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A climatology of tornado intensity assessments

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ABSTRACT: An increasing number of significant and violent tornado events in the United States have been documented and mapped at extremely high resolution by government, research and private entities using remotely sensed and post-event damage surveys; however, these assessments often generate inconsistent spatial measures of tornado strength, even for the same event. This investigation assembles a portfolio of contemporary tornado events that contain spatially comprehensive damage and/or wind velocity information from a diverse set of sources. Thereafter, the relationship between land-use/cover and tornado intensity is examined in order to quantify spatial measures of damage indicator bias in post-event tornado damage surveys. A climatology of both significant and violent tornado intensity assessments is then created, promoting the generation of synthetic, or model, paths with observationally constrained damage length and width metrics by the Enhanced Fujita scale magnitude. Results from the climatology and collection of synthetic paths are compared to previous observed, empirical and theoretical assessments, revealing differences in the spatial scale of the overall tornado footprint, as well as percentage contribution of swaths by Enhanced Fujita scale magnitude. The range of synthetic paths produced may be used to assess potential tornado damages to the population, the built environment and insurance portfolios.

KEY WORDS tornado; Fujita scale; intensity; Joplin, MO; survey; storm data

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1. Introduction

The number of casualties and extent of destruction from tornadoes is related to the length, width and intensity of the hazard at the surface, as well as how the hazard interacts with the natural and built environments (Wurman *et al.*, 2008; Simmons and Sutter, 2011; Simmons and Sutter, 2012; Ashley *et al.*, 2014; Paul and Stimers, 2014). Traditionally, post-event reports and climatological studies of tornadoes have focused on gross tornado attributes, which typically include length and maximum width as well as damage magnitude. These characteristics provide the basis for a theoretical footprint of a tornado and its peak damage magnitude. However, tornado strength varies greatly across both spatial dimensions of the path and as it traverses different types of land-use/land-cover (LULC). The variability in tornado spatial attributes is problematic when researchers employ the basic attributes of past events as a basis for examining potential tornado disasters in a scenario-based framework.

To account for variation in tornado intensity assessment techniques, a number of studies have calculated or modelled the percentage area by specific damage magnitudes or tornado intensities within the tornado path (Markee *et al.*, 1974; Abbey and Fujita, 1975; Fujita, 1978; Abbey and Fujita, 1979; Shreck and Sandusky, 1982; Ramsdell and Andrews, 1986; Ashley *et al.*, 2014). To improve and expound on this prior research, a comprehensive climatology is developed of the significant and violent tornado events in the United States that have been measured and mapped at high resolution from remotely sensed and post-event tornado damage surveys conducted by government, research and private entities. The climatology promotes the creation of synthetic tornado paths that can be applied to model realistic 'worst-case' tornado scenarios (Clarke, 2005). A synthetic tornado is a spatial aggregate form, or model, of a prototypical tornado developed from climatologically derived event metrics (i.e. length, width, percentage damage magnitude). A portfolio of realistic, high-end tornado synthetics will allow emergency planners and managers, catastrophe modellers and policy makers to estimate possible future tornado disaster effects and losses better.

2. Background

2.1. Tornado intensity assessments

In the late 1970s, the U.S. National Weather Service (NWS) adopted the first analytic tornado damage and intensity ranking system known as the Fujita scale (herein, FS) (Fujita, 1971; Fujita and Pearson, 1973; Abbey, 1976; Edwards *et al.*, 2013). The FS infers tornado wind speed magnitude and, therefore, intensity, from damage that has occurred to the built environment – most typically housing structures. Data such as tornado magnitude, path length, path width and so on are recorded by the National Climatic Data Centre (NCDC) as a public service and for use in meteorological, climatological and engineering studies (Edwards *et al.*, 2013).

Over the next 40 years, FS accuracy issues such as errors associated with the maximum degree of damage (DoD) for a damage indicator (DI) (Doswell and Burgess, 1988; Edwards *et al.*, 2013) and the lack of DIs in rural landscapes, which inhibits the accurate approximation of tornado intensity (e.g. Schaefer and Galway, 1982; Doswell and Burgess, 1988; Wurman *et al.*, 2007; Wurman *et al.*, 2008; Doswell *et al.*, 2009; Edwards *et al.,* 2013; Ashley *et al.*, 2014) were discovered, addressed and mitigated by a group of meteorologists and engineers from academia, the

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NWS and the National Severe Storms Laboratory. This collaborative dialogue resulted in the Enhanced Fujita scale (EF), a more accurate range of probable wind speeds associated with specific classes of structural damage (WSEC, 2006; Edwards *et al.*, 2013)

In the last two decades, geographic information science (GIScience) has been integrated with traditional, survey-based tornado assessment methods. Geographic information systems (GISs), global positioning systems (GPSs) and georeferencing and digitizing procedures have resulted in spatially referenced tornado damage survey information for an increasing number of significant and violent events (e.g. Camp, 2008; Camp *et al.*, 2014). Conventional surveys carried out by the NWS offices have often been supplemented, during extreme damage and/or spatially extensive tornado events, with tornado intensity evaluation techniques that include structure-by-structure damage surveys by engineers (Marshall *et al.,* 2008a, 2008b, 2012a, 2012b; Prevatt *et al.*, 2012; Roueche and Prevatt, 2013) and mobile Doppler radar wind measurements by research groups (Wurman and Alexander, 2005; Wurman *et al.*, 2007; Alexander and Wurman, 2008). The advantage in employing engineers as a source for tornado damage survey information is their knowledge of building construction, experience with assessing damage, as well as the accuracy, consistency and fine-scale resolution of their findings (e.g. Marshall *et al.,* 2008a, 2008b, 2012a, 2012b; Kuligowski *et al.,* 2013a, 2013b).

The other alternative tornado intensity evaluation process is *via* mobile Doppler radar wind measurements (Alexander and Wurman, 2005; Wurman and Alexander, 2005; Wurman *et al.,* 2007; Alexander and Wurman, 2008). A possible advantage of using these remotely sensed measurements to derive tornado intensity is the avoidance of potential errors introduced during post-event surveys due to lack of DIs along many tornado paths or determining the maximum DoD in a path (Wurman *et al.,* 2007; Edwards *et al.,* 2013). Although a relatively small number of tornadoes have been observed by mobile Doppler radar (over 150 in the last two decades), Snyder and Bluestein (2014) contend that Doppler radar observations of tornado intensity serve as a vital comparison to the more commonly used damage-based tornado survey methods (Wurman and Alexander, 2005; Edwards *et al.,* 2013; Snyder and Bluestein, 2014).

2.2. Spatial measures of tornado intensity

Although tornado damage and casualties are the result of complex interactions among many factors, they are most directly related to the spatial dimensions of the tornado and its intensity (Paul, 2011; Simmons and Sutter, 2011; Simmons and Sutter, 2012; Paul and Stimers, 2014). The maximum FS or EF damage rating along a tornado's path is often the primary attribute reported by government and media sources; however, EF magnitude and, ultimately, tornado intensity, can vary greatly across the length and width of a tornado's footprint. Early research modelling of areal tornado intensity estimations failed to address this variation in intensity by frequently assuming that the reported tornado intensity and inferred maximum wind speed was experienced equally across all areas within the tornado footprint (Markee *et al.,* 1974; Shreck and Sandusky, 1982; Ramsdell and Andrews, 1986). Others (Abbey and Fujita, 1975; Fujita, 1978; Abbey and Fujita, 1979) addressed this issue by applying an empirical Damage Area Per Path LEngth (DAPPLE) methodology to examine the distribution of damage severity by the FS along the tornado path. The DAPPLE is calculated as the damage area by FS magnitude divided by the path length; width information was not employed due to the lack of tornado path width data at the time (Fujita, 1987).

