Finescale Radar Observations of Tornado and Mesocyclone Structures

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ABSTRACT

A variety of vortex configurations observed at finescale with Doppler On Wheels (DOW) radars in and near the hook echoes of supercell thunderstorms are described. These include marginal/weak tornadoes, often with no documented condensation funnels, debris rings, or low-reflectivity eyes; multiple-vortex mesocyclones; multiple simultaneous tornadoes; satellite tornadoes; cyclonic–anticyclonic tornado pairs; multiple vortices within other multiple vortices; tornadoes with quasi-concentric multiple wind field maxima; lines of vortices outside tornadoes; and horizontal vortices. The kinematic structures of these different phenomena are documented and compared. The process of multiple vortex circulations evolving from and into tornadoes is documented. DOW observations suggest that there is no clear spatial-scale separation between multiple-vortex tornadoes and larger multiple-vortex circulations.

These different vortex configurations motivate a refined definition of what constitutes a tornado, excluding many multiple, weak, embedded, and tornado-associated vortices.

1. Introduction

> "Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity" (Richardson 1922).

Since 1995, the Doppler On Wheels (DOW) mobile radars (Wurman et al. 1997; Wurman 2001) have observed thousands of small-scale vortices in supercell thunderstorms, including more than 170 vortices categorized as distinct tornadoes (e.g., Wurman et al. 1996a; Wurman and Gill 2000; Burgess et al. 2002; Alexander and Wurman 2005, 2008; Beck et al. 2006; Dowell et al. 2005; Kosiba et al. 2008; Kosiba and Wurman 2010; Wurman et al. 2010, 2013; Markowski et al. 2011; Kosiba et al. 2013; Toth et al. 2013; Dowell et al 2002; Wurman and Alexander 2005; Wurman et al. 2007a; and Wurman and Kosiba 2008). Others also have documented several tornadoes and vortices using finescale radars (e.g., Bluestein and Pazmany 2000; Bluestein et al. 1997, 2003a,b, 2004, 2007b; Tanamachi et al. 2007). In addition to tornado observations, the DOWs have collected data in many nontornadic vortices associated with supercell thunderstorms, resulting in a large database of diverse vortex structures. DOW-observed vortices, including tornadoes, exhibited near-ground wind velocity differences (DV)[1] ranging from ~10 to 250 m s^{-1}, across diameters (DX)[2] ranging from ~20 to over 2000 m. Many of the tornadoes and other vortices did not match simple tornado vortex flow models (e.g., Davies-Jones 1986; Wurman et al. 2013), while others occurred in large circulations that may have been tornadoes or other submesocyclone-scale structures (Agee et al. 1976, hereafter A76; Agee and Jones 2009, hereafter AJ09; Rasmussen and Straka 2007; Potts and Agee 2002, hereafter PA02). This motivates the documentation and classification of the spectrum of vortical structures smaller than, or within, mesocyclones,[3] influenced by finescale radar observations of their kinematic structure.

2. Different types of vortices in supercell thunderstorms

The *Glossary of Meteorology*'s definition of tornado as "a violently rotating column of air, pendant from

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[1] Defined as the difference between the peak outbound and inbound Doppler velocities.

[2] Defined as the distance between the peak outbound and inbound Doppler velocities.

[3] Distinctions are sometimes made among mesocyclones, tornado cyclones, and minitornado cyclones (e.g., A76; PA02; Wurman and Alexander 2004; AJ09; Kosiba and Wurman 2008). Here, the term "mesocyclone" describes near-surface circulations with DX > 1 km not normally considered tornadoes.

a cumuliform cloud or underneath a cumuliform cloud, and often (but not always) visible as a funnel cloud'' (Glickman 2000) does not provide quantitative guidance concerning spatial scale and intensity (beyond the vague term ''violent''), would include both tornadoes and their component internal multiple vortices simultaneously (since both fit the definition), and does not even require that the rotation occur near the ground.[4]

Based on radar data, visual data, and damage swaths, A76 identified six scales of vortex systems, ranging in size from mesocyclone scale down to suction vortices. PA02 updated this classification, proposing a three-tier multiple-vortex classification scheme. Wurman and Alexander (2004) presented DOW observations of several strong larger scale (DX = 800 m–2 km) circulations, questioning whether these large vortices should be categorized as tornadoes. Kosiba and Wurman (2008, hereafter KW) presented an overview of some multiple vortex structures observed by DOWs, some corresponding to those discussed in PA02. AJ09 proposed that tornadic events could be divided into ''type 1'' (associated with supercell mesocyclones), ''type 2'' (associated with quasi-linear convective systems, tropical cyclone spiral bands, etc.), and ''type 3'' (landspouts, waterspouts, gustnadoes, hurricane eyewalls, and anticyclonic vortices near stronger cyclonic vortices). This taxonomy was criticized as not being sufficiently dynamically based [see comment and reply to AJ09 by Markowski and Dotzek (2010) and Agee and Jones (2010), respectively].

In this study, vortices observed by DOWs associated with supercell thunderstorms[5] were divided into several categories based on their radar-observed kinematic structure and their location relative to other vortices and storm structures. They are categorized as follows:

- tornadoes, mesocyclones, and multiple vortices in tornadoes, discussed extensively elsewhere in the published literature;
- marginal tornadoes (MTs);
- multiple tornadoes, under different broad surface circulations/mesocyclones/updrafts;
- multiple vortices within broad mesocyclones/surface circulations including satellite tornadoes (MVMCs);
- higher-order multiple vortices;
- tornadoes and other vortices with multiple, quasi-concentric, wind speed maxima;
- strings of and individual vortices in hook echoes;
- cyclonic–anticyclonic tornado pairs; and
- horizontal vortices (HV).

This categorization, as with those of A76 and PA02, is based on morphology, not deduced dynamics, although the underlying dynamics, of course, influence the vortex structure. An in-depth dynamical description of the variety of vortices observed in supercells is beyond the scope of this study, though some inferences can be made concerning the kinematic and underlying dynamics with even limited single-Doppler DOW data. Representative examples of some of these vortex types are presented below. These are snapshots or short periods during events that are evolving in complex fashions and are not intended to be detailed or complete case studies of the structure or evolution of these events.

a. Marginal tornadoes

Based on the analysis of ~50 DOW-observed vortices, Alexander and Wurman (2008, hereafter AW; C. Alexander and J. Wurman 2013, unpublished manuscript) developed criteria to objectively (and in a semiautomated fashion) distinguish tornadoes observed with proximate radars, such as DOWs, from other vortices. These criteria require, in part, that tornadoes exhibit DV $\geq$ 40 m s^{-1} and DX =< 2000 m. AW found that the median peak lifetime intensity of tornadoes was near DV = 70 m s^{-1}, far from the DV cutoff criterion, suggesting that tornadoes are a phenomena distinct from weaker vortices. This definition also agreed closely with more subjective determinations of what constituted tornadoes, based on radar and visual presentation, and observed damage. For a weak tornado, just meeting the DV $\geq$ 40 m s^{-1} criterion, moving at a typical speed[6] V_p of 13.5 m s^{-1}, peak winds on the right side of the vortex (relative to the direction of motion) would be DV/2 + V_p or 33.5 m s^{-1}. This is close to the ''severe'' thunderstorm wind speed criterion, 26 m s^{-1}, of the National Weather Service (http://www.crh.noaa.gov/bou/awebphp/svrguide.php), the lower wind speed bound for category 0 on the enhanced Fujita scale (EF0), 29 m s^{-1} (Edwards et al. 2013), and the threshold for hurricane force wind speeds, 33 m s^{-1} (http://www.nhc.noaa.gov/pdf/sshws_2012rev.pdf). AW found that there was a paucity

[4] The definition of tornado from the online and evolving version of the *Glossary of Meteorology* has the additional phrase ''in contact with the surface.'' This phrase is vague since it is not specified what it means to be ''in contact.'' Do the ''violent'' winds have to be present ''at the surface,'' at 0 m AGL, 0.001 m AGL, 10 m AGL, or just above the roof of a building or forest canopy?

[5] Observations of vortices associated with nonsupercellular cumiliform clouds (e.g., Golden 1971; Wakimoto and Martner 1992; Steiger et al. 2013; Wurman and Winslow 1998) are beyond the scope of this study.

[6] AW found median V_p = 13.5 m s^{-1}, with 25th and 75th percentile values of 9 and 18 m s^{-1}, respectively (among springtime supercell-associated tornadoes observed over the U.S. plains region). Extreme V_p values ranged from near 0 to over 25 m s^{-1}.

