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DOW OBSERVATIONS OF MULTIPLE VOREX STRUCTURES IN SEVERAL TORNADOES

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1. INTRODUCTION

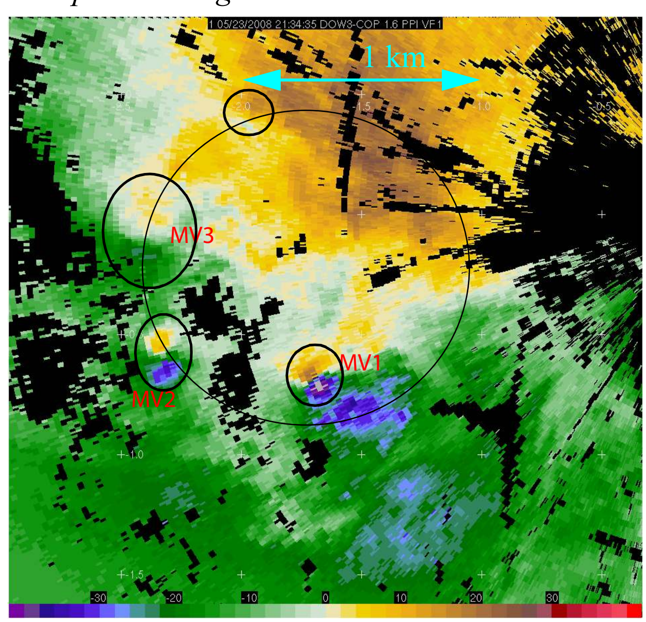
The objective of this study is to present the spectrum of multiple vortex structures of a variety of spatial and temporal scales during tornadic events observed by the DOW radars. By documenting the formation and subsequent evolution of these vortices, insight may be gained into the potential mechanisms that contribute to tornadogenesis and maintenance processes. In particular, the interaction between vortices appears to affect the properties of the subsequent flow and parent tornadoes.

The traditional notion of the multiple vortex structure consists of several subsidiary vortices rotating about their own axis while revolving about a common center. This cylindrical shearing instability can occur at both the mesocyclone and the tornado scale. In addition to this breakdown method of multiple vortex generation, the presence of misovortices and, in particular, the advection of these vortices into the main circulation, may provide a mechanism for multiple vortex production and/or enhancement. Other types of multiple vortex structures, such as the presence of 2 mesocyclones and the formation of cyclonic/anti-cyclonic vortex pairs, will also be discussed.

2. QUINTER, KS AND STRATFORD, TX

The tornadic event that occurred in Quinter, KS on 23 May 2008 exemplified the evolution of a multiple vortex mesocyclone into a single tornado vortex. Examination of the mesocyclone at 21:34:26 UTC (all times are in UTC hereafter), revealed the presence of subsidiary vortices at approximately its radius of maximum winds (Figure 1--21:34:35). These vortices persisted for a couple of minutes, revolving about the mesocyclone center at a rate of ~20 m/s. During this time period, two of the multiple vortices had a shear (delta-V) value that exceeded the threshold used in DOW analyses of tornado of 40 m/s (Figure 2--excel plot), and low level ground relative winds > 30 m/s. Then, by 21:37:03, only a single tornadic vortex is present in the flow. Repeat observations at the same altitude

Figure 1. Doppler velocity in tornado south of Quinter, Kansas on 23 May 2008. At least three multiple vortices are evident, embedded in a 1.4 km diameter circulation/tornado. Windspeeds in both MV1 and MV2 are individually 'tornadic'. One of these appears to develop into a singleton tornado.



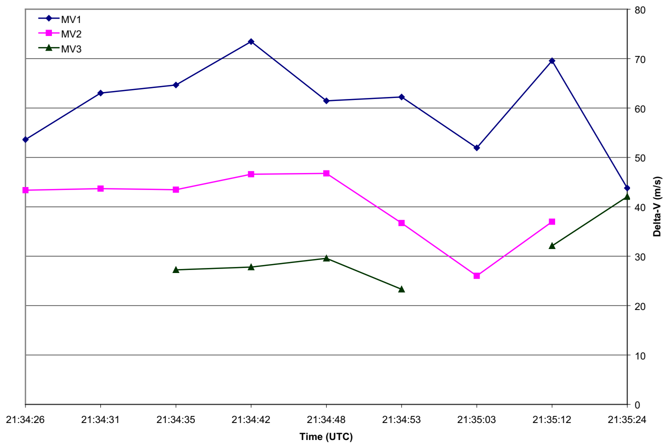


Figure 2. Time series of Doppler velocity shear across core flow region of each multiple vortex in the tornado south of Quinter on 23 May 2008. Both MV1 and MV2 maintain significant intensity during the genesis event.