Others have employed a Rankine vortex model (Rankine, 1882; Giaiotti and Stel, 2006; Wurman *et al.,* 2007; Wood and Brown, 2011) in combination with tornado path length to evaluate the theoretical distribution of wind speeds in a tornado footprint (Twisdale and Dunn, 1981; Reinhold and Ellingwood, 1982; Ramsdell *et al.,* 2007). More recent research, in an effort to incorporate empirical evidence, has integrated Rankine vortex models in conjunction with tornado tree-fall patterns to yield more refined spatial information on hazard wind speeds and damage intensity (Holland *et al.,* 2006; Bech *et al.,* 2009; Karstens *et al.,* 2013; Kuligowski *et al.,* 2013a).

While previous studies have sought to quantify the variability in tornado intensity across its path and as it traverses a landscape, these attempts have often ignored important variables such as the underlying LULC associated with the tornado event. Less developed landscapes (fewer people and structures) in addition to lower densities of DIs and related DoDs inhibit the proper and accurate estimation of tornado intensity (Schaefer and Galway, 1982; Doswell and Burgess, 1988; Doswell *et al.,* 2009; Snyder and Bluestein, 2014; Wurman *et al.,* 2014).

2.3. Tornado hazard modelling and loss assessments

Recent studies have illustrated that scenario strategies can be applied to evaluate the potential of tornado disasters by relying on GIS-ready damage surveys and measurements conducted by the NWS (Rae and Stefkovich, 2000; Paulikas and Ashley, 2011; Ashley *et al.,* 2014), engineers (Marshall *et al.,* 2012a; Ashley *et al.,* 2014) and/or wind measurements from mobile Doppler radars (Wurman *et al.,* 2007; Ashley *et al.,* 2014). These investigations have examined scenarios focused on potential 'worst-case' (Clarke, 2005) effects on populations and the built environment (Wurman *et al.,* 2007; Hall and Ashley, 2008; Paulikas and Ashley, 2011; Ashley *et al.,* 2014). A primary weakness of these studies is the overall small sample size of tornadoes used to derive models, as well as the exclusion of varying types of tornado intensity assessment methodologies. This study seeks to reduce potential error and bias from using singular or a small sample of tornado events by constructing a comprehensive portfolio of synthetic tornado paths derived from an extensive collection of tornado intensity evaluations.

3. Research methodology

3.1. Tornado data

Tornado event collection focused on significant (EF2+) and violent (EF4+) tornadoes because they are responsible for 98.8% of all tornado fatalities and a large majority of tornado damage (Ashley, 2007; Simmons and Sutter, 2011). Initially, tornado cases available in the NWS's Damage Assessment Toolkit (NOAA, 2014) were employed, which is a GIS-based framework for collecting, storing and retrieving damage survey data (Camp *et al.,* 2014). This toolkit provides a variety of tornado event filtering (tornado survey point, track, footprint and/or swath) and download options [key mark-up language (.kml) or shapefile (.shp)], supplying an initial sample of georeferenced damage assessments. In this study, a tornado footprint is defined as the maximum areal extent of tornado intensity inferred by the damage, wind speed measured directly by mobile Doppler radar, or assessed theoretically as the recorded length multiplied with the maximum width as reported in Storm Data. A tornado swath is

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the areal extent of a given tornado intensity magnitude assigned by the FS/ES or other metric, whereas a tornado path is the combination of tornado footprint and associated tornado swaths.

Next, a few, very high-resolution, structure-by-structure damage evaluations for more notable tornado events over the past decade were digitized and incorporated into the sample (Marshall, 2002, 2008a, 2008b; Marshall *et al.,* 2012a, 2012b). Surveys generated from mobile Doppler radar and Rankine vortex wind speed estimates were also included, which are available for some noteworthy tornado events (i.e. Doppler radar: Bridgecreek-Moore, Oklahoma 1999, Mulhall, Oklahoma 1999, El Reno, Oklahoma 2013; Rankine vortex: Joplin, Missouri 2011) as acquired from Wurman *et al.* (2007), Kuligowski *et al.* (2013a) and Wurman *et al.* (2014). The mobile Doppler radar tornado intensity measurements were based on wind speed thresholds rather than on damage (EF). To account for the difference in tornado intensity methodologies, previous research (Wurman and Alexander, 2005; Wurman *et al.,* 2007) was followed, which converted wind speed ($\mathrm{m\,s^{-1}}$) measurement thresholds to FS/EF damage classes. A sample of (114) post-event and remotely sensed tornado intensity surveys have been collected and used for the climatological assessment and synthetic path production.

3.2. Tornado intensity and LULC relationship

To quantify and mitigate the DI bias often present in the post-event tornado intensity assessments, the National Land Cover Database (NLCD) was employed. The NLCD is a 30 m gridded national LULC dataset derived from remotely sensed measurements that are classified into 16 LULC types (MRLC, 2014). These grid cells were then grouped into two categories: undeveloped (e.g. herbaceous, barren land, deciduous forest) and developed (i.e. high, medium, low and open space developed) (Jin *et al.,* 2013; MRLC, 2014). The proportion of developed and undeveloped LULC grid cells within a given tornado damage/intensity swath was determined by integrating the areal extent of tornado damage swaths with the underlying NLCD layer. The assimilation of tornado intensity swaths and LULC data, coupled with GIS techniques such as zonal statistics and zonal attribute tables, generated the spatial assessment of DI biases. The NLCD is available in four primary years (1992, 2001, 2006 and 2011) and, therefore, the NLCD dataset closest to the tornado event date was chosen as the LULC layer to be intersected with the tornado swaths.

3.3. Tornado assessment climatology

Initially, tornado counts and affiliated fatalities, as well as length (km) and width (m) attributes by tornado EF (EF0 through EF5, EF2+ and EF4+), from 1995 to 2013 were assessed. These data were acquired from the Storm Prediction Center's SVRGIS (http://www.spc.noaa.gov/gis/svrgis) and are based on NOAA's Storm Data (NOAA, 2007; Edwards *et al.,* 2013). The post-1994 period of analysis was chosen because, prior to this period, recorded tornado attribute information included mean path width instead of maximum tornado path width (McCarthy, 2003; Brooks, 2004). Similar to Ashley *et al.* (2014), the mean length and width of tornadoes during this period of analysis was calculated for a variety of EF magnitudes and classes to produce a set of initial climatological-derived, theoretical footprints.

At the outset, these theoretical footprints assume that the entire tornado path is comprised of maximum damage rating – tornadoes are labelled by their maximum surveyed damage; this labelling method suggests (unrealistically) that all locations within an EF4 tornado experience EF4 intensity winds. To correct for this misconception, a portfolio of cases from three different tornado intensity survey modes was developed, including: (1) traditional post-event surveys (hereafter, post-event swaths) that were typically executed by the NWS; (2) structure-by-structure, post-event surveys performed by engineer and meteorologist Tim Marshall (hereafter, Marshall surveys) and (3) remotely sensed tornado intensity assessments generated by research groups (Table 1; Figures 1(b)–(d)). Each of these methodologies contains tornado intensity attributes, inferred from damage incurred or remotely sensed observations of wind speeds, that were used to calculate a tornado intensity distribution (TID) for each EF magnitude and classification (e.g. significant, or EF2+, and violent, or EF4+). TID is defined as the total of swath damage area (a_{tot}) in km^2 by EF (a_{EFx}; Equation (1)), or

Table 1. Tornado intensity assessment and estimation types by count.

