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Remotely Visible Width and Discontinuity of 50 Tornado Damage Paths through Forested Landscapes

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ABSTRACT

Tornado damage-path width is a necessary component for calculation of area impacted, which allows estimation of hazards. To date, rarely has variation in damage path width or path discontinuity been a focus. In this paper, using a damage threshold of >25% canopy damage, we quantify width and discontinuity in 50 tornado paths in forested areas. Tornado-path starting and end points were overlaid on Google Earth imagery obtained ≤24 months after the tornadoes, and damage-path width (or absence of damage) was measured for severities >25% canopy loss, at fixed intervals. Width was measured only where both sides of the damage path were clearly defined by forest tree damage, thus many points were excluded from our analysis. Given our threshold level of forest canopy damage, no EF0 tornadoes showed remotely visible damage, and analyses were thus restricted to ≥EF1 tornado paths. Variation in remotely visible damage width was quantified as coefficient of variation, which ranged from 0.227 to 0.852, with a mean of 0.531 among the 50 paths. Discontinuity in remotely visible damage also varied among damage paths; up to 45% of the total number of measured points within a path lacked visible damage. Almost 40% of tornado damage paths exhibited such discontinuity along 20% or more of their path length. We suggest that the long, narrow EF-scale contours (particularly for ≥EF1) often reported after storm surveys may mask extensive width variation in severe damage and substantial portions of tornado paths with no severe damage.

1. Introduction

To understand the extent of tornado impacts on landscapes and the risks windstorms pose, we must understand the characteristics of tornado damage paths. To better characterize tornado damage paths, the length and width must be known (Schaefer et al. 2002; McCarthy 2003), yet there have been few studies on damage-path width. The studies that have focused (at least in part) on damage-path width (Brooks 2004; Elsner et al. 2014; Agee and Childs 2014; Strader et al. 2015) concentrated on comparing overall path widths between EF-scale categories (WSEC 2006; Edwards et al. 2013), with little attention having been given to width variability in a path. Similarly, there has been limited quantitative interest in documenting tornado-path discontinuity, even though it is a well-recognized occurrence (e.g., Johns et al. 2013).

The starting point for most research on this topic is the national tornado database maintained in *Storm Data* (published by NCDC, now NCEI), which contains the information gleaned from post-storm damage surveys. Among the data reported to *Storm Data* are estimates of the maximum EF scale observed, damage-path starting and ending points, and maximum path widths. National Weather Service (NWS) directives charge the local warning forecast offices with primary responsibility for investigating tornado damage (NOAA 2003). WFOs are directed to "ideally" initiate a post-storm damage survey the morning after an event. Damage is surveyed at a variety of locations along a damage path, by a team made up primarily of meteorologists but preferably to include structural engineers. Survey team

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members evaluate the level of damage to arrive at an EF-scale rating for each survey point, and typically document the structure's appearance and location using camera and GPS units. However, no specific instructions are given for where the survey points should be within a damage path. The directive document (NOAA 2003) emphasizes the perishability of some of the information that can be gathered immediately after a tornado event, urging survey teams to move quickly, but also clearly acknowledging that surveys must be done within the time allotted, often a few days. Once the field component is completed, the survey team develops a map of the damage using the survey points, most recently utilizing the online Damage Assessment Toolkit (DAT; Camp 2008): an online, GPS-enabled tool administered by the NWS for recording and analyzing observations of damage in a post-storm survey. These practical constraints of necessity limit the number of distinct points examined during ground surveys, with resulting risks of severe damage or maximal width locations being missed, particularly in remote areas.

To illustrate the consequences of these practical constraints, we examined a haphazard sample of ten Georgia and Alabama 2014 tornado tracks extracted from the DAT (Table 1). We used the "ruler" tool within the DAT to measure distances between damage survey points or tight clusters of points; of interest was the frequency and magnitude of large distances between adjacent survey points. The maximal distances between points in the ten tornado tracks were often >5 km, showing ample opportunity for width variation to be characterized incompletely.

Because the goal of comprehensive surveys must be balanced against limited time and manpower, NOAA (2003) recommends aerial surveys to complement ground surveys whenever possible. Aerial surveys can be completed in some areas at low or no cost due to agreements between NWS and the Civil Air Patrol. While aerial surveys cannot provide the detailed, fine-scale damage assessments of ground surveys, they offer a mechanism to survey difficult-to-access locations, can clearly indicate the most severely damaged locations within a damage path, and can confirm damage-path continuity or gaps. Nonetheless, aerial damage surveys remain optional rather than standard, in part because aerial resources have not been available for all tornado paths.

Due to the sometimes sparse nature of data recorded by the NWS storm-survey teams on path widths and discontinuities, estimates of area impacted may be imprecise. Imprecise measurements, in turn, may compromise calculation of hazards, as well as non-

Table 1: Distances between adjacent damage indicator points for ten 2014 Georgia and Alabama tornadoes in the Damage Assessment Toolkit.

Tornado number	Date	State and County	Greatest inter-point distances (km) (up to four)
547198	14 October	GA, Fulton	3.11, 2.93, 2.47, 1.10
518593	15 May	GA, Banks	2.58, 2.26, 1.53, 1.44
511203	29 April	GA, Whitfield	3.27, 0.84
496343	11 January	GA, Cherokee	2.72, 1.28
550480	23 November	GA, Lamar and Butts	12.69, 6.74, 5.08, 4.96
549832	23 November	GA, Monroe	9.71, 9.05, 3.88, 2.69
545640	13 October	AL, Marion	5.02, 3.28, 0.68
522872	29 April	AL, Marion	4.81, 3.19, 3.11, 0.73
522933	29 April	AL, Tuscaloosa	7.39, 5.31, 1.97, 1.51
548896	17 November	AL, Pike and Crenshaw	9.44, 7.56, 6.56, 4.76

meteorological quantities of interest such as area of forest damaged (e.g., Cannon et al. 2016). The variability in damage-path width as well as discontinuity through forested landscapes was the focus of our study. Utilizing tornado damage paths through forested terrain offers several advantages for a study on tornado damage (Forbes 1998; Fujita 1989; Blanchard 2013), and while tornado damage in forested areas may be difficult to assess in person, the use of remote imagery circumvents such impediments. Forests provide a dense, contiguous canopy of trees, which allows for much more high-resolution measurement of damage-path characteristics than in residential or suburban neighborhoods (Karstens et al. 2013; Kuligowski et al. 2014). For example, single-family homes (the most common EF-scale damage indicator) are typically spaced from ten to hundreds of meters apart, whereas forest canopy trees typically have an average spacing of 4–6 m apart.

