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THE STRUCTURE OF A TORNADO: GROUND-BASED VELOCITY TRACK DISPLAY (GBVTD) ANALYSIS OF MOBILE, W-BAND, DOPPLER RADAR DATA ON 15 MAY 1999 NEAR STOCKTON, KANSAS

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1. INTRODUCTION

High-resolution single-Doppler radar data of tornadoes are somewhat limited in their usefulness, in that they only provide information on the radial component of motion relative to the radar site. Information about the axisymmetric structure of the tornado (or deviations therefrom) from such data is limited. This paper illustrates an application of the Ground Based Velocity Track Display (GBVTD) technique developed by Lee *et al.* (1999) in order to deduce information about the two-dimensional wind field from data recorded by a high-resolution Doppler radar in the vicinity of a tornado.

2. TORNADO DATA

On 15 May 1999, during a University of Oklahoma storm intercept mission, high-resolution radar reflectivity and velocity data were collected from several minutes after tornadogenesis up until the end of the life of a tornado near Stockton, Kansas (Figure 1). The data were collected by a mobile, W-band Doppler radar furnished by the University of Massachusetts (U. Mass.) Microwave Remote Sensing Laboratory (MIRSL). Thirty-five sector scans were obtained between 19:56:19 CDT and 20:06:07 CDT, documenting the mature and dissipating stages of the tornado.

Figure 1. The U. Mass. radar collecting data in the Stockton, Kansas tornado on 15 May 1999. View to the northwest. Photograph © H. Bluestein.
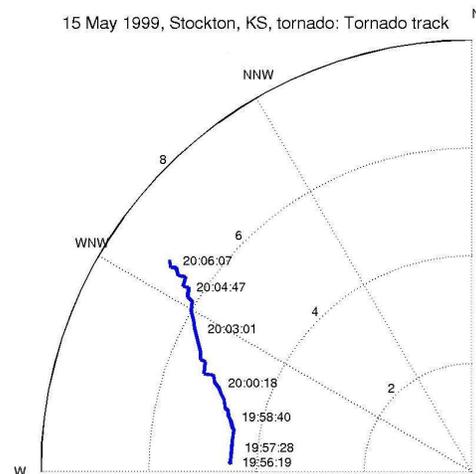

Figure 2. Track of the Stockton tornado in polar coordinates. The W-band radar was located at the origin, facing east. Range rings are in km, times are in CDT (UTC – 5 hours).

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A number of features of the tornado were readily apparent in the radar data. The tornado was marked by a single low-reflectivity "eye" whose radius generally increased from scan to scan until the tornado reached peak intensity, and then became more "ragged" as the tornado dissipated. This eye tracked slightly to the north-northwest, away from the radar (Figure 2). The tornado was also connected to its parent storm by a medium-reflectivity "umbilical cord" – presumably a precipitation curtain (Figure 3).

The annulus of high reflectivity around the eye exhibited significant variations in structure throughout the duration of the deployment. During later sector scans, the tornado exhibited two roughly concentric reflectivity annuli whose maximum reflectivity were lower than that of the preceding single annulus reflectivity structure (Figure 4).
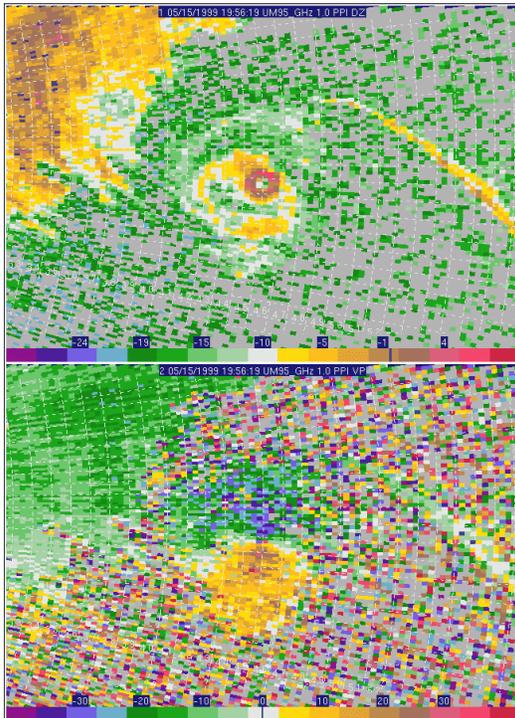