Mode	Number of surveys
Post-event footprints	105
Post-event paths with swaths	52
Marshall surveys	5
Modelled/remotely sensed	4

$$\mathrm{TID}\ \left(a_{\mathrm{tot}}\right) = \sum_{i=\mathrm{EFmin}}^{\mathrm{EFmax}} \mathrm{EF}_i = a_{\mathrm{EFmin}} + \ldots + a_{\mathrm{EFmax}} \qquad (1)$$

For example, an EF3 tornado footprint may contain four intensity swath classifications, where the percentage contributions by tornado swaths are 50% EF0, 30% EF1, 15% EF2 and 5% EF3. The percentage areal contribution by swath directly relates to the spatial extent of wind speed thresholds, tornado intensity throughout a tornado's path and the DI strength or lack thereof. TIDs were calculated for each event in the collection of tornadoes. Using mean percentages of area for each EF magnitude the three primary measures of tornado intensity were also created. To represent the most intense and best-sampled portion of the tornado path, a 1 km segment of each tornado path was extracted. The 1 km segment was chosen because this spatial dimension most accurately resolved the DI bias compared with all other tornado path clipping widths. A twofold methodology was employed to ensure there were sufficient quantities of DIs and that the most intense region of the surveyed tornado path was included. First, the identification of the maximum tornado intensity area according to the highest EF rating was selected. The 1 km segment was then determined by selecting the location where the highest EF rating and greatest density of NLCD developed grid cells and thus DIs, coincided. Similar to the complete paths, TIDs ($\mathrm{TID}_{1\mathrm{km}}$) were also calculated for the 1 km clipped portions of each path. The TID and $\mathrm{TID}_{1\mathrm{km}}$ calculations were then grouped into EF2+, EF4+ and EF5 path categories where the mean TID values were used in conjunction with the corresponding climatological tornado attributes (mean lengths and maximum widths) from 1995 through 2013 to create the EF2+, EF4+ and EF5 synthetic tornado paths. Similarly, the $\mathrm{TID}_{1\mathrm{km}}$ values were combined with the climatological tornado attributes from 1995 to 2013 in order to develop the $\mathrm{EF2+}_{\mathrm{sig}}$, $\mathrm{EF4+}_{\mathrm{vio}}$ and $\mathrm{EF5}_{\mathrm{max}}$ synthetic tornado paths. These synthetic tornadoes can then be employed in a variety of meteorological, climatological, engineering and emergency management and policy applications to evaluate damage from tornadoes to developed landscapes.

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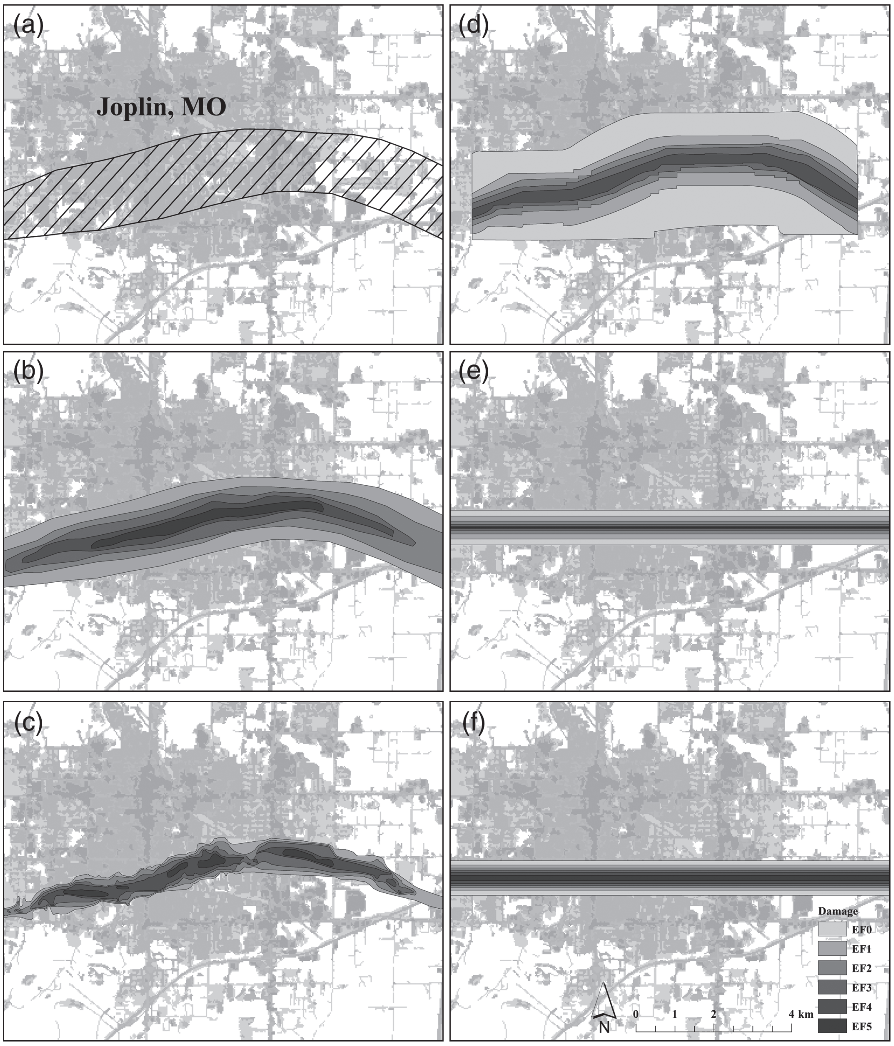

Figure 1. Examples of tornado intensity estimation types using the 2011 Joplin, MO EF5 tornado path. (a) Post-event survey path footprint; (b) post-event survey with damage/intensity swaths; (c) Tim Marshall (Marshall survey); (d) Kuligowski *et al.* (2013a) (National Institute of Standards and Technology −NIST) (Modelled/remotely sensed); (e) EF4+ synthetic (complete path tornado intensity distribution (TID) and *Storm Data* 1995–2013 mean length and width for EF4+ tornadoes); (f) $EF4+_{vio}$ (1 km TID (TID_{1km}) and *Storm Data* 1995–2013 mean length and width for EF4+ tornadoes). The basemap is National Land Cover Dataset (NLCD) defined developed land-use/cover classes [high (darkest shade), medium, low, open space (lightest) intensities]. [Correction added on 23 December after original online publication: the part labelling of Figure 1 has been amended.]

4. Results

4.1. Tornado path climatology

4.1.1. Historical tornado record (1950–1994) versus modern tornado record (1995–2013)

From 1950 to 2013 there were 57 328 recorded tornadoes with 11 745 rated significant. Of the significant tornadoes, 613 were classified as violent (Table 2; Figure 1). Following the change from mean path width to maximum path width in NOAA's Storm Data in 1994 (McCarthy, 2003; Brooks, 2004), the modern tornado record (1995–2013) yields 23 255 total tornadoes, 2606 significant and 141 violent. The modern period contains mean path lengths of 17.9 km (44 km) as well as mean path widths of 383 m (888 m) for significant (violent) tornadoes. The historical record (1950–1994) averaged 758 tornadoes *per* year with 9139 (26.8%) of all tornadoes classified as significant and 472 (1.4%) considered violent. Conversely, the 19 year modern tornado record averaged 1,224 tornadoes *per* year, with 2606 (11.2%) comprising significant tornadoes and 141 (<1%) classified as violent tornadoes. Employing the Mann–Whitney *U* test, there is a statistically significant difference (99.9% confidence level) between the 1950–1994 and 1995–2013 tornado path lengths as well as 1950–1994 and 1995–2013 path widths. The difference in path widths can be attributed to the 1994 Storm Data change from recorded mean path width to maximum path width.

