17.5 CHARACTERISTICS OF SUPERCELLULAR SATELLITE TORNADOES

Roger Edwards[1]
Storm Prediction Center, Norman, OK

1. DEFINITION and BACKGROUND

Since the early 1990s, a proliferation of imagery from storm observers has confirmed the anecdotally suspected existence of a form of accessory vortex (with respect to a larger, more persistent tornado) known as a satellite tornado (hereafter, ST). For the purpose of this examination, STs are defined as:

- Supercellular in origin;
- Occurring adjacent to a larger and/or longer-lived, mesocyclonic, main tornado (hereafter, MT) and entirely within the MT lifespan;
- Orbiting the MT in a direction matching the latter's rotational sense—thereby being under a common physical (mesocyclonic) influence;
- Clearly documented as separate from the MT and not a subvortex thereof, based on photographic evidence, video, mobile-radar data, and/or unambiguous description in either *Storm Data* or other meteorological literature.

In making these distinctions, the author acknowledges that tornadoes and related vortices of near-tornadic strength can occur across a spectrum of intensities and proximities. Tornadic or quasi-tornadic vortices often are difficult to segregate from each other in the mesocyclone, as in Wurman and Kosiba's (2013) complex and spectrally ambiguous grouping: "multiple vortices within broad mesocyclones/surface circulations including satellite tornadoes (MVMC)". This study attempts neither a dynamical definition for an ST, nor a resolution of the spectral conundrums for marginal or close-proximity multiple-vortex settings posed by Wurman and Kosiba (2013) for some mobile-radar cases.

Gust-front or flanking-line tornadoes, being removed from the immediate mesocyclone area, are not considered STs. Instead, this paper documents relatively clean observational ST examples that exhibit obvious separation from an MT, following the guidelines above, and that may be considered archetypical. Both MT subvortices and messy, ambiguous MVMCs that are not readily categorized as STs are excluded for now.

Mesocyclonic tornadoes that are widely separated in genesis space and time, within the same supercell, can interact in a brief "handoff" stage corresponding to the demise of the first and development of the second. Such an event was observed on 13 March 1990 near Goessel, KS. That event, along with a brief double-tornado vortex on 11 April 1965 near Midway, IN, were termed "binary tornado" by Fujita (1992). Handoff or binary tornadoes also are not included as satellite vortices herein. Because of the supercellular constraint, instances of concurrent, proximal, nonsupercellular tornadoes (a.k.a. "landspouts") also are not counted as STs.

Figure 1 shows a two-dimensional, conceptual, archetypical model, with the ST under the common mesocyclonic influence of the MT (regardless of its origin inside or outside the mesocyclone). Photographic examples of STs with their MTs appear in Fig. 2. In documenting these events, there are no exclusionary constraints on size, duration, rotational sense, or the ultimate fate of the ST itself (e.g., dissipating in situ or being absorbed by the MT).

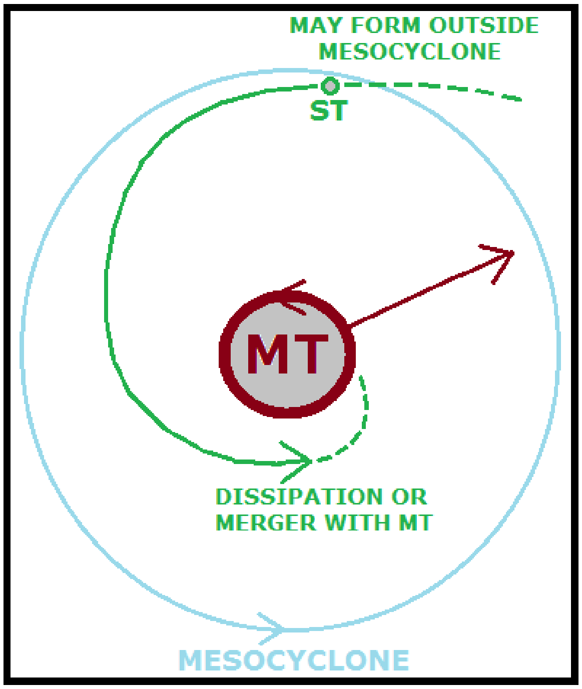

Figure 1: Archetypical, northern-hemisphere model of the ST and MT (labeled), based on cases examined herein and the author's observations. Arrows denote sense of rotation (MT, mesocyclone) and direction of translation (MT, ST). Actual MT may not be centered within mesocyclone. Relative sizes and radial positions of MT, ST and mesocyclone may differ considerably from this ideal. Distance scale not given since mesocyclone size is quite variable.

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[1] *Corresponding author address:* Roger Edwards, Storm Prediction Center, National Weather Center, 120 Boren Blvd #2300, Norman, OK 73072; E-mail: roger.edwards@noaa.gov

