EVALUATING THE VORTEX DETECTION AND CHARACTERIZATION (VDAC) TECHNIQUE USING REAL MULTIPLE-DOPPLER OBSERVATIONS OF SUPERCELL THUNDERSTORMS

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I. INTRODUCTION

The severe thunderstorm and tornado warning process becomes particularly challenging when forecasters do not have time to thoroughly interrogate all available radar data or when observations and model forecasts are only marginally supportive of severe weather prior to its onset. Radar-based detection algorithms become particularly important in these cases, serving to alert forecasters to important features they may otherwise have missed. Since the implementation of the Weather Surveillance Radar 1988-Doppler (WSR-88D) network, several algorithms have been developed to aid forecasters in real-time identification of intense convective vortices (e.g., the NSSL Tornado Detection Algorithm; Mitchell et al. 1998). Unfortunately, most of these techniques rely upon thresholds of gate-to-gate shear, and are therefore particularly sensitive to noise in the velocity data and to azimuthal offset of vortices from the radar beam. This results in a sharp tradeoff between the false alarm rate (FAR) and probability of detection (POD).

The Vortex Detection and Characterization (VDAC) technique described herein fits radial velocity data to an analytical vortex model in order to recover key characteristics of the vortex flow. This approach is less sensitive to noisy velocity data than are shear-based techniques. The ability of the technique to use data from multiple radars makes it comparable to the dual-Doppler Extended Ground-Based VTD (EGBVTD; Liou et al. 2006). However, unlike in the GBVTD, the model parameters in the VDAC method include the vortex center, making *a priori* knowledge of the location of the vortex unnecessary. This allows the technique to function as both a vortex detection algorithm and a vortex characterization algorithm. The VDAC technique is designed primarily for use in Collaborative Adaptive Sensing of the Atmosphere (CASA; Brotzge et al. 2010) and CASA-like radar networks, whose high observational resolution and overlapping coverage should permit more accurate detection and characterization of tornado- and mesocyclone-scale vortices than is possible with the WSR-88D network. However, the technique also shows promise in detecting and characterizing vortices > 1 km in diameter when velocity data from only one radar are available.

A complete description of the original VDAC methodology as well as tests of the technique using analytically-generated, numerically-simulated and one observed tornadic wind field were presented in Potvin et al. (2009). Important improvements to the technique as well as tests with additional radar observations of convective vortices are described in Potvin et al. (2011). An overview of the technique and selected results from Potvin et al. (2011) are presented herein.

II. VDAC TECHNIQUE

The low-order model to which the Doppler velocity data are fit is comprised of four idealized flow fields: a uniform flow, linear shear flow and linear divergence flow (together comprising the "broadscale" flow), and a modified combined Rankine vortex (MCRV; e.g., Brown et al. 2002). The use of the MCRV model is supported qualitatively by high-resolution mobile radar observations of tornadoes (Wurman and Gill 2000; Bluestein et al. 2003; Lee and Wurman 2005). The vortex and the horizontal broadscale fields are allowed to translate, allowing radar data to be used at their actual locations and times of acquisition and thus bypassing the need for temporal interpolation, moving reference frames or other ad hoc procedures. A total of 19 parameters (Table 1) characterize the wind field in the low-order model. The horizontal components of the broadscale flow are given by

$$V_x = a + b(y - v_b t) + c(x - u_b t) + gz,$$
$$V_y = d + e(x - u_b t) + f(y - v_b t) + hz.$$

The vortex azimuthal velocity field v_θ and vortex radial velocity field v_r are given by

$$v_\theta = \begin{cases} \dfrac{r}{R} V_T, & r < R, \\ \dfrac{R^\alpha}{r^\alpha} V_T, & r \ge R, \end{cases} \qquad v_r = \begin{cases} \dfrac{r}{R} V_R, & r < R, \\ \dfrac{R^\beta}{r^\beta} V_R, & r \ge R, \end{cases}$$

where

$$r = \sqrt{(x - x_0 - u_v t)^2 + (y - y_0 - v_v t)^2}$$

is the distance of a given (x, y) coordinate from the center of the vortex (located at x_0, y_0 at the analysis time t=0) at time t.

