Numerical simulation of sub-tornado-scale vortices

Statement of Problem

To numerically simulate features of tornado-like vortices that are not well-resolved by current radar technology and are difficult to determine from damage surveys, with the intent of ascertaining structure and intensity of these features based on various atmospheric/environmental conditions.

Significance of Problem

Hazardous weather phenomena in the United States are generally well-understood in their broad geographical distributions (e.g. Kelly et al. 1978; Kelly et al. 1985; Brooks et al 2003); however, smaller-scale spatial and temporal details remain a challenge to researchers. Tornadoes and their associated damage, in particular, are reported to the National Weather Service (NWS) by law enforcement officials, trained volunteer storm spotters, and the general public. When a tornado is deemed especially significant, trained evaluators will be dispatched to conduct damage assessments. Regardless of whether or not this assessment was conducted, all reports are incorporated into the official record as derived Enhanced Fujita (EF) Scale rankings (McDonald and Mehta 2006), a recent improvement to the original Fujita (F) Scale (Fujita 1981). Both versions of the scale attempt to relate tornadic wind speeds to damage to man-made structures, vegetation, etc.; these wind speed estimates are essentially uncalibrated and rely on accurate reporting of damage by the aforementioned parties. Furthermore, the dependence of the intensity ranking system on damage necessitates that the tornado not occur in the middle of a bare field for the system to function. Thus, our knowledge of low-level tornado intensity and structure has been limited by the information that can be obtained from these reports.

Motivated in part by a need for instrumental identification of storms capable of producing tornadoes and other severe hazards, the Weather Surveillance Radar – 1988 Doppler network was developed and implemented. The WSR-88D network consists of 159 Doppler weather radars with 3D scanning procedures that have provided coverage of most of the United States since the mid-1990's (Crum and Alberty 1993). Automated algorithms to detect both tornadic and mesocyclonic circulations (Mitchell et al. 1998; Stumpf et al. 1998) utilize radar reflectivity and radial velocity fields to identify areas of interest in real time on the operational level; they also have been applied to archived data to retrieve climatological information on, for example, the percentage of mesocyclones that produce tornadoes (e.g. Trapp et al. 2005). Two theoretical limitations inherent to WSR-88D observations have deterred the use of such measurements for assessment of tornado intensity, namely: (1) beam broadening, and (2) beam-height increases, both of which are directly dependent on range from the radar site, and both lead to an undersampling of the vortex. Hence, the WSR-88D cannot provide *direct* information about low-level features or wind speeds in tornadoes; we show below, however, that the information still has value, especially when combined with other data.

The Doppler on Wheels (DOW) is a mobile research radar capable of sampling the tornado at low levels with more frequent update intervals than the WSR-88D (Wurman et al. 1997). Due to its sampling strategy and position relative to the storm, it is not subject to the same limitations as the WSR-88D. The DOW has been used in multiple field programs, and the wind estimates made by the DOW have been shown to be accurate in comparison with reliable damage assessments (e.g. Burgess et al. 2002; Toth et al. 2012). Additionally, the instrument has been shown to be capable of identifying smaller spatial- and temporal-scale features at low levels, such as multiple vortex structures (Wurman 2002).

Despite the radar's frequent update intervals, the evolution of the tornado and its smaller scale features still occur over a time period that the DOW may not resolve. Furthermore, mobile radars are cost-prohibitive, which prevents their widespread use in an operational setting. Thus, the overarching objective of the research proposed herein is to develop an operationally viable method of determining low-level wind speeds in tornadoes.

Expanding on previous work: Improving Doppler radar estimates of tornado intensity

Our work thus far has focused on an assessment of the utility of WSR-88D data in light of the aforementioned limitations. We have attempted to statistically relate the velocities sampled by the WSR-88D to those sampled by the DOW at low levels. A relatively simple measure of intensity is often given as differential velocity, $\Delta V = V_{out} - V_{in}$, where, ideally, the tornado would line up in the middle of two WSR-88D beams so that radially inward (V_{in}) and outward (V_{out}) velocities can be measured in the center of two separate radar beams (Figure 1). For the DOW, it usually takes multiple radar beams to sample a tornado, but the maximum ΔV is still given by the maximum V_{out} and minimum V_{in}. Our analyses of fourteen tornado events of varying intensity and range to the WSR-88D (Figure 2) have suggested that a relationship exists between low-level, high-resolution DOW differential