Figure 3. W-band reflectivity (top) and Doppler velocity in dBZ (bottom) for the 15 May 1999 Stockton, KS tornado at 19:56:19 CDT. The azimuthal grid spacing is 1° and the radial grid spacing is 0.1 km. Because the radar was facing west, the coordinate system appears inverted.
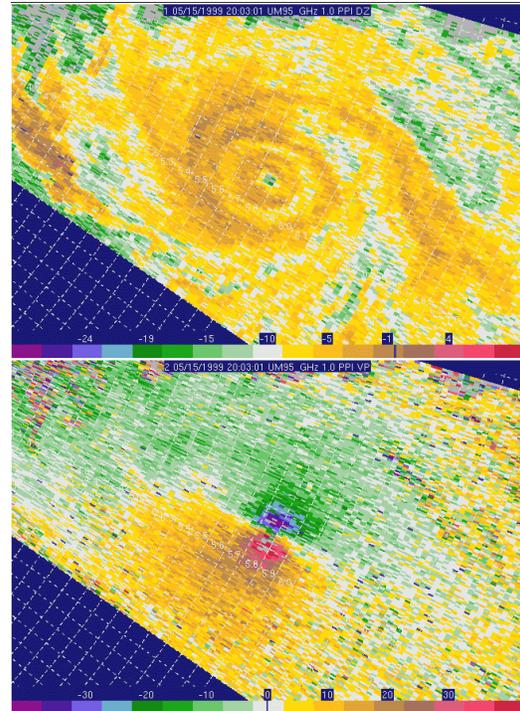

Figure 4. Same as Figure 3, but at 20:03:01 CDT, when the tornado was most intense, showing the "double annulus" structure that the tornado exhibited during later stages of its life cycle.

The maximum absolute Doppler velocity (Figure 5) measured in the vicinity of the tornado circulation was relatively high and persistent (close to the radar Nyquist velocity of 79 m s^{-1}) during the middle portion of the data collection interval.
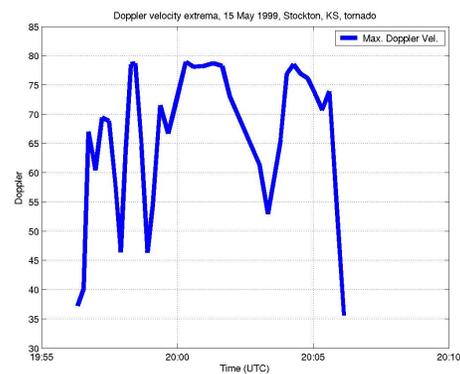

Figure 5. Plot of the maximum absolute Doppler velocity recorded within 100 m of the center of the tornado as a function of time. The velocity data were not thresholded on reflectivity as described in Section 3.

3. APPLICATION OF THE GBVTD TECHNIQUE

The Ground-Based Velocity Track Display (GBVTD) technique is used to compute vortex-centered azimuthal and radial winds from a velocity data set taken by a single Doppler radar whose location is not coincident with the center of the vortex. The GBVTD technique is a ground-based adaptation of the velocity track display (VTD) technique used on tropical cyclone radar data taken by an airborne radar (Lee *et al.* 1994).

The GBVTD technique is based upon the assumption that an axisymmetric vortex exists within the sector, and the Fourier transform of single Doppler velocities around the vortex center can be used to deduce the radial and tangential wind components of the vortex. The reader is referred to Lee *et al.* (1999) and Lee and Marks (2000) for a more detailed description of this technique. The (GBVTD) technique has been applied to radar data in order to ascertain information about the kinematic structure of tropical cyclones (Lee *et al.* 2000) and a tornadic vortex previously (Bluestein *et al.* 2003).

Application of this technique to the 15 June 1999 Stockton, Kansas tornado radar data set involved three procedures: (1) the remapping of each sector scan from a plan position indicator (PPI) grid in polar coordinates to a constant altitude PPI (CAPPI) 20 km grid in Cartesian coordinates, (2) the use of the simplex vortex center-finding algorithm (Lee and Marks 2000) to compute the exact center of the tornado vortex on the CAPPI grid, and (3) the computation of radial and tangential winds around the computed vortex center using the velocity track display (VTD) technique (Lee *et al.* 1994; Lee and Marks 2000). The final procedure also decomposed the tangential winds into azimuthally averaged wavenumber 0, 1, 2, and 3 angular harmonic components, as well as radial wind components, around the vortex center.

