Dakota south to central Texas and eastern Colorado eastward into western Iowa (Fig. 2).

3. METHODOLOGY

All DOW supercell observations are quality controlled with a series of software algorithms to navigate stationary and mobile radar data into ground-relative coordinates, threshold incoherent velocity data from clear-air and multiple-trip returns, dealias velocity measurements and eliminate ground-clutter.

An upward correction to the elevation angle is applied to DOW observations when the reported elevation angle is less than about a half beam-width (0.5 degrees) above the horizon to account for partial blockage of the primary lobe by the ground.

About two-thirds of the DOW supercell observations are collected while the radar is moving resulting in an additional Doppler velocity component. This additional component is removed from each scan during the quality control stage using the velocity of ground-clutter targets and/or the known position and heading of the radar at various times. The pitch and roll of the radar during mobile operations remain unknown yielding some uncertainty primarily in the elevation of observations, which scales as about O(100 m) vertical error at about O(10 km) range from the radar.

Following quality control, the radar observations have a series of algorithms applied to detect, track and extract tornado observations for additional analysis. About 20% of the DOW supercell scans (observations) contain features that are classified as a tornado detection by an algorithm that requires at least 40 m s^{-1} of Doppler velocity difference across no more than 2 km of horizontal distance at constant range from the radar (pure rotation). Furthermore, the feature is considered a coherent vortex if it can be tracked in two or more scans (observations) assuming the feature is moving at ground-relative speeds of less than about 25 m s^{-1}. More than one feature can be identified as a tornado in the same scan but they must be separated by more than about one core diameter associated with the stronger vortex.

Once all tornado observations are identified and isolated into individual coherent features in space and time, attributes of each observation are extracted including but not limited to an estimate of the vortex center point position, translational velocity of the vortex center point, peak velocity values in the vortex, distance between peak velocity values, peak ground relative velocity values and the Fujita Scale and Enhanced Fujita Scale equivalents of these peak ground-relative velocity values (Fujita 1971, 1992; Marshall 2004).

For tornado observations with large radar-sampling aspect ratios (i.e. smaller tornadoes and/or tornadoes at considerable range from the radar) a small aspect ratio correction is applied to increase the peak Doppler velocity values by no more than about 10% to account for the reduced amplitude of these lower-resolution Doppler velocity measurements (Wood and Brown 1997, 2000).

4. RESULTS

The output from all the analysis algorithms are integrated together to provide distributions of DOW-observed supercell tornado attributes. Some of the findings indicate a preferred translational speed, scale and intensity for tornadoes that are associated with mesocyclones of usually isolated supercell thunderstorms.

The translational speed of the tornadoes ranges from near stationary to nearly 25 m s^{-1} in the fastest cases with a median value near 13 m s^{-1} (Fig. 3).

The core diameter of the tornadoes (defined as distance from peak inbound to peak outbound velocity) is near 300 m in the median case (Fig. 4) although near 100 m when the core diameter is defined as twice the radius of maximum axisymmetric vertical vorticity across the vortex (not shown).

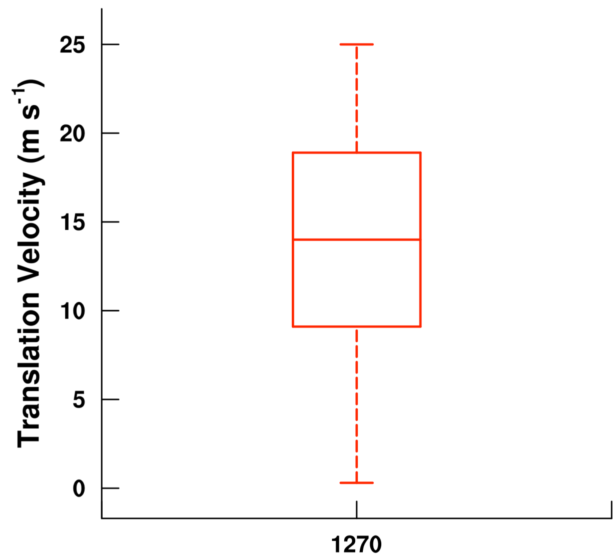

Fig. 3. Distribution of tornado translational speeds as observed by the DOWs showing minimum, 25th percentile, median, 75th percentile and maximum values for 1270 pairs of scans below 500 m AGL.

