Simulated Tornadic Vortex Signatures of Tornado-Like Vortices Having One- and Two-Celled Structures

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ABSTRACT

A tornadic vortex signature (TVS) is a degraded Doppler velocity signature that occurs when the tangential velocity core region of a tornado is smaller than the effective beamwidth of a sampling Doppler radar. Early Doppler radar simulations, which used a uniform reflectivity distribution across an idealized Rankine vortex, showed that the extreme Doppler velocity peaks of a TVS profile are separated by approximately one beamwidth. The simulations also indicated that neither the size nor the strength of the tornado is recoverable from a TVS. The current study was undertaken to investigate how the TVS might change if vortices having more realistic tangential velocity profiles were considered. The one-celled (axial updraft only) Burgers–Rott vortex model and the two-celled (annular updraft with axial downdraft) Sullivan vortex model were selected. Results of the simulations show that the TVS peaks still are separated by approximately one beamwidth—signifying that the TVS not only is unaffected by the size or strength of a tornado but also is unaffected by whether the tornado structure consists of one or two cells.

1. Introduction

The magnitude of the Doppler velocity signature of a tornado depends heavily upon the physical width of the radar beam relative to the size of the tornado (e.g., Brown et al. 1978). When the tornado's core diameter (distance between the peak rotational velocities) is significantly larger than the radar's nominal *effective beamwidth*, the vortex is well represented by Doppler velocity measurements, as exemplified by mobile Doppler radar measurements (e.g., Wurman and Gill 2000); an effective beamwidth is broader than the beamwidth of a stationary antenna (angular difference between the half-power points) because the antenna is rotating during the time period that a representative number of samples are being collected (Doviak and Zrnić 1993, 193–197). If the tornado's core diameter is smaller than the beam diameter, a "tornadic vortex signature" (TVS) results, which is characterized by extreme Doppler velocity values of opposite signs occurring approximately one beamwidth apart in the azimuthal direction (e.g., Brown et al. 1978). Not all tornadoes produce identifiable signatures because TVS detection is a function of tornado size and strength as well as the width of the radar sampling volume, which increases linearly with increasing ranges from the radar.

Early Doppler radar simulations used a uniform reflectivity distribution across an idealized, inviscid one-celled Rankine (Rankine 1882) vortex model to produce TVS profiles (e.g., Brown et al. 1978; Wood and Brown 1997). The motivation for this study was to determine whether other vortex models produce the same tornadic vortex signature characteristics. We selected the viscous one-celled Burgers–Rott (Burgers 1948; Rott 1958) and two versions of the viscous two-celled Sullivan (Sullivan 1959) analytical vortex models (Fig. 1). A one-celled vortex structure consists of upward motion everywhere with a maximum at the vortex axis. The two-celled Sullivan vortex model reflects the presence of weakly rotating downward motion along the vortex axis surrounded by an annular region of strongly rotating upward motion. Both Burgers–Rott and Sullivan vortices have more realistic tangential velocity profiles than the Rankine model because the former models have a smooth, rounded maximum at the core radius owing to eddy viscosity, whereas the Rankine model has a sharply peaked tangential velocity maximum that represents the absence of eddy viscosity (Fig. 1).