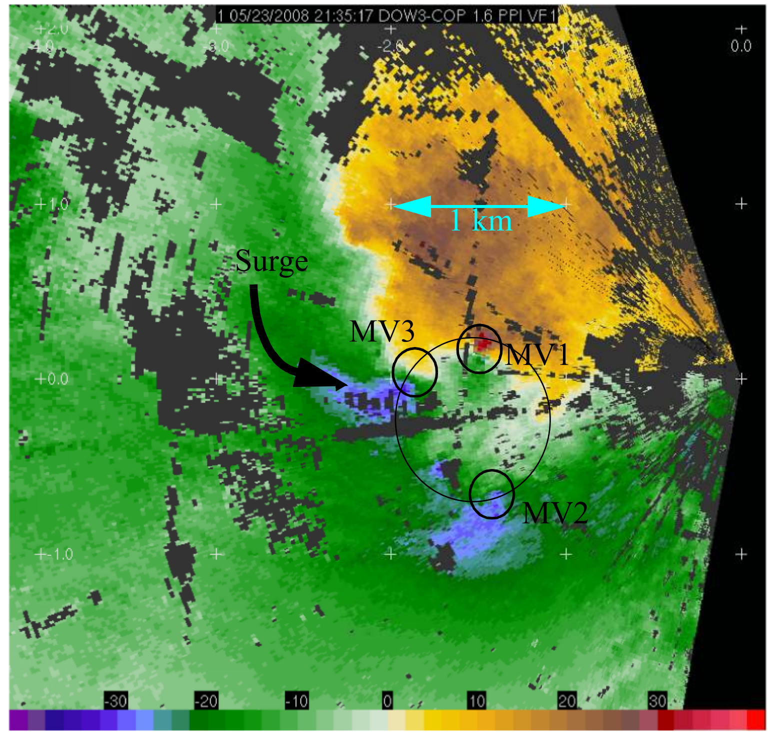


Figure 3: Multiple Vortex structure of tornado approaching Quinter, Kansas on 23 May 2008. MV3 is intensifying and becomes the eventual singleton tornado. Scale of larger circulation (tornado?) has contracted to < 1 km.

in these circulations were not obtained with sufficient temporal resolution to definitely characterize the evolution. However, the resolved evolution is suggestive. Examination of the data prior to the time of the single, tornadic vortex revealed a surge of flow into the western flank of the multiple vortex circulation (Figure 3--21:35:17). It is surmised that this surge provided the impetus for the adjacent multiple vortex to become the dominant flow feature and become the eventual single-vortex tornado.

While one of the Stratford, TX tornadoes of 15 May 2003 also exhibits a multiple vortex mesocyclone (Figure 4a--23:02:26), its structure and evolution are much more complicated than that of the Quinter storm. Numerous vortices exist, but the dominant vortex originates on the western flank of the circulation. It is not immediately obvious why this should be a favored location for vortex sustenance. The mesocyclone persists in this multiple vortex state for a few minutes until 23:06:39, at which time two distinct tornadic circulations, separated by ~4 km, dominate the flow (Figure 4b--23:06:39). The southwestern tornado appears to have originated from the prevailing multiple vortex, whereas the northeastern tornado may have stemmed from a developing convergence region (i.e., a new hook feature) in the northern flank of the larger circulation. These two tornadoes coexist at comparable strength for a substantial period of time (~ 6 min) until 23:13:01 when only one, large circulation remains. A new, highly multiple vortex tornado develops as the original northeast tornado dissipates by 23:14:14, (Figure 4c--23:14:14), by 23:15:27 it is a diffuse circulation, and then by 23:17:01 a double vortex structure (not shown).