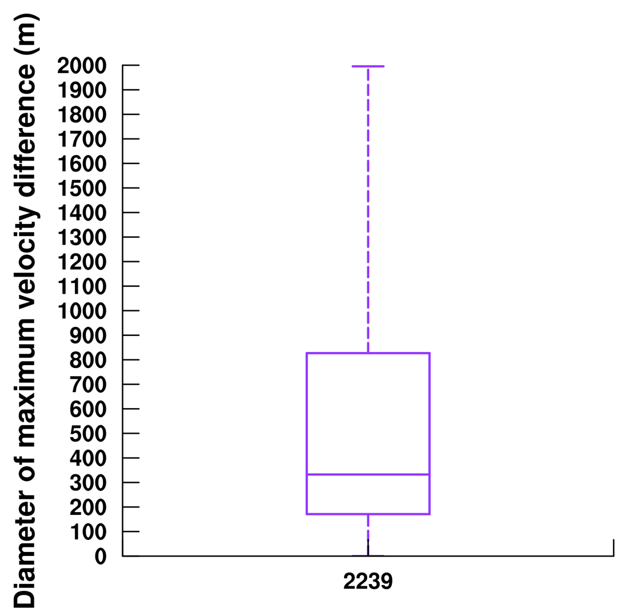

Fig. 4. Distribution of tornado core diameters as observed by the DOWs showing minimum, 25th percentile, median, 75th percentile and maximum values for 2239 scans below 500 m AGL.

The maximum velocity difference across each tornado observed below 500 m AGL has a median value between 80 and 90 m s^{-1} (Fig. 5) but can be in excess of 220 m s^{-1}, while the maximum ground-relative velocity has a median value between 55 and 60 m s^{-1} with peak values near 130 m s^{-1} (Fig. 6).

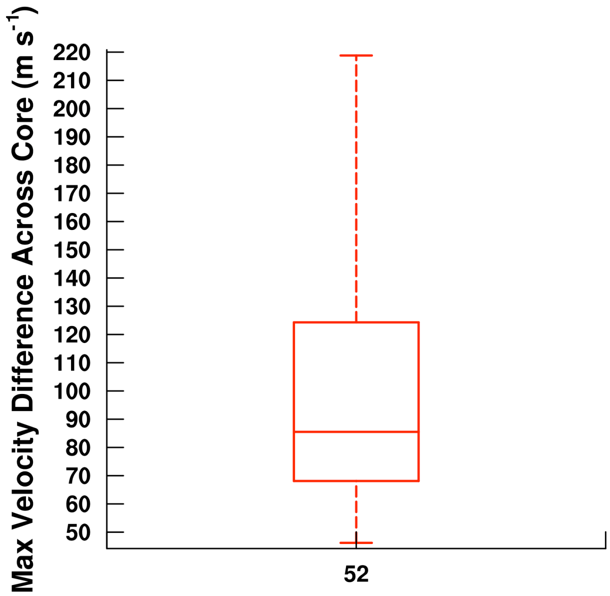

Fig. 5. Distribution of the maximum velocity difference in 52 tornadoes as observed by the DOWs below 500 m AGL showing minimum, 25th percentile, median, 75th percentile and maximum values.

Mapping the DOW-observed peak ground-relative velocities to either the Fujita Scale (Fig. 7) or the Enhanced Fujita Scale (Fig. 8) shows a preferred intensity in the F/EF2 range in a more bell-shaped (although possibly skewed) distribution. This distribution is striking when compared to the much more linear (or even exponentially decaying) damage-based intensity distribution from NCDC Storm Data.

A hypothesis for this discrepancy in supercell tornado intensity distributions is the overestimate of the number of weak tornadoes (F/EF 0-1) due to a lack of damage surveys and/or damage indicators resulting in a persistent low bias to intensity estimates of strong tornadoes (F/EF 2-3) (Doswell and Burgess 1988). Violent tornadoes (F/EF 4-5) may be infrequent enough and are usually well documented to permit an accurate characterization of the upper end of the intensity distribution.

It should be noted that the Storm Data tornado intensity distribution for the DOW-sampled tornadoes appears very similar to the Storm Data tornado intensity distribution in the central and southern plains (Nebraska, Kansas, Oklahoma and Texas) in April, May and June for all reported tornadoes between 1995-2003 (not shown). This similarity would preclude a field-project sampling bias as the primary source of the discrepancy between DOW-observed and damage-based intensity distributions.