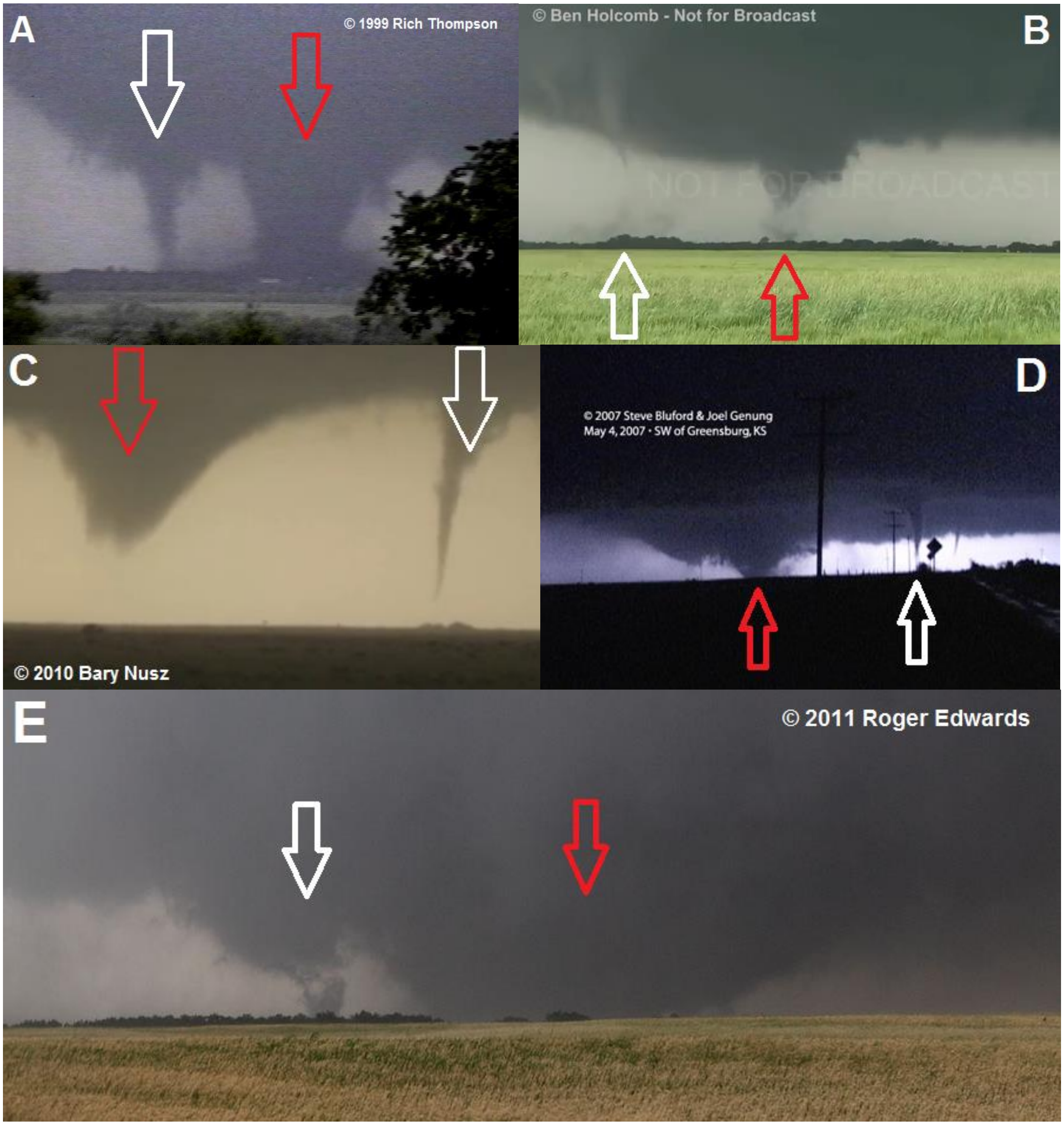

Figure 2: Images of STs (white arrows) and MTs (red arrows) from near: a) Chickasha, OK, 3 May 1999; b) Wakita, OK, 10 May 2010; c) Clayton, NM, 24 May 2010; d) Greensburg, KS, 5 May 2007 (nocturnal, silhouetted by lightning); and d) Piedmont, OK, 24 May 2011. Dates in UTC. A separate funnel cloud appears to the rear right of the ST in (d). *Due to two-dimensional flatness of these perspectives, STs were farther radially from the MTs than they appear here*. Images courtesy of labeled photographers/videographers and used by permission.

2. HISTORY and NOTABLE EXAMPLES

As of this writing, the earliest ST documented with confidence accompanied the Tri-State tornado in eastern Franklin County, IL, on 18 March 1925—a recent finding of Johns et al. (2013). This was one of two probable STs associated with the Tri-State event, the other being shortly down the MT path in southwestern Hamilton County, IL. Each destroyed homes 0.8–1.2 km (0.5–0.75 mi) south of the MT before apparently moving into the MT path with unknown processes of demise.

The first explicit description of a "satellite tornado" found in the literature involved a complex series of strong and violent supercellular tornadoes in northeastern Kansas on 19 May 1960, and associated with a famous set of hook echoes in S-band radar reflectivity (Garrett and Dockney 1962). According to them, "Several cases of spot damage occurred well to the south of the main damage path." One of those

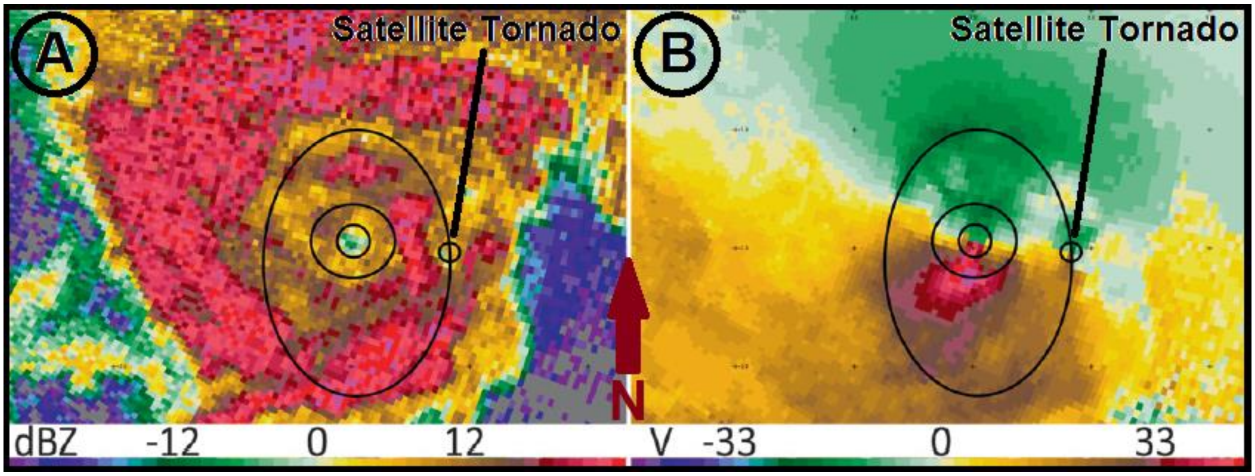

Figure 3: Simultaneous images derived from Doppler on Wheels data from near Chickasha, OK, 3 May 1999: a) uncalibrated reflectivity (dB*Z*); b) radial velocity (m s^{-1}). ST signature annotated. Radar was located west-northwest of the image centroids; therefore, attenuation through the MT may have influenced ST depiction. ST was 0.9 km (0.6 mi) from center of MT. Fig. 2a photo of these tornadoes is ~1 min later. Adapted from Wurman and Kosiba (2013).

was termed specifically as an ST inside the northeastern city limits (at that time) of Topeka. At closest approach to the MT path near Meriden, KS (rated F4 by Grazulis 1993), the claimed ST was 10.5 km (6.5 mi) farther south. This indicates that the secondary tornado actually was well-removed from the MT's mesocyclone—either in a flanking part of the same supercell or in a separate thunderstorm altogether. Given its position relative to the MT at the time, the lack of prior reflectivity south of the well-defined MT's hook echo on their radar imagery, and the authors' descriptions ("new weak development" south of the hook, evolving into "a solid short line intersecting the hard echo of the former hook at an angle of almost 90°"), the northeastern Topeka event appears to have been a flanking-line tornado, instead of an ST by current definition.