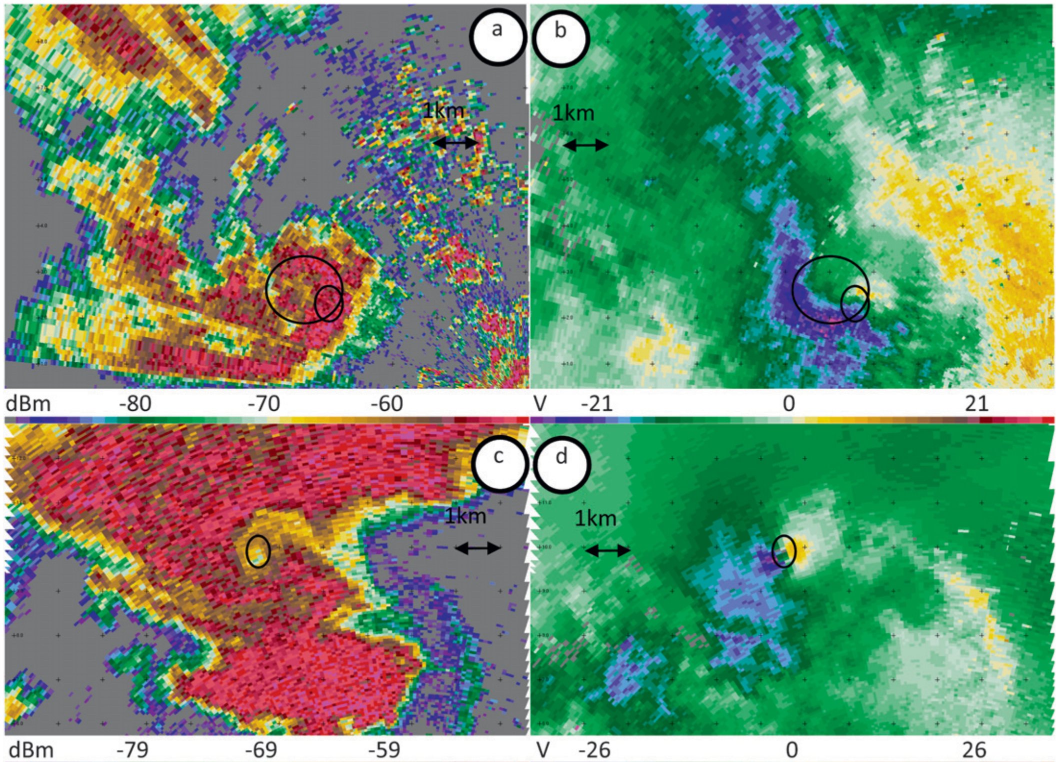

FIG. 1. MTs observed during VORTEX2: (a),(b) received power (dBm) (left) and Doppler velocity (m s^{-1}) (right) fields observed in an MT near Amity, MO, on 7 Jun 2009 (all times are in UTC) embedded in a ~1.5-km-scale circulation, both indicated with black ovals. An indistinct LRE is associated with the larger circulation. (c),(d) Same fields in an MT near Mullinville, KS, on 9 Jun 2009. An LRE is associated with the MT, indicated with a black oval. Both MTs were rated EF0 by the National Weather Service and minor damage was documented by researchers in Amity. Tick marks are at 1-km intervals, and 1-km scale is indicated. North is up.

of vortices with 30 m s^{-1} < DV < 50 m s^{-1}, and/or 50 m < DX < 150 m, suggesting that there was not a continuum from frequently occurring small/weak vortices to rare large/intense vortices. Analysis of the dynamical differences between intense (i.e., tornadic) and weak vortices is beyond the scope of this paper.

While AW has shown that tornadolike vortices with DV ~ 40 m s^{-1} are uncommon, several MTs, with DVs near 40 m s^{-1}, have been documented by DOWs. MTs may or may not exhibit visible condensation funnels,[7] and may or may not have pronounced radar reflectivity features commonly documented with tornadoes [e.g., a low-reflectivity eye (LRE), debris ring echo (DRE), or debris ball (DB); e.g., Burgess et al. (2002). Some recent examples of MTs were observed on 7 and 9 June 2009 near Amity, Missouri, and Mullinville, Kansas, respectively, by the DOWs during the Second Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX2; Wurman et al. 2012). DOW data revealed MTs that persisted for several minutes and exhibited DVs up to about 35 m s^{-1} in Amity and 45 m s^{-1} near Mullinville, over DX = 200–600 m (Fig. 1). Additionally, both MTs had relatively indistinct LREs and no DREs or DBs were observed. Proximate DOW teams did not document condensation funnels, but a VORTEX2 team in Amity observed damage to trees, and both MTs are listed officially as EF0 tornadoes (http://www.ncdc.noaa.gov/IPS/sd/sd.html). Other examples of MTs, during which condensation funnels were not reported and minor or no damage was noted, include MTs documented by Dowell et al. (2002), Wurman et al. (2007b,c; second tornado), Chan et al. (2011), Wakimoto et al. (2011, 2012), Atkins et al. (2012), and Kosiba et al. (2013; 2152–2200 UTC). Some of these studies analyzed

[7] Visual observation of the presence of a condensation funnel depends not only on vortex intensity, but humidity, vortex diameter, and structure, including the rate of decay of wind intensity at increasing distance from the vortex center [$V = f(R)$], affecting the magnitude of the pressure deficit at the center of the vortex (see Lee and Wurman 2005), proportional to $\int (V^2/R)\, dR$, viewing location, elevation angle, lighting, back lighting, and the opacity and reflectance of the intervening atmosphere and precipitation and, thus, is a poor, but unfortunately commonly employed, discriminator of what constitutes a tornado.

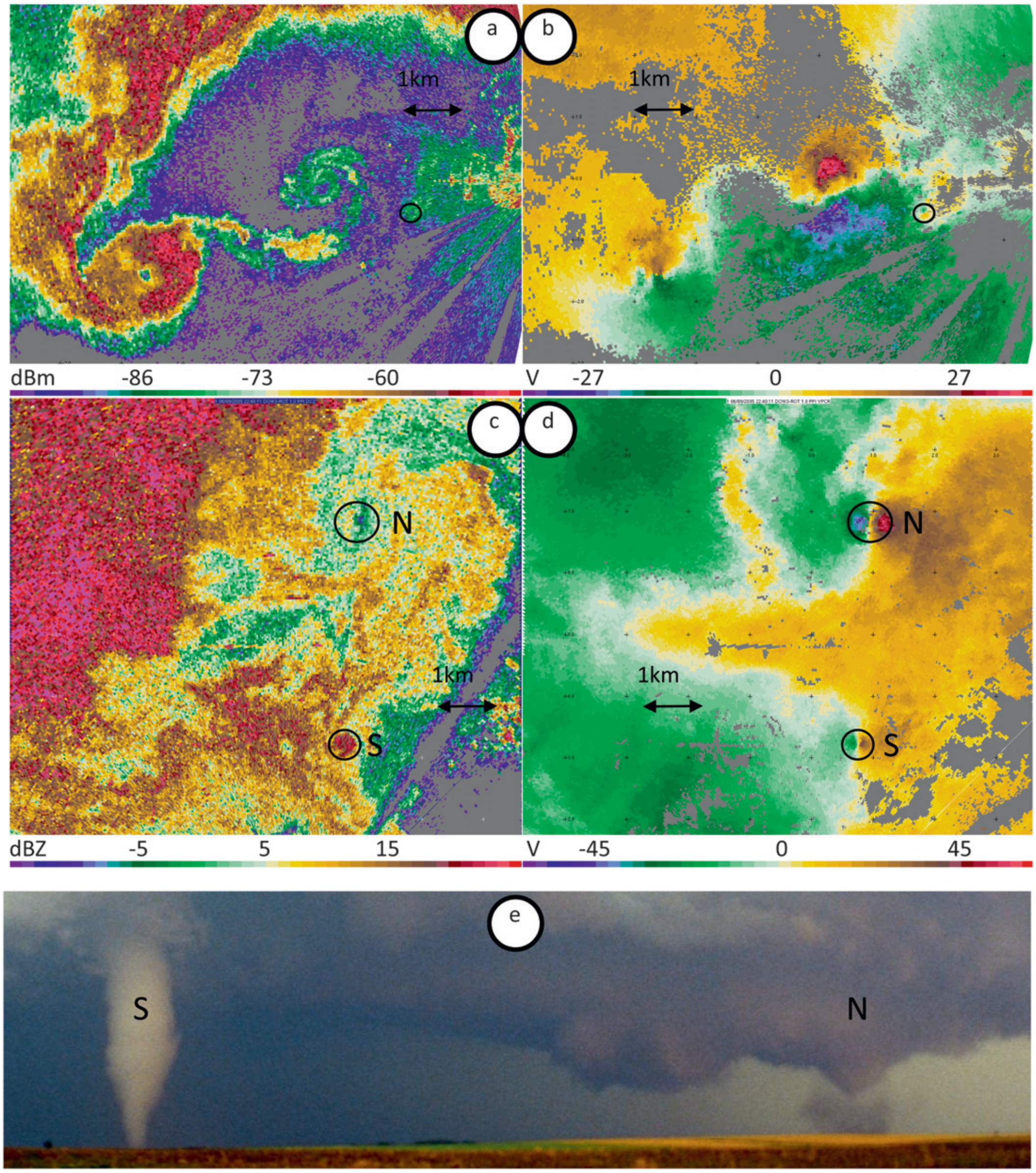

FIG. 2. Multiple simultaneous tornadoes. Fields are as in Fig. 1 except as noted. (a),(b) Multiple simultaneously occurring tornadoes during a cyclic tornadogenesis event near Protection, KS, on 24 Apr 2007. A weaker and anticyclonic third vortex (black oval) is visible and has a weak LRE. (c) Uncalibrated reflectivity and (d) Doppler velocity in simultaneously occurring tornadoes associated with different mesocyclones near Hill City, KS, on 9 Jun 2005. (e) The larger stronger tornado (N) had a LRE and was visually manifested by dust. The smaller weaker tornado (S) exhibited a DB and a prominent condensation funnel extending to the ground. [Photo courtesy of S. Blair.]

tornadoes that were observed to form from, and/or decay into, weaker-than-tornadic-intensity vortices with DV < $40\,\mathrm{m\,s^{-1}}$. During portions of these transitions, these vortices could be characterized as MTs. Since intensity, either described as "violence" or DV > $40\,\mathrm{m\,s^{-1}}$, is a defining characteristic of tornadoes, only vortices that exhibit DV reasonably near $40\,\mathrm{m\,s^{-1}}$, or close to "violent" characteristics (i.e., causing damage), would be well described as MTs, thus excluding the plethora of weak vortices often associated with supercell thunderstorms.

b. Multiple tornadoes under different broad circulations/mesocyclones

The process of cyclic tornadogenesis frequently is observed to occur with the formation of a new or extended hook echo and a new distinct near-surface