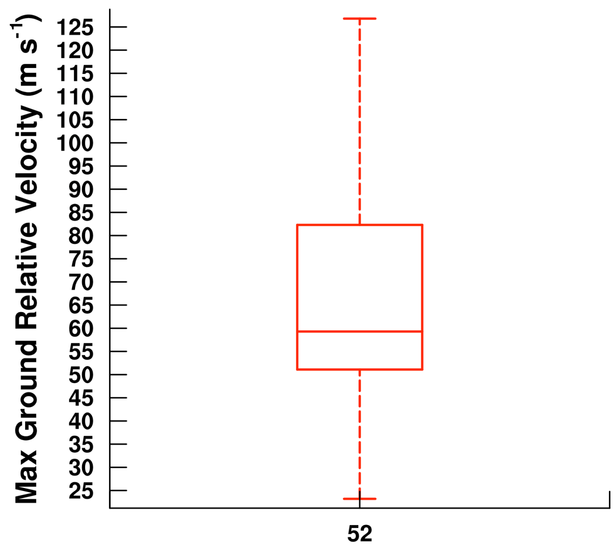

Fig. 6. Distribution of the maximum ground-relative velocity in 52 tornadoes as observed by the DOWs below 500 m AGL showing minimum, 25th percentile, median, 75th percentile and maximum values.

The vertical vorticity across the tornado cores (the component orthogonal to the radar-beam of twice the maximum velocity difference over the distance of the difference) typically range from 0.2 s^{-1} to 1.2 s^{-1} with extreme values approaching O(10 s^{-1}) (Fig. 9).

The horizontal divergence across the tornado cores (the component parallel to the radar beam of twice the maximum velocity difference over the

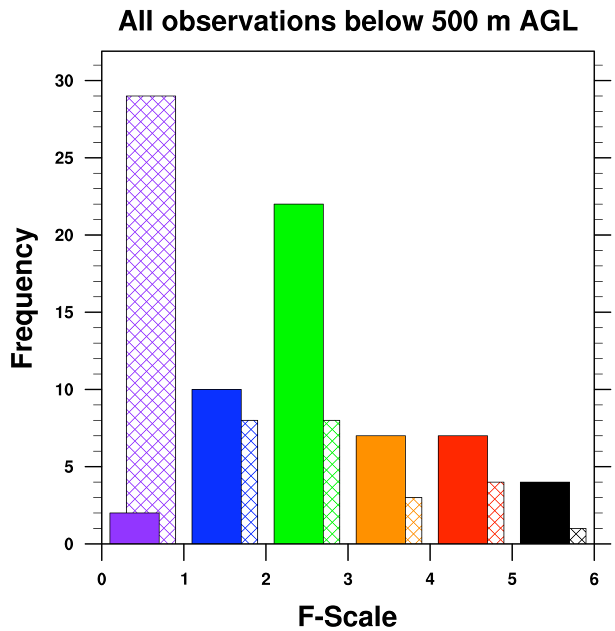

Fig. 7. Frequency distribution of tornado intensity for 52 tornadoes observed by the DOWs below 500 m AGL using the maximum ground-relative velocity estimated from DOW observations and mapped to the Fujita Scale (solid). The Storm Data damage-based tornado intensity distribution for the same tornadoes is shown for comparison (hatched).

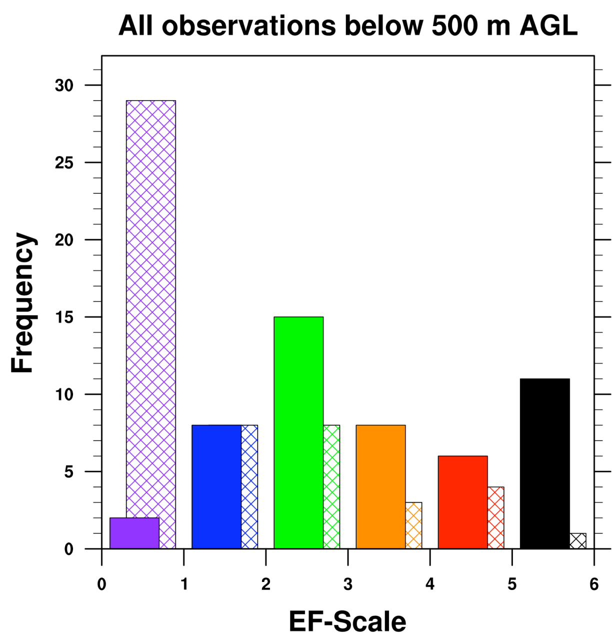

Fig. 8. Frequency distribution of tornado intensity for 52 tornadoes observed by the DOWs below 500 m AGL using the maximum ground-relative velocity estimated from DOW observations and mapped to the Enhanced Fujita Scale (solid). The Storm Data damage-based tornado intensity distribution for the same tornadoes is shown for comparison (hatched).

distance of the difference) is usually an order of magnitude smaller than the vorticity component and usually ranges from -0.05 s^{-1} (convergent) to 0.14 s^{-1} (divergent). There exists a considerable bias toward divergent flow signatures for the very shallow layer within 50 m AGL (Fig. 10). This bias would indicate extremely shallow inflow layers of O(10 m) AGL that are not being sampled, a dominate two-cell tornado vortex structure (Fiedler and Rotunno 1986) and/or a bias in the radar sampling introduced from debris centrifuging. The latter seems unlikely except in the most intense tornadoes moving through regions containing sources of larger debris (Dowell et al. 2005).