Examining the distributions of path length, width and theoretical footprint area (recorded path length multiplied with maximum path width) of the modern tornado record illustrates clear differences among tornado intensity rating distributions (Figures 2(a) and (b)). As expected, violent tornadoes encompass the greatest path lengths, widths and total area compared to non-violent tornadoes. The greatest variance in tornado path length is exposed in the EF4 and EF4+ tornado paths, while the EF3 and EF4+ paths indicate the most considerable variability in tornado path width distributions. In comparison to all other intensity categories, EF5 paths exhibit the largest total theoretical footprint area and greatest variability for the 1995–2013

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Table 2. Mean length (km), width (m) and theoretical area (km^2) attributes by damage class for 1950–2013 (complete tornado record), 1950–1994 (historic tornado record) and 1995–2013 (modern tornado record) US tornadoes.

	EF Damage	Count	Mean length	Mean width	Maximum width	Area
1950–2013	EF0	26 207	1.63	37.54	–	0.06
	EF1	19 409	5.08	84.09	–	0.43
	EF2	8 767	11.15	157.86	–	1.76
	EF3	2 365	23.96	327.22	–	7.84
	EF4	554	44.28	533.99	–	23.65
	EF5	59	62.78	767.24	–	48.17
	Total (EF0+)	57 328	5.65	89.13	–	0.50
	Significant (EF2+)	11 745	15.55	212.77	–	3.31
	Violent (EF4+)	613	46.06	556.44	–	25.63
1950–1994	EF0	11 922	1.29	27.145	–	0.03
	EF1	13 040	4.47	61.086	–	0.27
	EF2	6 851	10.57	121.24	–	1.28
	EF3	1 816	22.88	249.99	–	5.72
	EF4	427	44.91	445.81	–	20.02
	EF5	45	62.37	565.81	–	35.29
	Total (EF0+)	34 101	6.15	76.848	–	0.47
	Significant (EF2+)	9 139	14.88	164.18	–	2.44
	Violent (EF4+)	472	46.58	457.25	–	21.30
1995–2013	EF0	14 208	1.88	–	46.22	0.09
	EF1	6 369	6.33	–	131.20	0.83
	EF2	1 916	13.22	–	288.82	3.82
	EF3	549	27.55	–	582.68	16.05
	EF4	127	42.16	–	830.46	35.01
	EF5	14	64.08	–	1414.71	90.66
	Total (EF0+)	23 255	4.89	–	107.25	0.52
	Significant (EF2+)	2 606	17.92	–	383.17	6.87
	Violent (EF4+)	141	44.33	–	888.47	39.39

From 1950–1994 mean width values are based on the Storm Data recorded mean path widths, while from 1995–2013 mean width values are constructed from *Storm Data* recorded maximum path width.

period (Figure 2(c)). Relating the length and width distributions to Brooks (2004), the 1995–2013 distributions follow the same upward trajectory of increasing tornado path lengths and widths by intensifying EF classes. The post-event metrics yield greater mean lengths and maximum widths compared to the Storm Data of 1995–2013 (Figure 3(c)). All (EF2+) post-event surveyed paths comprise a mean path length of 30.6 km (12.7 km greater than 1995–2013 Storm Data recorded mean path lengths) and a mean maximum path width of 785.1 m (402.1 m greater than 1995–2013 Storm Data recorded mean maximum path widths). The EF4+ post-event tornado paths illustrate greater mean lengths and widths compared with the modern tornado record with differences of 20.9 km in path length and 386.4 m in path width. However, the modern tornado record contains EF5 mean path lengths and widths of 64.1 km and 1414.7 m, while the post-event survey EF5 mean path lengths and widths are 69.3 km and 1513.9 m, respectively. Calculating the post-event theoretical footprint path area yields a mean significant (EF2+) tornado path area of 37 km^2, whereas using a GIS to determine the actual area of the tornado footprint results in a mean significant tornado path area of 24.9 km^2. This difference in computed tornado footprint area is approximately 12 km^2, or a 39% mean overestimation by the theoretical footprint area calculation.

Temporal analyses of the modern tornado record indicate a large increase in mean path widths and theoretical footprint areas between the 1995–2006 and 2007–2013 time periods. From 1995 to 2006, there were 14 503 tornadoes recorded with a mean path width of 87.1 m and a mean footprint area of 0.37 km^2. Conversely, from 2007 to 2013, there were 8752 tornadoes with a mean path width and mean footprint area of 140.7 m and 0.84 km^2, respectively. Reasons as to why this increase in mean path width and mean footprint area are unclear, but it should be noted that this change is essentially a step function. The difference between the two periods of examination is most evident in EF0+ tornado path mean widths where a 62% increase (from 87.1 to 140.7 m) is observed. These differences in tornado path metrics are manifest in the mean theoretical footprint areas where, for instance, there is an increase in footprint area between the 1995–2006 and 2007–2013 periods of 127% for all tornadoes, 77% for significant events and 141% for violent cases.

4.2. Spatial damage indicator bias

All (52) post-event surveyed tornado paths traversed largely (>80%) undeveloped landscapes (Table 3). EF0 tornado swaths contained the lowest mean percentage (7.3%) of NLCD developed grid cells, while EF4 swaths were associated with the greatest mean percentage (19.9%) of developed LULC cells. The high intensity developed NLCD grid cells were the least (0.5%) frequently intersected, followed by medium (1.8%), low (3.8%) and open space (6.1%) developed classes. The lower overall number of highly developed classified grid cells affected is primarily due to the smaller (0.11%) concentrations of high density developed grid cells compared with all other LULC landscape classes throughout the conterminous United States. A direct relationship between the percentage of developed LULC and tornado swath intensity is apparent while an indirect relationship exists between the percentage of undeveloped LULC grid cells and tornado swath intensity (Table 4; Figure 4). Significance testing employing the F-test on the trends associated with percentage of developed and undeveloped LULC grid cells