On 8 June 1995, separate violent (F4) tornadoes passed near Mobeetie and Allison, TX—each accompanied by satellite vortices according to *Storm Data* (NCDC 1995) and Grazulis (1997,2001) respectively. The *Storm Data* entry for the Mobeetie (a.k.a. Kellerville) event vaguely states, "This last tornado had two small satellite tornadoes with it and crossed the county line between Gray and Hemphill at 1755 CST," but offers no individual entries, nor time and location specifications for the STs, that could be used herein[2]. A formal study of cyclic tornado production by the same supercell (Dowell and Bluestein 2002a) depicts just one Mobeetie ST (per their Fig. 5c photo, and mapped in their Fig. 3). This ST occurred after the mid-path truncation point for an otherwise highly detailed Kellerville MT survey by Wakimoto et al. (2003), and therefore, does not appear in the latter study. Observationally derived analyses of the Kellerville supercell's low-level vorticity budget (Dowell and Bluestein 2002b) also ended prior to the ST, an unfortunate circumstance for the sake of physical understanding of ST processes.

The nearby Allison supercell apparently produced several satellite vortices (Grazulis 1997,2001). One passed over a mobile-mesonet vehicle affiliated with the Verification of the Origin of Rotation in Tornadoes Experiment (VORTEX; Rasmussen et al. 1994; C. Crosbie 2014, personal communication), and another was videotaped while its lower extent was advected into the F4-rated MT (Fig. 390 in Grazulis 1997). Other than one aforementioned Mobeetie ST, no specific path data are published for the 8 June 1995 STs; however, the author used available VORTEX communications logs and correspondences with two project participants (Crosbie and Straka 2014, personal communications) to determine details for two of the Allison STs. Other STs probably occurred with each tornado, based on vague descriptions and anecdotes; however, despite being covered by a major field project, they are too poorly documented to tally. These events exemplify the reporting ambiguities and uncertainties that precluded use of possible STs on this and several other dates.

Thorough and specific National Weather Service (NWS) survey documentation of four Oklahoma STs from the 3 May 1999 outbreak was performed by Speheger et al. (2002), whose guidelines for defining STs form the basis for those used in section 1. Two of the STs, accompanying successive significant (F3 and F5) tornadoes from "Storm A", were videotaped and photographed by numerous storm observers. The first of these STs, near Chickasha, OK (Figs. 2a and 3), also was scanned by mobile Doppler radar when located 0.9 km (0.6 mi) east of the MT (e.g., Fig. 3) and was obviously cyclonic in nature (Fig. 3b). The Chickasha ST, also witnessed by the author, made a nearly complete MT-relative circumnavigation during the ST's 2–3 min visual lifespan. Another supercell later produced two STs near Kingfisher, OK.

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[2] Fortunately, a storm observer (D. Ewoldt 2014, personal communication) has provided time and location details on both STs near Mobeetie.