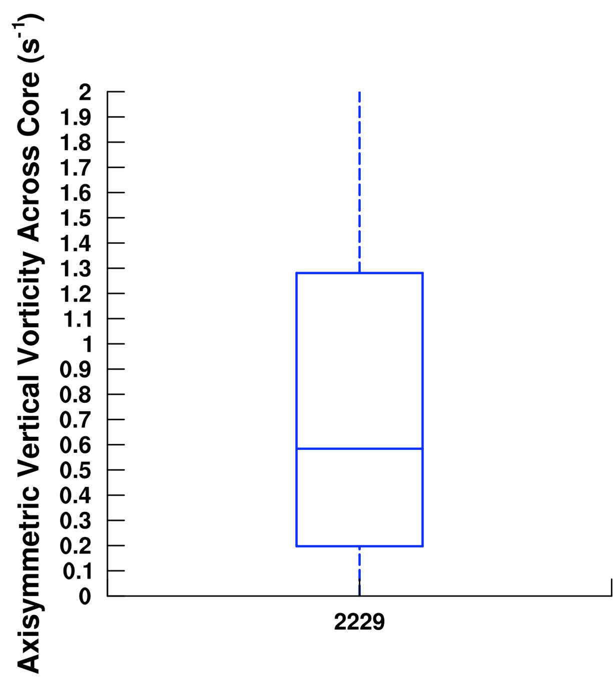

Fig. 9. Distribution of the axisymmetric vertical vorticity across a tornado core as observed by the DOWs showing minimum, 25th percentile, median, 75th percentile and maximum values for all 2229 scans below 500 m AGL.

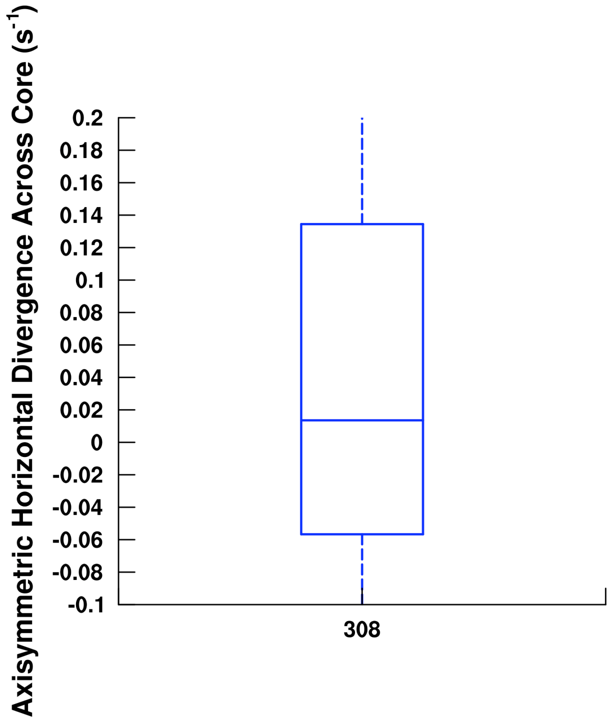

Fig. 10. Distribution of the axisymmetric horizontal divergence/convergence (positive/negative) across a tornado core as observed by the DOWs showing minimum, 25th percentile, median, 75th percentile and maximum values for all 308 scans below 50 m AGL.

Tornado intensity as measured by velocity difference across the core is effectively uncorrelated to core diameter (Fig. 11) that should eliminate the notion that tornado size and intensity have a strong positive correlation.

Tornado intensity does appear to have a stronger dependency on height AGL where the greatest dynamic range in velocities is observed within a few 100 m AGL (Fig. 12). The uniformity of mid-level tornado/mesocyclone intensity (5 km AGL) poses significant challenges to operational tornado detection and intensity estimation using conventional radar networks.