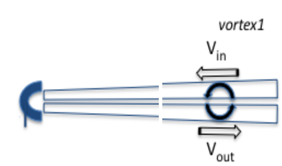

Figure 1: Illustration of vortex sampling by Doppler radar.

velocity (ΔV_{DOW}) and the associated higher-level, lower-resolution WSR-88D differential velocity (ΔV_{88D}). The results of these analyses have been incorporated into a simple linear regression model derived from Figure 2:

$$I = \Delta V_{DOW} = \alpha \Delta V_{88D} + \beta \tag{1}$$

where I represents one measure of tornado intensity, and α and β are the empirical coefficients (equal to 2 and -24, respectively, with an R^2 value of 0.83, and statistical significance of the slope at the 95% confidence interval). This use of DOW velocity data rather than EF-Scale ratings is neither dependent on damage assessments for intensity estimates nor does it return an uncalibrated range of approximate wind speeds.

Although tornado intensity estimates by WSR-88Ds have only been made in a few cases (e.g. Burgess et al. 2002, Wurman and Alexander 2005), our analyses (Figure 3) show that the dismissal of the platform for velocity estimates may be premature; the range of wind speeds exhibited at various ranges and vortex offsets in an idealized model still falls within an Enhanced Fujita scale margin of error. We re-created the radar model developed in Wood and Brown (1997) to estimate the hypothetical best and worst WSR-88D sampling of the tornado at various ranges and positioning relative to the vortex center. Our results, in combination with knowledge of WSR-88D scanning strategies and storm translation, suggest that the radar is capable of making reasonable velocity estimations that can be downscaled to low-level intensities with the linear regression determined from the observational data.

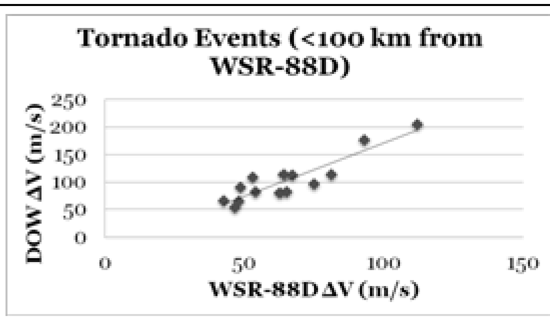

Figure 2: Scatterplot relating ΔV_{DOW} to ΔV_{88D} for fourteen tornado events.

Due to our interest in developing a broadly applicable downscaling model, our observationally-based low-level intensity estimates do not take into account perturbations to the classic conception of a Rankine-combined vortex, such as multiple vortices (Agee et al. 1976). These variations may be the result of environmental factors and/or the dynamical process of vortex breakdown (also influenced at least partially by the environment). It has been hypothesized that these "suction vortices" may exhibit different characteristics and higher wind speeds than the vortex in which it is contained (Fujita 1971), and observations with mobile radars have corroborated this in relatively recent years (Wurman 2002). Wurman analyzed radar observations of multiple vortices in an intense tornado and found that these vortices did not exhibit the same solid-body rotation as the parent vortex, with shear across the vortices located over a much smaller distance (<100 m) and greater wind speeds contained within the vortices than in their parent tornado. In order to better determine the applicability of our linear regression, we must investigate the variability in vortex structure and intensity introduced with these low-level dissimilarities.

Plan of Research

Numerical model simulations of tornado-vortices will facilitate such an investigation, and more generally will help to fill our gaps in physical understanding of the tornado dynamics. Models have been utilized in numerous studies of tornado structure and dynamics (e.g. Wicker and Wilhelmson 1993, Trapp and Fiedler 1995, Lewellen et al. 1997). With increasing computational resources, more sophisticated models have been developed which have the ability to better simulate both isolated vortices as well as tornadoes in association with their parent storm (see Fiedler 1995). The former method allows for increased resolution of the vortex and its associated features, and will therefore be the approach we take to our problem of low-level tornado intensity and structure.

The specific model that will be used for these experiments is the NCAR/Penn State Cloud Model 1 (CM1), a nonhydrostatic numerical model that can be run efficiently with sufficiently small grid spacing to resolve most known multiple vortex structures (Bryan and Fritsch 2002). Model setup will be based on the methodology of Trapp and Fiedler (1995), which successfully created tornado-like vortices. Using CM1 in its 3D form and imposing an updraft into the closed domain, boundary conditions will be varied to determine impacts on the features and formation of the primary vortex.