Because of the range from the W-band radar to the tornado (which increased from 4.5 – 6.2 km during the scanning time), the small half-power beamwidth of the W-band antenna (0.18°), and the low elevation angle of the radar data (< 10.0°), the data satisfied the GBVTD requirement that the radar beams in the sector scans be nearly parallel to one another (Bluestein *et al.* 2003). The range-to-horizontal beamwidth ratio for this data set was on the same order of magnitude as that given for the typhoon case study by Lee and Marks (2000).

The simplex center-seeking algorithm (Lee *et al.* 2000a) is highly sensitive to anomalous data points in the Doppler velocity data. The low-reflectivity eye often contained highly "speckled" velocity data (e.g. Figure 3). In order to reduce the effects of such data points, a reflectivity threshold was applied to the velocity data, using NCAR SOLOII radar data processing software. Any velocity data point associated with a reflectivity data point recorded as -18 dBZ or less was ignored, as the velocity data from such points was considered suspect. A few obviously erroneous velocity data points were also manually edited out. This procedure effectively obscured the anomalous velocities measured inside the tornado eye, and permitted the simplex center-seeking algorithm to determine the tornado vortex center with a high degree of accuracy. These computed centers were then input into the velocity track display (VTD) software along with the CAPPI-gridded reflectivity and velocity data, in order to obtain azimuthal and radial wind profiles of the tornado.

4. RESULTS

The application of the GBVTD technique to the 15 May 1999 Stockton, Kansas U. Mass. W-band radar data set yielded a set of GBVTD analyses of the two-dimensional wind field output for all thirty-five sector scans. An example is shown in Figure 6.

The intensity of the tornado, as measured by the maximum azimuthally averaged azimuthal wind speed, reached a peak of 45 m s^{-1} in the scan taken at 20:03:01 CDT. The radial profile of azimuthal velocity for this scan bore a strong resemblance to a Rankine vortex (Figure 7). Within about 60 m from the center, the azimuthally averaged radial wind component increased with distance from the center, indicating divergence and sinking motion aloft. Between 60 m and 175 m, the azimuthally averaged radial wind component decreased with distance from the center, indicating convergence and rising motion aloft. The vortex thus looked like a two-celled vortex, with sinking motion near the center and rising motion near the radius of maximum wind (RMW). The azimuthally averaged azimuthal wind then quickly decreased over the next three minutes as the tornado dissipated (Figure 8).
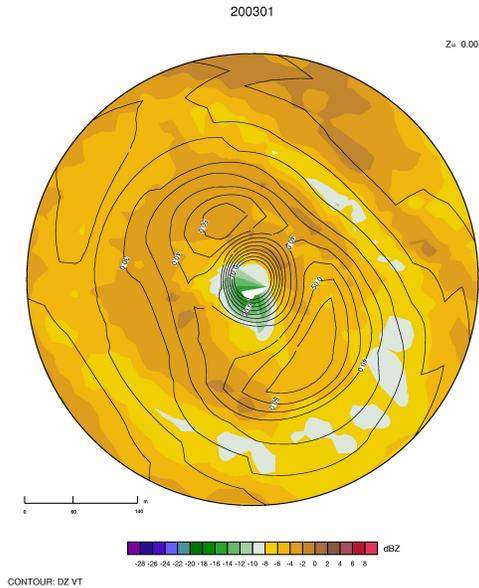
Figure 6. Vortex-centered GBVTD analysis of the Doppler radar reflectivity field (filled color contours) and total azimuthal wind (contours of 5 m s^{-1}) for the sector scan taken at 20:03:01 CDT, when the tornado was at peak intensity. This scan contains azimuthal winds in excess of 50 m s^{-1} with a pronounced wavenumber-2 component (two diametrically opposed lobes of relatively high velocity just outside the tornado eye).
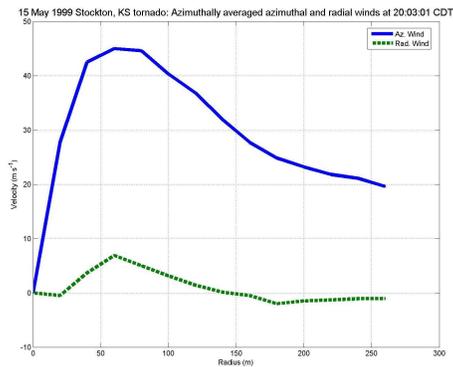