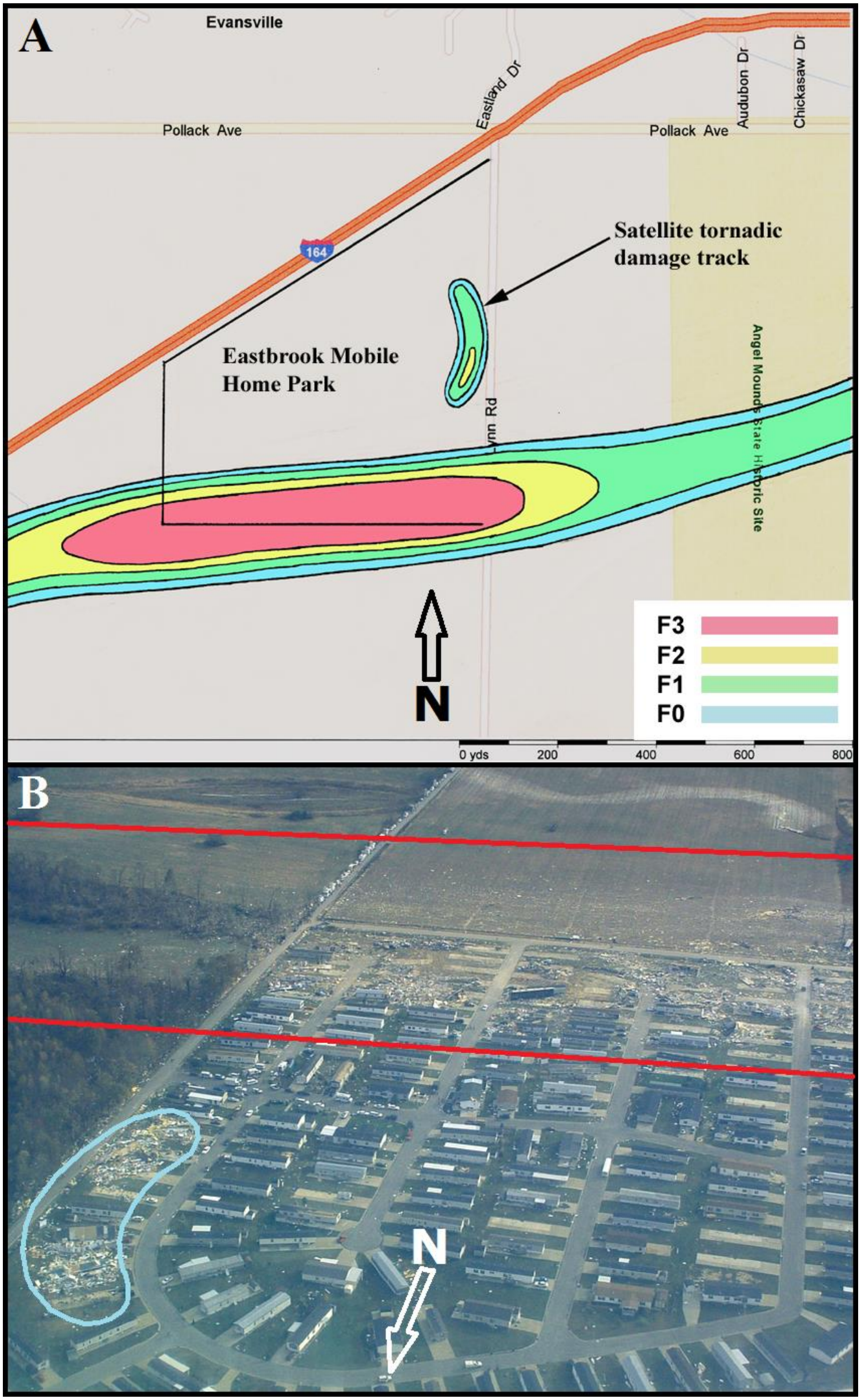

Figure 4: Survey imagery for the 6 November 2005 MT and ST at Evansville, IN: a) plan-view damage-contour map, MT and ST tracks per legend, and b) aerial photograph zoomed into the Eastbrook Mobile Home Park, with approximate MT path in red and ST in blue. Adapted from imagery provided by R. Przybilinski, NWS St. Louis, MO.

As with the 3 May 1999 event, a violently tornadic, central Oklahoma supercell on 24 May 2011 produced two STs---this time accompanying a single, long-track, EF5 MT near El Reno and Piedmont. Both STs were witnessed and photographed by the author (not shown); however, the first wasn't recognized for certain as an ST in real time due to distance, subcloud darkness, intervening precipitation, and the relatively large apparent size of what turned out to be the ST. The first ST crossed U.S. Highway 81 north of El Reno and was unusually intense—nearly as strong as the MT for a brief interval—based on mobile-radar and WSR-88D data (not shown). This vortex developed just outside then became entrained within the mesocyclone, before helically encircling then merging into the MT (French et al. 2014). This is the only known case where both the ST and MT were deep and strong enough to yield distinct signatures in WSR-88D presentations, and where they interacted nearly as equals[3]. Following the merger, the MT enlarged greatly, intensified (based on mobile-radar data) and developed a massive, wedge-shaped appearance. The second ST (Fig. 2e) formed out of view somewhere to the west or northwest of the now-enlarged MT southwest of Piedmont, OK, then orbited southwest through east of the MT, assuming a ragged appearance with a distinct debris cloud before dissipating. A later, separate supercell's brief ST near Newcastle, OK, was associated with an EF4 MT and occupied the same tornado-detection signature on radar (Bodine et al. 2013).

The latest documented (after 0800 UTC) nocturnal STs occurred around the EF3 Evansville, IN, MT of 6 November 2005. Because of darkness and heavy precipitation, the STs were not seen visually; only the MT was witnessed, including via a security camera at an Evansville hospital (not shown). However, an NWS Central Region Quick Response Team (R. Przybilinski, personal communication) revealed their occurrence through ground and aerial damage surveys (e.g., Fig. 4). While damage from an ST is likely to be obscured by that of the MT where their paths cross, multi-platform survey work can reveal the occurrence of STs that otherwise may go unrecorded.

A very unusual and well-documented ST event occurred on 10 April 2010 in Sac, Buena Vista and Pocahontas Counties, IA. Within 32 min, between 0224–0256 UTC, an atypically large (≈2400-m), EF3-rated MT was linked to five STs—not quite matching the known ST record of six set by the Greensburg, KS, MT of 05 May 2007. However, the final four of the Iowa STs were underway at once. A counterrotating (cyclonic/anticyclonic) ST pair constituted the middle two of that quartet, in terms of genesis chronology. Moreover, the first and fourth STs of that quartet merged, after the former produced an ST-record EF4 level of damage. To accentuate the rarity of the event, this is the only case yet documented where an ST produced more intense damage than its MT.

After several other well-defined STs were documented by storm observers in the 2003–2010 time frame (e.g., Fig. 2b–d), the El Reno supercell of 31 May 2013 offered an extreme variety of tornado-scale circulations (Wurman et al. 2014; Theim et al. 2014). This included: 1) two reasonably well-defined STs before the MT enlarged to record width and turned northeastward, as well as 2) a messy assortment of MVMCs thereafter whose classifications remain too unclear to include in this study's collection of relatively archetypical ST cases. The El Reno event was historic for many reasons (including the first tornadic storm-chaser fatalities; Wurman et al. 2014); however, it also yielded unprecedented dual-polarization mobile-radar scanning of satellite tornadoes (e.g., Fig. 5 herein and Theim et al. 2014). The El Reno STs offered reflectivity and velocity patterns similar to other STs (e.g., Fig. 5a,c), as well as miniaturized, lower-intensity dual-polarization analogs to common MT signatures (e.g., Fig. 5b,d). Even at a distance >4 km (2.5 mi) from a mobile radar, one of the STs exhibited a low-reflectivity, bounded weak-echo region, or eye, where reflectors (rain and small debris) were centrifuged away from its circulation center (Fig. 5a).

3. THE "SATTOR" DATASET

The nature of STs has made their documentation erratic and uncertain, even in the best of circumstances that characterize modern tornado-survey and verification efforts. True ST frequency and distribution (spatially or temporally) is unknown. Specific path characteristics of many STs in this study are unclear outside documented damage indicators (DIs) or, barring existence of impacted DIs, locations estimated with respect to the path of the MT based on photos or video (e.g., Fig. 2). Visual documentation of STs is easier in areas of relatively flat terrain and free of tall vegetation that have been frequented by storm observers for the past few decades—hence the predominance of Great Plains events in this study.