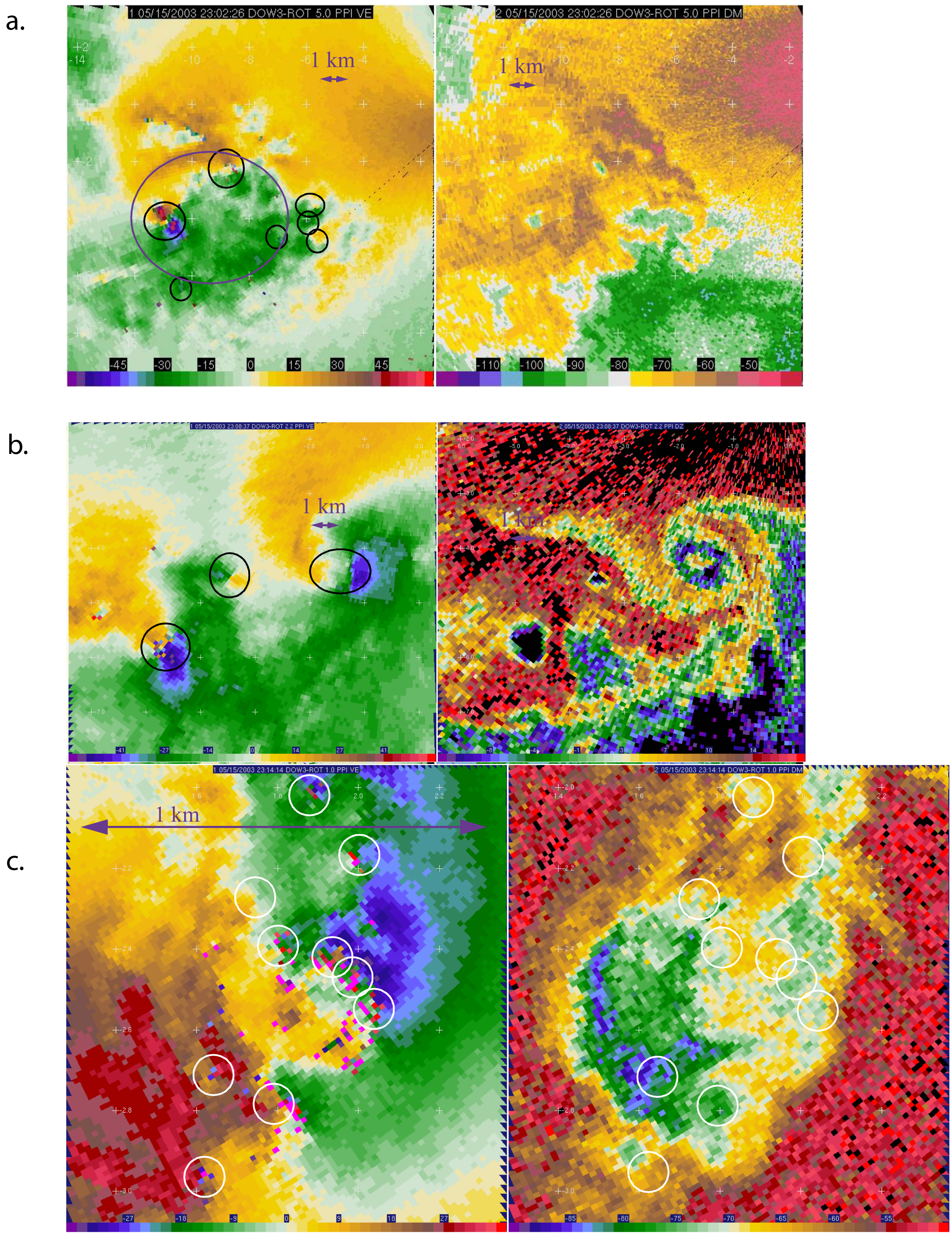


Figure 4. Different scales of multiple-vortex structure in a tornadic storm. (a) Many vortices embedded in a broad circulation. One is tornadic strength. (b) Two distinct tornado strength vortices. At times an intense anti-cyclonic vortex is between these two. The northeastern tornado had a multiple vortex structure that was unobservable by the DOW at >10 km range, but was observed visually and in situ pressure data. (c) Higher resolution image at a later time of 3rd tornado revealing finer-scale many-multiple vortex structure inside a large, but not very intense, 1.5 km diameter tornado.

The initial multiple vortex state in the Stratford storm does not appear to be dominated by cylindrical shearing instabilities. Several vortices, and one predominantly strong vortex, appear scattered throughout the larger circulation (Figure 4a). In particular some of these vortices appear to be located along and/or adjacent to a misocyclone-producing shear line. As noted above, that shear/convergence line eventually evolves into the northeast tornado at 23:06:39. The much finer-scale multiple vortex sub-tornado structure that evolves by 23:14:14 in the 3rd tornado has its strongest subsidiary vortices to the north and to the east of the circulation center.

Although not presented in detail here, it is worth noting that the evolution of the Geary, OK tornadoes (29 May 2004) share some similarities with the aforementioned storms. At the initial time of interest, a strong tornado (A) is embedded within a stronger 2-3 km-scale circulation. Tornado (A) dissipates and 3 subsequent, intense vortices (B, C, and D) revolve about the larger circulation. One of these, vortex D becomes a persistent and strong single-vortex tornado (see http://www.cswr.org/dataimages/rotate/geary-summary-2004-0711fp.pdf for more information).

3. SEWARD, KS

The Seward, KS storm (05 May 2007) exhibited several multiple vortex features that contributed to the formation of a large, intense tornado. The merger of a low-level mesocyclone and tornado produce a very large, intense circulation with winds at the lowest measured level of 96 m/s (Figures 5a, b, and c). This new circulation is comprised of several subsidiary vortices, with the most intense of these vortices persisting near the southern edge of the flow (Figures 5d and e). This location appeared to be favored for subvortex maintenance due to its proximity to the misocyclone-producing shear line (Figure 5d). Given the divergent signature at the radius of maximum winds (and hence an inferred two-celled structure; Figure 6), it is likely that the multiple vortices originated from the growth of inertial shear instabilities. But, the persistence of an intense vortex adjacent to the horizontal shear line supports the conjecture that the advection of misovortices into the larger circulation may act to enhance vortex strength. Along the western circumference of the larger circulation, away from the shear line, multiple vortices persist, although diminished in strength (Figure 5e).

4. GLEN ELDER, KS

The Glen Elder, KS storm of 29 May 2008 provides a good example of the formation and evolution of a cyclonic/anticyclonic tornado pair. Although this structure has been documented by Fujita and Wakimoto (1982) and by Brown and Knupp (1980), the DOW measurements allow for the resolution of fine-scale features that further illuminate the processes underlying this phenomenon, particularly in a case where both cyclonic and anticyclonic tornadoes co-existed.