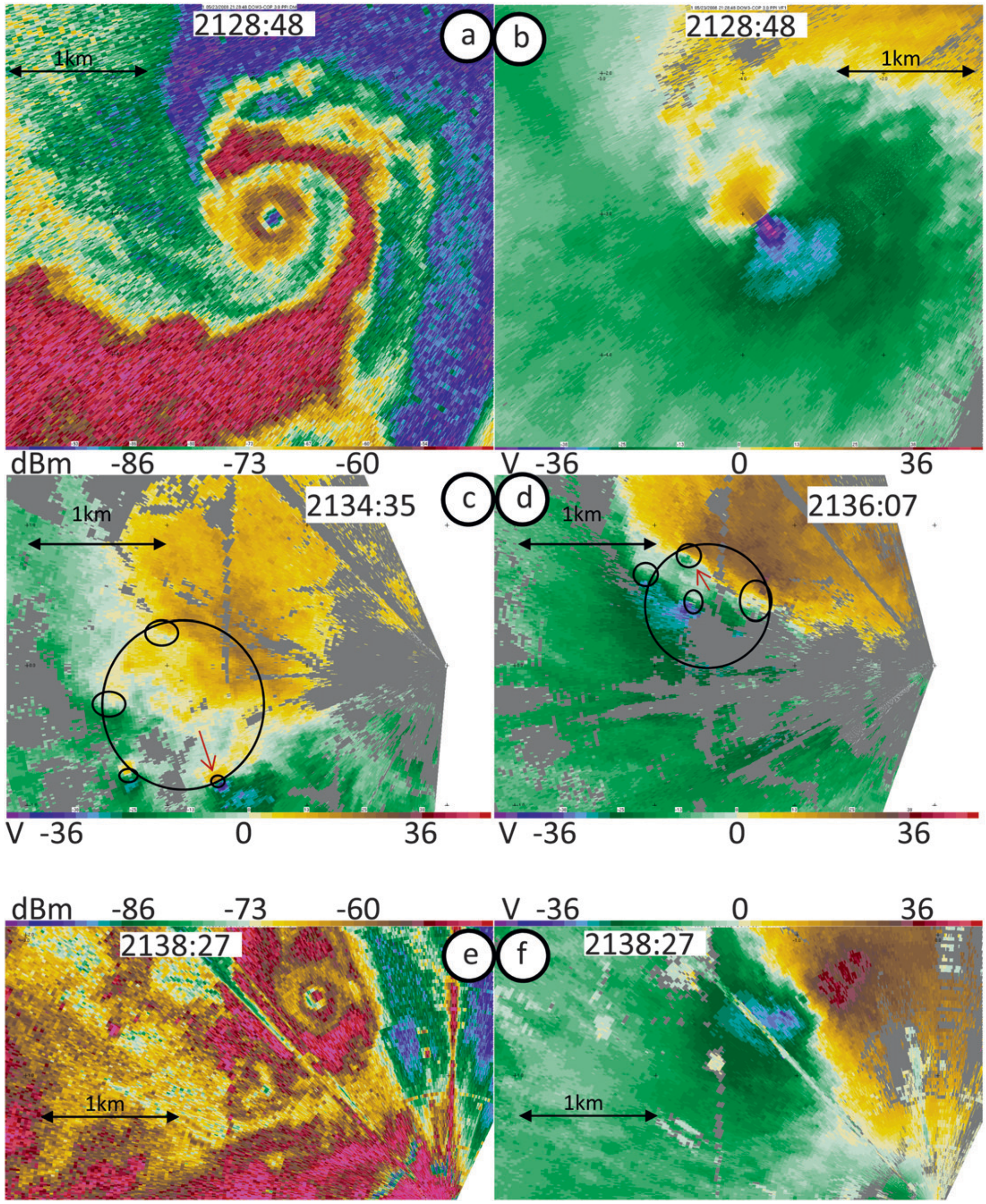

FIG. 3. Evolution of an MVMC from tornado to MVMC to new tornado. Fields are as in Fig. 1, but the left panel (c) shows Doppler velocity. Times are HHMM:SS UTC. (a),(b) Weakening tornado with DR and LRE approaching Quinter, KS, on 23 May 2008. (c),(d) Additional vortices (small ovals) develop as vortex remnant of the tornado (red arrow) weakens as it revolves around the larger circulation (large ovals). (e),(f) The circulation contracts, the vortices dissipate, and a new singlet tornado with a DB evolves.

circulation, or as the old tornado moves away from the inflow region and is replaced by a new tornado, as they both revolve about a near-surface circulation (e.g., Dowell and Bluestein 2002a,b). The old and new tornadoes may coexist for prolonged periods. A complicated cyclic evolution was observed on 24 April 2007 near Protection, Kansas, when two tornadoes persisted for an extended period, each tornado fluctuating in intensity and size (Figs. 2a and 2b). After the time shown in Figs. 2a and 2b, the western tornado intensified, exhibiting a well-developed funnel extending to the ground and a pronounced dust cloud. Although researchers within

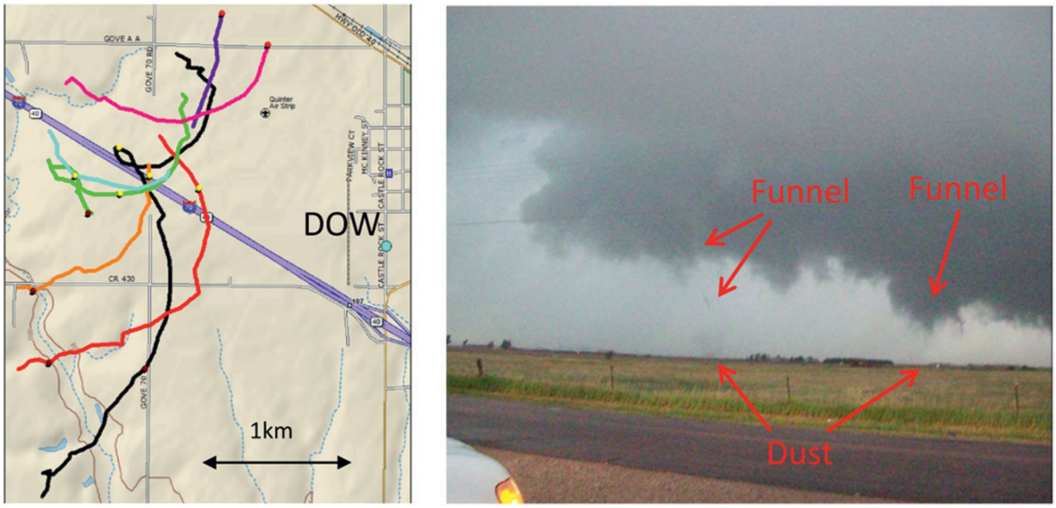

FIG. 4. (left) Tracks of first (black) and second (purple) tornadoes, and additional vortices associated with the MVMC period near Quinter, KS, on 23 May 2008. Brown, yellow, and red dots show locations of vortices at 2134:35 UTC (time in Fig. 3c and 11s before photograph to right), 2136:07 UTC (time in Fig. 3d), and 2138:08 UTC (after new tornado is well formed), respectively. Blue dot is DOW. (right) Photograph pointing west-southwest from DOW location at 2135:24 UTC showing two funnels and associated raised dust. [Photo courtesy of R. Humphrey, Center for Severe Weather Research (CSWR).]

1 km of the eastern tornado did not observe a funnel, a funnel was visible from the DOW at a range of 3.7 km to the northeast. At the time of this image, radar indicated a third, much weaker and anticyclonic, vortex with an LRE to the southeast. At other times, weak cyclonic vortices, at least one associated with a small funnel, were observed by radar and visually.

Simultaneous tornadoes also occurred near Hill City, Kansas, on 9 June 2005 (Figs. 2c and 2d). The two tornadoes manifested differing visual and radar morphologies, likely due to local environmental differences. The larger and more intense (DX = 400 m, DV = 104 m s^{-1}) northern tornado was manifested visually by a funnel part way to the ground and substantial rotating dust, while the southern smaller and weaker (DX = 200 m, DV = 78 m s^{-1}) tornado had a visible funnel to the ground (Fig. 2e).

c. *Multiple vortices within broad surface circulations/mesocyclones*

Multiple-vortex configurations in intense atmospheric vortices are attributed to an inertial instability in the core flow, with higher wavenumbers occurring as the radial shear of the tangential velocities increases (Snow 1978; Emanuel 1984). PA02 and A76 document broad near-surface circulations containing multiple vortices, some of which appear visually to be tornadoes. A circulation near Quinter, Kansas, on 23 May 2008 underwent evolution from a strong singlet tornado, to an MVMC with several tornado-intensity and sub-tornado-intensity vortices, then back to a singlet tornado over a period of about 600 s. After 2128:48 UTC (Figs. 3a and 3b) a weakening singlet tornado, DV = 80 m s^{-1}, DX = 100 m, evolved into an MVMC (DX = 1.2–2 km) (Fig. 3c). The MVMC contained four individual vortices revolving about the center of circulation, one of which was the remnant tornado, with DXs = 60–160 m, and typical DVs = 37–66 m s^{-1}, with the more intense vortices on the right and forward side of the circulation relative to its direction of motion. These vortices were associated with reflectivity swirls, but no LREs, and condensation funnels were observed. While the circulation at 2128 UTC would likely meet any reasonable tornado definition, what is the best description of the complex circulation at 2133–2136 UTC? The revolving vortices and their associated reflectivity swirls and funnels could be tracked (Fig. 4). Some of the small individual vortex components of the MVMC exhibited ground-relative wind speeds V_g exceeding 50 m s^{-1} (but usually 40 ±5 m s^{-1}), particularly when revolving through the southern sector of the larger-scale circulation, with DVs as high as 66 m s^{-1}. Their transient and plural nature, however, makes categorizing them as several simultaneously occurring distinct tornadoes problematic. Visual reports include a ‘‘large wedge tornado,’’ a simultaneous ‘‘second tornado,’’ and minor damage beginning at 2135 UTC (http://www.ncdc.noaa.gov/IPS/sd/sd.html). A photograph taken by a DOW crewmember at 2135 UTC shows possible funnels and surface dust whirls (Fig. 4b), but no unambiguous evidence of a tornado. By