The tendency of STs to be relatively brief and to cross portions of the typically much larger and more damaging MT swath further obfuscates their path details. As such, individual records of path length, path width and perhaps even peak rating for STs should not be taken literally. Furthermore, tornado records in the Storm Prediction Center (SPC) "ONETOR" dataset (Schaefer and Edwards 1999) offer only starting and ending points. As a result, where STs are specifically documented in SPC and *Storm Data* entries, they still do not resolve the path eccentricities common to STs.

This study uses a list of STs (SATTOR) based on a combination of: *Storm Data*, formal and informal literature, local NWS input since related *Storm Data* preparation, and anecdotal storm-observer accounts of sufficient detail to determine time, location and reasonable certainty of the event's satellite-vortex character (e.g., photo, video, radar, and/or detailed damage assessment where possible). Some ST records herein are not in official datasets such as *Storm Data* and ONETOR. For example, some STs associated with the Greensburg, KS tornadic supercell of 4 May 2007 (5 May in UTC; Fig. 1 in

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[3] This may have been a brief binary tornado or merger-aborted handoff process, but is treated here as an ST-MT interaction given observed path characteristics common to the Fig. 1 archetype.

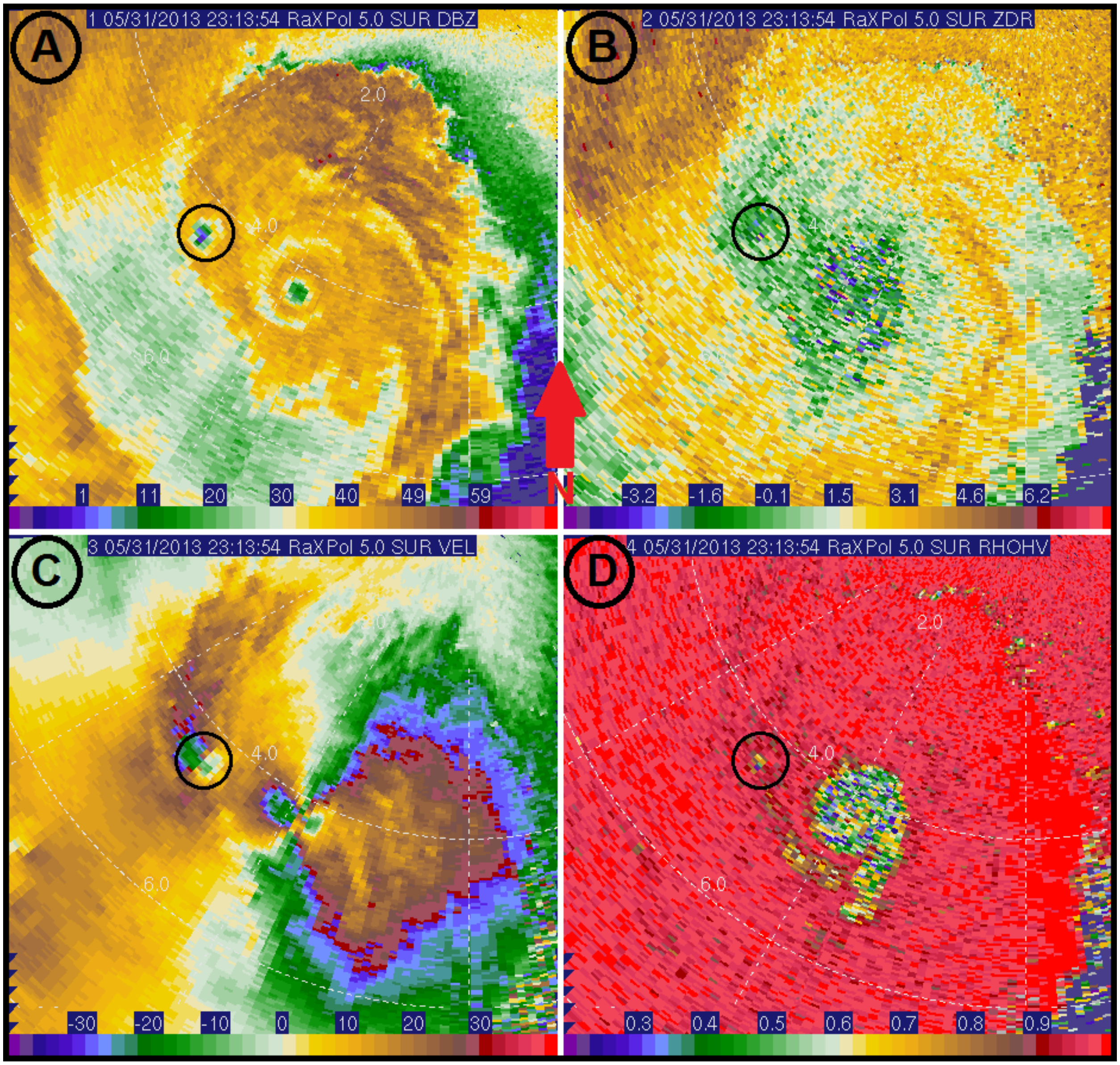

Figure 5: Contemporaneous images derived from mobile, rapid-scanning, X-band, polarimetric (RaXPol; Pazmany et al. 2012) radar data near El Reno, OK, 31 May 2013: a) reflectivity (dB*Z*); b) differential reflectivity (dB); c) radial velocity (m s^{-1}); d) copolar correlation coefficient (unitless). Cyclonic ST signature outlined by black circle. Radii every 2 km (1.25 mi) in dashed white with tornadoes centered slightly >4 km (2.5 mi) southwest of the radar. Each panel is centered on MT eye. Time stamps are ≈40 s slow. Imagery courtesy of J. Snyder and OU Advanced Radar Research Center. *Click here for reflectivity and velocity animation*.

Lemon and Umscheid 2008) were discovered via examination of storm chasers' videos months after NWS submission of *Storm Data* (M. Umscheid 2013, personal communication). Storm observers (listed in the Acknowledgments) have provided the author with compelling photo and video evidence for some STs not listed in *Storm Data* (nor yet present in ONETOR).