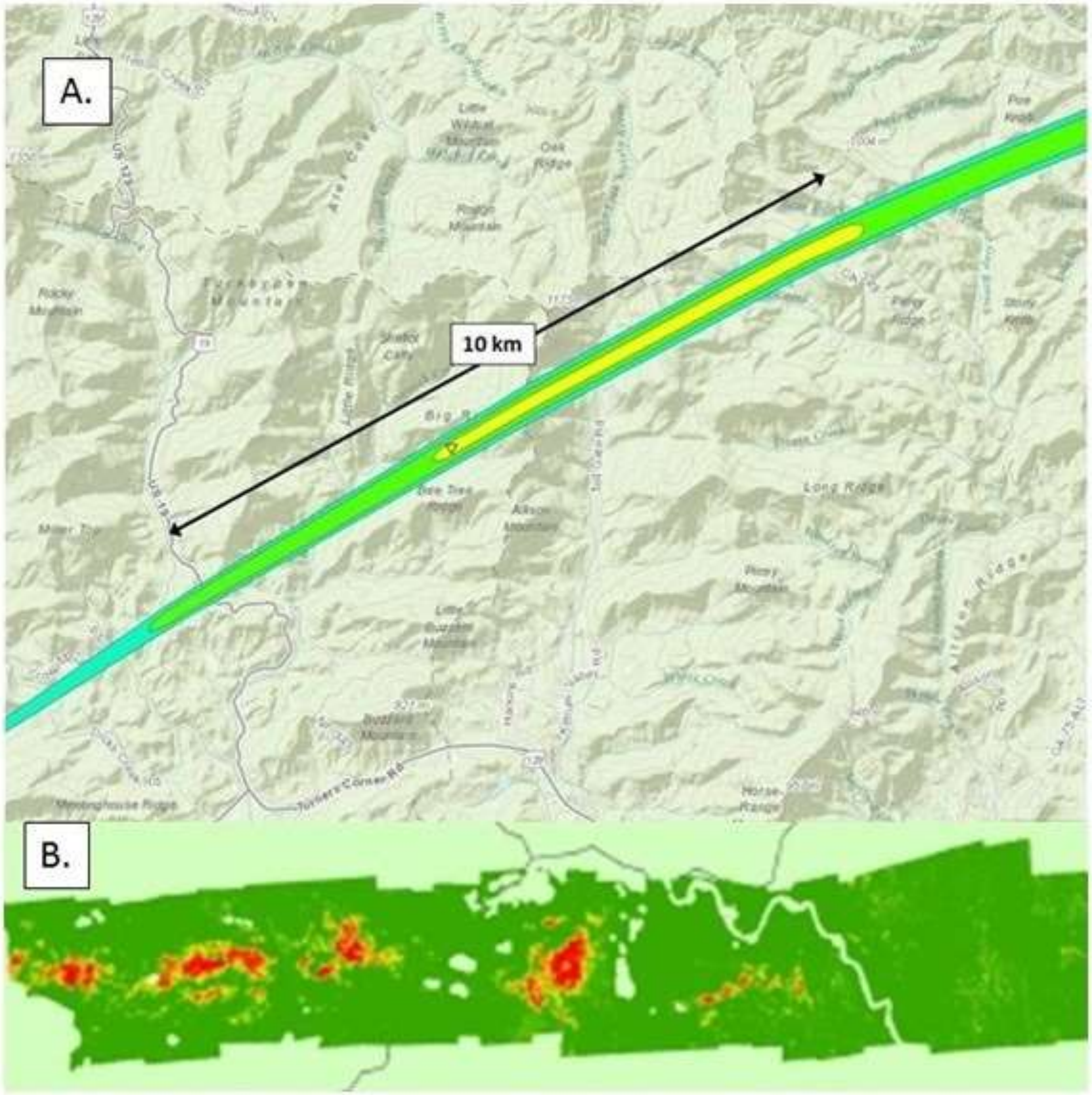
Beyond the relative lack of quantitative examinations of width and discontinuity, an additional motivation for the research reported herein was recent analyses of two tornado damage paths through forested and mountainous terrain. Cannon et al. (2016) performed GIS analyses of aerial imagery (20-cm pixel resolution) of two of the 27 April 2011 tornadoes, revealing striking patchiness (discontinuity), and extreme variation in width of the tornado damage path through densely forested areas of the southern Appalachians (Fig. 1). To determine if such patterns are typical, we could find no published meteorological studies that quantified variation in damage-path width, and very few attempts to quantify discontinuity (e.g., Johns et al. 2013). Better estimates of discontinuity and variability in width are necessary to accurately estimate area impacted, as well as various hazards (e.g., Ashley et al. 2014; Strader et al. 2015). Figure 1 illustrates the discrepancy between the rather uniform and continuous damage polygons typically reported (Fig. 1a), and the reality of highly patchy and discontinuous forest damage observed (Fig. 1b). Clearly, basing calculation of area impacted and hazard on Fig. 1a could be inaccurate at best and misleading at worst.

A final impetus for examining damage-path width and discontinuity is that improving knowledge of tornado damage paths through forests will inform how windstorms affect the carbon cycle after impacting large forest areas. One of the greatest uncertainties in modeling continental-scale carbon cycling is the lack of knowledge on how forest disturbances (e.g., fire, windstorms, insect outbreaks) affect carbon uptake and release into the atmosphere. Better prediction of carbon trends in coming decades will depend on filling in these gaps in our knowledge, and such improvements will require more-accurate estimates of forest area affected by tornadoes and other windstorms.

The near-absence of related studies in width variation or extent of discontinuities provides little basis for formulating expectations. Both Brooks (2004) and Elsner et al. (2014) reported that damage-path maximum width and total length both increase with increasing F or EF scale. Although neither of those two studies explicitly reported a positive correlation between length and width, the mutual increase with EF scale suggests that length and width may be correlated. Elsner et al. (2014) presented box-and-whisker graphs of tornado-path widths showing greater width variability in wider damage paths.

Johns et al. (2013) reported that the infamous 1925 “Tri-State tornado” had a total length of 378 km, and exhibited 32 gaps >1.6 km long across its length, for a total of 124.6 km in gaps, or 33% of the total length (Johns et al. 2013). The Johns et al. study was conducted >80 y after the event, and if data had been collected soon after the event, conclusions about gaps may have differed. While they concluded that some gaps indicated dissipation of one vortex and formation of the next, in some cases, gaps were interpreted to be a part of a continuous tornado.

Although we cannot say whether gaps in our data actually indicate a single or multiple serial tornadoes, it is difficult to imagine that the 6–8 “bulls-eye”-shaped damage patches shown in Fig. 1b represent many separate tornadoes within 10 km. Johns et al. (2013) did assume that wider damage paths near gaps implied that the tornado was continuous; on the basis of their assumption, we may expect that damage-path width and amount of discontinuity will be negatively correlated. Based on all of the above, our tentative expectations are that: 1) wider damage paths will show greater width variability; 2) tornadoes with higher EF-scale ratings will have wider damage paths; 3) damage-path length and width will be positively correlated; and 4) wider damage paths will have less of the total path length in discontinuities.



<u>Figure 1</u>: Comparison of the damage polygon (from the Damage Assessment Toolkit) of the 27 April 2011 tornado in Chattahoochee National Forest, GA, with quantified forest damage determined from GIS analysis of aerial photos. a) DAT screenshot of ≈15 km near the beginning of the damage path—blue, green and yellow portions of polygon represent estimated EF0, EF1 and EF2 damage, respectively. The triangle indicates a post-storm damage-survey point. b) Graphic from Cannon et al. (2016) showing extreme variation in damage path width and extensive discontinuity. Path segment in (b) covers roughly the portion of (a) indicated by the thick black arrow. Color-coding in (b) indicates severity of forest canopy damage, ranging from green (undamaged) to yellow (>20% damage) to red (>90% damage). Dark green represents undamaged forest in aerial photographs obtained in July 2011 [path rotated clockwise in (b) to save space].

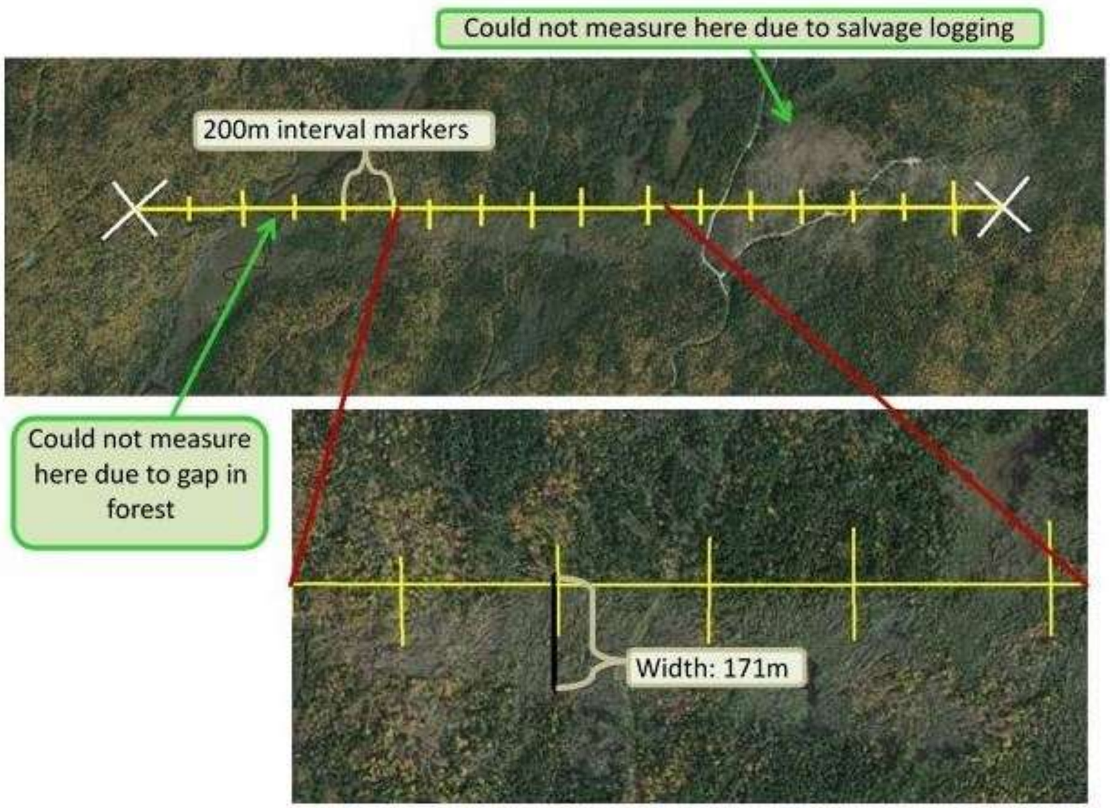


Figure 2: Tornado damage-path width measured at regular intervals as marked on Google Earth. Locations along the path that were not forested or where the damage path was altered were not measured. Width was measured perpendicular to the general path direction (horizontal yellow lines). While large changes in path direction would cause width overestimation, such substantial directional changes were rare.