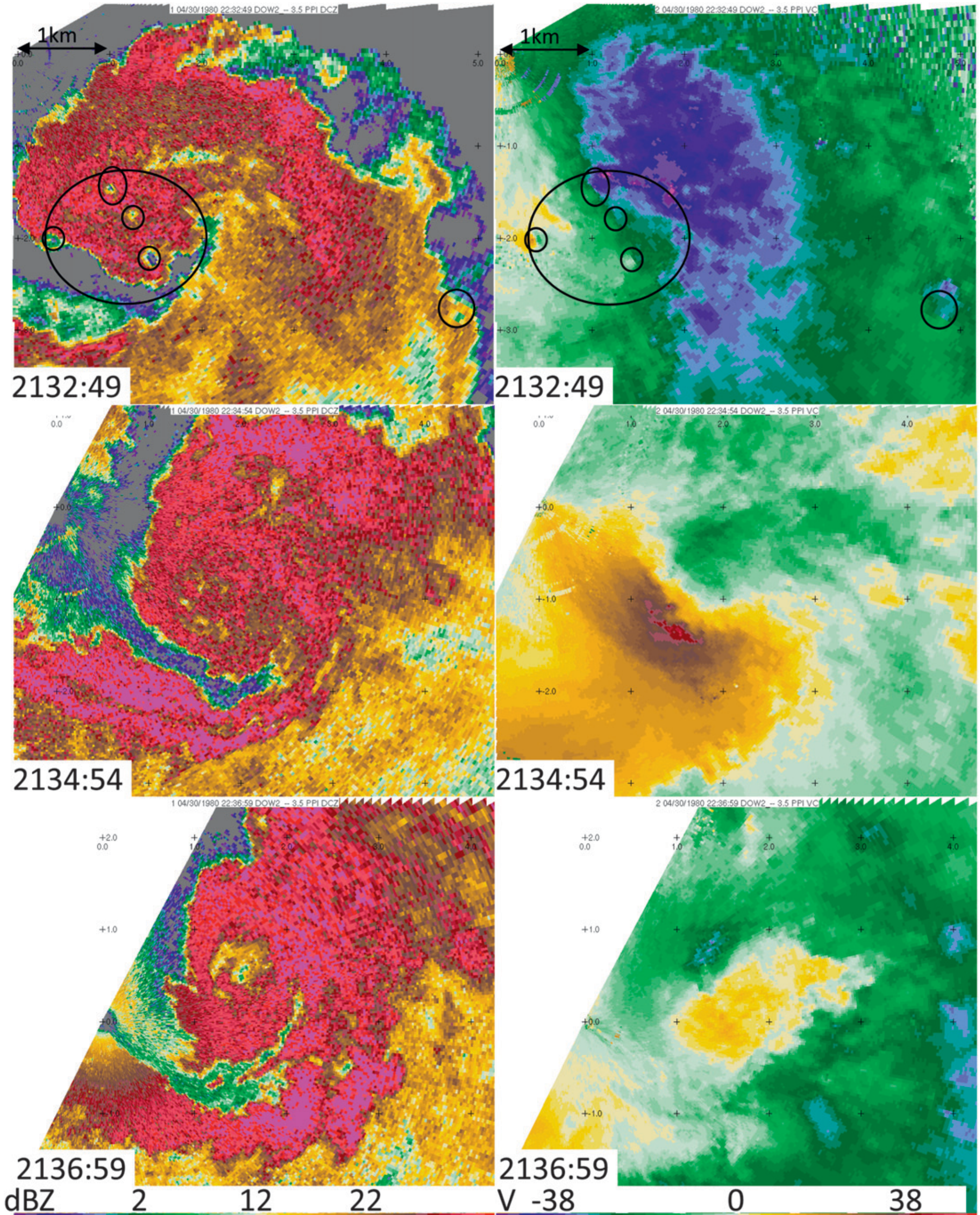

FIG. 5. MVMC structure evolving into a singlet tornado. Panel layout is as in Fig. 1, but left panels show uncalibrated reflectivity. Times are in hours (HH), minutes (MM), and seconds (SS) in the form HHMM:SS UTC. Velocity uncorrected for DOW motion. MVMC during tornadogenesis near Oklaunion, TX, on 30 Apr 2000. Vortices, with individual LREs at the edge of the hook and interior to the tip of the hook in the MVMC, revolve as the circulation contracts into a singlet tornado with a single LRE.

2136:06 UTC the circulation contracted to DX ~ 1 km (Fig. 3d), and still exhibited at least four smaller circulations. By 2138:27 UTC the circulation had contracted into a singlet tornado, with a distinct LRE (Figs. 3e and 3f), DV = 82 m s^{-1}, DX = 400 m, and condensation funnel. The tornado exhibited multiple wind speed maxima with DX = 50–600 m (see section 2d). A similar evolution was observed on 5 June 2009 (Kosiba et al. 2013), when an MT observed during VORTEX2 weakened briefly and exhibited multiple

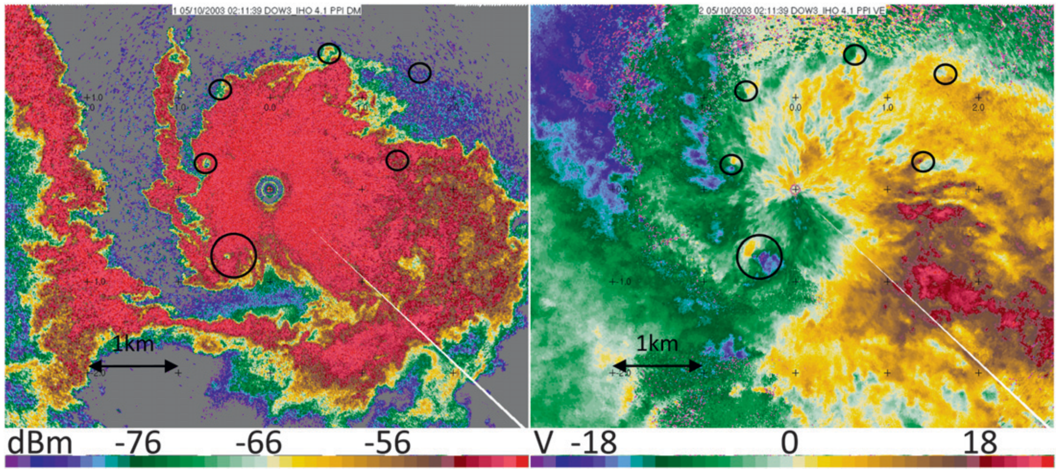

FIG. 6. MVMC with weak vortices along edge of hook echo. DOW observations from inside an MVMC with weak vortices during a several-minute period between singlet tornadoes near Binger and Cogar, OK, on 10 May 2003. Panel layout is as in Fig. 1.

circulation centers, then quickly reintensified into a stronger long-lived tornado.

Another circulation evolving from an MVMC into a singlet tornado was observed near Oklaunion, Texas, on 30 April 2000, in a supercell that had previously produced tornadoes (Marquis et al. 2008). Several weak vortices, with DV = 12–41 $m s^{-1}$, some with LREs and miniature hooks, revolved about the larger-scale circulation at 2232 UTC (Fig. 5) as the large circulation contracted into a singlet tornado during 2235–2241 UTC (after the times shown in the figure), with maximum DV = 86 $m s^{-1}$.

The widened/coiled tip of a hook echo and MVMC passed over a DOW west of Cogar, Oklahoma, on 10 May 2003.[8] While not a preferred deployment location due to the potential risk of tornadic intensity winds, it afforded the opportunity to map small multiple vortices along the edge of the hook echo (Figs. 6a and 6b). As vortices passed 260–900 m from the DOW, extremely finescale observations were possible (at 260-m range, DOW beamwidth = 4 m, oversampled every 1.3 m azimuthally, with gate length = 12.5 m, resulting in overlapping 21 m^3 samples,[9] every 12 s, probably the finest-ever scale measurements in such a phenomenon). Vortices, with DX = 45–100 m and DV = 27–36 $m s^{-1}$ (both cyclonic and anticyclonic) and with peak V_g near 30 $m s^{-1}$, revolved around a larger circulation at ~19 $m s^{-1}$. One vortex exhibited multiple quasi-concentric wind speed maxima (see section 2d), and several vortices were associated with LREs or reflectivity swirls. No condensation funnel was observed by DOW teams with the MVMC or with any individual vortex, as the data were collected well after sunset. Whether any of the individual vortices or the entire MVMC should be characterized as MT-type tornado(es) is unclear. The weakness of the individual vortices and the broadness of the MVMC would likely make it fail this manuscript's proposed definition (below). This MVMC structure evolved from an earlier singlet MT observed by the DOW from 0202 to 0208 UTC that was rated EF1 by the National Weather Service (http://www.srh.noaa.gov/oun/?n=events-20030509-caddo-canadian), and into another singlet tornado after about 0218 UTC. Since the vortices were concentrated on the edge of the hook echo, and because the larger circulation was difficult to resolve with observations from within, it is less clear if these were multiple vortices within the larger circulation or shear-induced vortices such as those described in section 2e.