Although anticyclonic vorticity should exist in conjunction with cyclonic vorticity (as the result of vortex tube tilting), development of the anticyclonic member is not favored due to adverse vorticity conditions. In the case of Glen Elder, although weaker than the cyclonic tornado, the anticyclonic vortex reaches tornadic strength (Figure 7). Contributing to this cyclonic/anticyclonic vortex pair is a surge of the rear flank downdraft, which is detectable in asymmetric wind field of both

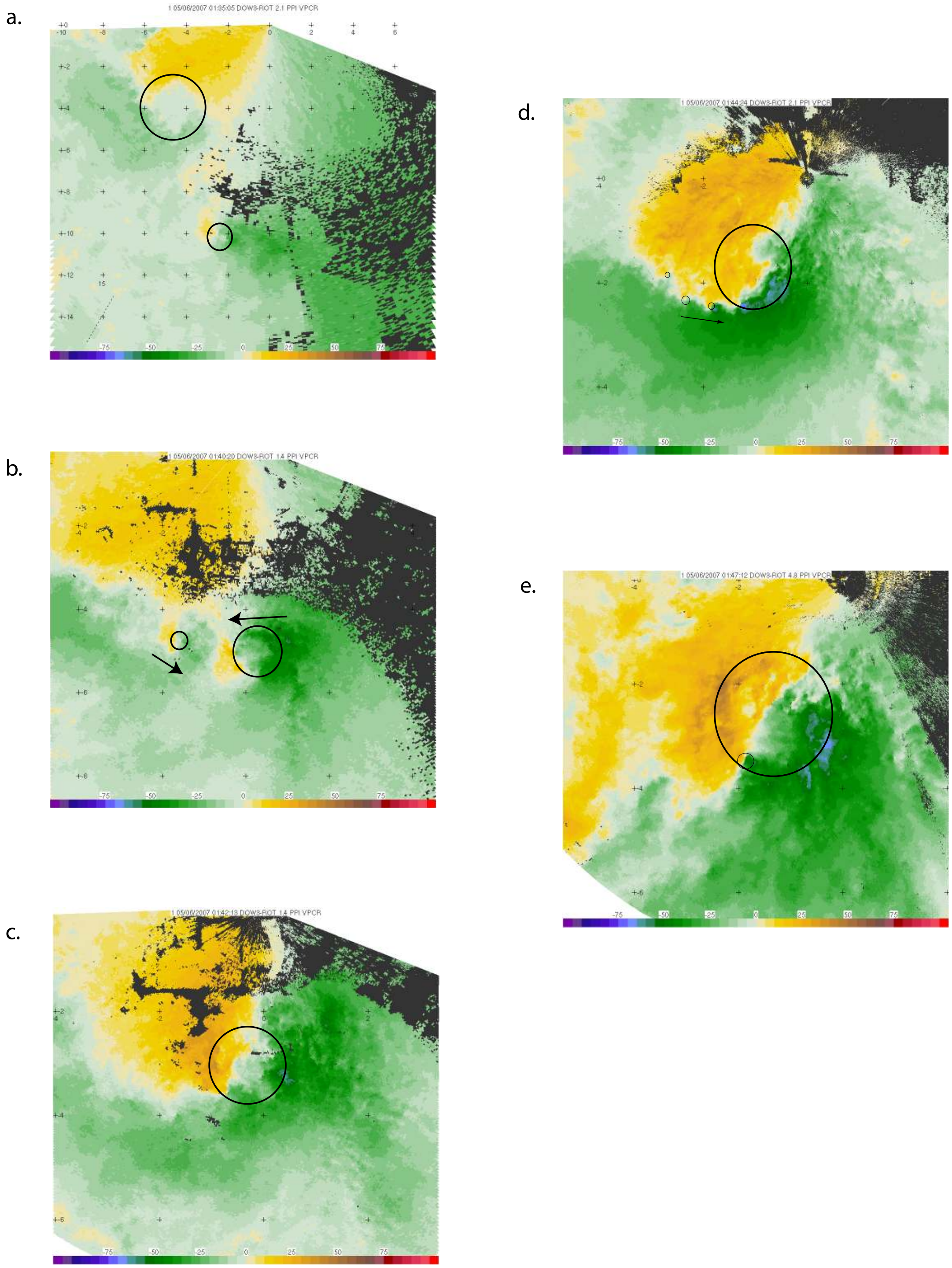


Figure 5. Evolution of the Seward, KS tornado starting from (a) the coexistence of a low-level mesocyclone and a tornado, (b) the merging of these 2 different vortical flows, (c) the resultant large multiple vortex circulation, (d) the advection of misocyclones into the southern flank of the tornado and (e) the persistence of a strong subsidiary vortex on the southern flank.