2. Methodology

The data on all recorded tornadoes from 2011 through 2014 were extracted from the national tornado database derived from *Storm Data*, and accessed via the Storm Prediction Center website (http://www.spc.noaa.gov/wcm/#data). Using the reported starting and ending points, each tornado path was located in Google Earth. If the default images in Google Earth were from >2 y after the tornado, forest regrowth began to obscure the damage path and therefore imagery <24 months post-event was sought. We set a threshold of 25% forest-canopy damage to differentiate damaged from undamaged areas. If the tornado path was visible as damage through forested areas, the width of the damaged path was measured at regular intervals, beginning from its start (Fig. 2). All measuring was performed manually using the ruler tool found on Google Earth. Initially, measurement intervals varied from 200–500 m, depending on if the length of damage path was less than or more than 9 km respectively; as analyses proceeded, it became clear that the more closely spaced measurement intervals better represented the width variation in damage paths, and all subsequent paths were analyzed with 200-m measurement intervals. The damage path's width was only measured if both edges were clearly defined by forest tree damage (i.e., the area between these edges had >25% forest-canopy damage; Fig. 2). If an edge of a damage path could not be seen clearly because of lack of trees, due to a body of water or human development, then the width was not measured at that point along the path, and a "CNM" (cannot measure) was recorded for that point. Consequently, substantial portions of many tornado paths were excluded. Measurement points that were well-forested but without any remotely observable damage along the tornado path were assigned a path width of zero. Note that this approach in all likelihood does not detect minor damage (e.g., defoliation or loss of small branches), and therefore quantifies only

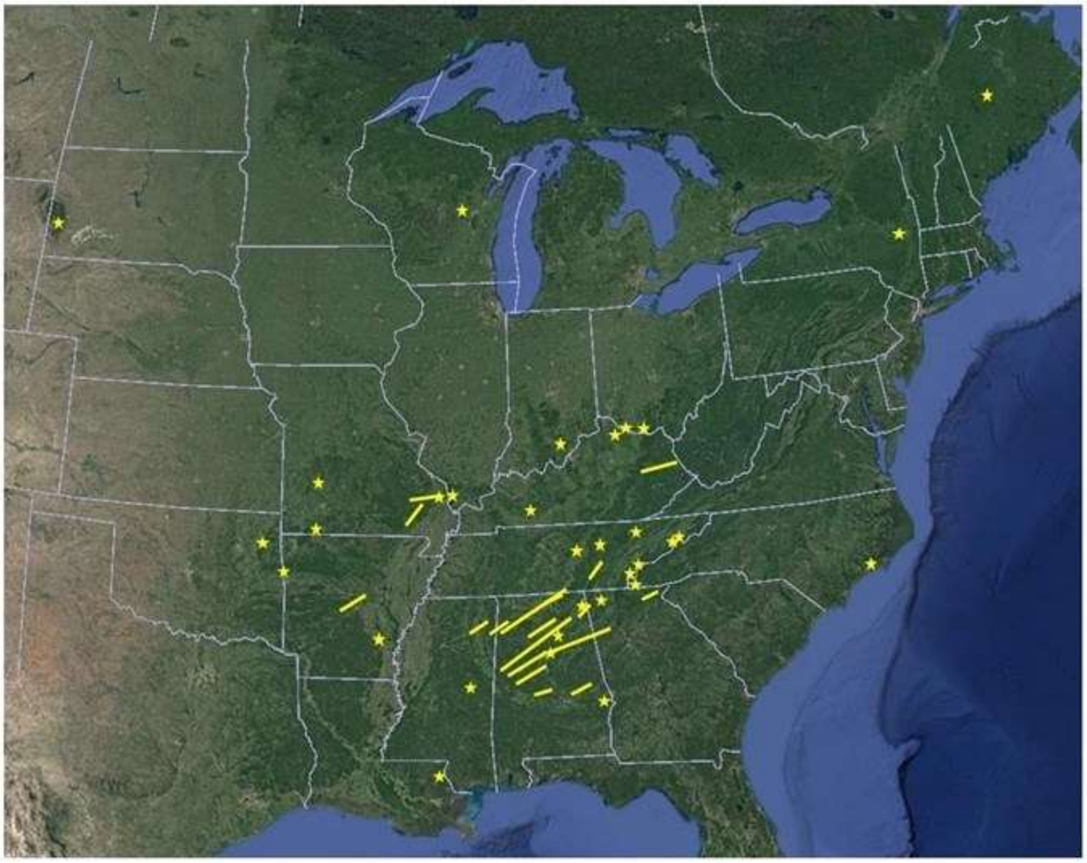


Figure 3: Locations of the 50 tornado damage paths reported herein. Shorter paths marked with a star, longer paths with a line.

damage that is remotely visible as >25% canopy loss. Thus, the true maximal extent of damage is undoubtedly somewhat wider than the measurements reported here; a potential correction factor is discussed below.

While measurements in this initial study simply were recorded in an Excel spreadsheet, future work could save measurements within Google Earth as a KML file to facilitate additional reproducibility of the research. Note also that this approach results in width measurements (when possible) at regular intervals, potentially yielding many estimates of width (longer damage paths in our analyses had >300 width measurements). This likely contrasts with widths derived from fewer locations in traditional ground damage surveys—Fig. 1a shows only a single damage survey point in the roughly 15 km encompassed by the DAT screenshot. McCarthy (2003) points out that reporting mean damage-path width (prior to 1994) required many more width measurements (to calculate the mean), whereas the switch in 1994 to recording maximum path width requires fewer width measurements.

Although >1000 tornado paths from the database were reviewed for use in our study, due to measuring constraints outlined above, only 48 of these were suitable for use; they were combined with two additional tornado paths studied in Cannon et al. (2016) to yield a total of 50 paths (Fig. 3; see state-scale path locations in Appendix). These select tornado paths were found across 17 states and ranged in severity from EF1–EF5; EF0 tornado paths did not exhibit damage severe enough to be visible in the Google Earth imagery and therefore were excluded. Consequently, the conclusions presented here are based on tornado damage paths rated EF1–EF5. EF0 tornadoes produce modest tree damage such as defoliation and/or small-branch removal, or fall of widely scattered, highly vulnerable trees. Such damage is usually not visible in aerial imagery, although it would be discernable from the ground to observers in the forest (Peterson, personal observations). We suspect therefore that our 25% damage threshold corresponds roughly to lower-to-mid-range EF1 damage. This perspective is supported by the fact that while the American EF scale does not consider proportion of trees down in a given area as an official degree of damage, in the Canadian EF-scale criteria, 20–50% of trees downed is a DoD 4, corresponding to expected wind speeds of 93 mph (42 m s^{-1}), near the middle of the EF1 range of wind speeds (Sills et al. 2014). Note that with this approach, it is impossible to determine if forest areas varied in tree-species composition or other characteristics; thus, some variation in damage-path width could have resulted from the vortex striking areas with trees of greater vulnerability or greater wind firmness. Research continues in order to quantify inherent variation among species in wind resistance (Peterson and Claassen 2013; Cannon et al. 2015).