While the Mulhall (1999) tornado (Wurman 2002; Lee and Wurman 2005), with peak DV > 200 $m s^{-1}$, DX = 1600 m, cross-track width of potentially damaging $V_g > 30 m s^{-1}$ greater than 4.5 km, and a documented "wedge" type condensation funnel, is considered an extremely large multiple-vortex tornado, some very intense, often multiple-vortex, 1–2-km-scale circulations are difficult to categorize (Wurman and Alexander 2004). A DX = 1–2-km circulation near Seward, Kansas, on 6 May 1997 exhibited peak V_g = 96 $m s^{-1}$ and DV = 126 $m s^{-1}$ (Fig. 7). It contained several persistent and intense internal vortices on the right side of the circulation (relative to the circulation's direction of motion), with DVs

[8] All dates are based on UTC time, even when before midnight local time.

[9] Nonoversampled resolution volumes: 221 m^3.

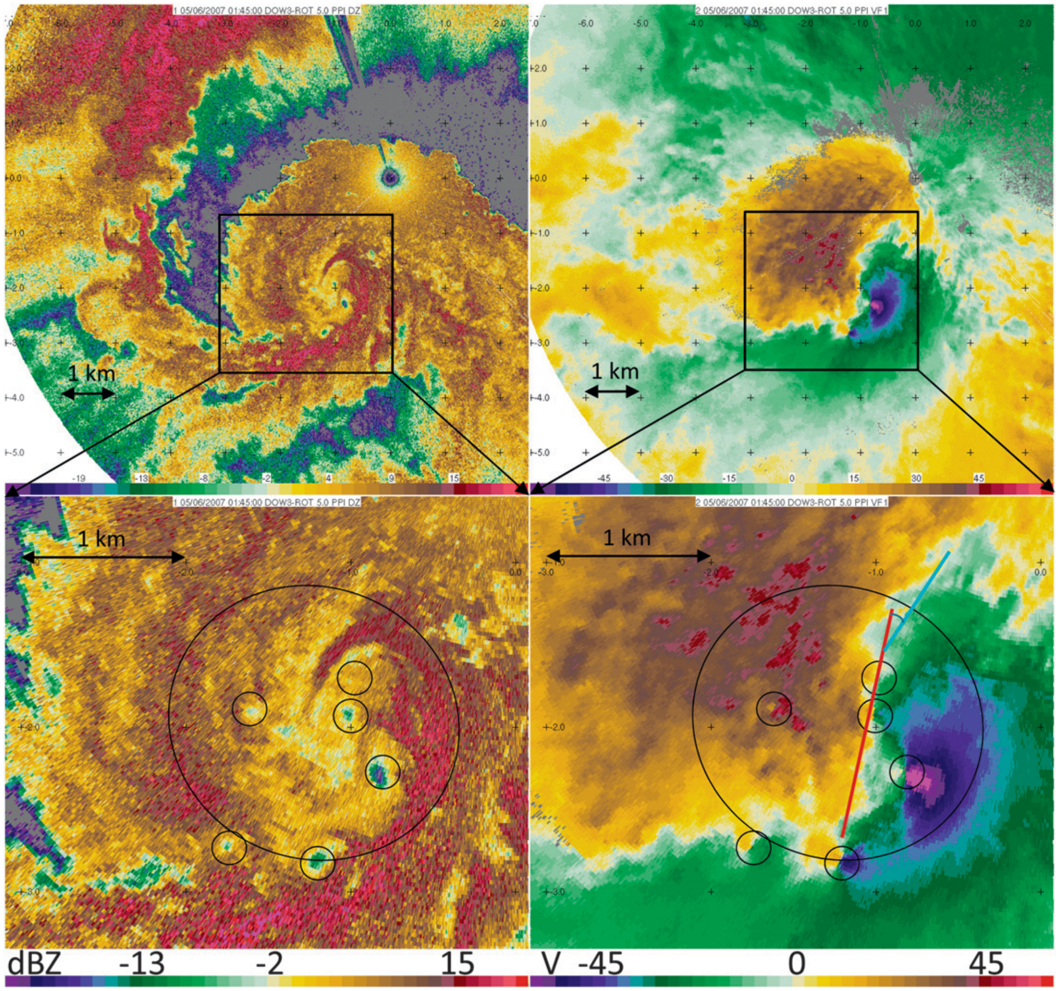

FIG. 7. Intense MVMC or tornado with intense persistent vortices. Panel layout is as in Fig. 1, but left panels show uncalibrated reflectivity. MVMC observed near Seward, KS, on 6 Jun 2007 in a high-precipitation-type supercell. (top) The hook echo region, and (bottom) zoomed-in on the MVMC. Vortices (small ovals) with V_g up to 96 m s^{-1} and pronounced LREs revolve around ~1.5-km-wide MVMC (large oval). MVMC exhibits broad weak LRE. Angle between radar observation direction (blue) and zero-isodop line (red) through core of MVMC suggests divergence. This event, which occurred after dark in rural terrain, was rated by the NWS as a 250-yard-wide EF1 tornado.

up to 110 m s^{-1} over DXs as small as 30–40 m (estimated vertical vorticity of up to 7 s^{-1}), but some with DX = 100–400 m, similar in character to those observed in the Mulhall tornado. The vortices were associated with LREs, but no DRE/DBs. No funnels were observed by proximate, even in situ, research teams, but it was after sunset and raining heavily. Vortices closer to the center of the larger-scale circulation were more intense, while more distant vortices had DVs < 40 m s^{-1}. The National Weather Service listed this event as a single 250-yard-(230 m) wide EF1 tornado (http://www.ncdc.noaa.gov/IPS/sd/sd.html). Whether this event is an MVMC and, if so, whether the individual very intense vortices containing very strong winds should be considered multiple tornadoes, or whether the larger circulation is a very large MV tornado, is an open question. Complicating the issue further and recalling the opening quotation, one of the multiple vortices itself contained subvortices (see section 2f).

Other MVMC morphologies have been observed. During the 3 May 1999 tornado outbreak in Oklahoma, a "satellite tornado" (A76) was associated with a distinct funnel cloud reaching the ground (http://www.srh.noaa.gov/images/oun/wxevents/19990503/maps/bigoutbreak.gif). The DOW observed a vortex with DV = 45 m s^{-1} a distance of 0.9 km to the east of a larger tornado (believed to be tornado A6 from http://www.nws.noaa.gov/om/assessments/ok-ks/report7.pdf) (Fig. 8). An intense circulation impacted a DOW on 29 May 2004 near Geary,

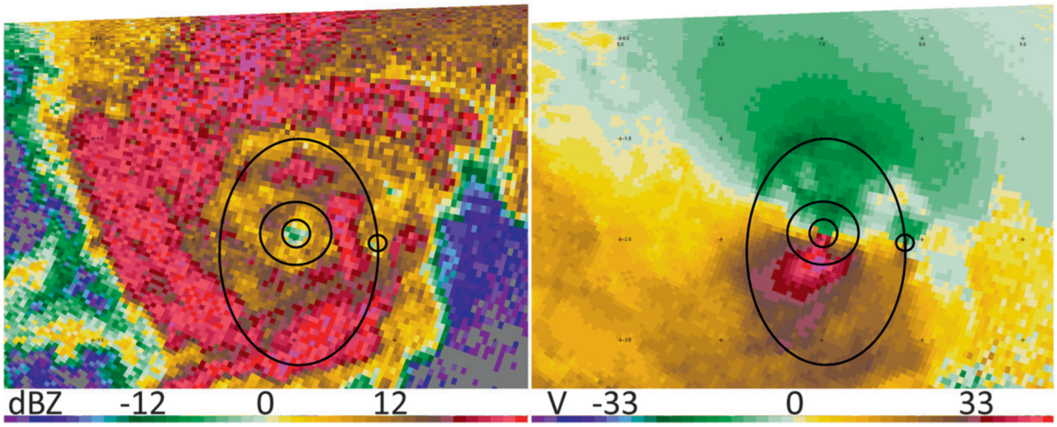

FIG. 8. Satellite tornado. Panel layout is as in Fig. 1, but left panels show uncalibrated reflectivity. A tornado with a satellite tornado, embedded in a 1–2-km-scale circulation event on 3 May 1999 near Chickasha, OK.

Oklahoma. A strong tornado with DV = 92 m s^{-1} over a DX = 200 m, and peak ground-relative winds of 60 m s^{-1} (Fig. 9), was surrounded by an even more intense circulation with DV = 145 m s^{-1} and DX ~ 1.6 km causing V_g = 87 m s^{-1} at 12 m AGL. Was this a mesocyclone containing an internal tornado, or a tornado with multiple wind speed maxima (see section 2d)? Another example of a complex MVMC/tornado structure was observed on 15 May 2003 near Stratford, Texas (Fig. 10). A large circulation (black ovals), with DX > 1 km contains a complex arrangement of smaller vortices and wind field maxima. A large LRE (blue oval) is roughly correlated with the maxima in Doppler velocity. A small LRE (small oval) is associated with one of the smaller embedded vortices. Peak DV in the large vortex is 68 m s^{-1} (74 m s^{-1} in previous radar volume). Peak V_g is 35 m s^{-1} at this time (44 m s^{-1} in previous volume).

d. *Tornadoes and other vortices with multiple, quasi-concentric, wind field maxima*

DOW observations of tornadoes (e.g., Wurman et al. 1996b; Wurman 1998; Wurman and Alexander 2004; Wurman and Samaras 2004; Kosiba and Wurman 2008) reveal complex wind field structures within or associated with tornadoes not well described as multiple vortices. For example, one of the first tornadoes observed by

