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Diagnosis of 3D Wind Structure of a Tornado Using VTD Analysis

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1. Introduction

Tornadoes are among one of the most violent storms in the world. Because of their small temporal and spatial scale, tornadoes have mostly eluded Doppler radar (e.g., WSR-88D) observations until the mobile X-band Doppler on Wheels (DOW, Wurman et al. 1997; Wurman 2001a) was placed in service in 1995. DOWs can be deployed as close as 1.5 km from a tornado to sample high-resolution single- and dual-Doppler radar measurements (Wurman and Gill 2000). Some tornado structures, such as maximum wind and peak vorticity, can be inferred from single Doppler radar mesocyclone signature (Wurman 2001b). This paper intends to demonstrate that the axisymmetric and asymmetric vortex structures of a tornado can be deduced from single DOW data using the ground-based velocity track display (GBVTD, Lee et al. 1999) technique. Kinematic and dynamic characteristics of this tornado are compared with laboratory and numerically simulated tornados.

2. Storm overview and data processing

On 3 May 1999, a supercell thunderstorm with a pronounced hook echo and an intense cyclonic circulation, was identified by the Norman, OK WSR-88D radar. This thunderstorm, observed by the DOW from 0310-0328 UTC, produced an exceptionally large and powerful tornado with ~800 m in peak wind radius and peak wind speed exceeding 100 m/s. Multiple vortices were identified embedded in the parent tornado circulation (Wurman 2001b). Scanning was conducted through ~85° azimuthal sectors at 12 stepped elevation angles from 0-17°. The core region of the tornado moved to a range of ~3.5-4.5 km from the DOW, resulting in a radar beam width of 65 m, and 25-37.5 m gate spacing. Staggered pulse repetition frequency resulted in a Nyquist velocity of ±128 m/s. The data were edited using the NCAR SOLO software. The radar beams were partially blocked by terrain and trees below approximately 1.5° elevation angle at various azimuth angles resulting in possible contamination of the circulation. The return power is used in this paper because the reflectivity factor cannot be reliably computed due to problems in calibration and receiver saturation from large debris and precipitation of the tornado at close range (Wurman 2001b).

The GBVTD analysis was performed with a 100 m increment in r (200 m ≤ r ≤ 3 km) and z (100 m ≤ z ≤ 1.2 km) axes. The vorticity centers of the parent tornado circulation at each altitude were determined using the GBVTD-simplex algorithm (Lee and Marks 2000). Then, the asymmetric tornado circulation was deduced up to wavenumber 3. The axisymmetric angular momentum, vorticity, perturbation pressure and swirl ratio were computed using the GBVTD-derived axisymmetric tangential (v) and radial (u) winds. The radial pressure equation in cylindrical coordinates is:

$$\rho\left(\underbrace{u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}}_{Advection}\ \underbrace{-\frac{v^2}{r}}_{Cyclostrophic}\right)=-\frac{\partial p}{\partial x} \qquad \textbf{(1)}$$

where ρ is the density of air while p is the perturbation pressure obtained by integrating the pressure gradient from the outer domain at r=3 km at each altitude. The swirl ratio (S) is defined as:

$$S=\frac{1}{4}c\tan\theta=\frac{1}{4}\cdot\frac{2R}{h}\cdot\frac{v_R}{u_R} \qquad (2)$$

where R, h, u_R, and v_R are the updraft radius, inflow depth, radial and tangential winds at R (Rotunno 1978).

3. Results

Figure 1 illustrates the axisymmetric structure of the tornado at 0310 UTC, 4 May 1999. The gray scale represents the return power. The axisymmetric v (Fig. 1a) shows a maximum exceeding 70 m/s at r=900 m and z=100 m. v decreases and tilted outward slightly with height (Fig.2). The strength of the tornado (i.e., peak tangential wind) decreases with time (Fig. 3) and the radius of maximum wind (RMW) reduces with time. The axisymmetric u (Fig. 1b) shows a deep layer of inflow (~1 km) converging with the outflow from the tornado center at r=~900 m, the RMW. The peak inflow at z=100 m exceeds 20 m/s while the peak outflow of 12 m/s inside the RMW is located at r=500 m and z=200 m. The axisymmetric vertical velocity, w, is obtained by integrating the mass continuity equation upward using the axisymmetric convergence field computed from u. It is evident that a "two-celled"

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structure (e.g., Rotunno 1978; Ward 1972) is resolved with an intense downdraft (~25 m/s) at r=300 m and z=900 m. Wurman and Gill (2000) estimated a similar magnitude of downdraft in the tornado core region. The "two-celled" structure persisted for the next 8 volumes. The depth of the inflow is ~600 m except for the first volumes (Table 1). Because of the debris got lofted by the tornado, it is possible that DOW is measuring the debris motion instead of the air motion. Debris and large raindrops would likely be thrown out of the tornado circulation due to centrifugal force and the convergence field may be biased (Wurman and Gill 2000; Dowell et al. 2001). Preliminary estimates of centrifuging effects in this storm indicate that they introduce convergence and divergence that are small relative to the term calculated in this work. Unfortunately, it is not possible to clarify this point with existing data. The authors assume that DOW measured Doppler velocities approximate the air motion.