Doppler NOT corrected for DOW motion

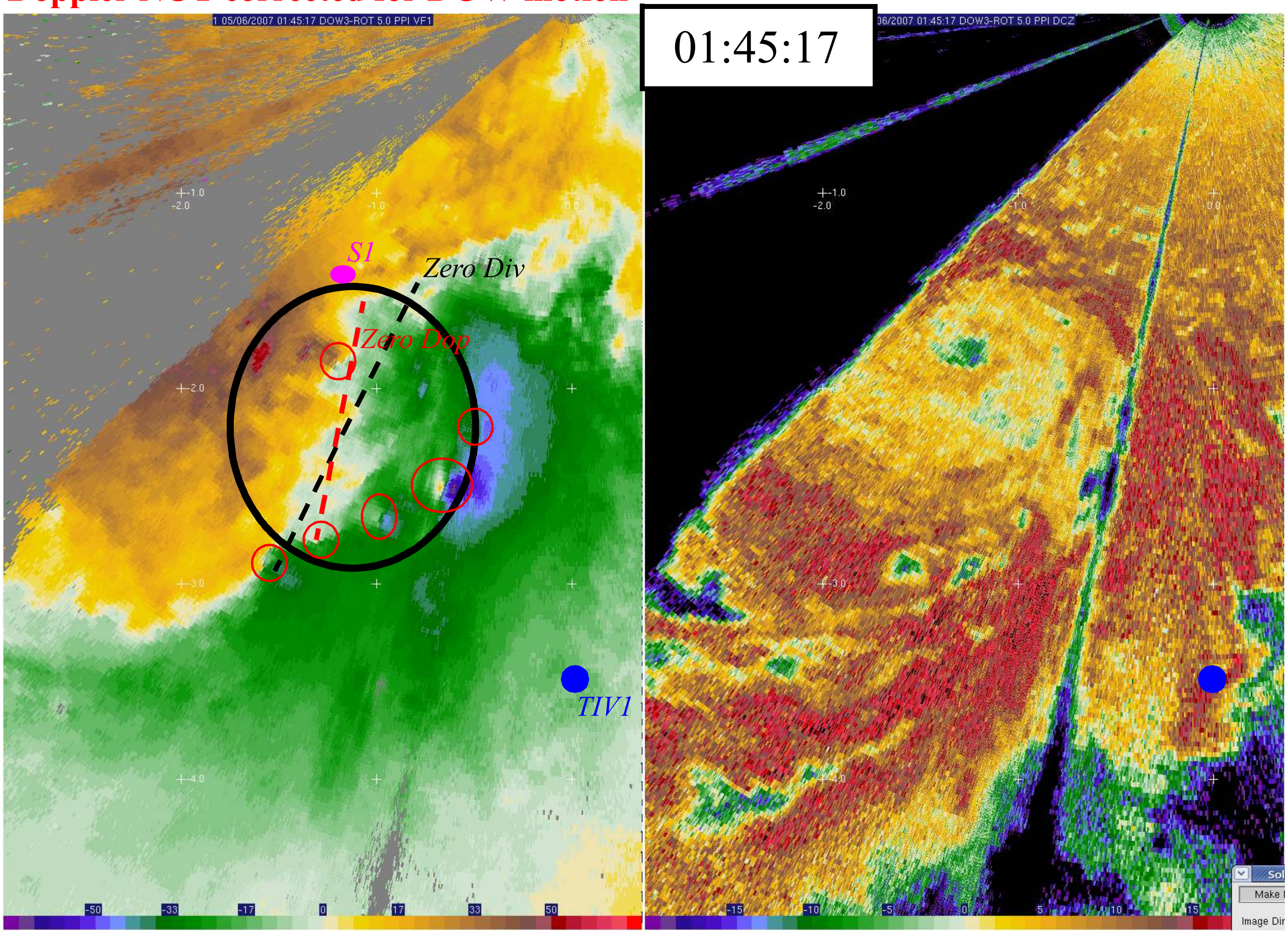
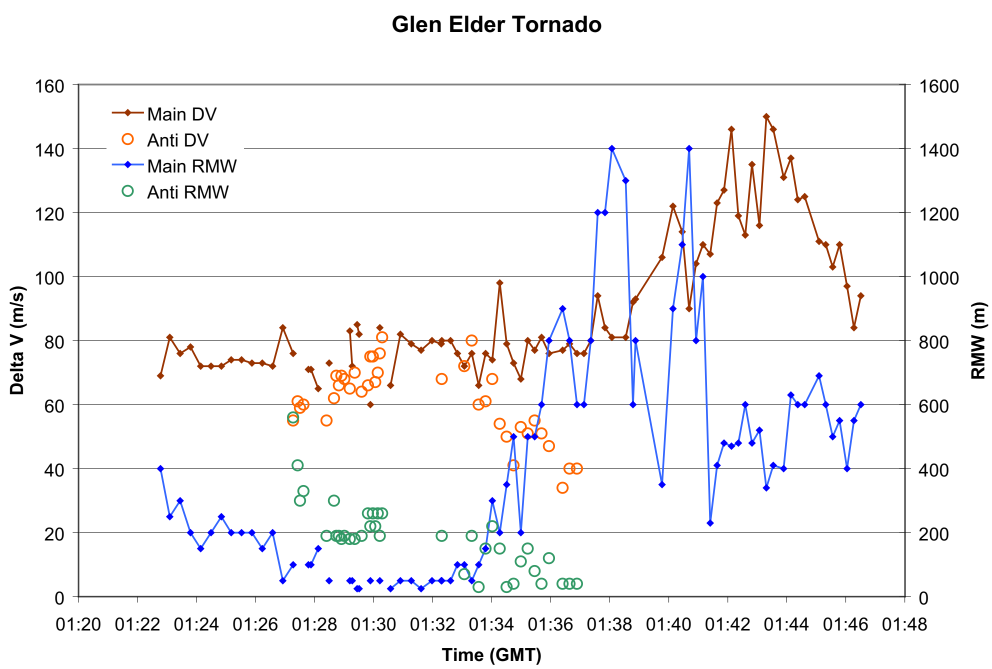


Figure 6. Several sub-tornado vortices near the radius of maximum winds in an apparently divergent parent tornado vortex. The radius of maximum winds in the parent tornado is nearly 1000 m.

Figure 7. Evolution of RMW and velocity shear across cyclonic and anticyclonic tornadoes occurring near Glen Elder, Kansas on 30 May 2008. Both vortices were of tornadic intensity simultaneously.