Given all these caveats, the data, analyses and conclusions offered herein should be treated as incomplete and not necessarily representative of the entire natural population of STs. Table 1 lists the 51 events preliminarily included in SATTOR, as of this writing. As with the SPC tropical cyclone tornado (TCTOR) dataset (Edwards 2010), SATTOR will be flexible and subject to revision with new events and as sufficient evidence appears to include, remove or revise older tornadoes. Unlike TCTOR, SATTOR is not presently a subset of ONETOR due to longstanding *Storm Data* problems described above; however, the datasets are planned to be reconciled at some point.

4. ANALYSES and INTERPRETATIONS

STs are mostly a warm-season phenomenon, with only one associated MT occurring during astronomical autumn and two others in late winter (March), shortly before spring equinox (Table 1). No known STs have caused human deaths or injuries, although (as with any tornado) they present a safety hazard to those caught in the path—including storm observers (section 5). Geographically, STs have been observed

Table 1: Preliminary SATTOR listing as of December 2014. Damage ratings in Fujita (F) scale before 2007 and Enhanced Fujita (EF) from 2007 onward. U is unknown or unrated. Black denotes singular ST events. Adjacent, like-colored STs were associated with a common MT. 1957 events were separated in space around the MT and may not have been simultaneous, but have the same time, location and rating in the SPC database.

DATE (UTC)	TIME (UTC)	NEAR TOWN	COUNTY	RATING
18 March 1925	2106	Thompsonville IL	Franklin	U
18 March 1925	2115	Braden IL	Hamilton	U
20 May 1957	2050	Aurora KS	Cloud	2
20 May 1957	2050	Aurora KS	Cloud	2
20 May 1957	2050	Aurora KS	Cloud	2
13 June 1976	2045	Luther IA	Boone	2
13 June 1976	2050	Boone IA	Boone	3
28 June 1992	0101	Fritch TX	Moore/Hutchinson	1
28 June 1992	0106	Fritch TX	Hutchinson	2
9 June 1995	0005	Mobeetie TX	Wheeler	U
9 June 1995	0007	Mobeetie TX	Wheeler	U
9 June 1995	0103	Allison TX	Wheeler	1
9 June 1995	0103	Allison TX	Wheeler	U
1 March 1997	2135	Vimy Ridge AR	Saline	2
3 May 1999	2307	Chickasha OK	Caddo	0
4 May 1999	0010	Newcastle OK	McClain	0
4 May 1999	0155	Kingfisher OK	Kingfisher	0
4 May 1999	0203	Kingfisher OK	Kingfisher	0
25 June 2003	0027	Esmond SD	Kingsbury	0
20 April 2004	2315	Ottawa IL	LaSalle	U
23 May 2004	0035	Daykin NE	Jefferson	0
29 May 2004	2305	Jamestown KS	Cloud	0
6 November 2006	0800	Evansville IN	Vandenburgh	2
6 November 2006	0813	Boonville IN	Warrick	1
6 November 2006	0814	Boonville IN	Warrick	0
5 May 2007	0208	Coldwater KS	Kiowa	1
5 May 2007	0218	Greensburg KS	Kiowa	0
5 May 2007	0225	Coldwater KS	Kiowa	0
5 May 2007	0225	Greensburg KS	Kiowa	0
5 May 2007	0235	Greensburg KS	Kiowa	0
5 May 2007	0234	Greensburg KS	Kiowa	1
10 May 2010	2040	Wakita OK	Grant	U
24 May 2010	0155	Clayton NM	Union	0
17 June 2010	2215	Bluffton MN	Otter Tail	U
17 June 2010	2351	Armstrong MN	Freeborn	1
10 April 2011	0138	Early IA	Sac	0
10 April 2011	0224	Nemaha IA	Sac/Buena Vista	2
10 April 2011	0254	Varina IA	Pocahontas	4
10 April 2011	0255	Varina IA	Pocahontas	1
10 April 2011	0255	Varina IA	Pocahontas	1
10 April 2011	0256	Pocahontas IA	Pocahontas	2
24 May 2011	2133	El Reno OK	Canadian	U
24 May 2011	2139	Piedmont OK	Canadian	0
24 May 2011	2345	Newcastle OK	McClain	0
26 May 2012	0244	LaCrosse KS	Rush	1
26 May 2012	0245	LaCrosse KS	Rush	2
28 May 2013	2119	Corning KS	Nemaha	U
31 May 2013	2312	El Reno OK	Canadian	0
31 May 2013	2313	El Reno OK	Canadian	0
11 May 2014	2213	Cordova NE	Seward	U
11 May 2014	2216	Beaver Crossing NE	Seward	U

primarily over relatively open country in the Great Plains and Midwest states. However, given their relative brevity and smallness (below), nonmeteorological factors may influence their scant documentation in areas of denser tree cover and/or rougher terrain. Because of the small sampling of STs so far, a single productive tornado day can influence the analyses strongly. In fact, nearly a quarter (24%) of SATTOR events occurred with two supercells: one on 5 May 2007 and another on 10 April 2011 (UTC) (Table 1).

a. Comparisons with ONETOR: 1995–2013

In order to make comparisons with the known tornado population at large, and to do so under a relatively consistent baseline practice for data-gathering (the "modernized" NWS era of WSR-88D-based warning and verification practices), ONETOR data are used only from 1995 on. This reasoning for starting in the mid-1990s is the same as for the temporal range of TCTOR (Edwards 2010), and minimizes (but does not guarantee the absence of) the impacts of major tornado-data secularities discussed in Brooks et al. (2003) and Doswell (2007).

The SPC ONETOR data already combine multi-county segments from Storm Data and additionally have been filtered for this analysis to combine multi-state segments. Given the smallness of the temporally matching subset of the SATTOR sample, only rudimentary and preliminary results can be offered for now, with unknown representativeness for STs as a whole (see Doswell 2007 regarding small sample-size concerns in analyzing tornado data). Nonetheless, some very clear characteristics emerge regarding the occurrence of STs and MTs versus tornadoes as a whole.

During the 1995–2013[4] period, each MT associated with STs was compared to the population of recorded tornadoes in ONETOR. Distributions for path length and width appear in Fig. 6. No interquartile overlap exists between the far larger path characteristics of ST-producing MTs and those of the tornado data as a whole. In fact, for path width, the 10th percentile of MTs exceeds the 90th of all tornadoes.