Figure 1c and 1d illustrate the retrieved perturbation pressure from the advection and cyclo-strophic term in (1), respectively. The cyclostrophic pressure is in response to the swirling part of the tornado circulation while the pressure from advection terms is in response to the secondary circulation. The central cyclostrophic pressure (Fig. 1d) at z=100 m is ~75 mb lower than the pressure at r=3 km. The pressure gradient is consistent with observed pressure drop in a similar storm (Winn et al. 1999). The pressure from advection terms is roughly 10% of the pressure from the cyclostrophic balance. A low-level high pressure perturbation near the center and the peak convergence is consistent with the radial outflow near the center and the slow down of *u* near the convergence zone.

Figure 1e and 1f illustrate the angular momentum and vorticity of this tornado. The angular momentum increases with radius. Hence, the low-level inflow brings in higher angular momentum. The peak vorticity of 0.2 s^{-1} is located slightly inside the peak tangential winds. Negative vorticity exists outside the RMW.

The swirl ratio of the tornado can be computed in (2) using the GBVTD-derived axisymmetric circulation (Table 1). This is the first attempt to compute swirl ratio in the true tornado scale using Doppler radar derived quantities. Both the laboratory and numerical simulations of tornado vortex suggest that a "one-celled" vortex transits into a "two-celled" vortex at S=0.5 while multiple vortices appear when S>1.0 (e.g., Davis-Jones 1973; Rotunno 1978). Because the swirl ratio was first defined in the parameters of the tornado vortex chamber (Davies-Jones, 1973), uncertainties in choosing the value of each term in real data (e.g., see Fig. 1a and 1b) may easily introduce a factor of 2 error in the computed swirl ratio. Nevertheless, the swirl ratios in Table 1 are clearly greater than 1. The swirl ratio is consistent not only with the "two-celled" structure but also with the multiple vortices observed in this tornado (Wurman 2001).

4. Summary and future work

This study shows that the GBVTD-derived tornado circulation exhibit characteristics consistent with laboratory and numerically simulated tornadoes. It is now feasible to examine tornado dynamics using the GBVTD-derived wind fields. In the future, the asymmetric structure of this tornado will be studied to examine the multiple vortex structure evident in the return power.

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UTC	*R (km)*	*H (km)*	u_R *(m/s)*	v_R *(m/s)*	*S*
1310	2	1.0	16	35	2
1311	1.5	0.6	16	40	3.1
1312	1.5	0.6	15	65	5
1313	1.5	0.6	10	40	5
1314	1.5	0.6	15	40	5
1315	2	0.6	10	35	5.8
1316	1.5	0.6	16	40	3.1
1317	1.5	0.6	8	32	5

Table 1: The swirl ratio (S) for 8 volumes of DOW data from 0310-0317 UTC computed using equation (2).