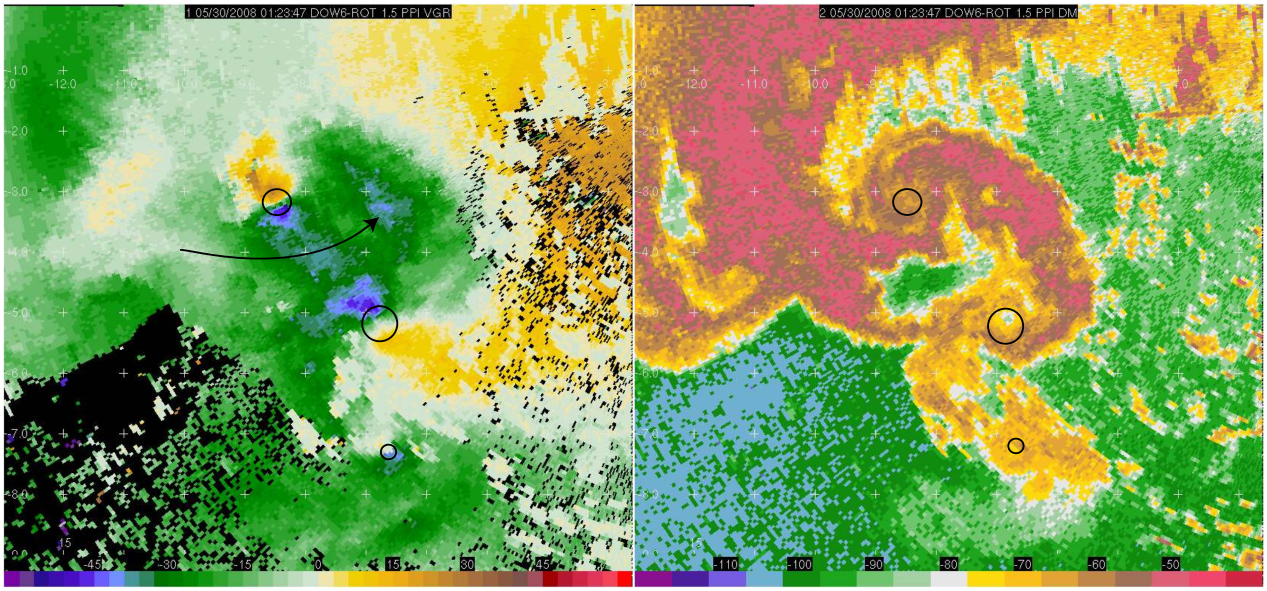


Figure 8. Simultaneous cyclonic and anticyclonic tornadoes southwest of Glen Elder, Kansas on 30 May 2008. The anticyclonic tornado rotates around the cyclonic tornado, eventually crossing to its northwest before dissipating. The cyclonic tornado changes structure and grows in scale, eventually evolving into the tornado that hits the town of Glen Elder. A third vortex, cyclonic, exists about 2 km to the south of the anticyclonic tornado. It is persistent, but not of tornadic intensity.

vortices and the arching of the reflectivity field (Figure 8). The anticyclonic member is located to the southeast of the cyclonic member and is separated by a distance of ~2 km. Also present in this complicated flow in a cyclonic vortex of tornadic strength located several kilometers to the south of the cyclonic/ anticyclonic vortex pair. The data suggest that the anticyclonic tornado revolved northward around the cyclonic tornado, then weakens and is ingested. As this occurs, the scale and intensity of the cyclonic tornado increase and the cyclonic tornado moves northward into the town of Glen Elder, causing moderate damage.

5. OTHER STORMS

The multiple vortices present in the Oklaunion, TX storm (30 April 2000) evolved from a large, rather disorganized structure (Figure 9a--22:33:33) into smaller, single-vortex tornado (Figure 9b --22:41:12). The apparent disorganization of the initial multiple vortex structure may be a result of the deformation of the main circulation in response to multiple vortex instabilities. The causal relationship between the sub-tornado scale vortices and the genesis is not clear since the eventual tornado vortex does not appear to evolve from one of these smaller vortices.

Other multiple vortex structures, such as those in Spencer, SD (30 May 1998; Wurman 2001)(not shown), and Mulhall, OK (3 May 1999; Wurman 2002, Wurman and Lee 2005)(Figure 10) and Stuttgart, AR (5 May 2008) (not shown here) typify a multiple vortex tornado structure that is maintained solely by the growth of perturbations in a barotropically unstable flow. Several vortices persist along the radius of maximum winds at any given time and do not appear to be