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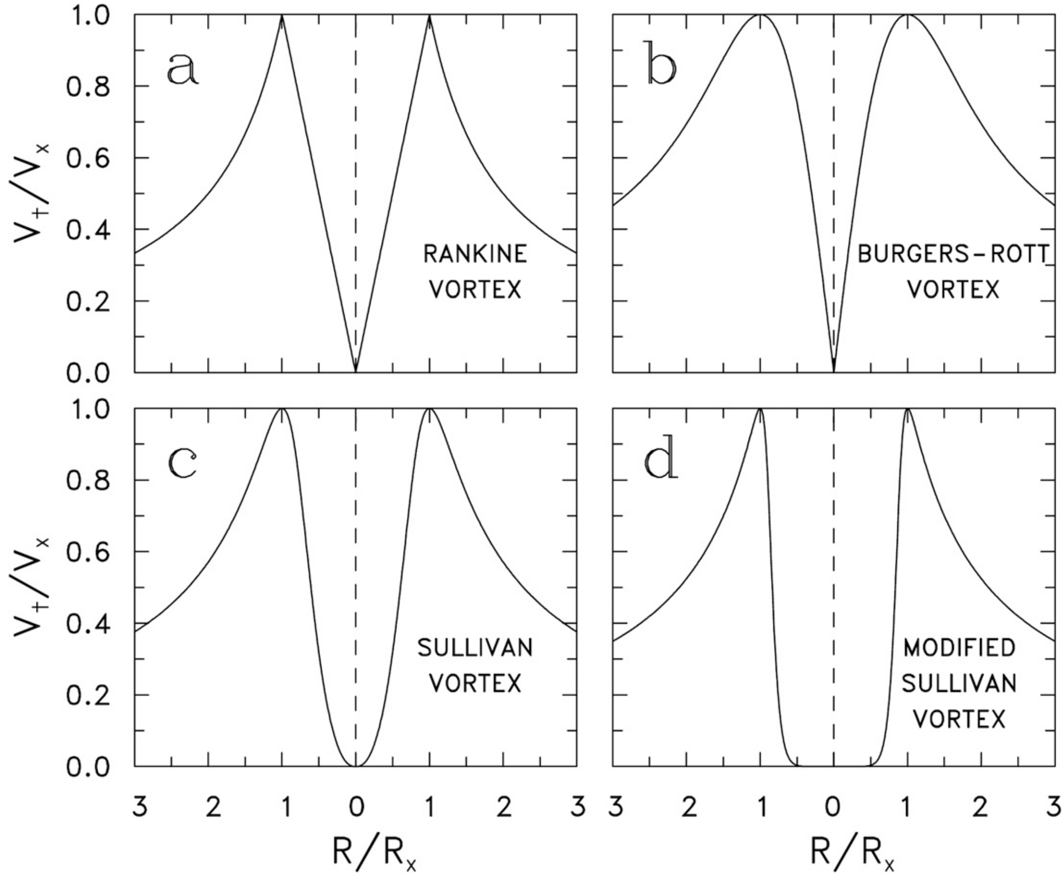

FIG. 1. Radial profiles of normalized tangential velocity V_t/V_x in the analytical (a) Rankine, (b) Burgers–Rott, (c) Sullivan, and (d) modified Sullivan vortex models. Normalized radial distance is represented by R/R_x, where R is the radial distance from the vortex center and R_x is the radius at which the tangential velocity maximum V_x occurs.

2. Analytical vortex models

a. Rankine vortex

The Rankine vortex model (Rankine 1882) is a simple vortex model that frequently is used as a first approximation to an atmospheric vortex. It consists of tangential velocity that increases linearly from zero at the center of the vortex to a maximum value at the core radius (solidly rotating core region) and then decreases, with velocity being inversely proportional to distance from the center (Fig. 1a). Tangential velocity V_t is expressed as a function of radius R as

$$V_t = V_x(R/R_x)^{\alpha}, \tag{1}$$

where V_x is the peak tangential velocity that occurs at the core radius R_x and α is a power-law exponent that is equal to 1 within the core region ($R \leq R_x$) and equal to -1 outside the core region ($R > R_x$).

b. Burgers–Rott vortex model

Recent Doppler radar observations indicate that the viscous one-celled Burgers–Rott vortex model (Burgers 1948; Rott 1958) is a better fit to the tangential velocity profile in one-celled tornadoes than the Rankine vortex model is (e.g., Bluestein et al. 2007; Tanamachi et al. 2007; Kosiba and Wurman 2010). According to Davies-Jones (1986) and Davies-Jones and Wood (2006), the Burgers–Rott model can be expressed as

$$V_t = 1.4V_x(R/R_x)^{-1}\{1 - \exp[-1.2564(R/R_x)^2]\}. \tag{2}$$

c. Sullivan and modified Sullivan vortex models

Tornado-like vortices produced in laboratory vortex chambers (e.g., Ward 1972; Snow 1982) reveal that some vortices have two cells. Two-celled vortices also have been measured by Doppler radar (e.g., Bluestein et al. 2004). Sullivan (1959) obtained an exact solution to the