Parameters	Description
a, d	uniform flow velocity components (m s^{-1})
b, e	horizontal shear components (s^{-1})
c, f	horizontal divergence components (s^{-1})
g, h	vertical shear components (s^{-1})
R	vortex radius of maximum wind (m)
V_R, V_T	max radial, tangential winds (m s^{-1})
x_0, y_0	vortex center location at t=0 (m)
u_b, v_b	broadscale translational velocity (m s^{-1})
u_v, v_v	vortex translational velocity (m s^{-1})
α, β	decay exponents for vortex radial and tangential winds

TABLE 1: Low-order model parameters.

The model parameters are retrieved by minimizing a cost function J that sums the (squared) discrepancies between the observed and model radial wind fields within the analysis domain [see Potvin et al. (2009) for the derivation of the model radial wind component]. Retrievals are conducted within circular analysis domains in regions objectively identified as possibly containing intense vortices (due, among other factors, to the existence of strong radial shear in both radar's radial velocity fields). As with other minimization problems, multiple minima in J can prevent the desired minimum (which in our problem may not be the global minimum) from being reached. Multiple minima in the current application can result from the intrinsic non-linearity of the problem, as well as from areas of missing data and departures of the observed wind field from the model (e.g. multiple proximate vortices). The VDAC technique uses several strategies to address the multiple minima issue.

First, retrievals are performed for a multitude of first guess vortex centers within each identified region to maximize the probability of detecting all intense vortices. The parameters of detected vortices that are similar to each other in size and location are averaged together to produce a single description of each intense vortex identified in the radar domain.

Second, rather than retrieving all the low-order model parameters simultaneously, a multiple-step procedure is used which helps prevent smaller vortices embedded in larger, weaker vortices from going undetected due to the larger "footprint" of the latter (e.g., tornado within a mesocylone). The broadscale flow is retrieved, subtracted from the observed radial wind field, and then the vortex parameters are retrieved. The process is repeated within a new analysis domain that is centered on, and spatially scaled to, the preliminarily retrieved vortex.

Third, the detection criteria, used to distinguish between intense vortices and weak or spuriously-retrieved vortices, are designed to account for the vortex solution non-uniqueness that occurs when the vortex is poorly resolved in the observations (Potvin et al. 2009). In such cases, large errors in the retrieved vortex parameters can cancel with each other to produce a model vortex that resembles the true vortex on observable scales. Rather than relying solely upon the vortex model parameters, which may be highly inaccurate when the vortex is poorly resolved, we instead use vortex characteristics computed from the vortex model parameters *and verified by the velocity data* to distinguish between intense and weak or spurious vortices (see section 4 of Potvin et al. 2011). Such characteristics include an observationally-supported lower bound on the maximum vortex tangential winds, and the vortex radii of various tangential wind speeds.

III. EXPERIMENTS WITH SMART RADAR OBSERVATIONS OF THE 30 MAY 2004 GEARY, OKLAHOMA SUPERCELL

A supercell that spawned a series of tornadoes across Oklahoma on 30 May 2004 (Bluestein et al. 2007) was observed by a pair of Shared Mobile Atmospheric Research and Teaching (SMART; Biggerstaff et al. 2005) radars near Geary and Calumet, OK. The VDAC technique was tested using base elevation (0.5°) data collected by the radars at 0022 UTC, 0027 UTC, 0033 UTC, 0038 UTC and 0052 UTC. The range and azimuthal sampling intervals for both radars were approximately 67 m and 1°, respectively, and the half-power beamwidth was about 1.5°. The distance between each of the radars and the analysis domains varied between roughly 20 km and 50 km in these tests, yielding azimuthal sampling intervals of between 350 m and 850 m.

An unusually large (1-2 km diameter) surface circulation produced F-2 damage throughout the experimental period. Several smaller vortices formed and decayed within this larger circulation during the SMART radar observing period. These vortices are indicated in the individual radars' wind fields by regions of enhanced shear. Since the smaller-scale vortices are not readily visually discernable from the surrounding mesoscale vortex flow, this is a useful test case for our algorithm.