To calculate tornado-path percentage lacking remotely visible damage, the number of "internal" (i.e., bracketed by positive width) measurement intervals that had zero width was divided by the total number of "internal" points that were measured in the path. More precise and objective examination of discontinuity is possible via GIS analysis of higher-resolution imagery such as was done in Cannon et al. (2016). The total number of measured points for each path does not include points that were excluded from measurement due to lack of forest. Coefficient of variation (CV, standard deviation divided by mean) was used to compare variability in width of remotely visible damage between tornado paths while controlling for large differences in mean width.

Table 2: Summary statistics and characteristics of 50 tornado damage paths used in analyses.

Tornado number	State	Start lat.	Start long.	End lat.	End long.	EF	Re-ported length (km)	Re-ported max. width (m)	Mea-sured max. width (m)	Mea-sured mean width (m)
301829	AL	34.391	85.978	34.766	85.524	5	58.9	1207	1225	477
301925	AL	34.621	85.981	34.843	85.580	4	44.6	1152	696	291
301943	AL	34.076	87.010	34.494	86.363	4	75.5	805	337	257
307109	AL	33.251	88.181	34.283	86.349	4	205.7	1287	811	406
309488	AL	34.104	88.148	35.086	86.151	5	212.4	2012	301	97
314625	AL	33.030	87.935	33.631	86.744	4	129.9	2377	727	384
314725	AL	32.615	88.054	33.152	86.990	3	116.0	1609	770	393
314829	AL	33.679	86.570	34.190	84.990	4	156.6	1609	1178	406
315331	AL	32.617	86.193	32.920	85.523	4	71.1	805	998	426
316096	AL	34.760	86.953	34.948	86.399	3	54.7	229	143	101
364295	AL	33.623	86.741	33.720	86.496	3	25.3	732	665	221
364350	AL	32.716	87.275	32.876	86.632	2	64.1	805	684	280
522952	AL	33.586	87.005	33.628	86.932	2	8.9	1646	473	294
523250	AL	32.465	85.234	32.568	85.080	3	18.3	1097	824	415
355495	AR	34.193	91.727	34.319	91.473	2	27.4	274	580	179
504758	AR	34.779	92.652	35.142	92.079	4	66.1	1207	615	176
305268	GA	34.874	85.178	34.987	85.048	4	17.2	536	1163	609
306267	GA	34.666	83.943	34.927	83.379	3	59.5	823	1278	423
359708	IL	37.556	89.521	37.611	89.167	2	31.9	274	656	176
359390	IN	38.515	85.876	38.541	85.759	1	10.6	55	953	764
368695	KY	37.905	83.615	38.033	82.535	3	95.8	1445	770	354

Table 2: Continued.

Tornado number	State	Start lat.	Start long.	End lat.	End long.	EF	Reported length (km)	Reported max. width (m)	Measured max. width (m)	Measured mean width (m)
369380	KY	38.835	84.353	38.859	84.233	3	10.8	402	317	138
424832	KY	37.060	87.054	37.120	87.000	2	8.2	297	145	105
298933	LA	30.615	90.049	30.635	89.954	3	9.8	137	214	117
467638	ME	46.203	69.100	46.189	69.060	1	3.4	274	431	170
307045	MO	36.815	90.849	37.349	90.310	3	76.3	1097	568	286
364194	MO	36.622	93.460	36.658	93.024	2	39.1	366	262	110
365575	MO	37.398	90.533	37.509	89.886	2	51.3	732	875	357
368234	MO	37.469	89.905	37.481	89.766	2	12.4	110	80	51
422623	MO	37.976	93.611	38.025	93.466	1	13.8	366	216	133
303562	MS	34.045	88.445	34.323	87.892	5	59.7	1207	636	188
309257	MS	32.799	89.109	33.020	88.697	5	45.5	823	598	180
515209	MS	34.226	88.824	34.473	88.371	3	49.9	402	376	257
291732	NC	34.950	77.010	34.988	76.956	2	7.6	183	206	70
366756	NC	35.094	84.264	35.117	83.885	2	34.6	366	875	197
445879	NY	42.846	74.203	42.801	73.801	2	20.6	1609	131	65
369380	OH	38.859	84.233	38.898	83.986	3	22.0	402	273	101
370174	OH	38.811	83.518	38.842	83.316	2	17.9	302	352	179
422660	OK	35.605	94.498	35.704	94.394	1	14.5	640	354	142
436302	OK	36.375	95.079	36.401	95.025	1	5.6	320	69	45
475901	SD	43.904	103.59	43.886	103.58	1	2.1	27	386	198
297632	TN	36.106	82.702	36.205	82.491	3	21.9	914	335	239
300459	TN	35.340	85.420	35.680	84.870	4	64.7	805	1070	479
347518	TN	36.035	82.808	36.150	82.573	3	25.4	1372	766	461
353666	TN	35.532	84.050	35.663	83.846	4	23.2	1207	853	419
362592	TN	35.972	85.853	36.017	85.593	1	23.8	183	205	89
362596	TN	36.089	85.110	36.117	85.005	2	10.0	274	255	116
374085	TN	35.368	84.306	35.441	84.068	2	23.0	366	839	300
526284	TN	36.469	83.977	36.437	83.903	3	7.6	732	310	147
459677	WI	44.349	88.838	44.324	88.643	1	15.9	114	164	87

3. Results

The 50 tornado paths (Table 2) ranged in reported length from 2.1–205 km, with mean (± standard deviation) of 43.6 ± 44.4 km. Reported maximum widths ranged from 27 to 2377 m, with mean of 741 ± 546 m. Mean measured width of remotely visible damage varied from a low of 44.9 m (for a given path) to a high of 764.1 m. The least-variable damage path had a CV in measured width of 0.227, while the most-variable damage path had a CV of 0.852; across all 50 damage paths, the mean CV for measured, remotely visible width was 0.531 (± 0.145). Wider tornado paths tended to have less-variable damage-path widths: $r = -0.278$, $p = .051$, where r is Pearson correlation coefficient; p is probability of Type II error; Fig. 4). There was also a slight trend toward less discontinuity in wider damage paths (correlating measured mean

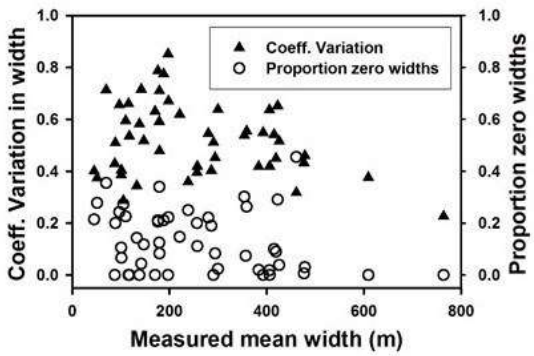


Figure 4: Coefficient of variation (CV) in measured width (black triangles), and proportion of measured points with zero width (discontinuities, open circles) as a function of path mean measured width for 50 tornado-damage paths in forested landscapes.

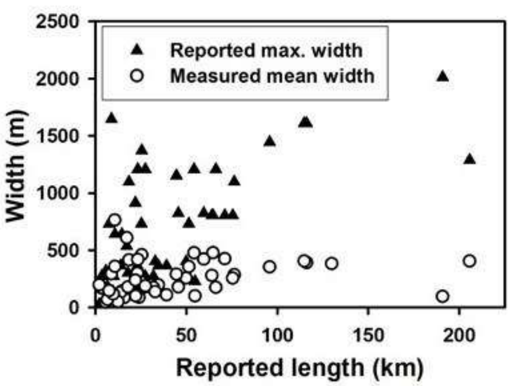


Figure 5: Reported maximum width (black triangles) and measured mean width (open circles) as a function of reported total path length for 50 tornado damage paths in forested landscapes.

Reported tornado-path length was not correlated with mean measured remotely visible width ($r = 0.238$, $p = .096$, Fig. 5), CV in measured width ($r = 0.034$, $p = .814$), or proportion of path length undamaged ($r = -0.086$, $p = .551$), although reported length and reported maximum width were highly correlated ($r = .683$, $p \ll 0.01$).

The mean width of remotely visible damage differed significantly [nonparametric analysis of variance on ranks (Zar 2010), $p = 0.014$] among EF-scale ratings (Fig. 6), with EF4 damage paths being the widest. Because wider tornadoes produced somewhat less-variable paths, those in higher EF-scale categories may be expected to have less variation in width, but the data do not show a significant trend (Fig. 6).