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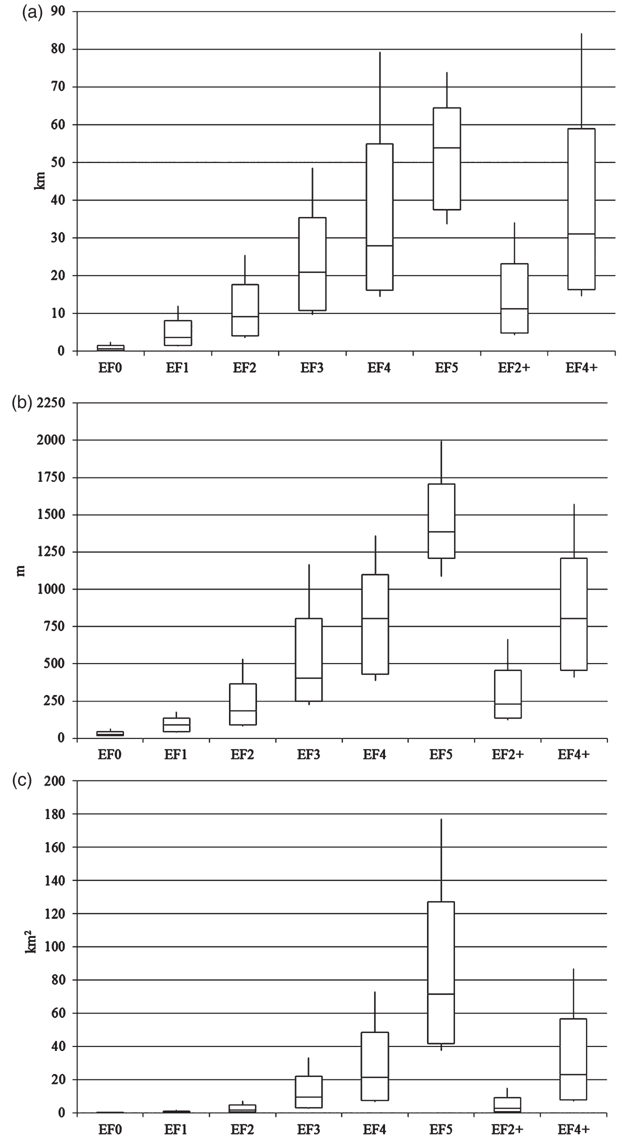

Figure 2. Box-and-whisker plots for the distribution of the modern tornado record (1995–2013) for path (a) length (km), (b) width (m), (c) theoretical footprint area (km^2). The tops and the bottoms of the boxes represent the 75th and 25th percentiles, and the tops and bottoms of the whiskers indicate the 90th and 10th percentiles.

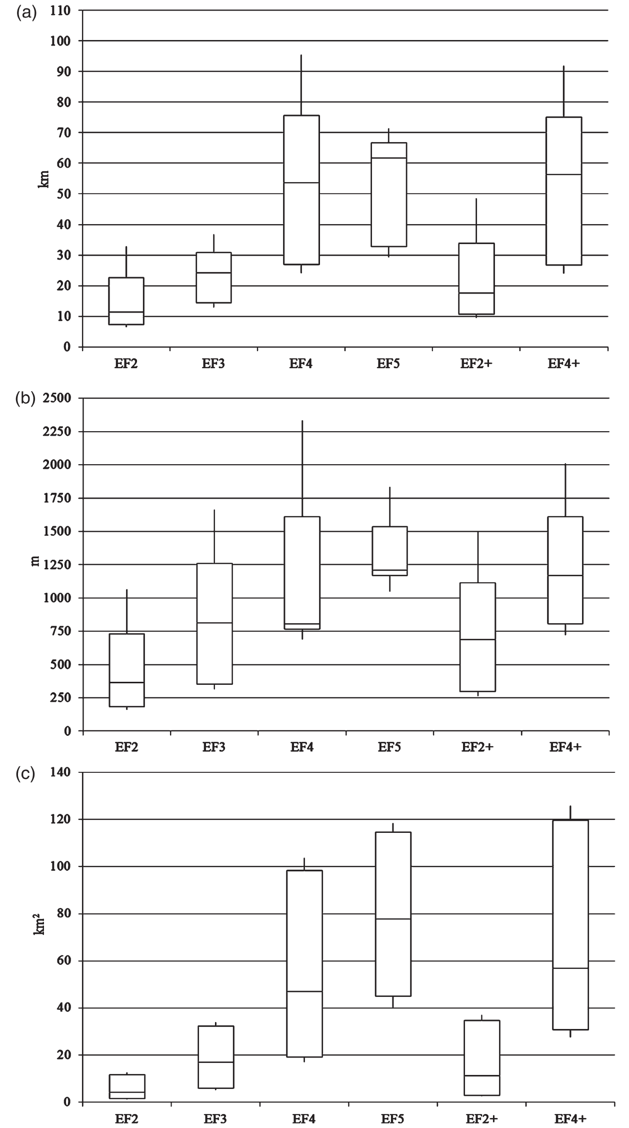

Figure 3. Box-and-whisker plots for the distribution of the post-event surveyed tornado path (a) *Storm Data* recorded length (km), (b) *Storm Data* recorded width (m), (c) footprint damage area (km^2) calculated in a geographic information system (GIS). The tops and bottoms of the boxes represent the 75th and 25th percentiles, and the tops and bottoms of the whiskers indicate the 90th and 10th percentiles.

by swath intensity determined, with 99.9% confidence, that these relationship trends are different than zero. The relationship between swath intensity and developed LULC produces statistically significant outcomes for open space (95%) and medium intensity (90%), yet no statistically significant outcome for high intensity developed LULC landscapes. The small sample size (area) of high (11 km^2) and medium (36 km^2) intensity developed LULC grid cells associated with tornado swaths likely resulted in the overall significance at lower confidence levels and insignificance for the medium- and high-intensity landscape and tornado swath intensity relationship trends. Similar to previous studies (Schaefer and Galway, 1982; Doswell and Burgess, 1988; Doswell *et al.,* 2009), these results suggest that rural areas, those landscapes with a lower number and density of DIs (i.e. undeveloped), tend to lead to an underestimate in tornado intensity, and those tornadoes that affect locations with a greater number or density of DIs (developed landscapes) are typically rated as more intense.

4.3. Tornado intensity distribution (TID)

4.3.1. Complete path

The post-event, Marshall survey paths and modelled/remotely sensed paths illustrate the variability in mean TID results among all significant tornado paths (EF2 through EF5) as well as highlight the disparity among the different tornado intensity estimation techniques (Tables 5 and 6). Among the complete path, post-event TID calculations, the EF2+ paths represent the greatest mean percentage of violent tornado swaths with a cumulative 11.6%. Similarly, post-event surveyed EF2+ tornado paths are associated with the largest mean percentages of significant tornado swaths with 41.9% of the entire path area comprising EF2+ swath areas. EF4+ post-event assessed tornado paths encompass the second greatest mean percent significant (36.9%) and violent (7.3%) tornado swaths. The Marshall surveyed paths contain a mean 75% significant and 30.1% violent tornado swaths

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Table 3. Post-event surveyed tornado paths by damage rating, year, and location with associated injuries, fatalities, path length, path width and total footprint area. For US state abbreviations see https://www.usps.com/send/official-abbreviations.htm