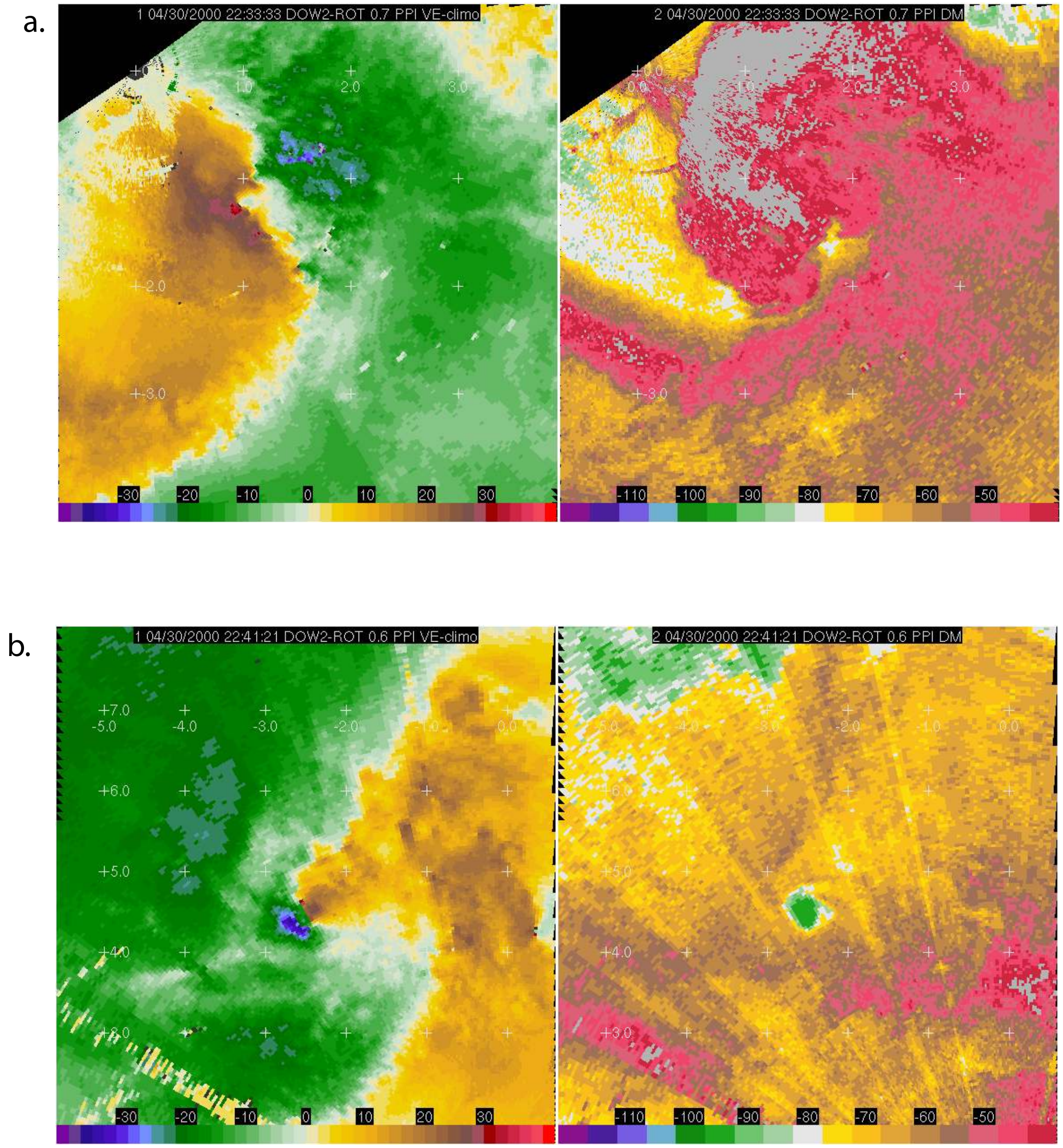


Figure 9. Genesis of a tornado near Oklaunion, Texas on 30 April 2000. A complex and apparently multiple-vortex structure rapidly evolves into a single vortex short lived tornado.

enhanced or linked to their immediate environment. Often this flow regime is transient and the tornado fluctuates between a multiple and single vortex state. Large velocities can be associated with these perturbations (Stuttgart 101 m/s, Mulhall 109 m/s, Spencer 115 m/s).

6. NON MULTIPLE-VORTEX COMPLEXITIES IN TORNADO STRUCTURE.

While this manuscript discusses multiple vortex-like perturbations to simple tornado structure, many tornadoes exhibit complexities that cannot be characterized as multiple vortices or misovortices. Well known tornadoes such as Kellerville, Kansas