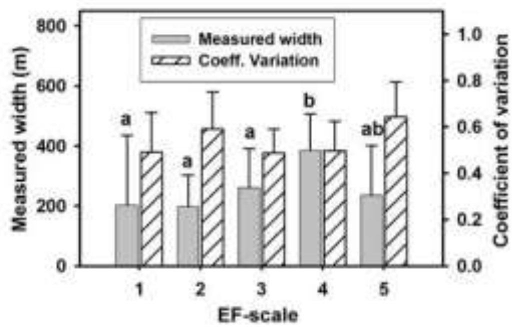


Figure 6: Mean and standard deviation of measured widths and CV in width for 50 tornado paths, by EF-scale rating. Sample sizes were: 8 EF1, 14 EF2, 14 EF3, 10 EF4, and 4 EF5. Error bars represent one standard deviation about the mean. Letters above bars indicate which width means differ significantly by nonparametric ANOVA.width with proportion zeroes, $r = -0.247$, $p = .084$). The proportion of a damage path with a remotely visible damage width of zero (i.e., lacking severe forest damage) varied from none to 45% of the measurement points in a given tornado path; the mean proportion of such points was 13% (± 11.8%). Nineteen of the 50 investigated tornado paths were undamaged along 20% or more of the measurement points.

4. Discussion

Although the tornado-research community is undoubtedly well aware that tornado damage paths often exhibit substantial variability in width, and long sections of a path may lack severe damage, to date there have been few attempts to measure such features. Our preliminary study begins to address such knowledge gaps, but these findings must be interpreted within the limitation that the methods used here are unlikely to detect the slight damage expected from low-end tornadic winds, and thus these results apply only to areas with ≥25% forest canopy damage.

Because the EF scale specification (WSEC 2006) does not speak to the proportion of forest canopy damaged, it is not possible to equate the damage levels reported here rigorously to any particular EF-scale category, although we suspect that our damage threshold roughly corresponds to lower-to-midrange EF1. To help place these findings in the context of published research that includes EF0 damage, Table 3 presents width data derived from five well-studied tornado damage paths. For each of the five tornado paths, the EF1 and EF0 damage-path width were measured at 200-m intervals on the published damage contour maps, and an EF0 / EF1 ratio calculated. Multiplying the damage-path widths reported in this study by such ratios would allow estimation of potential EF0 damage width that our method did not capture. Thus, the mean ratio across the five tornadoes in Table 3 is 2.25, suggesting that EF0 damage widths typically may be ≈225% of the widths of EF1 damage. Therefore, since the widths reported here are based on a 25% forest-canopy damage threshold, the damage-path width that encompasses all damage (even very slight) may be 225% of the remotely visible damage reported here.

Some of our findings agree with the few published studies of widths or discontinuities. For example, similarly to Brooks (2004) and Elsner et al. (2014), we found tornadoes of higher EF scale tend to leave paths of greater remotely visible width; although there is considerable overlap. However, we did not find any significant correlations of damage-path length with mean width, variation in width, or amount of discontinuity. Considering those studies and Strader et al. (2014), the lack of correlation between length and width may have been the result of a modest sample size. As suggested by Brooks (2004), length may be a rough indicator of width, but the relationship between length and width only emerges in large samples.

The data most commonly used in studies of tornado length and width (Brooks 2004; Elsner et al. 2014; Ashley 2014; Strader et al. 2014) are derived from post-event damage surveys, available through the *Storm Data* database. However, storm-survey teams often have faced numerous practical hindrances, such as inadequate time and difficult or restricted access. Those may severely limit the number of locations where the storm-survey teams can determine damage levels, path width and/or discontinuity. Moreover, there is a justifiable emphasis on recording damage to structures, although the result of such an emphasis may be that areas (such as forests) with few or no structures get little attention in storm surveys (Edwards et al. 2013). Consequently, reported width measurements conveyed to *Storm Data* may be based on only a small percentage of the actual damage path. If the locations are widely spaced, storm-survey teams entirely may miss wider segments of the damage path that are in between the surveyed points. Similarly, width measurements at widely spaced intervals may miss substantial discontinuities completely (Fig. 1). These factors together contribute to incomplete representation of tornado damage paths, and make obvious the advantages of including aerial or satellite imagery to complement ground-based damage surveys.

Table 3: Damage-track widths at EF1 and EF0 levels for five well-studied tornado damage paths.

Tornado	Citation	Mean EF 1 (± std. dev.) (m)	Coeff. Varn. EF1	Mean EF0 (± std. dev.) (m)	Mean EF0 / EF1 ratio*
Teton-Yellowstone, WY, 1987**	1	924 ± 851	0.92	2302 ± 777	3.84
Kellerville, TX, 1995**	2	578 ± 228	0.39	958 ± 448	1.66
Joplin, MO, 2011	3	724 ± 308	0.42	1268 ± 563	1.83
El Reno, OK 2013	4	1394 ± 881	0.63	3279 ± 1767	2.42
Newcastle-Moore, OK, 2013	5	491 ± 245	0.50	715 ± 319	1.51

*Using only measurements with positive width for both EF1 and EF0 damage.

**Damage severity based on F-scale.

(1) Fujita 1989; (2) Wakimoto et al. 2003; (3) Marshall et al. 2012; (4) Wakimoto et al. 2016; (5) Burgess et al. 2014

Aside from the practical constraints on field surveys, these results also highlight the limitations in the current use of a single number to summarize tornado damage level or width. The amount of variation found within a path is sufficiently high that a single measurement is not enough to characterize the damage path accurately for purposes that involve calculation of area impacted. An effective representation of tornado damage-path width needs a higher-resolution survey that includes multiple width measurements along each path, as well as a mechanism for reporting the variability in such measurements. Numerous, accurate width measurements can be made rapidly using remote imagery, either via manual inspection as done here, or through GIS analyses. Using aerial or satellite imagery allows surveyors to circumvent access impediments to damaged areas, and readily exposes discontinuities in the damage path. In fact, with rapid advances in resolution of satellite imaging (e.g., Womble et al. 2016), and steady reduction in satellite-image pricing, the door may be opening to bypass aerial imagery and make widespread use of satellites for remote damage assessments that complement and extend ground surveys.

The majority of investigated tornado paths include obvious discontinuity, possibly resulting from several distinct, serial tornadoes that formed from the same parent storm (Johns et al. 2013). The obvious implication is that the area impacted is actually less (sometimes substantially so) than estimates based on some version of “length × width”. The data presented here hint that such overestimates may be smaller in wider and more intense tornadoes, but rigorous demonstration of such a trend awaits analyses with larger sample sizes.

The great width variation reported here may result from a variety of causes. A thorough discussion of these is beyond the scope of our paper. Nevertheless, variation in damage-path width could result from at least three processes beyond simply variation in the radius of the vortex itself. Karstens et al. (2013) documented damaged areas that, based on direction of treefall, resulted from either rear-flank downdrafts, or channeling of high-velocity inflows along narrow valleys and ravines. The effect the valleys and ravines had on wind flow led Karstens et al. (2013) to suggest that observed variation in damage path width may be influenced by local topography. A third possibility is that some of these damage paths result from multivortex tornadoes. The procedures used here do not allow that distinction, but combining the methods used here with analysis of treefall direction (e.g., Fujita 1989; Karstens et al. 2013) may reveal the effects of vortex number (single or multiple) on variation in damage-path width.

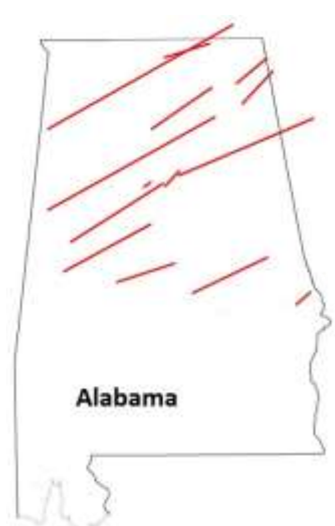
Tornadoes with a greater mean width leave more regular damage paths. Wider paths tended to have fewer undamaged portions and were more continuous. Since EF4 and EF5 tornadoes tend to be wider (Brooks 2004), a potential inference is that more-intense vortices may fluctuate in diameter less than weaker tornadoes. Nevertheless, tornadoes of all sizes and intensities vary substantially in the levels of damage caused, even over quite small spatial scales (Fig. 1b). Calculations of risk therefore will have wide errors on parameters, and must be made and interpreted with caution.