Maximum damage rating	Year	Location	Injuries	Fatalities	Length (km)	Width (m)	Total area (km^2)
EF5	1990	Plainfield, IL	300	29	26.4	548.0	11.7
EF5	1999	Bridge./Moore, OK	583	36	59.5	1307.6	49.5
EF5	2008	Parkersburg, IA	70	9	65.9	1920.2	113.0
EF5	2011	El Reno, OK	181	9	101.5	1609.3	99.1
EF5	2011	Hackleburg, AL	145	72	212.4	2011.7	155.0
EF5	2011	Joplin, MO	1150	158	34.8	1463.0	45.7
EF5	2013	Newcastle/Moore, OK	377	24	22.5	1737.3	23.3
EF4	1999	Mulhall, OK	26	2	56.3	1609.3	67.4
EF4	1979	Wichita Falls, TX	1740	42	75.6	1609.3	67.8
EF4	2008	Darien Co., GA	9	0	17.7	640.1	6.9
EF4	2008	Jackson Co., AL	12	1	17.5	603.5	10.0
EF4	2008	Lawrence Co., AL	23	4	26.9	804.7	22.3
EF4	2011	Catoosa Co., GA	335	20	77.2	731.5	12.4
EF4	2011	Pocohontas, IA	0	0	47.3	2414.0	99.8
EF4	2011	Chick./Newcastle, OK	48	1	53.6	804.7	27.1
EF4	2011	Cullman, AL	48	6	75.4	804.7	38.1
EF4	2011	Lake Martin, AL	30	7	71.1	804.7	32.7
EF4	2011	Shoalscreek, AL	85	22	156.6	1609.3	185.8
EF4	2011	Wash./Goldsby, OK	61	0	37.1	804.7	13.1
EF4	2013	Hood, TX	54	6	4.0	365.8	2.4
EF4	2013	Lake Thunderbird, OK	10	2	37.0	1371.6	35.0
EF3	2011	Boones Chapel, AL	4	3	15.0	365.8	4.4
EF3	2011	Coaling, AL	0	0	32.6	182.9	4.3
EF3	2011	Dade/Walker Co., GA	12	2	29.0	965.6	32.0
EF3	2011	Haleyville, AL	25	0	51.2	1207.0	48.1
EF3	2011	Meriwether, GA	0	2	34.9	804.7	14.3
EF3	2011	Sac Co., IA	0	0	16.3	1609.3	7.4
EF3	2011	Sawyerville, AL	50	7	116.1	1609.3	127.8
EF3	2011	Shottsville, AL	100	7	29.7	1207.0	26.1
EF3	2011	St. Tammany, LA	4	0	9.8	137.2	2.1
EF3	2012	Forney, TX	7	0	12.4	137.2	4.6
EF3	2013	Bartow Co., GA	17	1	35.1	823.0	19.0
EF3	2013	Belmond, IA	0	0	10.0	182.9	1.0
EF3	2013	Carney, OK	4	0	33.5	1097.3	28.9
EF3	2013	Cleburne, TX	7	0	12.5	1584.7	20.8
EF3	2012	Royse City, TX	3	0	5.37	365.8	3.5
EF2	2011	Equality, AL	2	0	33.4	1207.0	23.2
EF2	2011	Keach/Friarson, LA	2	0	68.2	777.2	80.7
EF2	2011	Lumpkin/White, GA	1	1	59.5	823.0	12.4
EF2	2011	Sac Co., IA	0	0	13.4	603.5	4.3
EF2	2011	Sidell, LA	0	0	3.0	228.6	0.8
EF2	2011	Troup, GA	6	0	11.3	402.3	3.1
EF2	2012	Creston, IA	2	0	26.7	731.5	10.0
EF2	2012	Kennedale, TX	7	0	10.3	137.2	3.5
EF2	2012	Lancaster/Dallas, TX	10	0	22.0	182.9	8.4
EF2	2013	Alexander, IA	0	0	8.4	274.3	1.0
EF2	2013	Fenton Township, MI	0	0	8.2	457.2	2.5
EF2	2013	Goodrich, MI	0	0	7.4	274.3	1.2
EF2	2013	Mansfield, GA	1	0	17.8	160.0	0.9
EF2	2013	Chalmers, IN	0	0	6.7	274.3	1.2
EF2	2013	Toledo, OH	0	0	18.2	91.4	8.3
EF2	2014	Dublin, GA	0	0	27.4	182.9	7.5

within the entire path area. The Marshall surveys focus on the portion of the tornado path that resulted in the greatest losses (e.g. loss of life, severe damage to buildings) as opposed to the entire tornado path, which results in the elevated Marshall mean TID percentage values. Though the modelled/remotely sensed methods are based on the complex interaction between Doppler radar wind speed measurements or damage surveys and objective Rankine vortex models, they exemplify mean TID values similar to those associated with the post-event surveys with mean significant and violent TID percentages of 39.2 and 12.3%, respectively.

4.3.2. *One kilometre segments*

Although the complete path TIDs capture the variation in tornado intensity throughout the entire path length and across path width, the 1 km TIDs control better for this variability by focusing on the best-sampled (i.e. a sufficient number of DIs) and most

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Table 4. Mean percentage of NLCD defined developed landscapes (open space, low, medium and high intensity) by post-event tornado path swath magnitude/intensity.

	Developed				All Developed	Un developed
	Open	Low	Medium	High		
EF0	4.51	1.90	0.58	0.30	7.32	92.68
EF1	7.38	2.89	1.30	0.46	12.03	87.97
EF2	6.15	2.25	0.67	0.31	9.40	90.60
EF3	7.94	4.18	2.45	0.68	15.26	84.74
EF4	10.82	5.63	2.92	0.47	19.85	80.15
EF5	7.05	5.71	2.64	0.82	16.22	83.78

All developed mean percentages are the sum of the four NLCD developed classes while the undeveloped mean percentages are all other NLCD land-cover classifications (barren rock, deciduous forest, cultivated crops, etc.)

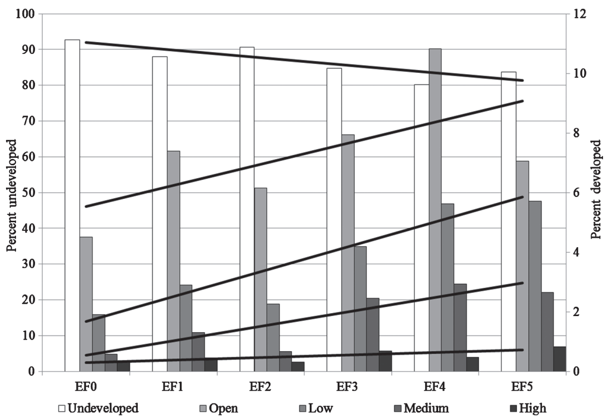

Figure 4. National Land Cover Database (NLCD) mean percent developed and undeveloped grid cells by Enhanced Fujita scale (EF) swath for all post-event survey tornado paths. Trend lines from top to bottom: undeveloped, open space developed, low intensity developed, medium intensity developed, high intensity developed landscapes.

intense portion of the tornado path. Collectively, the 1 km tornado segments comprise a mean of 40% developed grid cells within the clipped tornado area. As a comparison, the percentages of developed grid cells for conterminous United States and east of the Continental Divide are 5.9 and 7%, respectively. The higher percentage concentrations (40%) of developed grid cells related to tornado paths and associated intensity swaths further supports the hypothesis that tornadoes tend to be rated higher when they move over locations with a greater concentration of developed landscapes and DIs. Though the post-event damage surveys often suffer from spatial inaccuracies due to time, financial and personnel constraints, the TID_{1km} results indicate that selecting the area of the tornado path that contains the most intense and greatest density of developed LULC grid cells leads to TIDs similar to those associated with the Marshall surveys. Given the small sample size (5) and relative rarity of published Marshall surveys over the last two decades, the Marshall TIDs are subject to subtle areal differences in the percentage of EF swaths throughout the tornado paths; thus, the TID_{1km} percentages can be used as an alternative means of high-quality assessment of accurate tornado intensity.

The TID_{1km} EF2+ tornado paths (i.e. tornadoes in the sample that were rated EF2+) contain cumulative 62.4 and 33.7% significant and violent swath percentages, while EF4+ paths have swath contributions of 57.4% significant and 31.9% violent

Table 5. Mean complete path area (km^2) by intensity (EF0 through EF5; significant EF2+; violent EF4+) for all post-event, Marshall and modelled/remotely sensed tornado intensity estimation types.