Because all MTs documented so far were rated as significant (Sig, EF2–EF5), their path length and width similarly were compared to only the significant tornadoes from 1995–2013 (Fig. 6). Although some overlap exists between the MT and Sig groups, MT path-length values at all sampled percentiles but the 90th approximately triple to quadruple the Sig events as a whole. No interquartile overlap was found between widths of MTs and all Sig events. Even with a low MT sample size, a substantial signal is emerging to suggest that *ST-associated MTs occupy the upper ranges of not only the whole tornado*

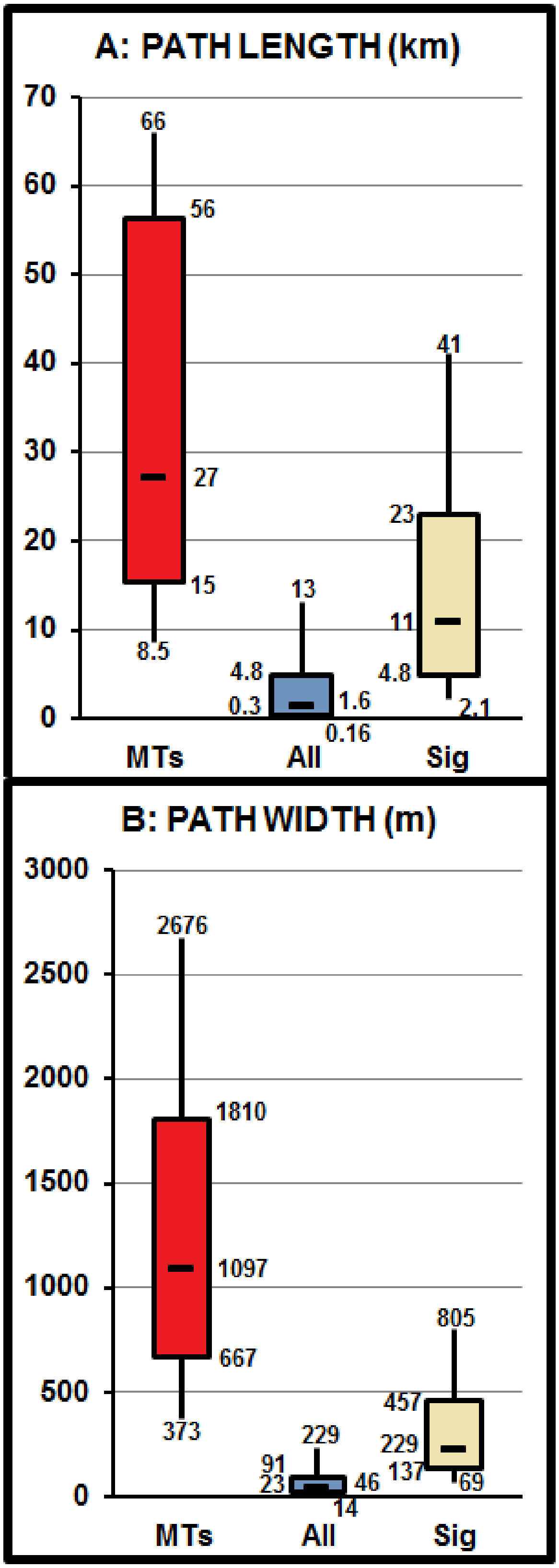

Figure 6: Box-and-whisker diagrams of 1995–2013 distributions of ST-associated MTs, all tornadoes, and significant (Sig, EF2–EF5) tornadoes by a) path length and b) path width as labeled. Boxes represent 25th–75th percentiles and whiskers extend to 10th and 90th percentiles. Sample sizes: MTs = 23; All = 23 865; Sig = 2628.

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[4] Though ONETOR was not finished for 2014 as of this writing, *Storm Data* was ready for the lone ST-accompanied MT. Its county segments were combined the same way as in ONETOR for Table 1, but it is not used in the 1995-2013 comparisons.

population, but also of significant tornadoes, in terms of path length and width.

b. ST–MT comparisons

Path properties of STs and MTs were compared, both with and without the two 18 March 1925 Tri-State events because of 1) unknown path specifics for the STs accompanying the 18 March 1925 Tri-State tornado, and 2) the extreme nature of the Tri-State MT in many respects. The average path length (width) for all STs was 2.2 km (95 m), while the average path length (width) for their MTs was 49 km (1382 m). Without Tri-State, the mean MT length dropped to 37 km, but the mean MT width without Tri-State slightly *increased* to 1392 m—another testament to the MTs' typically enormous size.

The most striking differences between STs and MTs, other than known path characteristics, was damage rating[5]. When including events such as the Tri-State associated STs with damage level unknown (EFU), all 51 events can be compared (e.g., Fig. 7). Of those, the majority (39, 55%) of STs were rated as weak (EF0, EF1) with another 11 (22%) unknown, and 24% significant (EF2–EF4). Significant STs are a much higher proportion than in the ONETOR dataset (e.g., Fig. 6). In contrast, all MTs were significant; in fact, a slight majority of MTs (55%) were violent (EF4, EF5). As earlier described, only one ST produced more intense damage than its MT.

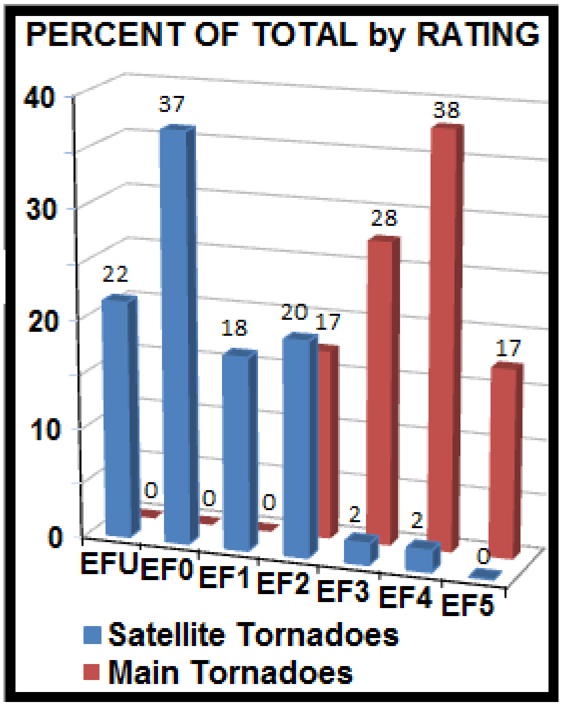

Figure 7: Percentage (ordinate and bar values) of all STs (blue, 51 events) and ST-associated MTs (red, 29 events) with each EF-scale rating.

