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Nomogram For Evaluating Tornadic Vortex Signatures: Example Using KDDC WSR-88D Data Collected In The 1995 Garden City Tornadic Storm

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1. Introduction

When a WSR-88D radar scans past a tornado whose horizontal dimension is smaller than the radar's beamwidth, a tornadic vortex signature (TVS) arises (Brown and Lemon 1976, Brown et al. 1978). The signature is a smeared representation of the tornado with the signature's diameter being larger than the tornado's diameter and the signature's peak velocities being weaker than the tornado's peak rotational velocities.

When doing research studies of TVSs and especially when constructing time-height plots of TVS magnitude, one typically plots either the difference between the measured peak Doppler velocity values or the average of the two values. However, for more consistency in plotted values as a function of height and time, one would like to know the true peak values of the TVS.

In this note, a technique is discussed for estimating the true peak values of the TVS as well as estimating the azimuth of the vortex center. The technique is based on theoretical curves derived by Brown and Lemon (1976) and Brown et al. (1978) using the radar simulation model of Zrnic and Doviak (1975) scanning horizontally through a Rankine combined vortex (e.g., Brown and Wood 1983). The technique is applied to Doppler velocity data collected by the Dodge City (KDDC) WSR-88D radar in the Garden City, KS storm of 16 May 1995. The storm produced several tornadoes along a track from Garden City east-northeastward to Rozel (NOAA 1995).

2. TVS Characteristics

TVS curves made by a simulated radar collecting data continuously in azimuth are shown in Figure 1 (Simulated azimuthal profiles for a radar scanning in a continuous manner through the center of a tornado for various beamwidth to core radius ratios. Maximum tangential velocity in the simulated tornado is 100 m s-1. From Brown et al. (1978).) The curves represent Doppler velocity measurements in a tornado having peak rotational velocities of 100 m s-1 for various ratios of radar beamwidth to core radius of the simulated tornado; core radius is defined as the radius of the tornado's maximum rotational velocities. When the ratio of beamwidth to tornado core radius is 3, for example, the peak TVS value is only 53% of the tornado's peak rotational velocity. With the curves in Figure 1 plotted as a function of azimuthal distance divided by beamwidth, a basic feature of the tornadic vortex signature is evident: namely, as a tornado's core diameter decreases relative to the beamwidth, the core diameter of the TVS does not become any smaller than approximately one beamwidth--regardless of tornado size or strength. (This feature also is found at far ranges when a mesocyclone's core region is smaller than the radar beamwidth.)

As mentioned, the curves presented in Figure 1 represent data collected continuously in azimuth. However, WSR-88D measurements are not continuous in azimuth, but are made at azimuthal intervals of about 1.0o. Owing to the radar's fast rotation rate, the nominal 0.93o beamwidth is broadened to an effective beamwidth of about 1.29o (± 3% depending on the specific choice of radar variables--Wood and Brown (1997); see Doviak and Zrnic (1993, section 7.8) for a discussion of effective beamwidth). With the true TVS peaks being separated by about 1.29o and the azimuthal sample interval being 1.0o, both the positive and negative peak values will never be sampled for a given TVS. In fact, it is a matter of chance that either true peak will be sampled.

3. A nomogram for estimating TVS peak velocities

Brown et al. (1978) showed that Doppler velocity measurements in the 1973 Union City, OK tornado and 1975 Stillwater, OK tornado fitted theoretical TVS curves derived from Figure 1 (see Figure 7 (Theoretical Doppler velocity profiles through center of Union City tornadic vortex signature shown in Fig. 10. The three curves (from Fig. 7) represent vortices with various maximum tangential velocities (V max) chosen to produce extreme TVS values of 145 m s-1. Dots are observed Doppler velocity values (from Brown et al. 1978).) and Figure 8 (Theoretical Doppler velocity profiles through center of Stillwater tornadic vortex signature. The three curves (from Fig. 7) represent vortices with various maximum tangential velocities (V max) chosen to produce extreme TVS values of 140 m s-1. Dots are observed Doppler velocity values (from Brown et al. 1978).)). With TVSs now being observed operationally, it was decided to refine the approach used by Brown et al. to make it easier for the technique to be used for operational research studies.

A nomogram consisting of a family of curves was constructed to represent various peak Doppler velocities for TVSs (Figure 2 (Azimuthal variation (normalized by beamwidth) of simulated TVS curves labeled according to the peak value of each curve.)). Each curve is an average of three curves having the same peak TVS velocity for beamwidth/core radius ratios of 3, 5, and 10. Figures 7 and 8, from Brown et al. (1978), show the relationships among the three individual curves for peak TVS velocities of 45 and 40 m s-1, respectively; those figures also indicate the core radii and peak rotational velocities of the simulated tornadoes that produced the respective TVS curves.

The procedure is to plot the Doppler velocity values of a TVS on a grid, as shown in Figure 3 (Grid for plotting WSR-88D Doppler velocity data points in a TVS. Vertical lines represent the normalized spacing between adjacent WSR-88D data points.). The vertical lines have a normalized azimuthal separation of 0.775--azimuthal interval of 1.0o divided by the typical effective beamwidth of 1.29o--so they represent normalized intervals that are consistent with the curves in Figure 2. One of the data points near the center of the TVS is plotted on the vertical line labelled 0. Then Doppler velocity data to the right (clockwise) and left (counterclockwise) of that point are plotted on the adjacent vertical lines. The KDDC WSR-88D data points plotted in Figure 4 (Plot of six data points measured within a TVS by the KDDC WSR-88D radar at about 2323 UTC on 16 May 1995 at 77.9 km range and 2.4o elevation angle (3.6 km height). The azimuth angles of the data points are listed along the bottom of the grid.) are from the Garden City TVS at about 2323 UTC on 16 May 1995.