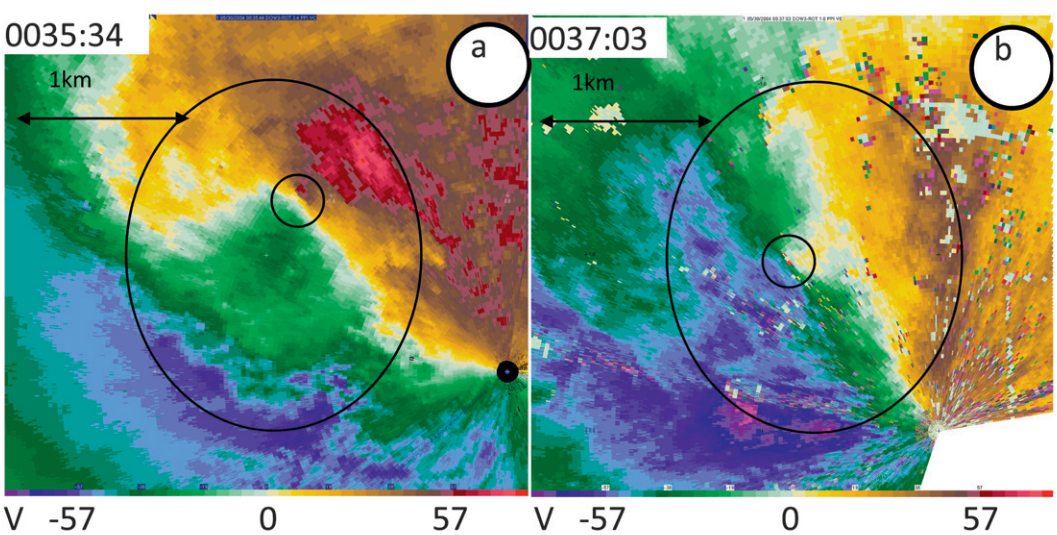

FIG. 9. Intense MVMC or tornado with an internal vortex. Doppler velocity only; otherwise, panel layout is as in Fig. 1. Times are in HHMM:SS UTC. (a) Circulation with DX ~1.5 km (large oval), with an intense internal circulation observed near Geary, OK, on 30 May 2004. Internal vortex (small oval), at 900-m range from DOW, exhibits peak V_g = 70 m s^{-1}. Which of these circulations were tornadoes? (b) Larger circulation that impacted a DOW and measured V_g = 87 m s^{-1} at 12 m AGL.

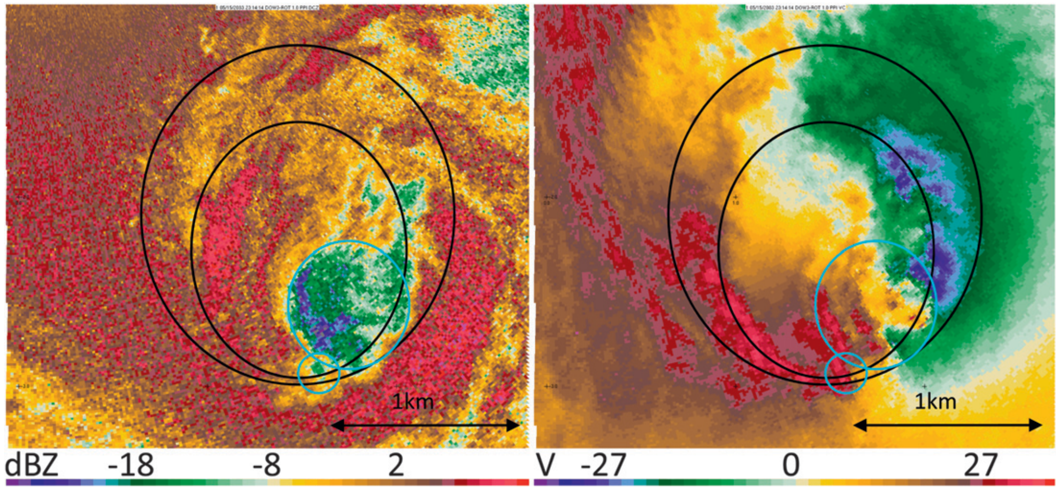

Fig. 10. MVMC or tornado with complex structure. Panel layout is as in Fig. 1, but left panel shows uncalibrated reflectivity. An MVMC exhibiting complex structure including multiple embedded vortices and multiple wind field maxima near Stratford, TX, on 15 May 2003. Black ovals roughly outline rotation scales. Blue ovals outline LREs. Wind field features are not well correlated with reflectivity features.

a DOW, on 9 June 1995 near Kellerville, Texas, exhibited transient multiple wind field maxima associated with a rapidly changing reflectivity presentation and DRE (Fig. 11). The inner wind speed maximum was sometimes stronger than the outer one, but sometimes weaker (similar to the Geary event) and sometimes even absent altogether.

Multiple wind speed maxima sometimes associated with spiraling reflectivity bands are commonly observed in tornado and related vortices. Two noteworthy examples were observed in a weak tornado near Rolla, Kansas, on 31 May 1996, and in a strong tornado near Harper, Kansas on 13 May 2004 (Kosiba et al. 2008) (Fig. 12). The Rolla tornado exhibited several quasi-concentric Doppler wind maxima, inbound and outbound, associated approximately with spiral reflectivity bands. Peak DV and V_g were 75 and 40 m s^{-1}, respectively. No visual evidence of the multiple wind field maxima was documented by the DOW team at a range of 2 km. The intense Harper, Kansas tornado, with peak V_g = 94 m s^{-1} and peak DV of 164 m s^{-1} contained a strong and very small, DX ~ 21 m (gate-to-gate shear at a range of 1690 m), central vortex surrounded by multiple wind field maxima. Peak winds were often stronger in these outer wind field maxima. At the time shown in Fig. 12, respective values of peak V_g and DV were 55.5 and 102 m s^{-1} for the inner vortex and 64.3 and 116 m s^{-1} for the outer vortex. Multiple quasi-concentric DREs were evident.

As mentioned earlier in this study, multiple wind field maxima were observed in the vortices/tornadoes/MVMCs observed in the Quinter, Kansas, Cogar, Oklahoma, and Stratford, Texas storms (Figs. 3, 6, and 10). Multiple wind field maxima complicate the description of the size of tornadoes, since any or all of the quasi-concentric rings delineate "violently rotating columns of air."

e. Strings or individual vortices in hook echoes

Vortices are also observed well away from the broad circulation but still in the hook echoes, sometimes associated with strong horizontal wind shear (e.g., along the rear-flank gust fronts). The Oklaunion hook echo contained such a vortex well to the east of the developing tornado (Fig. 5 2132:49 UTC). A line of weak (DV ~ 30 m s^{-1}) anticyclonic vortices was observed at 700 m AGL along a gust front near Jewell, Kansas, on 30 May 2008 (Figs. 13a and 13b) and was associated with only weak reflectivity perturbations. A line of cyclonic vortices with DV ~ 25–30 m s^{-1} was also evident, as were other small vortices not obviously grouped. It is surmised that the vortices located outside of the primary circulation and along reflectivity gradients formed along horizontal wind gradients and were briefly vertically stretched when they encountered updrafts.

f. Higher-order multiple vortices (subMV)

Multiple vortices can themselves contain multiple vortices, as observed during the 6 May 2007 Seward event (Figs. 13c and 13d). One subvortex of the large MVMC itself contains several intense subvortices. These sub-MVs have DV = 28–61 m s^{-1} and DX = 20–80 m. The simultaneously occurring 1–2-km-scale MVMC, its internal and external subvortices, and the subsub vortices are all "violently rotating columns of air pendant

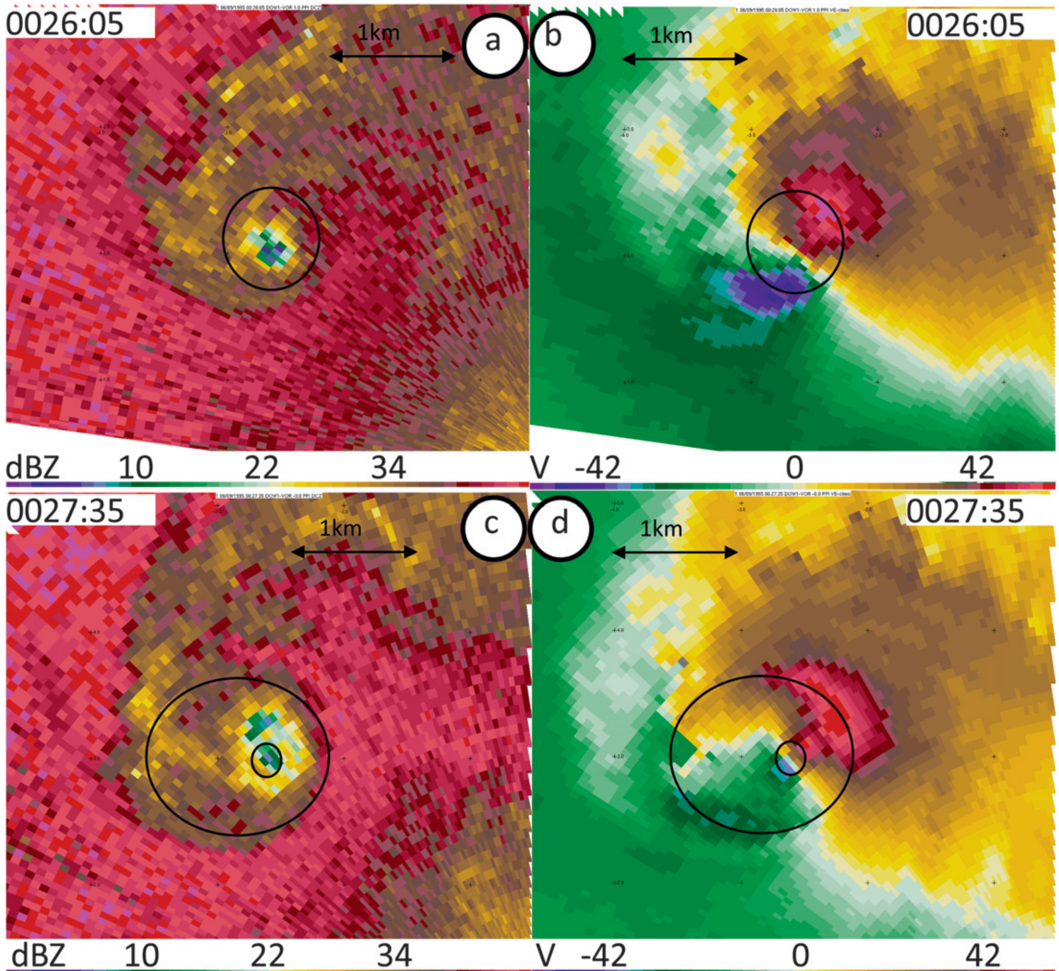

FIG. 11. A tornado near Kellerville, TX, on 9 Jun 2005 with transient multiple wind speed maxima. Panel layout is as in Fig. 1, but left panels show reflectivity. Times are in HHMM:SS UTC. At 0026:05 UTC the tornado exhibits a single wind speed maximum with DX ~ 800 m. By 0027:35 UTC there are two maxima, with DX = 100 and 1200 m, and a DRE. By 0029 UTC (not shown), the inner maximum has disappeared.