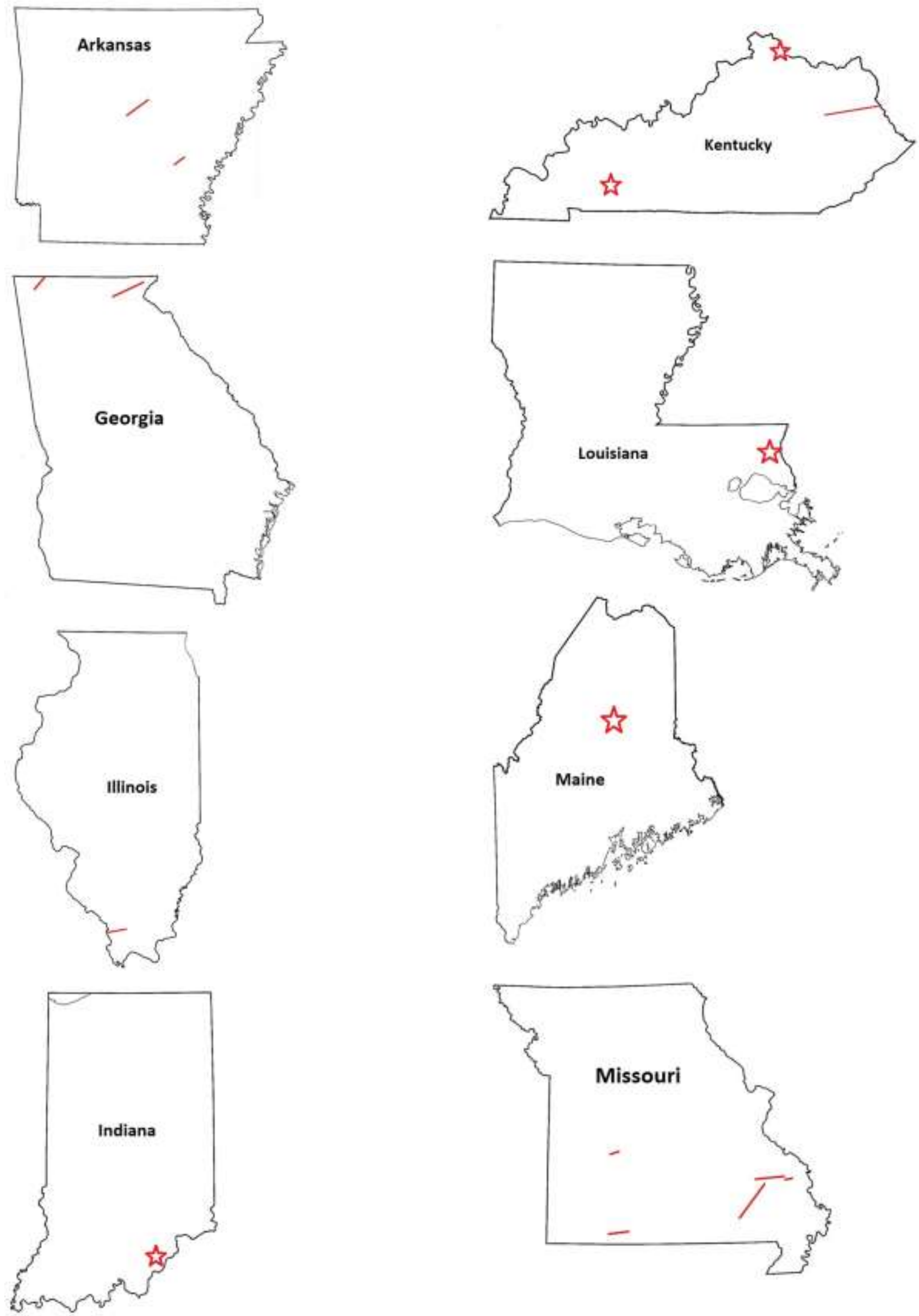
ACKNOWLEDGEMENTS

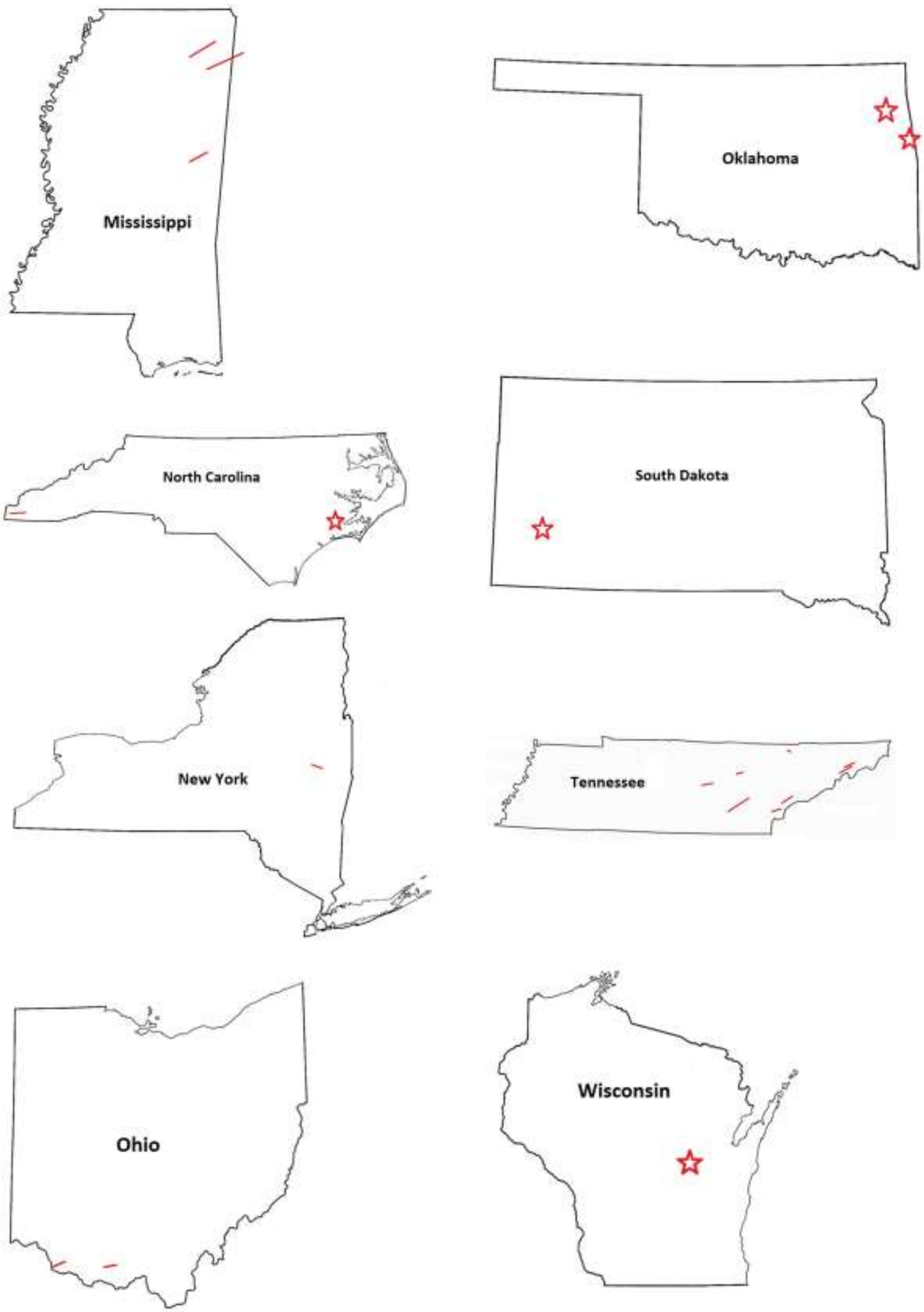
The authors would like to thank NOAA for their support during preparation of this manuscript through VORTEX-SE grant NA150AR4590229.

APPENDIX

State-scale maps of tornado tracks used in the analyses are reported here. Tracks long enough to appear linear at this scale (varies depending on size of state) are shown as lines, short tracks as stars.




Arkansas
Kentucky
Georgia
Louisiana
Illinois
Maine
Indiana
Missouri


Mississippi
Oklahoma
North Carolina
South Dakota
New York
Tennessee
Ohio
Wisconsin

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Donald W. Burgess):

Initial Review:

Recommendation: Accept with major revisions.