Figure 7. Radial profile of GBVTD-analyzed azimuthally averaged azimuthal and radial winds at 20:03:01 UTC, when the tornado was at peak intensity. Positive radial velocity indicates flow away from the tornado vortex center.
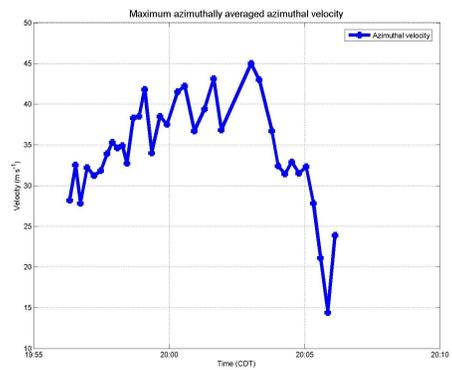

Figure 8. Maximum azimuthally averaged azimuthal (tangential) velocity, as calculated by the GBVTD technique, as a function of time.

A plot of the estimated RMW, taken here as the radius of maximum azimuthally averaged azimuthal velocity as computed by the GBVTD technique, is shown in Figure 9. The RMW exhibited a general tendency to decrease with time. This tendency, in combination with the decrease in the azimuthally averaged azimuthal wind with time, suggests a decay mode for this tornado consisting of a simultaneous decrease of its RMW and average azimuthal velocities. This behavior stands in contrast to the decay mode described by Bluestein *et al.* (2003) in the 5 June 1999 Bassett, Nebraska tornado, in which the RMW increased as the average azimuthal winds decreased.
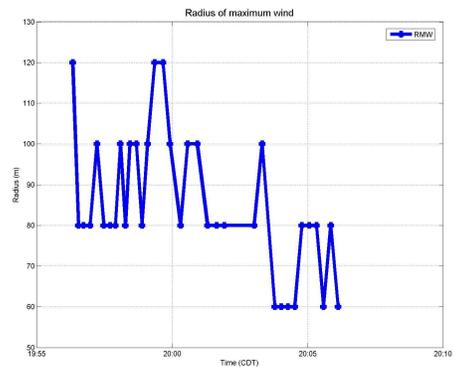

Figure 9. Radius of maximum wind as a function of time, as computed by the GBVTD technique.

Figure 10 shows the evolution of the azimuthally averaged azimuthal wind structure as a function of time and radius. The maximum azimuthally averaged azimuthal wind increases in both magnitude and radius as the tornado proceeds through its life cycle, and displays good temporal continuity.
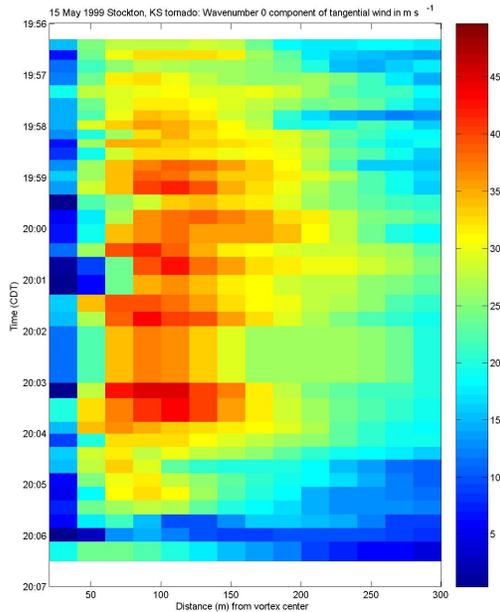

Figure 10. Hovmoeller diagram of the azimuthally averaged wavenumber 0 component of the azimuthal (tangential) wind as a function of radius in the 15 June 1999 Stockton, Kansas tornado, as computed by the GBVTD analysis. The diameter of the eye approached 50 m around 20:01 CDT. Tornado threshold velocity is 35 m s^{-1}.