from a cumuliform cloud,'' with V_g up to 96 m s^{-1}, so distinguishing which of these vortices should be considered tornadoes is problematic.

g. *Cyclonic–anticyclonic tornado pairs*

The occurrence of anticyclonic reflectivity flares (and associated anticyclonic circulations) in hook echoes has been documented by researchers over the last several decades (e.g., van Tassel 1955; Fujita and Wakimoto 1982; Brown and Knupp 1980; Kosiba et al. 2013). Vortex line analysis in the vicinity of low-level mesocyclones suggests that cyclonic–anticyclonic vortex pairs are created in the hook-echo region due to vortex line arching in the vicinity of the rear-flank downdraft (e.g., Markowski et al. 2008), but the anticyclonic vortex member usually has a short lifetime due to adverse environmental conditions. A rare, well-developed cyclonic–anticyclonic tornado pair (Figs. 13e and 13f) was observed near Glen Elder, Kansas, on 30 May 2008. The cyclonic tornado had a DV = 74 m s^{-1} over DX = 500 m, while the anticyclonic tornado exhibited DV = 59 m s^{-1} over DX = 800 m. A third, cyclonic, vortex, with DV = 49 m s^{-1} over DX = 200 m, was present to the south. It is hypothesized that the formation and longevity of the anticyclonic vortex was aided by a strengthening of the rear-flank downdraft, as evidenced by an increase in the inbound Doppler velocities and a bowing of the reflectivity field. Strong cyclonic–anticyclonic vortex pairs have also been observed by the DOWs on 15 May 2003 near Stratford, Texas; on 9 June 1995 near Kellerville, Texas; on 13 May 2004 near Harper, Kansas; on 3 June 1995 near Dimmit, Texas; and on 10 May 2003 near Binger, Oklahoma.

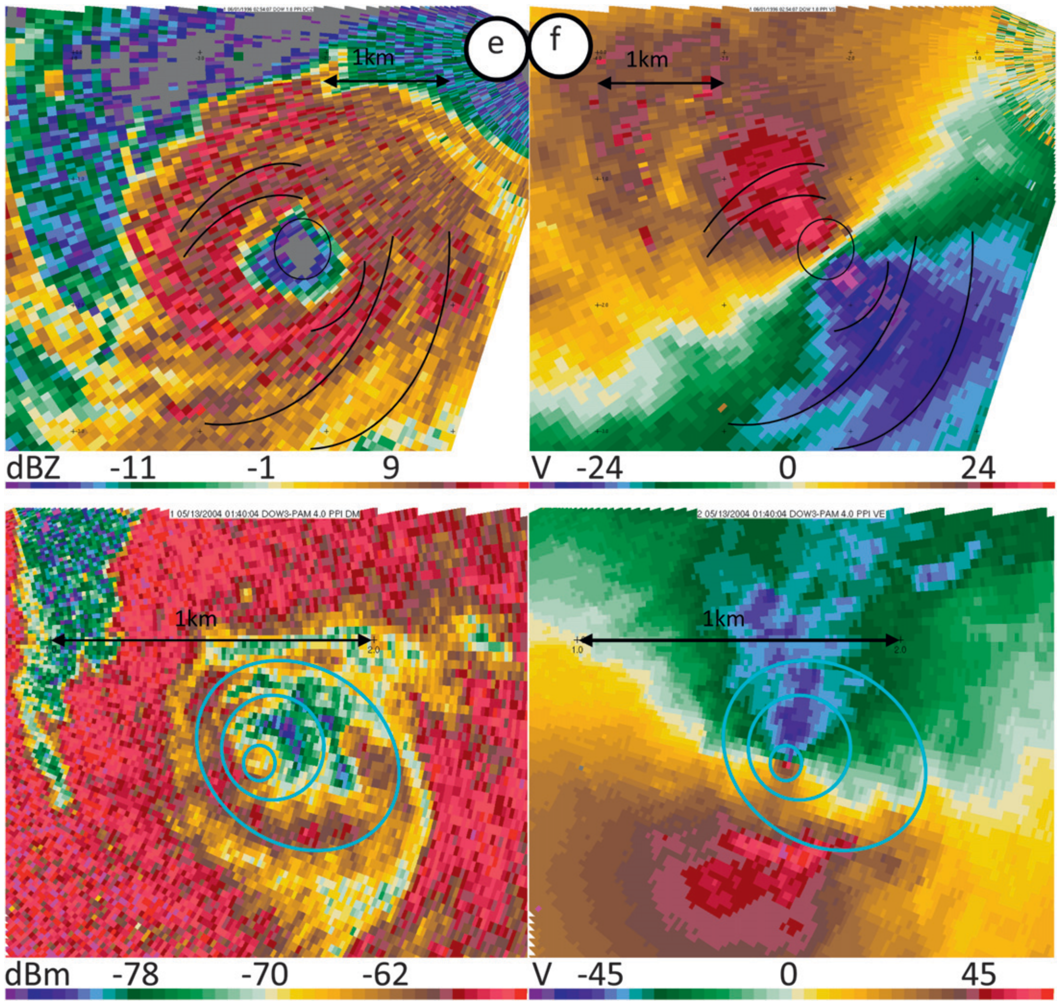

FIG. 12. (top) A large weak tornado with multiple wind speed maxima near Rolla, KS, on 1 Jun 1996. Doppler wind maxima do not correlate well with reflectivity maxima. (bottom) Intensifying tornado with a very narrow central vortex and more intense outer wind speed maxima near Harper, KS, on 13 May 2004. Rare multiple quasi-concentric LREs are present (blue ovals). Panel layout is as in Fig. 1.

h. Horizontal vortices

Most finescale studies of tornadoes have focused on quasi-vertically-oriented vortices, but quasi-horizontally-oriented vortices (HVs) have occasionally been documented. Bluestein et al. (2007b) document an HV in a vertical radar slice near a tornado. Evidence of HV structures, visible in conventional horizontal radar sweeps, is shown in a tornado in southern Oklahoma (3 May 1999) (DV = $55\,\mathrm{m\,s^{-1}}$) and over Canton Lake, Oklahoma (24 May 2011) (Fig. 14). In both cases, the HV was located just outside of the tornadic circulation, prominent on the right flank and slightly forward of the tornado circulation center, and along a reflectivity gradient near/at the edge of the hook echo. The mechanism for HV formation has not been definitively established, though the location and orientation of these HVs observed by the DOWs suggest that, in some cases, the HVs might form near the leading edge of the rear-flank downdraft, along the boundary of outflow and environmental air masses.

3. Conclusions and refined definition of tornado

While many tornadic storms contain simple singlet tornadoes associated with condensation funnels and/or dust, others exhibit a variety of more complex structures, often containing MVMCs and tornadoes with multiple wind speed maxima. Observed vortices associated with supercells vary widely in their intensity, the number occurring simultaneously, and their location