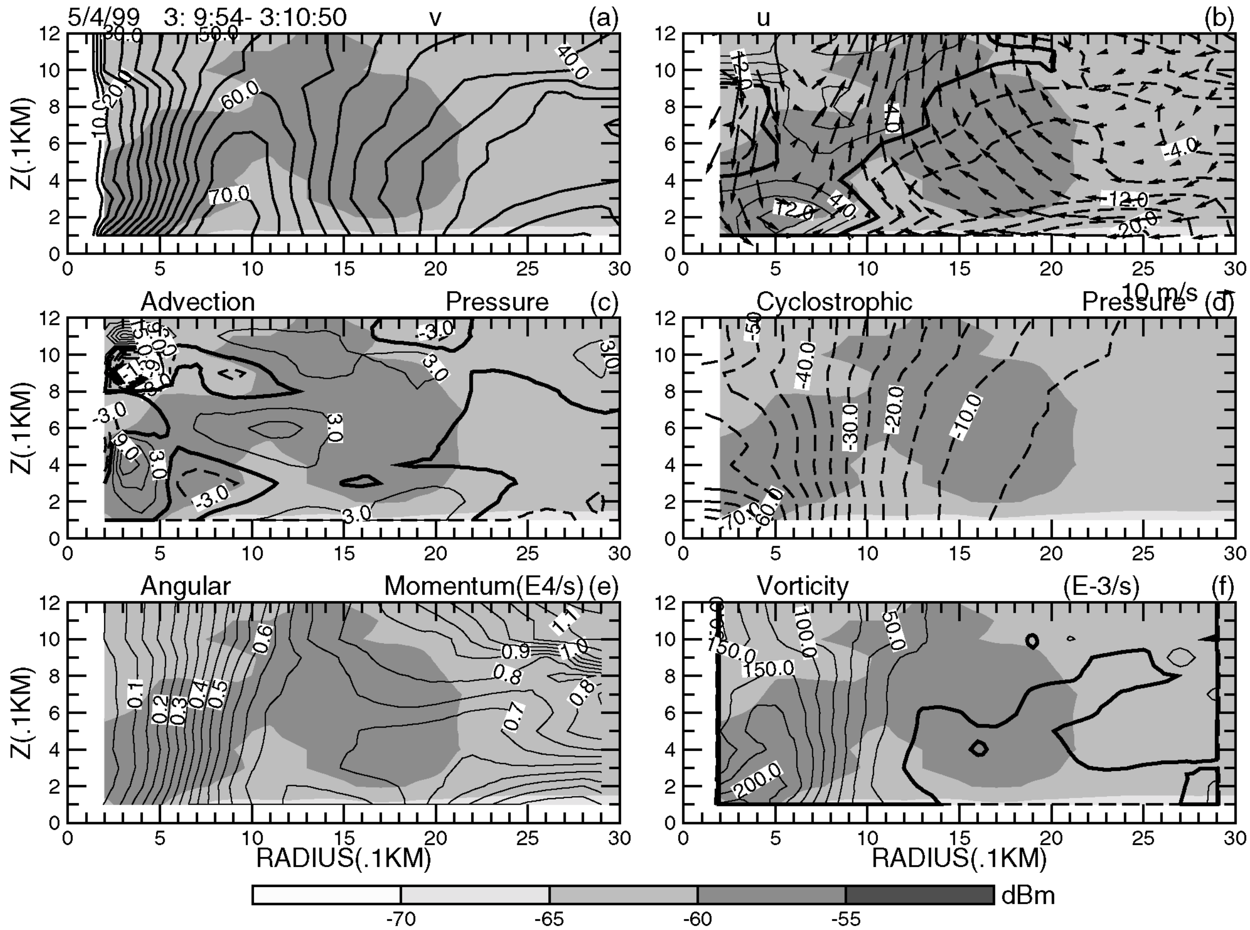

Figure 1: The axisymmetric circulation of the 5/4/1999 tornado at 0310 UTC where (a) tangential wind, (b) radial wind (contour) and velocity vector, (c) advection pressure, (d) cyclostrophic pressure, (e) unit mass angular momentum, and (f) vorticity. The return power is in gray shades.

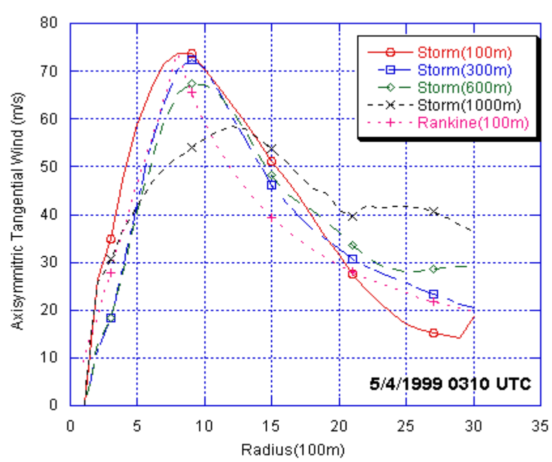

Figure 2: The radial profiles of axisymmetric tangential winds at different altitude for the 5/4/1999 tornado at 0310 UTC. Also shown is the Rankine vortex profile using the peak winds at z=100 m.

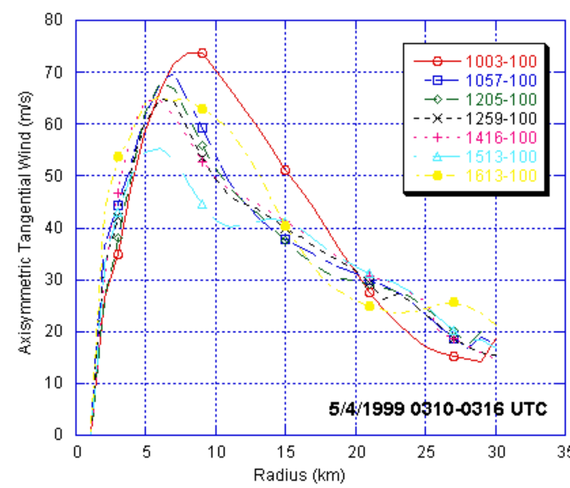

Figure 3: The radial profile of axisymmetric tangential winds at z=100 m for seven different volumes of the 5/4/1999 tornado from 0310-0316 UTC.