In order to evaluate how well the mean retrieved vortex characteristics represent the actual vortex in each case, the radial component of the retrieval most closely approximating the mean retrieval for each analysis time was plotted and compared to the observed radial velocity field (0033 UTC retrieval shown in Figure 1). In all five cases, the broadscale portion of the model, though linear, recovered the larger-scale (parent vortex) circulation sufficiently well that the embedded vortices were salient in the residual flow. The embedded vortices were subsequently accurately retrieved on observed scales. Trends in the mean retrieved vortex characteristics (not shown) were consistent with the observed wind fields at successive analysis times. Fortunately, no false detections were made.

IV. EXPERIMENTS WITH DOW RADAR OBSERVATIONS OF A WEAK TORNADO

The technique was next applied to a Doppler on Wheels (DOW; Wurman et al. 1997) dataset of a weak tornado that occurred near Argonia, KS on 5 June 2001 (Marquis et al. 2011). The azimuthal sampling interval for both DOW radars averaged less than 0.4° and the radial sampling interval varied between 50 m and 75 m. The azimuthal distance between observations near the tornado averaged around 50 m. Both radars had a 0.93° half-power beamwidth.

Fortunately, the technique detected the smallest intense vortex that could be subjectively inferred from the observed radial velocity fields at each of the analysis times. Futhermore, no false detections were made. Comparisons of the observed and final retrieved radial wind fields at 0031 UTC are presented in Figure 2. The values and trends of the retrieved vortex characteristics were again consistent with the observed radial wind fields. That the technique was able to not only detect but reasonably characterize this tornado is especially encouraging given its relatively small size and weak intensity.

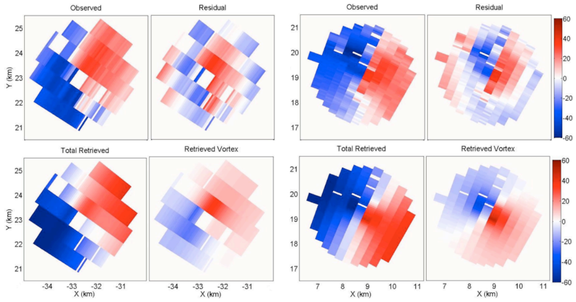

FIGURE 1: Observed, residual (observed minus retrieved broadscale), retrieved vortex, and retrieved total radial velocity fields for SMART radars located (left) southeast and (right) southwest of the 30 May 2004 Geary, OK tornadoes at 0033 UTC.

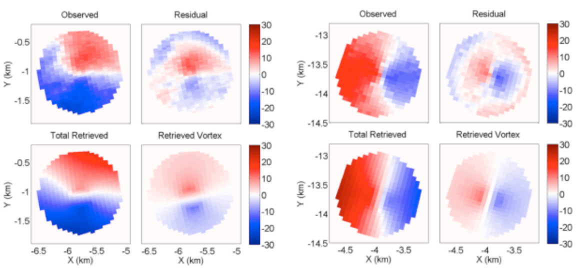

FIGURE 2: As in Fig. 1 but for DOW radars located (left) east and (right) north-northeast of the 5 June 2001 Argonia, KS tornado at 0031 UTC.

V. SUMMARY AND CONCLUSIONS

Tests with real Doppler observations of intense vortices indicate the VDAC technique is capable of detecting and characterizing vortices reasonably well, even when they are embedded within a complex wind field or a larger, stronger vortex. The vortex characteristic estimates output by the technique could help forecasters to triage storms during severe weather outbreaks, thus facilitating timely identification of tornadoes, mesocyclones and other significant convective vortices. The technique is capable of detecting and characterizing larger-scale vortices such as mesocyclones even when only single-Doppler data are available (see Potvin et al. 2011). It may therefore be useful to run the mesocyclone-retrieval configuration of the technique in real-time on WSR-88D data, at least for shorter radar ranges.

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