Post-event	Swaths						Total
	EF0	EF1	EF2	EF3	EF4	EF5	
EF2	8.35	2.30	0.54	–	–	–	11.18
EF3	6.83	7.16	8.44	2.95	–	–	25.39
EF4	15.16	15.46	9.87	4.12	2.19	–	46.81
EF5	37.84	22.81	13.57	12.84	3.96	1.61	92.64
EF2+	12.15	9.79	6.26	5.14	2.78	1.61	37.74
EF4+	20.50	17.78	11.10	6.88	2.78	1.61	60.66
Marshall	EF0	EF1	EF2	EF3	EF4	EF5	Total
EF4+	–	0.81	0.76	0.78	0.79	0.22	3.35
Modelled/ remotely sensed	EF0	EF1	EF2	EF3	EF4	EF5	Total
EF2+	21.77	91.61	39.72	10.42	9.39	13.47	186.37

Total area values vary slightly as a result of rounding.

Table 6. Mean complete path tornado intensity distribution (TID) by intensity (EF0 through EF5; significant EF2+; violent EF4+) for all post-event surveys, Marshall surveys and modelled/remotely sensed paths.

Post-event	Swaths						Total
	EF0	EF1	EF2	EF3	EF4	EF5	
EF2	74.65	20.56	4.79	–	–	–	100.00
EF3	26.92	28.21	33.25	11.61	–	–	100.00
EF4	32.39	33.03	21.09	8.81	4.68	–	100.00
EF5	40.85	24.62	14.65	13.86	4.28	1.74	100.00
EF2+	32.19	25.95	16.60	13.63	7.37	4.27	100.00
EF4+	33.80	29.32	18.31	11.34	4.59	2.66	100.00
Marshall	EF0	EF1	EF2	EF3	EF4	EF5	Total
EF4+	–	24.03	22.57	23.30	23.62	6.48	100.00
Modelled/ remotely sensed	EF0	EF1	EF2	EF3	EF4	EF5	Total
EF2+	11.68	49.16	21.31	5.59	5.04	7.23	100.00

Total percentage values vary slightly as a result rounding.

(Tables 7 and 8). Compared to the complete path TID calculations, the TID_{1km} have greater overall mean percentages of significant and violent swaths within the post-event survey paths. The TID_{1km} statistics by path intensity have a more uniform distribution and less variance in mean EF2+ (94.6% less), EF4+ (86.6% less) and EF5 (73.2% less) swath percentages compared to the complete path TID values.

In comparison to the historical measures of tornado intensity, the TID and TID_{1km} demonstrate the irregularity between varying types of tornado intensity estimation techniques (Table 9). There is little difference among the DAPPLE and Nuclear Regulatory Commission (NRC) intensity estimations; all EF mean swath percentages are within 10% of each other. However, comparing these percentages of EF swaths with the mean TID and TID_{1km} swath proportions, the historical measures (DAPPLE and NRC) exemplify greater EF0 and lesser EF2+ percentages, overall. The NRC 1982 results illustrate the highest percentage

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Table 7. Mean area (km^2) within a 1 km clipped damage/intensity swath (EF0 through EF5; significant EF2+; violent EF4+) for all post-event surveys, Marshall surveys and modelled/remotely sensed tornado intensity estimations.

Post-event	Swaths						Total
	EF0	EF1	EF2	EF3	EF4	EF5	
EF2	0.19	0.17	0.10	–	–	–	0.46
EF3	0.18	0.21	0.17	0.21	–	–	0.78
EF4	0.25	0.16	0.13	0.12	0.21	–	0.86
EF5	0.46	0.32	0.21	0.21	0.16	0.18	1.54
EF2+	0.23	0.19	0.14	0.18	0.20	0.18	1.12
EF4+	0.30	0.20	0.15	0.15	0.20	0.18	1.18

Total area values vary slightly as a result of rounding.

Table 8. Mean percentage area within a 1 km clipped tornado intensity distribution (TID_{1km}) by damage/intensity swath (EF0 through EF5; significant EF2+; violent EF4+) for all post-event surveys, Marshall surveys and modelled/remotely sensed paths.

Post-event	Swaths						Total
	EF0	EF1	EF2	EF3	EF4	EF5	
EF2	42.37	36.47	21.16	–	–	–	100.00
EF3	23.13	27.18	22.35	27.33	–	–	100.00
EF4	28.60	18.12	14.57	14.20	24.51	–	100.00
EF5	30.10	20.51	13.49	13.87	10.39	11.65	100.00
EF2+	20.26	17.35	12.63	16.06	17.62	16.09	100.00
EF4+	25.46	17.20	12.83	12.63	16.67	15.22	100.00

Total percentage values vary slightly as a result rounding.

of non-significant tornado swaths (87%) as well as the lowest percentage of significant (13.2%) and violent (1.1%) tornado swaths. The largest share of significant (23.9%) and violent (5%) tornado swaths is exemplified within the NRC 2007 tornado swath percentages. While the NRC 1982 percentages are based on post-event tornado damage surveys from 149 tornadoes that occurred on 3–4 April 1974, the NRC 2007 percentages are derived from the weighted combination of a one-third tornado model (stationary Rankine vortex) and two-thirds empirical damage survey data from NRC 1982 (*cf* Reinhold and Ellingwood's (1982) Table 7(c)).

4.3.3. *The 2011 Joplin, MO EF5 tornado case study*

The 2011 Joplin, MO, tornado is an ideal one for comparison among the varying types of tornado intensity estimation methodologies because it (1) was the deadliest (158 direct fatalities) tornado event in the United States since 1947, (2) is a contemporary example of a catastrophic tornado scenario in a highly developed area and (3) is a prime illustration of a tornado in which both post-event surveys and modelled/remote sensing estimation techniques were conducted to determine the tornado intensity (Ashley *et al.,* 2014) (Figure 1, Table 9). The Joplin, MO NIST (National Institute of Standards and Technology) case is a modelled/remotely sensed path that combines tree fall patterns, post-event damage assessments and a theoretical Rankine vortex model to estimate tornado intensity, while the Joplin NWS, Marshall and Ashley *et al.* (2014) tornado intensity assessments are all solely based on post-event damage surveys. The subtle variation in these measures of tornado intensities yields considerable differences in the tornado swath percentages. Moreover, the 2011 Joplin tornado represents a rare instance when an engineer was consulted and relied upon to determine better the spatial damage attributes within the tornado footprint (Marshall *et al.,* 2012a). Comparisons between the Joplin NWS post-event and Marshall surveys indicate that the NWS post-event survey overestimates the percentage of EF1 swath area by 14.1% and underestimates EF3 and EF4 swath percentages by 5.1 and 10%, respectively.

The NWS post-event and Marshall surveys of Joplin also did not document damage less than EF1 due to the sporadic character of the damage associated with these lower wind speed thresholds (Marshall, 2012, personal communication). Consequently, no EF0 swaths were developed for the Marshall and post-event surveys. Ashley *et al.* (2014) sought to address this shortcoming by approximating EF0 swath based on the Storm Data reported maximum path width in the region of south Joplin (1463 m). This swath, coupled with Marshall's existing EF1-EF5 swaths, represented the complete areal extent of the tornado path and subsequent EF0 swath percentage area. This additional swath resulted in a shift across the percentage swath area distribution where 51.1% of the total tornado path area was redistributed to the EF0 swath, while the remaining 48.9% was allocated among EF1 (10.9%), EF2 (10.8%), EF3 (12.7%), EF4 (11%) and EF5 (3.6%) swaths (Table 8). The Ashley *et al.* (2014) swath intensity percentages include a greater percentage contribution of EF0 damage area within the path compared to the EF5, EF2+ and EF4+ mean TID_{1km} EF0 swath percentages (31%).