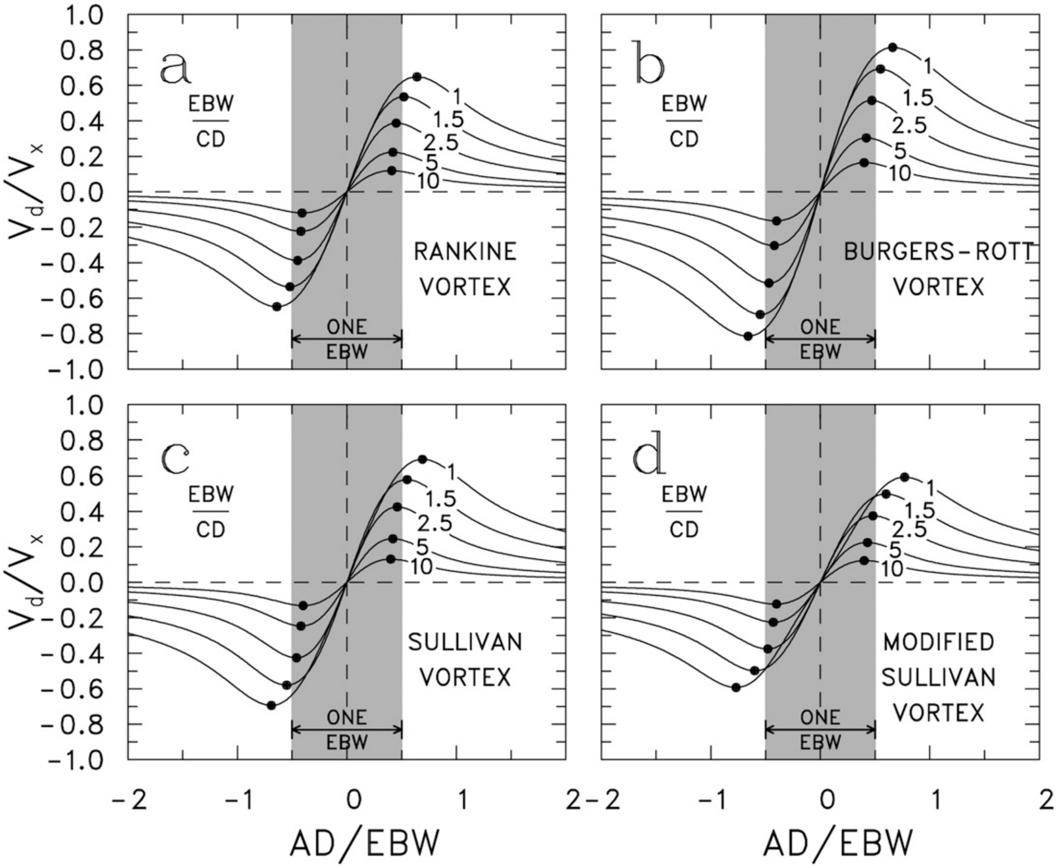

FIG. 2. Simulated azimuthal profiles of normalized Doppler velocity V_d/V_x through the center of TVSs for various ratios of EBW to CD for the analytical (a) Rankine, (b) Burgers–Rott, (c) Sullivan, and (d) modified Sullivan vortices. The ratio of AD to EDW relative to the vortex center is indicated along the abscissa. Along the ordinate, Doppler velocity V_d is normalized by the maximum tangential velocity of the respective vortex V_x. Dots denote the peaks of the TVS curves. Vertical shading represents one effective beamwidth. See text for definitions of EBW, CD, and AD.

Navier–Stokes equation in the form of a steady, viscous two-celled vortex. Because the equation is complicated, the Wood and White (2011) parametric equation was fitted to the Sullivan tangential velocity profile, resulting in the following analytical expression:

$$V_t = V_x(R/R_x)^{2.4}[0.3 + 0.7(R/R_x)^{7.89}]^{-0.435}, \quad (3)$$

which is plotted in Fig. 1c.

We also created a modified Sullivan vortex that has a broader downdraft region that occupies the vortex center (Fig. 1d), expressed as

$$V_t = V_x(R/R_x)^{10}[0.091 + 0.909(R/R_x)^{22}]^{-0.5}. \quad (4)$$

This tangential velocity profile is very similar to one measured in "dust devil B" by Bluestein et al. (2004) using a mobile W-band Doppler radar.

3. Doppler radar emulator

Doppler velocity measurements of the four model vortices were simulated using a Doppler radar emulator that approximates the basic characteristics of a Weather Surveillance Radar-1988 Doppler (WSR-88D); see the appendix of Wood and Brown (1997) for details. Following is an overview of assumptions made. The reflectivity across the vortex was assumed to be uniform. Instead of the radar beam consisting of a main lobe and side lobes, it consisted only of a main lobe that was represented by a Gaussian distribution. The radar beam consisted of only one range gate that scanned through the center of the vortex. Furthermore, it was assumed that the radar measurements were continuous and free of noise. Instead of averaging radar pulses to produce simulated mean Doppler velocity values, mean Doppler velocity values were computed by averaging distributed tangential velocity values within the effective beamwidth

(1.0° for WSR-88D when data are collected at 0.5° azimuthal intervals and 1.4° when data are collected at 1.0° intervals; e.g., Brown et al. 2002).