A common observation among tornadoes observed by DOWs during their genesis stage is the tendency for horizontal scale contraction to occur through a deep-layer O(1km) in a nearly simultaneous fashion. An example of such

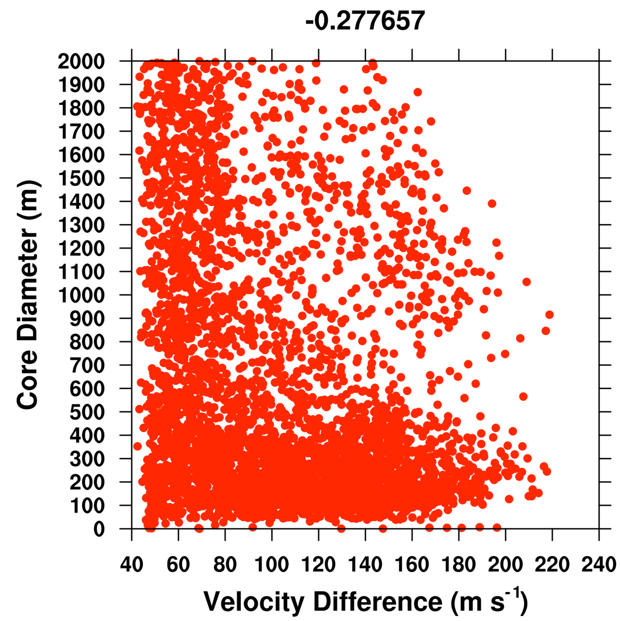

Fig. 11. Scatter plot of the DOW-observed velocity difference when paired with the diameter of the velocity difference for all scans across 69 tornadoes. The R-squared value is shown above the plot.

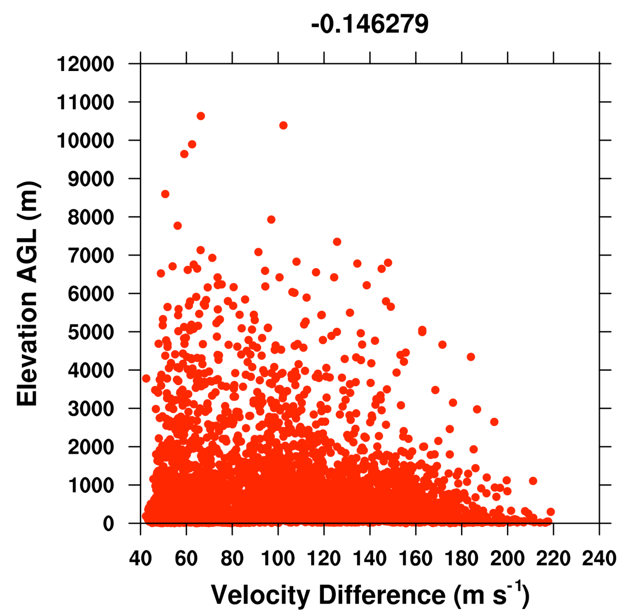

Fig. 12. Scatter plot of the DOW-observed velocity difference when paired with the elevation of the velocity difference for all scans across 69 tornadoes. The R-squared value is shown above the plot.

contraction was observed in a developing supercell tornado on 4 June 1999 near Thedford, NE by DOW3 (Fig. 13). There appears to be very little indication in DOW-observed genesis cases that the tornado-scale vortex contraction develops downward from aloft or upwards from the surface (Trapp and Davies-Jones 1997).

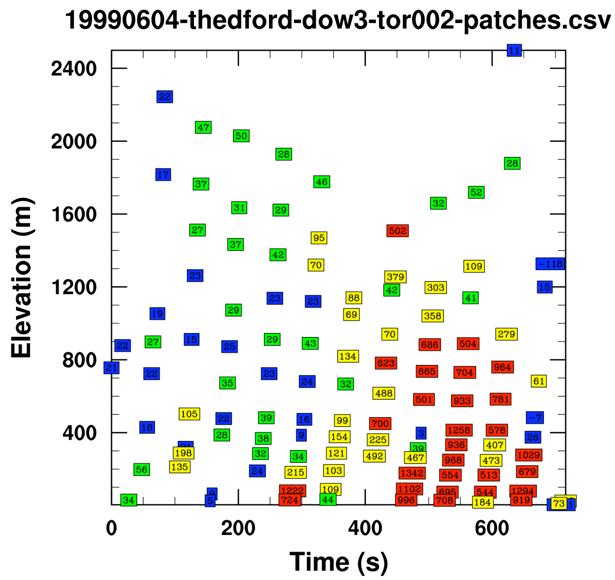

Fig. 13. Time-height plot of axisymmetric vertical vorticity (x10^{-3} s^{-1}) across a developing tornado as observed by DOW3 on 4 June 1999 near Thedford, NE. Vorticity values comprising the smallest 25% of the observations are shown in blue, between 25% and 50% in green, between 50% and 75% in yellow, and above 75% in red.

5. ACKNOWLEDGEMENTS

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