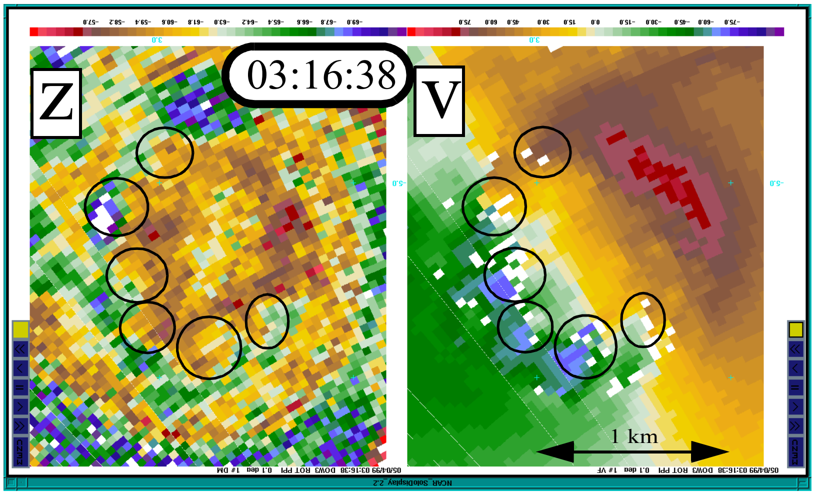
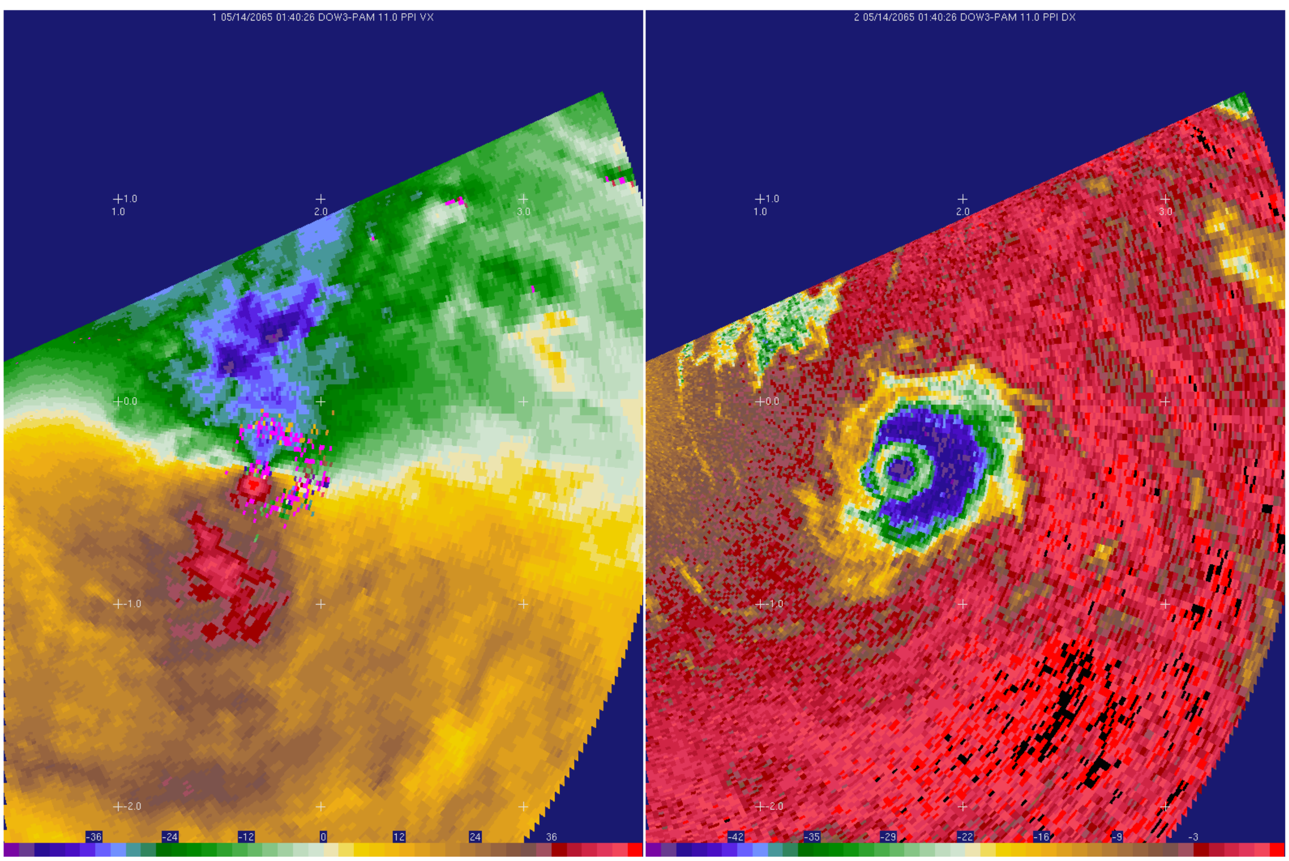


Figure 10 (left). A more 'classic' multiple vortex structure is evident in the Mulhall, Oklahoma 3 May 1999 tornado. Several persistent sub-tornado scale vortices revolve around the parent tornado, at the RMW, and apparently propagate upstream relative to the background circulation. (From Wurman 2002)

Figure 11 (below). Complex velocity structure, not apparently multiple-vortex, exhibited by a tornado near Harper, Kansas on 12 May 2004. In this case a small tornado is surrounded by a larger scale, more intense 1.5 km scale circulation.



exhibited multiple, sometimes transient inner and outer circulations. This was also true of the Rolla, Kansas 31 May 1996 tornado (both not shown here), and one of the tornadoes that occurred near Attica/Harper Kansas on 12 May 2004 (Figure 11).

7. CONCLUSIONS

As discussed above, a variety of multiple vortex structures/configurations can simultaneously exist at different scales within the same storm. While these cases were chosen to illustrate the diversity in vortical flows, these events are not presumed unique. At both the mesocyclone and the tornado scale, a surplus in angular momentum (i.e., swirl) may prevent the convergence and contraction of the vortical flow into a single vortex. Changes in the environment surrounding the vortical flow or the proximity of a subsidiary vortex to a favorable environment may cause a multiple vortex to dominate the flow or to become more intense than the other multiple vortices, as was illustrated in the Quinter, Stratford, and Seward storms. The merging of disparate vortices, such as in Seward and Glen Elder, resulted in a more intense vortex than the contributing vortices. Although the possible mechanisms for tornadogenesis and maintenance presented above await further verification through quantitative analysis, they illuminate the role that multiple vortex structures have in shaping the resultant flow.