4. Influence of vortex tangential velocity profiles on tornadic vortex signatures

When Brown et al. (1978) discovered the TVS in the 1973 Union City, Oklahoma, tornadic storm, they used the Doppler radar emulator of Zrnić and Doviak (1975) to determine whether a TVS arises when a tornado is smaller than the width of the radar beam. They represented the tornado using a Rankine vortex that had uniform reflectivity across it. Their simulations indicated that a TVS does occur when a tornado is narrower than the beamwidth. They found that the peak Doppler velocity values of the TVS are separated by approximately one beamwidth regardless of tornado size or strength. With data collected at discrete azimuthal intervals, the data points will not necessarily occur at the TVS peaks (e.g., Wood and Brown 1997).

In this study, we were interested in determining whether the peak TVS values also are separated by about one beamwidth for other vortices that have different tangential velocity profiles with uniform reflectivity across the vortices. To accomplish this objective, we scanned the simulated Doppler radar in a continuous manner across each of the four vortices at appropriate ranges where the ratios of effective half-power beamwidth (EBW) to vortex core diameter (CD) were 1.0, 1.5, 2.5, 5.0, and 10.0. The resulting normalized TVS curves are plotted in Fig. 2 as a function of azimuthal distance (AD) from the center of the vortex relative to the effective beamwidth. It is obvious that there are no significant differences in the distance between the peaks of given EBW/CD curves among the four vortices. A subtle difference is that the curves for the Burgers–Rott vortex have larger peak values (Fig. 2b) because the radial profile of the Burgers–Rott tangential velocity in the annular zone that encompasses the tangential velocity maxima is significantly broader than for the other vortices (Fig. 1). Also, the peaks of the modified Sullivan vortex curves for EBW/CD values of 1 and 1.5 are slightly farther apart than are the peaks for the other three vortices. This situation undoubtedly arises from the presence of the wide region of weak tangential velocities at the center of the vortex (Fig. 1d).

The most obvious feature in Fig. 2 (summarized in Fig. 3) is that the peaks of those curves having EBW/CD ratios of 1.5 and greater are separated by roughly one effective beamwidth regardless of how much wider the radar beam is relative to tornado size. It may be noted in Fig. 3 that the spread in the separation of the TVS peaks among the four vortex models decreases as the beam becomes increasingly wider than the tornado.

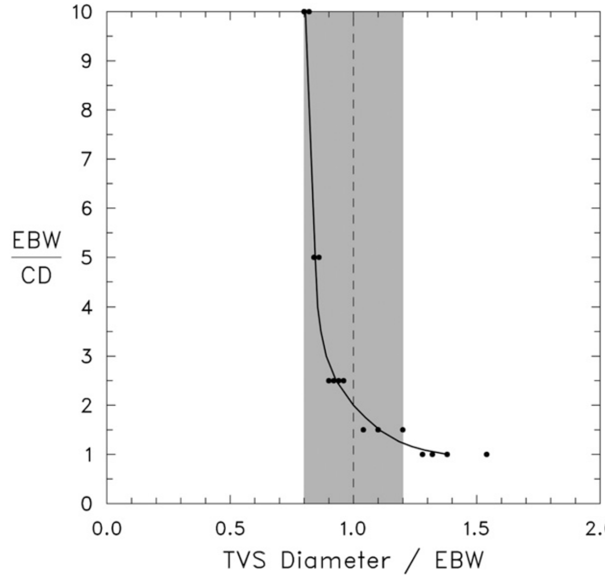

FIG. 3. Diameters of the peak values of Doppler velocity TVS curves normalized by the effective half-power beamwidth of the sampling radar. Dots (some overlapping) represent the normalized diameters for the four individual vortices; the rightmost dot represents the modified Sullivan vortex. The curve depicts the variation of the mean normalized TVS diameter as a function of EBW/CD. The shaded area indicates normalized values of 1.0 ± 0.2.

5. Concluding discussion

A tornadic vortex signature arises when the effective half-power beamwidth of a Doppler radar is wider than the core diameter of a tornado. On the basis of the simulations of Brown et al. (1978), where the tornado was assumed to have uniform reflectivity and a Rankine tangential velocity profile, it was found that the Doppler velocity peak values of a TVS are separated by approximately one effective beamwidth.

In this study, we wanted to determine whether the choice of vortex model resulted in significant differences in the basic characteristics of a TVS. We found that there were no significant differences when the radar's effective beamwidth was at least 1.5 times the core diameter of the vortex. In addition to the TVS being approximately one beamwidth wide regardless of tornado size or strength, we found that in general the width of the TVS also is not dependent on whether the tornado's structure consists of one cell (axial updraft) or two cells (axial downdraft surrounded by annular updraft). Although these results were obtained using the characteristics of a simulated WSR-88D, they are applicable—through normalization by the effective beamwidth—to measurements made by any Doppler radar.

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