The true peak Doppler velocity associated with a given TVS can be estimated by adjusting the theoretical nomogram curves (Figure 2) as a transparent overlay on top of the plotted data points in Figure 4. The adjustment process consists of the following steps:

(a) the overlay curves are moved up or down to subtract the contribution due to tornado and storm motion

(b) the overlay is moved to the left or right to permit proper fit of the data points relative to the tornado center

(c) the final adjustment is the best fit of the curves to the data points.

Typically, only the three or four points closest to the TVS center fit one of the curves or lie the same proportional distance between two curves. A minimum of three points is required. Points farther from the center may depart from the TVS curve owing to a contribution from the background mesocyclone. If the TVS is strong and overpowers the parent mesocyclone signature (as in Figures 7 and 8 from Brown et al. (1978)), all of the TVS points (4-6) should be in the same position relative to the curves.

The final position of the theoretical TVS curves on top of the KDDC data points is shown in Figure 5 (Superposition of Figures 2 and 4 to produce the best fit for the three data points closest to the vortex center.). Since at least the three centermost data points fit the curves and the outermost points decrease in magnitude with distance from the vortex center, we can be confident that this feature is a TVS. The true peak TVS velocity is approximately 33 m s-1, as compared to a measured peak value of only 29 m s-1, based on the average of the measured extreme values of +16 and -42 m s-1. The shift of the curves downward by 10 m s-1 indicates that superimposed on the basic TVS Doppler velocities was an overall Doppler component of 10 m s-1 toward the radar (owing primarily to tornado and storm motion).

In some cases, there can be two equally probable fits of three adjacent data points to the theoretical curves. When this occurs, the estimated tornado center remains between the same extreme values but is shifted by a few tenths of a degree. One solution has two data points to the left of tornado center and the other has two points on the right side of the center. In this situation, an average is taken of the two estimated peak values.

In most cases, the extreme measured Doppler velocity values in a TVS are at adjacent azimuths (1o apart). However, when the center of the radar beam falls near the tornado center, the Doppler velocity value measured there is relatively close to zero (in a tornado-relative sense) and the extreme values are 2o apart.

In addition to estimating the peak Doppler velocity values associated with a TVS, the center azimuth (to the nearest tenth or two of a degree) for the TVS, and therefore for the tornado, can be determined from Figure 5. The center of the Garden City tornado was at a range of 77.9 km and azimuth of 282.4o at the height and time of these measurements.

4. Life cycle of the TVS associated with the Garden City, KS tornado

On 16 May 1995, an evolving supercell thunderstorm produced a series of tornadoes for three hours as it moved from Garden City east-northeastward to Rozel in southwestern Kansas. The subject of this study is the first tornado, which passed just southeast of Garden City. According to Storm Data (NOAA 1995), the tornado lasted 19 min and, although the damage was rated F1 on the Fujita scale, it was given a rating of F3 based on the tornado's visual characteristics.

Figure 6 (Time-height plot of the estimated true peak TVS values. The shaded areas with Ss represent marked shear regions where Doppler velocity values did not fall off with azimuth like a TVS. The contour interval is 5 m s-1. The hatched bar along the bottom indicates when the tornado was on the ground according to Storm Data (NOAA, 1995).) shows a time-height plot of the estimated true peak TVS values in the Garden City tornado based on the nomogram approach. Within the shaded regions, cyclonic shear (S) was present but the Doppler velocity values on one or both sides of the velocity discontinuity remained essentially constant rather than falling off as in a vortex.

Evolution of the TVS is consistent with the reported duration of the tornado on the ground (shaded bar at the bottom of Figure 6). It appears that the TVS formed at midaltitudes in the storm and remained strongest aloft during its entire lifetime. Evolution of TVS peak values reasonably indicates that the tornado became stronger and/or larger during the first half of its existence and then became weaker and/or smaller during the latter half.

It is customary to plot either the difference between the extreme measured TVS values or the average of the extreme values (one-half the difference). When this is done, the contours are not as smooth as those in Figure 6. Vasiloff (1993) showed a number of time-height plots of TVS velocity difference and most of them had small-scale minima, maxima, and bulges. The small-scale features likely arose from the fact that, with time and height, the radar beam was centered at different positions relative to the tornado (Wood and Brown 1997). The nomogram approach discussed here corrects for the relative position problem.

Differences were computed between (a) the peak TVS value deduced using the nomogram approach (for example, 33 m s-1 based on Figure 5) and (b) the average of the measured extreme TVS values (for example, 29 m s-1 based on Figure 4) for all of the data points in Figure 6. The estimated true values always were larger with differences ranging from 2 to 9 m s-1.

5. Concluding comments

A technique has been discussed that deduces the peak rotational velocity for a tornadic vortex signature. The approach is to compare the Doppler velocity values within a suspected TVS with a set of theoretical TVS curves. If at least the three data points closest to the vortex center fit the curves, and the other points decrease with distance from the center, then the peak value associated with the TVS can be determined. Use of this approach in research studies (using reproduced copies of Figures 2 and 3) can produce peak TVS velocities that are more consistent in time and height than those computed directly from the extreme measured values.

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7. References

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