Main point 1: Throughout the manuscript, the authors equate remotely sensed forest/tree damage [sometimes sensed as much as two years (perhaps longer) after occurrence] as documenting all damage caused by the tornadoes they study. They offer no proof via reference to back the claim. The only possible reference would be Cannon et al, a manuscript still in the review process…the exception being where they state that, "EF0 tornado paths were found generally without damage and excluded due to their small size and low intensity." This apparently leads the authors to the conclusion that EF0 tornadoes don't damage trees, but EF1 tornadoes damage trees enough that the damage is still visible years after occurrence, a conclusion with which I strongly disagree.

Several items need a response here. First, we acknowledge that our wording about the age (time elapsed after tornado) of the images we used was not explained clearly, and have addressed that. All imagery used was <24 months after the tornado. Second, see below for further information about the Cannon et al. (2016) paper. Third, upon reading this criticism, it is now obvious that we did not make clear what we intended, which was to state that these findings only apply to damage >25% of forest canopy. Certainly EF0 winds cause modest levels of damage, and we did not intend to imply otherwise. Our intent was to convey that we could not find damage paths in forest with >25% of canopy damaged, when examining the tracks of tornadoes rated as EF0. See in particular opening paragraph of Discussion. Fourth, it is noteworthy that for the two tornado tracks that were analyzed in the Cannon et al. (2016) paper, we documented a strong correlation ($r = 0.773$, $n = 73$ ground survey plots) between ground-surveyed basal area damage (a surrogate for canopy damage) and the damage severity inferred from GIS analyses of aerial imagery. While these are only two of the 50 tornado tracks, and the other 48 were analyzed somewhat differently, this correlation confirms that examination of remote imagery can in fact document levels of actual damage found from ground surveys.

Instead, in going from EF0 (65–85 mph), to EF1 (86–109 mph), and to EF2 (110–137 mph), I would expect gradients in tree damage…things like loss of a minority of small branches with EF0, increasingly larger and more tree branches (but not all trees and not all large branches) lost with EF1, uprooting/breaking of trees beginning with a few with EF1 and continuing to more (but not all with EF2). Only with EF3 winds (136–167 mph) would I expect all (or almost all) uprooted/completely broken trees. Of course, what I've just made is a general statement, and I'm sure the true result is highly modulated by tree type, age, health, terrain, and other factors. But, the point still remains: there should be gradients in damage from very little to complete. No information is furnished on the gradients and where the line seen in the aerial photography is drawn (i.e., different colors for damage/no damage seen in Figure 2).

We wholeheartedly agree with the referee that with increasing wind speeds, there will be a gradient of levels of tree damage. As mentioned above, our approach attempted to differentiate the damage track based on a threshold of greater or less than 25% canopy damage. In the Google Earth imagery, the loss of a single canopy tree can be seen where the forest canopy is dense, and when multiple trees are down, the tree trunks can be distinguished in the imagery. We are confident that our method can separate areas with >25% canopy damage from intact or lesser-damaged forest.

Based on my participation in a number of well-done surveys (see point #2), I believe that the points/lines being taken from the aerial photography for width calculation are not the edges of ~EF1 damage, but closer to the edges of ~EF2 damage. Even if I'm wrong and the points/lines do demark the beginning of EF1 damage, that still ignores all the EF0 damage that should be included in tornado width calculation. From the well-done surveys, it has been estimated that 30–70% of indicators with damage come from EF0 winds and even higher percentages when EF1 winds are added. I believe the manuscript's findings of decreased width and more discontinuities come from only surveying the stronger (~EF2+) damage area of sampled tornadoes. The manuscript should either prove that all damage is being included or back off its claims about widths and breaks in the path. The statements about and calculations of "undamaged tornado track" either needs to be proven some way or withdrawn…undamaged tornado track means NO EF0 damage.

We have modified text in several locations (in particular the opening paragraph of the Discussion), and often used the term "remotely visible damage" to remind readers that our conclusions apply to forest damage that is remotely visible, and may therefore exclude minor damage from winds in the range of EF0. We differ a bit with the referee in suspecting that our 25% canopy- damage threshold is probably mid-EF1, rather than close to EF2. But in fact currently available data on tree damage in forests does not allow this to be defined with precision; we simply do not know enough (yet!) about how forest tree damage scales with wind velocity to state succinctly whether our 25% threshold is crossed in the middle or upper end of the EF1 range, or perhaps even outside of the EF1 range. Research is underway that will give us a clearer picture within the next 5–10 y, but the relevant data are not yet available.

Main Point 2: The manuscript shows one NWS survey (Fig. 1) and compares it to the aerial survey technique being used. The text comments on the poor comparison between aerial technique and the NWS survey, and points out some of the reasons why NWS surveys are limited.

One of the major points regarding limitations to existing on-the-ground damage surveys is the often large distances between DIs. To document this, we selected a haphazard set of 10 tornado tracks from Georgia and Alabama that were available in the Damage Assessment Toolkit. Using the "measure" tool within the DAT, we measured the linear distance between single DIs or tight clusters of DIs for each of these 10 tornado tracks, and have added a new table summarizing these additional findings. For many of the tornado tracks, maximal distances between DIs exceed 3 km.

I agree that NWS surveys are limited and (without correction) should not be used for calculation of tornado-track statistics. However, there are other surveys, not referenced in the manuscript, that do more fully document tornado paths and can be used for statistical purposes. Unfortunately, there are limited numbers of well-done surveys, but they should still be referenced, used in discussion, and used to generate statistics…even corrections. Some of the well-done surveys are referenced in Burgess et al (2014, *Wea. Forecasting*), but none of those are in forested areas. A large number of well-done surveys were performed by Ted Fujita and colleagues during the 1950s–1980s. At least a few of the Fujita surveys were done in forested areas (i.e., 3 April 1974 outbreak). Fujita's students Roger Wakimoto and Greg Forbes also have contributed several well-done surveys, including in forested areas (i.e., Forbes for 31 May 1985). Hopefully, the well-done surveys (particularly the ones in forests) could be used to estimate the edges of lesser tornado damage probably not observable in the aerial technique being used in the current manuscript. If so a correction might be applied to the current calculations to better estimate the full width of the tornadoes being studied.

This last comment is a very helpful suggestion, and we have attempted to implement it. We found five publications from "well-done surveys" that presented damage track maps with isopleths delineating different EF-scale levels of damage (some, e.g., Speheger et al. 2002) pooled EF0 and EF1 damage in one isopleth and therefore were not useable. Using the damage track maps in those publications, we measured EF0 and EF1 damage width perpendicular to the tornado centerline, every 200 m. We present results in a new table in the manuscript, which allows the damage widths documented in our analyses to be placed in the context of typical greater lateral width of EF0 damage compared to EF1 damage. We included one Fujita publication and two Wakimoto publications in the five measured; the 1998 preprint by Forbes presenting findings from the May 1985 Pennsylvania outbreak does not have any damage track maps and thus cannot be used for this purpose.

Main Point 3: The details of the aerial technique used in the analysis are contained in Cannon et al. That manuscript is still in review. It's probably best not to rely on as-yet unpublished work in another manuscript. More details of the technique could be added to this manuscript, or this manuscript could be held in waiting until the other manuscript is accepted for publication.

The methods in Cannon et al were used only for the last two of the 50 tornado tracks analyzed; we therefore felt that including all of those details would unduly burden this manuscript. All of the remaining 48 tornado tracks were analyzed using the methods of this manuscript (i.e., not making use of GIS software). In regards to the other manuscript, Cannon et al. is now out; it is in the November 2016 issue (volume 31, issue 9) of the journal Landscape Ecology, pp. 2097–2114. The references and [citations] have been updated appropriately.

One good example of missing information that might be important to readers is a listing of the tornado events that were used in the analysis.

A table summarizing each of the tornado tracks has been added (see Table 2 in new version).

Main Point 4: No mention is made of multivortex tornadoes. Many tornadoes, including stronger ones, are observed (either visually or with radar) to possess multiple vortices that are responsible for some of the damage some of the gradients/gaps in damage. Are multivortex tracks observed in the aerial damage swaths? Could multivortex tracks be responsible for some of the gaps/breaks in the observed tornado paths? Not all tornadoes possess multiple vortices, but the multivortex mode of damage needs to be addressed somewhere within the manuscript.