The GBVTD analysis also produced azimuthally averaged radial profiles of higher order angular harmonics of the azimuthal wind (wavenumbers 1, 2, and 3, not shown). While these components have not been thoroughly analyzed, some of their more noteworthy features will be mentioned. The wavenumber 1 component of the azimuthal wind was strongest at large radii as the tornado increased in intensity. The azimuthal winds of the tornado exhibited a relatively strong wavenumber 2 feature in many scans with a magnitude at or exceeding 5 m s^{-1}; however, these features were not persistent. (It has been noted by the authors that GBVTD analyses of tornado radar data tend to exhibit a prominent wavenumber 2 component. The reason for this feature is currently unknown and may become the subject of future investigation.) The wavenumber 3 component exhibited a "trough" in magnitude

that increased in radius as the tornado proceeded through its life cycle.

The azimuthally averaged radial wind component of the tornado reached a positive maximum of approximately 10 – 15 m s^{-1} at roughly the same radii and times as when the tornado was most intense (Figure 11). This suggests some amount of outflow from the tornado at the level at which the scan was taken.
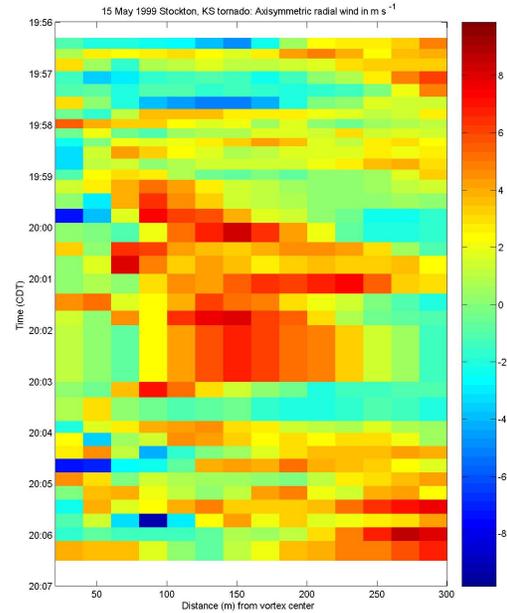

Figure 11. Hovmoeller diagram of the axisymmetric component of the radial wind in the 15 May 1999 Stockton, Kansas tornado, as computed by the GBVTD analysis. The strongest outflow (positive radial velocity) occurs when the tornado is ramping up to its peak intensity.

5.   CONCLUSIONS

The GBVTD technique provided useful information on the mature and dissipating stages of a tornado for which an exceptionally good W-band radar data set was collected. This study highlights how basic assumptions about the tornado structure, combined with high-resolution radar data of tornadoes, can enhance our understanding of tornado wind fields at various stages of the tornado life cycle.

6.   ACKNOWLEDGMENTS

7. REFERENCES

Bluestein, H. B. W.-C. Lee, M. Bell, C. C. Weiss, and A. L. Pazmany, 2003: Mobile Doppler radar observations of a tornado in a supercell near Bassett, Nebraska, on 5 June 1999. Part II: Tornado-vortex structure. *Mon. Wea. Rev.*, **131**, 2968 – 2984.

Lee, W.-C., F. D. Marks Jr., and R. E. Carbone, 1994. Velocity track display – A technique to extract real-time tropical cyclone circulations using a single airborne Doppler radar. *J. Atm. Ocn. Tech.*, **11**, 337 – 356.

Lee, W.-C., B. J.-D. Jou, P.-L. Chang, and S.-M. Deng, 1999: Tropical cyclone kinematic structure retrieved from single-Doppler radar observations. Part I: Doppler velocity patterns and the GBVTD technique. *Mon. Wea. Rev.*, **127**, 2419 – 2439.

Lee, W.-C., and F. D. Marks Jr., 2000a: Tropical cyclone kinematic structure retrieved from single-Doppler radar observations. Part II: The GBVTD-Simplex center-finding algorithm. *Mon. Wea. Rev.*, **128**, 1925 – 1936.

Lee, W.-C. B. J-.D. Jou, P.-L. Chang, and F. D. Marks Jr., 2000b: Tropical cyclone kinematic structure retrieved from single-Doppler radar observations. Part III: Evolution and structures of Typhoon Alex. *Mon. Wea. Rev.*, **128**, 3982 – 4001.

Roux, F., and F. D. Marks, Jr., 1996. Extended Velocity Track Display (EVTD): An improved processing method for Doppler radar observations of tropical cyclones. *J. Atm. Ocn. Tech.*, **13**, 875 – 899.