Taken together, these results suggest that STs not only are far smaller than MTs, but substantially weaker and shorter-lived, consistent with both the author's more limited direct observations, reports of other observers, and the processes implied by the Fig. 1 conceptual model. The results above also imply that even within settings favoring significant tornadoes, STs usually (but not always) occur in environments that produce anomalously large, long-tracked and damaging MTs.

5. SUMMARY and DISCUSSION

The definition proposed herein for satellite tornadoes is archetypical in the context of photographic and video documentation, and not rooted in any sort of dynamical threshold (i.e., baseline value of vertical vorticity or vorticity per unit area). The former—observed characteristics of STs documented so far—fits the ST into Agee's (2014) tornado taxonomy Type 1a: "Discrete supercell with mesocyclone (typically a hook echo) with supportive values of CAPE and storm-relative helicity (SRH) with low-level directional shear". The latter (a dynamical definition) likely needs to wait for either

- A large sample of close-range, mobile-radar scans of STs, or
- Appropriately scaled numerical simulations that adequately represent tornadic vortices behaving in ways similar to archetypical STs.

As such, some storm-scale simulations of supercells with strong-to-violent tornadoes should include STs. Unfortunately for that purpose, observational corroboration of the interplay between the dynamics of STs vs. MTs, and STs within their parent mesocyclones, remains elusive at this time. Such analyses—likely based at least partly on existing (e.g., cases shown in Figs. 3–4) and additional mobile-radar data—will help not only to understand the physical mechanisms and roles of STs within their supercells' vorticity budgets, but why STs develop in some strongly to violently tornadic supercells and (apparently) not most others.

A comprehensive climatology of STs probably is not possible. Even in episodes of observationally intensive field work such as the VORTEX programs, ST documentation has been fragmented and ambiguous. Speheger et al. (2002) described a problem with ST tornado documentation that is likely to persist: "Even with video evidence, it is sometimes difficult to define when a tornado actually begins or ends. The existence of satellite tornadoes is not widely known, and confusion with multivortex tornadoes is possible." Uncertainties involving various spatiotemporal scales of vortices in the near-tornadic environment of 31 May 2013 (El Reno, OK) case—especially after the STs documented herein—either can bridge or smudge the distinction between STs and MTs, depending on the perspective (e.g., Wurman and Kosiba 2013; Wurman et al. 2014).

Only four UTC days currently in SATTOR featured ST production from more than one supercell: 24 May 2011 in central Oklahoma, 17 June 2010 in Minnesota, 3–4 May 1999 in central Oklahoma, (Speheger et al. 2002), and 9 June 1995 in the Texas

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[5] The NWS adopted the Enhanced Fujita (EF) scale in 2007, climatologically considered level with the original F scale (Edwards et al. 2013). As such, EF notation is used here for all events.

Panhandle. Therefore, the sample size is much too small to infer specific characteristics of such events. Preliminary results suggest that STs overwhelmingly occur in environments favoring very wide, long-track tornadoes. Though the 3 May 1999 environment clearly was suitable for multiple, violent tornadic supercells (e.g., Thompson and Edwards 2000; Edwards et al. 2002), other tornado outbreaks of comparable or greater violent-tornado production have not yielded multiple, documented, ST-producing storms. Aside from their strong association with long-tracked and/or violent tornadoes (section 3), the relationship between ST production and the environment at bigger than storm scales needs further exploration for any operationally useful predictive value. Because of the small sample size of ST cases temporally overlapping the 2003–2013 version of the SPC storm-environment database (Schneider and Dean 2008), no environmental analyses have been performed yet. This is an open area for exploration as the number of events grows, whether through additional ST occurrences, temporal expansion of the environmental-analysis period (e.g., Bothwell et al. 2014), or both.

Dynamic and spectral ambiguities aside, explicit observation and recording of relatively obvious STs (e.g., Fig. 2) should continue to become more specific and thorough, given greater awareness of them and the near-ubiquity of electronic recording devices for storm observers and the public at large. This offers a clear benefit in terms of documentation and understanding of the phenomenon, but also, some challenges.

Consistent resolution and description of STs is desirable for *Storm Data* and ONETOR. Existing tornado databases offer inconsistent means of ST documentation, from textual only to detailed path descriptions to complete omission. As noted above, ONETOR also contains only beginning and end points for paths, which can grossly misrepresent strongly curved tracks such as those common to STs. Finer texturing of tornado-path data (proposed by Edwards et al. 2013) would help, including 1) explicit segregation of STs from MTs such as Speheger et al. (2002) performed for the 3 May 1999 event, 2) integrated (as opposed to point) characteristics, and 3) consistently formatted metadata. These best practices would enable explicit sorting of tornado types and behaviors where possible. This would not reconcile all MVMC ambiguities on the tornado-vortex spectrum, but at least would parse the clearly distinct STs for both database accuracy and targeted research.

Storm spotters and conscientious chasers can be highly valuable to the integrated warning system (Doswell et al. 1999). Their safety already is at an enhanced level of risk from other thunderstorm- and road-related hazards, and is jeopardized further by STs. Positioning close to the MT, at or within the radius of the boundary-layer mesocyclone, leaves the observer vulnerable to being struck by an ST—as with a VORTEX crew on 8 June 1995. Fast translational speeds of some STs around the parent storm-scale circulation, the potential for them to form overhead and without notice, and the natural tendency of observers to fixate on the MT, all contribute to this risk. While keeping a safe viewing distance always is encouraged for storm observers, extra strategic caution and keen, 360° visual awareness of storm behavior should be taught in spotter training and maintained by observers for meteorological settings forecast to support a risk of violent tornadoes.

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