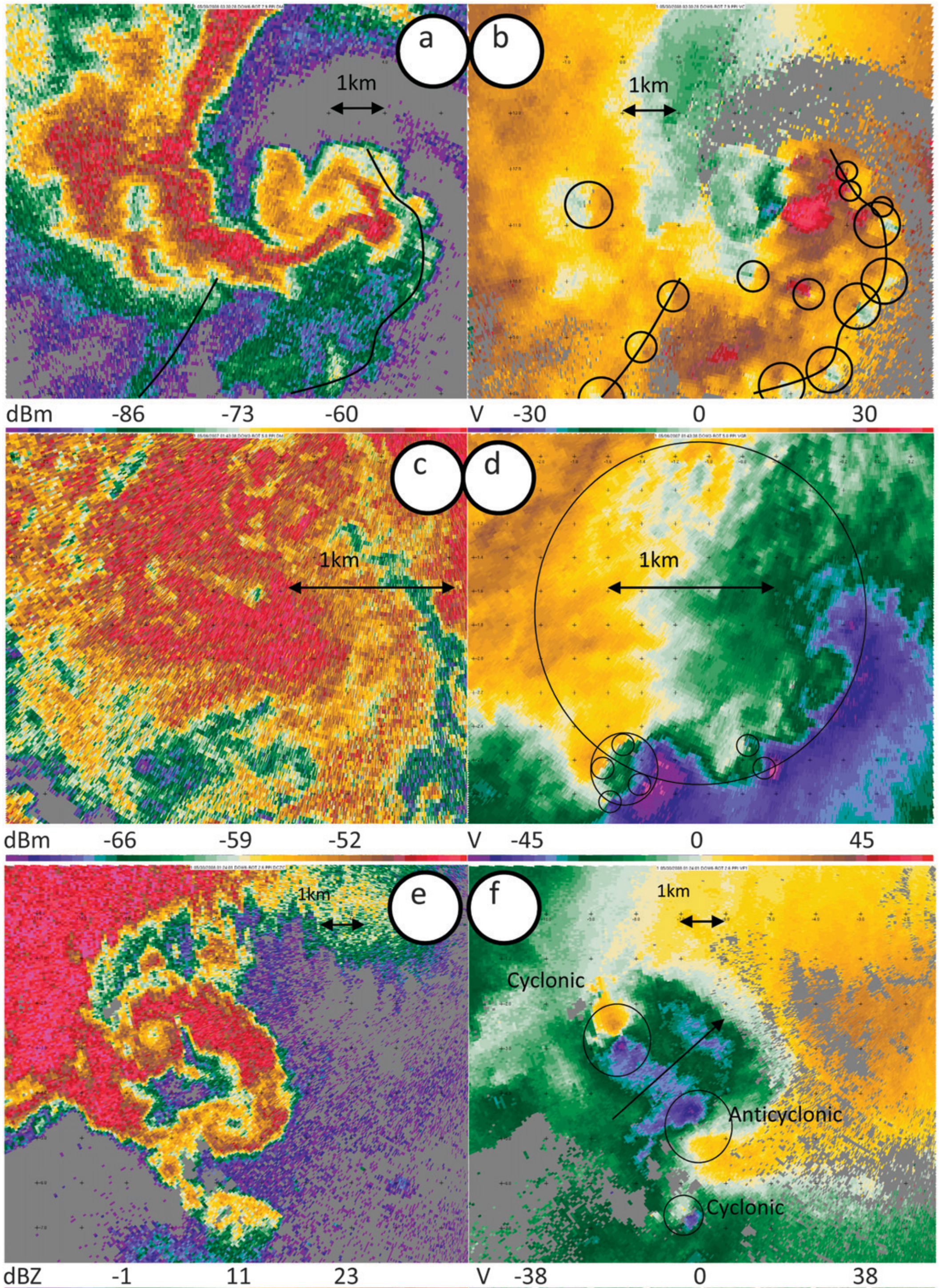

FIG. 13. (a),(b) Lines of anticyclonic and cyclonic vortices near a tornado near Jewell, KS, on 30 May 2008. (c),(d) Multiple vortices (small ovals) within a subvortex (medium-sized oval) of a large tornado or MVMC (largest oval) near Seward, KS, on 6 May 2007. (e),(f) Cyclonic–anticyclonic tornado pair near Glen Elder, KS, on 30 May 2008. Enhanced inbound Doppler velocities associated with the rear-flank downdraft are annotated with an arrow in (f). A second cyclonic vortex is south of the anticyclonic tornado. Panel layout is as in Fig. 1, but panel (e) shows reflectivity.

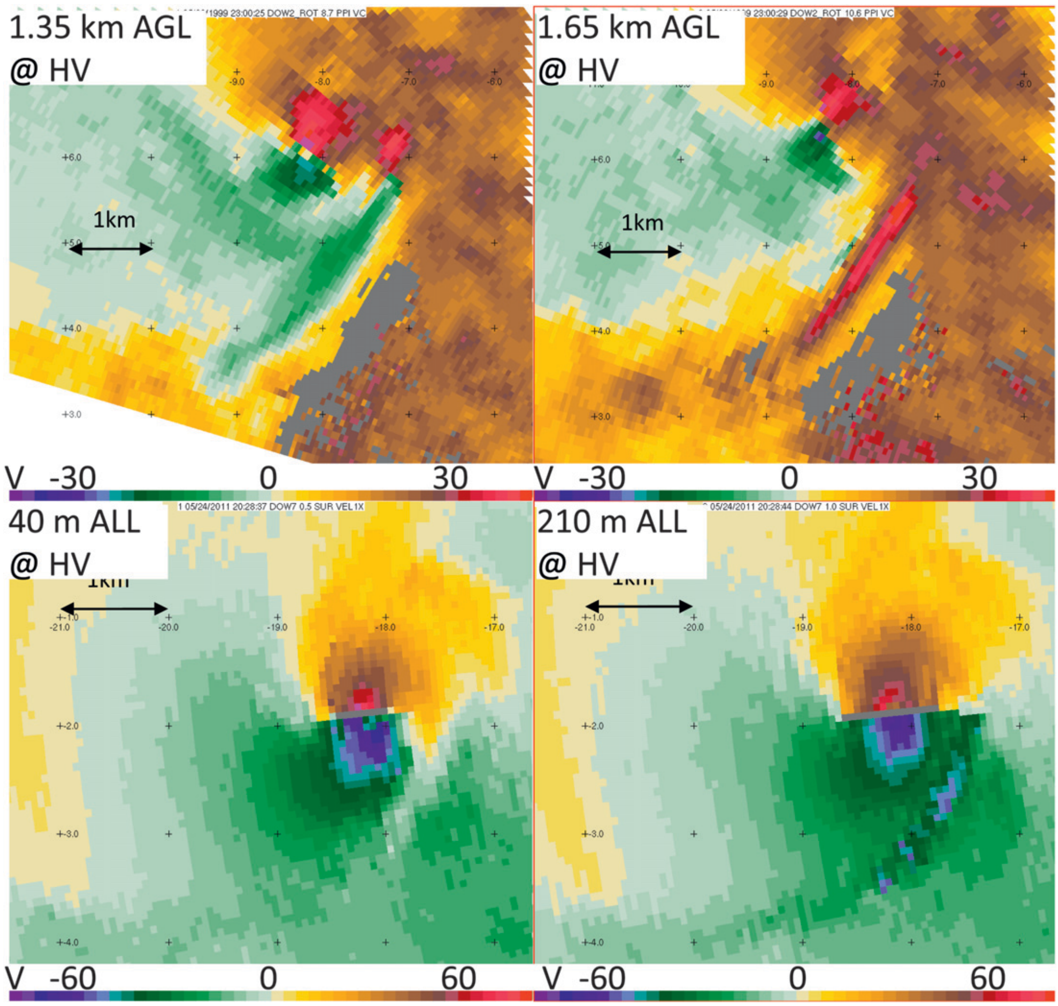

FIG. 14. HVs in tornado in (top) OK on 3 May 1999 and (bottom) Canton Lake, OK, on 24 May 2011. Panel layout is as in Fig. 1, but for Doppler velocity fields only. HVs are indicated by lines of differing velocity, with the sign of the difference switching at different elevations. Beam heights above ground (AGL) and at Canton Lake (above lake level, ALL) are indicated.

relative to ongoing tornadoes. Additionally, some vortices occur when no tornado is present.

DOW observations suggest that, in contrast with the apparent natural separation in rotational intensity (DV) between tornadic and nontornadic vortices (AW), there may be a continuum of spatial scales (DX) of multiple vortex phenomena, often with one or more embedded vortices (some as large as small tornadoes) revolving within larger circulations (some as small as large tornadoes). Relative to the direction of motion of the larger circulations, these vortices often form or intensify on the right sides and weaken or dissipate on the left sides of the larger circulations.

The diversity of vortices observed in supercell hook echoes motivates a revision of the *Glossary of Meteorology*'s definition of tornado (see quoted definition in section 2). As the above examples illustrate, the *Glossary* definition is inadequate to distinguish tornadoes from the wide variety of other vortices associated with supercell thunderstorms. Specifically, ''violently'' is not defined. The definition is so broad as to include ''rotating columns of air,'' which are not tornadoes, or are components of tornadoes, or multiple circulations that are components of MVMCs. No guidance is given concerning the scale of what should be considered a tornado. As discussed above, the *Glossary* definition allows for MVMCs, embedded subvortices, and even sub-subvortices all to be considered as distinct (but overlapping) tornadoes, and for tornadoes and their embedded multiple vortices to be characterized as separate tornadoes since all are separately, and combined, violent rotating columns of air. In cases such as that in Geary, Oklahoma

(2004), both the inner and outer circulations would pass the *Glossary of Meteorology* definition. In Rolla, Kansas (1996), up to five concentric circulations would each individually pass the definition.

We propose an updated and more precise operational definition of what constitutes a tornado including specific, estimable, or measureable (through visual, damage, and/or direct or remote sensing observations) metrics:

> "Tornado: *A rotating column of air, usually <2-km diameter (of maximum winds), with a maximum wind velocity difference across the column near the ground (typically below 200 m AGL) usually exceeding (by measurement, visual inference, or damage indication) 40 m s^{-1}, not embedded within, or within 2 km of, another vortex meeting these criteria, under a cumuliform cloud, frequently visible as a funnel cloud, raised dust, and/or debris.*"

This definition, while longer than that in the *Glossary of Meteorology*, has several advantages. First, it provides a quantitative definition for intensity, excluding weaker vortices, even if embedded in "violent" wind fields (excluding very weak vortices embedded in hurricanes, gust fronts, and strong rear-flank downdrafts). Second, it requires that the tornadic criteria exist near the ground, excluding vortices observed by radar or other means only above 200 m AGL. Third, it excludes closely spaced multiple vortices and multiple wind speed maxima within tornadoes and other circulations in order to preclude describing both a tornado and its component multiple vortices and wind speed maxima as several separate and overlapping and/or concentric tornadoes. Fourth, it provides guidance concerning the scale and intensity of phenomena normally considered tornadoes, with the goal of excluding very weak and broad wind field perturbations. As with the *Glossary of Meteorology* definition, the new definition does not exclude landspouts or waterspouts. No conclusions are made through this operational definition concerning the dynamical similarities or differences among included or excluded phenomena. Similarly, atmospheric vortices not associated with cumuliform clouds (such as dust devils, fire devils, and flow around obstacles such as buildings) continue to be excluded in the new definition.

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