The methodology used does not allow detection of multiple vortices. Without doubt the referee is correct to note that some of the phenomena our study documented could be due to multiple vortices, and we have mentioned this possibility in the revised manuscript.

[Minor comments omitted...]

Second Review:

Reviewer recommendation: Accept with minor revision.

Summary: The revised manuscript is much-improved from the first version. Significant new material has been added that strengthens the paper. Forest-canopy damage observed in satellite imagery is no longer equated to the entire path of tornado damage, but just EF1 and stronger damage. However, I still have a question about that conclusion (Main Point). Other than the main point, there are still a few lesser points to clean up. I will leave it up to editor's good judgement about whether more should be done in defining the beginning of forest canopy damage. I would be remiss if I did not add that I really liked the analysis (Table 3) and inclusion of the text about using other data to extend the current results to weaker tornado damage, including whatever part of EF1 and EF0...to the point of even suggesting a correction factor. Other than a final decision on the definition of the edge of canopy damage, and after cleaning up the lesser points, I think the paper is ready for publication.

Main Point: The authors conclude that the edge of observed canopy damage is the beginning of EF1 damage. It is stated that this conclusion comes from the experience of Chris Peterson. I certainly have respect for Chris and will accept that as the justification if there is nothing else upon which to support the conclusion. I was hoping to see some sort of analysis of the edge of the canopy damage (a close-up view of a representative damaged canopy edge from the ground, or a reference to a well-done ground survey that includes the damaged canopy edge, or a numerical model study of canopy damage, or something like that) to support the conclusion that the edge of the remotely observed canopy damage is the boundary of EF0 and EF1 damage. If nothing else is available beyond the experience of Chris, I would add some comment about his long number of years of experience.

We know of no analyses that could directly confirm our suspicion that the 25% canopy damage threshold is roughly the beginning of EF1 damage, mostly because our analyses are entirely in forested areas, and there appear to be no quantitative studies that quantify both level of forest-canopy damage as well as very nearby structural damage. Our thanks to referee Burgess for the above compliments, although we agree that even expert opinion based on long experience should be used only as a backup if more objective data are available. Although we know of no such analyses or data, we do spell out in the latest revision that the Canadian EF-scale implementation (Sills et al. 2014) does consider the proportion of trees down in a given area as an official degree-of-damage criterion. In the Canadian system, 20%–50% of trees down corresponds to DOD 4, with an expected wind speed of 93 mph, roughly in the center of EF1 in the American scale.

[Minor comments omitted...]

REVIEWER B (Christopher D. Karstens):

Initial Review:

Reviewer recommendation: Accept with major revisions.

General comments: This study utilizes a few statistical and geospatial techniques in developing a new method aimed at better understanding the variability of tornado damage path width and discontinuities in damage occurring along the path. The analysis highlights limitations associated with how attributes associated with tornado damage paths are collected and prioritized. The findings likely support a broad anecdotal view of *Storm Data* held by the readership of EJSSM. Nevertheless, the findings provide succinct quantification of tornado damage attribute variability that is of importance to new/cross-disciplinary research and efforts to evolve the collection of tornado damage information that informs *Storm Data* in the future. I believe the paper could be acceptable for publication pending major revisions.

Substantive comments: The authors point out that tornado damage paths exhibit considerable variability in width and intensity along the track, information that is not accurately represented in *Storm Data* or in a collection of events obtained from the NWS Damage Assessment Toolkit (DAT) for the present study. This discussion would be better balanced by adding more information detailing the procedures that NWS follows when generating these observational datasets. What resources are used to generate such information, and under what time constraints? Are there standard methods used that are part of standard training provided by NWS? Are these methods part of a directive? This investigation could yield some insight into how NWS is making their estimates and under what conditions, relative to the method proposed in the present study.

We have responded to this with two long paragraphs in the Introduction, explaining some of the directives for performing damage surveys, as expounded in the 2003 U.S. Dept. of Commerce/NOAA document. We have also explored the online training modules managed by the Warning Decision Training Division, and their directives do not differ substantively relative to issues discussed here. It should be noted, that responding to this comment could have entailed pages of procedure description; we have attempted to be both brief and informative.

Related to the first question, is it possible for NWS to use aerial imagery to compose damage paths? I ask this question knowing that it is possible for some tornadoes, particularly high-end events, but it would be interesting to know more about the availability of such information to NWS.

This is a great question, and ongoing active discussions explore when and how often remote imagery can and should be used to augment in-person ground surveys. We have added a modest amount of additional text to very briefly touch on the complex question of whether and how often to use remote imagery, mostly in section 1, but also somewhat in section 4. Aerial imagery may often be available for low or no cost through the Civil Air Patrol where damage paths hit populated areas, but that leaves unresolved damage *tracks in less populated areas. We've made note that falling prices and wider availability of very high resolution (30–50-cm pixels) satellite imagery may change this scenario in the near future.*

The type of width attribute being analyzed is not always clear. In *Storm Data*, the width is reported as maximum width, a change from mean width that occurred in the 1990s I believe. In the present study, mean and max widths are calculated, but in a way that is perhaps different than how NWS performs the calculation (see comment #1). Later in section 3, the terms "reported" and "measured" are used, and I would suggest carrying these terms throughout the paper to distinguish between information obtained from SPC and information computed as part of the current study.

We noted where appropriate what aspect (mean or maximum) of width is being discussed, and mentioned the 1994 change in the database, from mean to maximum width. We have added the words "reported" or "measured" where appropriate to differentiate widths that we derived from our examination of the Google Earth satellite imagery, from widths reported in the database.

[Minor comments omitted...]

Second Review:

Reviewer recommendation: Accept with minor revision.

General Comments: The authors have made a substantial effort to address the substantive comments posed in the first round of review, and therefore I believe the manuscript is acceptable for publication. Specifically, the integration of NWS procedures into the introductory section of the paragraph provides a nice contextual background for the readers relative to the methods proposed in the manuscript. Clarifications made throughout the methodology and elsewhere should help with the reproducibility of this work. I have two minor suggestions that I'll leave to the authors' discretion for inclusion in the manuscript.

[Minor comments omitted...]

REVIEWER C (Ernest J. Ostuno):

Initial Review:

Recommendation: Accept with minor revisions.

General comments: This paper is a much-needed reference in that it includes a method for assessing tornado damage path width, and the results of applying that method to a sample of 50 tornado damage paths of varying intensities and lengths. I have a few suggestions for improvement, but these should not require major revisions.

Substantive comments: I would like to see the Methodology section include a more detailed description of how the measurement intervals were determined for each tornado track. The description given was rather brief but implied that the interval length increased with increasing track length. I'd like to see a bit more discussion on how someone trying to reproduce this methodology would go about determining a measurement interval for a tornado damage path of a given length.

Reviewer B also raised a similar question; we have explained the length of the intervals in Section 2.

It is implied in the Methodology section that measured path width using forest damage has a lower bound of EF1 and EF0 damage is not accounted for. If this is true, it should be stated more prominently, including in the Abstract of the paper. There could also be a discussion of what type of forest damage occurs in EF0 winds and if it could be recognized from a ground survey, if not an aerial survey. Although this may be getting outside the scope of the paper, it would be helpful to the damage-assessment community.

We have added some brief text in Section 2 to address this request.

Was there a deliberate method used to determine these measurement intervals?

This has been stated more clearly (as also requested by Reviewer B) in Section 2 (Methodology), paragraph 1.

Aerial survey photos/video are occasionally available to NWS and could have been used for path width estimation in some of the tornadoes in Storm

have added a modest amount of additional text to very briefly touch on the complex question of whether and how often to use remote imagery, mostly in Section 1 (Introduction), but also somewhat in Section 4 (Discussion).

It probably should be elaborated that even in intense tornadoes, there are often highly variable levels of damage within the path as indicated by Fig. 1b, and this has important implications for calculating risk.

Yes, very true. [A cautionary statement was added] about analysis and interpretation of damage paths in light of the discontinuities, as well as extensive variability in width and in tornado intensity.

[Minor comments omitted...]

Second Review:

Reviewer recommendation: Accept.

General comments: The changes made in this revision to the original draft sufficiently addressed my initial comments. I thought the Discussion section did an excellent job of tying together all the issues dealt with in the preceding sections. There are a couple details below that can be addressed without me having to see the paper again before publication.

[Minor comments omitted...]