As previously mentioned, in addition to the development of the primary vortex, we have interest in the structure and intensity of subsidiary vortices. Observations obtained from mobile radars still have spatial and temporal limitations in discerning very small-scale vortex evolution. By isolating the tornado-like vortex in the model and implementing some sort of grid nesting or adaption scheme, we should be able to better resolve these features without excessive computational expense. Based on previous work (e.g. Snow 1978, Lewellen et al. 2000), we will place emphasis on boundary layer environmental characteristics (e.g. inflow layer depth) and parent tornado strength (as measured by shear, vertical vorticity, and related parameter values), which may affect the formation and/or structure of the associated subsidiary vortices.

We hope to expand on the results of these intensity estimates by re-incorporating our simple radar model into the experiments. The velocities output by the numerical model will be interpreted by the radar at various ranges and azimuthal offsets, as was done with the idealized Rankine-combined vortex. This exercise will allow us to determine the effect of radar sampling on a more realistic vortex over a short time period (< 5 minutes, the time period of a typical WSR-88D volume scan); this is a difficult feat to accomplish observationally, even utilizing rapidly scanning mobile radars.

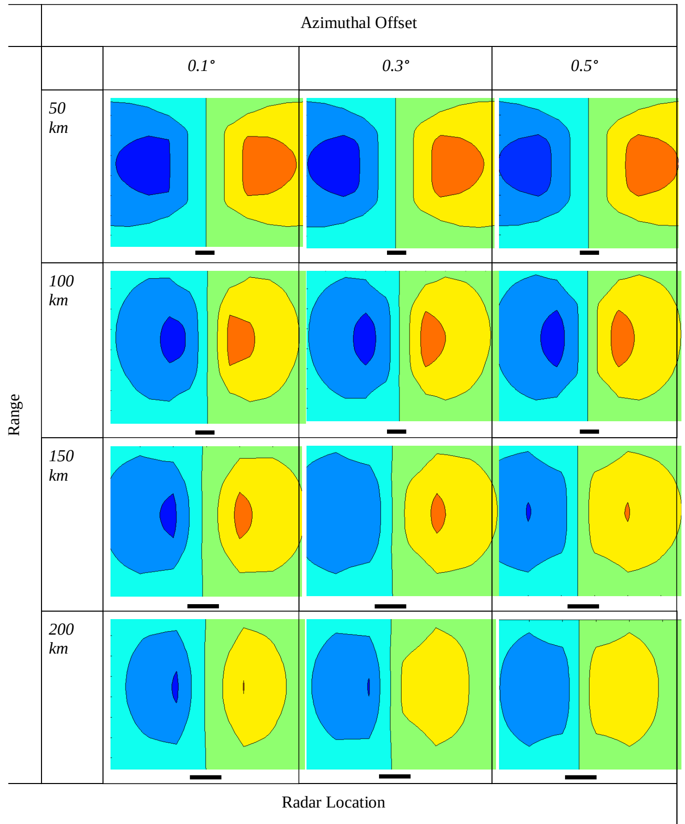

Figure 3: Model output of an idealized radar sampling an idealized vortex.

Expected Outcomes

Recently, Parker (2012) showed the ability of CM1 to model tornado-like vortices in both two and three dimensions, following the Trapp and Fiedler (1995) methodology (Figure 4). Similarly, we will first test the model in 2D and 3D to determine differences in simulated characteristics and maximum velocities, as well as related intensity parameters. The Parker simulations confirm that we should expect to be able to create an isolated vortex with multiple vortices in the dry version of this particular model. Based on the work of Fujita (1971) and supporting evidence from modeling (Fiedler 1998) and radar observations (Wurman 2002), we anticipate the suction vortices to be at least slightly more intense (as measured by our aforementioned parameters) than their parent tornado.

Additional work relating the numerical model output to our simple radar model has the potential to improve our observational understanding of these sub-tornado scale vortices. It is uncertain whether a discernable relationship will be present between the upper levels of our isolated vortex and its surface perturbations; in general, hypothetical and observational work account primarily for decreasing velocities with increasing height. Our current sample of observational events, however, does not take into account varying near-surface level vortex structures, which may significantly impact the intensity of the tornado at the ground. This portion of the project will provide beneficial information to researchers and forecasters alike on the limitations of our observational linear regression relationship.

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