The NIST (Kuligowski *et al.,* 2013a) tornado path also includes an EF0 damage/intensity swath but does not contain an EF5 swath. The exclusion of an EF5 swath in the NIST survey was based on, according to their survey, the lack of damaged structures throughout the tornado damage area (footprint) that could not withstand EF5 wind speeds (Kuligowski *et al.,* 2013a). Nonetheless, the Joplin NIST path does represent a similar percentage EF0 contribution (47.3%) to that of Ashley *et al.* (2014) and closely mirrors the EF1 and EF2 swath percentages of the NWS and Marshall survey paths.

Taken together, these four Joplin, MO, tornado intensity assessments illustrate substantial variability among percentage EF swaths throughout the tornado path as well as among all intensity estimation types. The large variation in tornado intensity estimations among both historic measures and the Joplin, MO, tornado evaluations demonstrate the need for a comprehensive approach to modelling potential losses from tornadoes and future disasters. As technological advancements happen and survey techniques improve in the decades to come, a greater understanding of the distribution of tornado damage and associated intensity will arise.

4.3.4. *Synthetic tornado paths*

The TID and TID_{1km} calculations were used to create a portfolio of synthetic tornado paths that can be applied to estimate potential losses to places and populations from a hypothetical event (Figures 1(e) and (f), Figures 5 and 6). Comparing these synthetic tornado paths with those previously generated (Wurman *et al.,* 2007; Ashley *et al.,* 2014), the TID and TID_{1km} closely match those associated with the Ashley *et al.* (2014) tornado paths. This similarity is attributed to the analogous synthetic creation techniques, the use of percentage damage swaths associated with post-event surveys, and *Storm Data* recorded climatological mean lengths and widths. The Wurman *et al.* (2007) paths were derived and generated from the observed mobile Doppler radar maximum recorded wind speed and mean path length (60 km) recorded from the tornado events of 3 May 1999 Mulhall and Bridgecreek-Moore, OK (Wurman *et al.,* 2007; Ashley *et al.,* 2014). The relative widths of these tornado paths [e.g. 8.8 km

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Table 9. Historical measures (percentage area) of tornado damage/intensity distributions by EF throughout a tornado path.

	Swaths						Total
	EF0	EF1	EF2	EF3	EF4	EF5	
DAPPLE (Fujita, 1978)	58.00	24.00	10.00	4.00	2.00	1.00	100.00
NRC (Reinhold and Ellingwood, 1982)	63.20	23.60	8.80	3.30	0.90	0.20	100.00
NRC (Ramsdell *et al.,* 2007)	53.80	22.30	11.90	7.00	3.30	1.70	100.00
Joplin, MO (NOAA NWS, 2011)	–	36.44	22.35	20.91	12.63	7.67	100.00
Joplin, MO (Marshall *et al.,* 2012a) (EF1–EF5)	–	22.30	21.62	26.05	22.58	7.45	100.00
Joplin, MO (Ashley *et al.,* 2014 based on Marshall *et al.,* 2012a)	51.10	10.90	10.80	12.70	11.05	3.64	100.00
Joplin, MO NIST (Kuligowski *et al.*, 2013a)	47.30	23.80	14.00	9.90	5.00	–	100.00

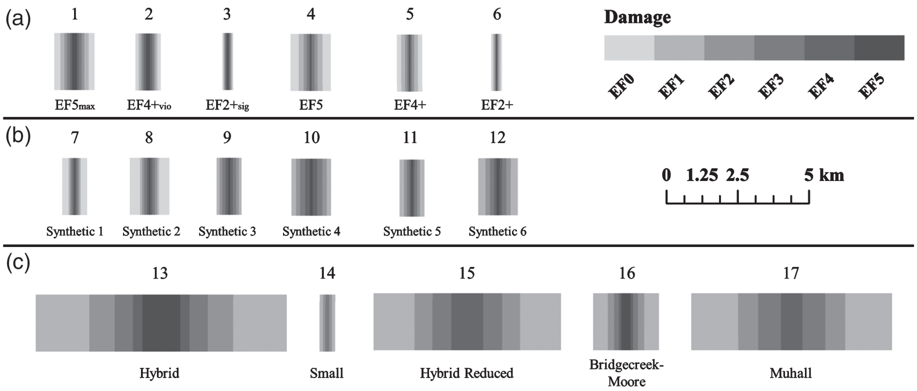

Figure 5. Tornado and intensity width segments for the (a) Strader *et al.* (this study), (b) Ashley *et al.* (2014) and (c) Wurman *et al.* (2007) synthetic tornado paths. The numbers above each synthetic tornado path segment correspond to the complete synthetic tornado path illustrated in Figure 6.

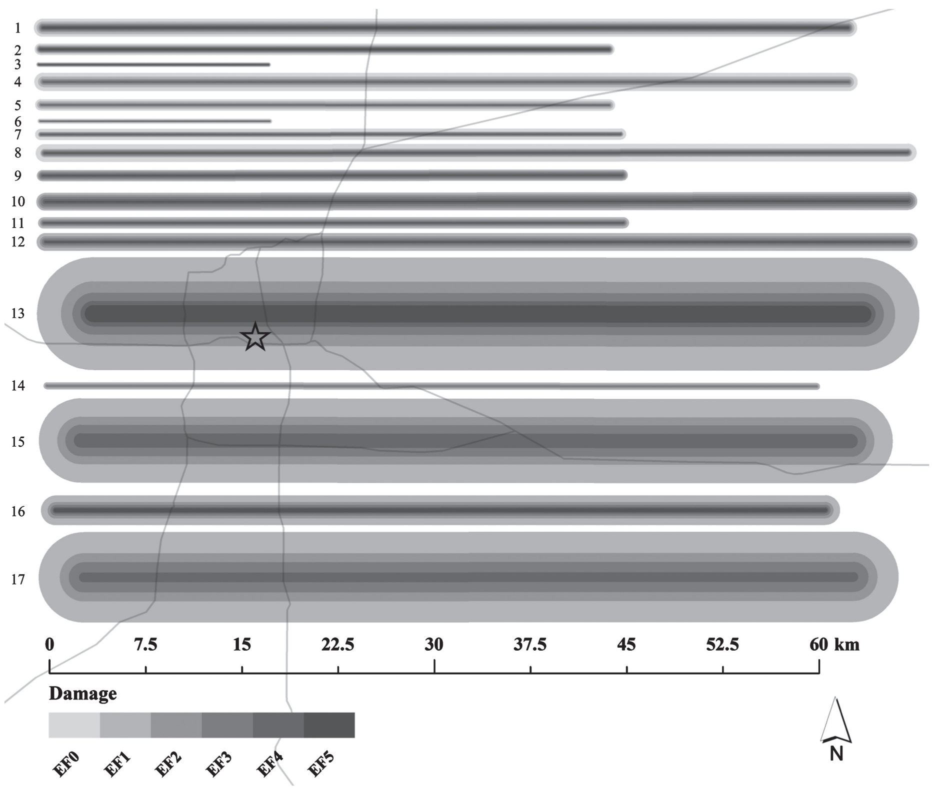

Figure 6. Synthetic tornado paths for: Strader *et al.* (this study) (1–6), Ashley et al. (2014) (7–12), and Wurman *et al.* (2007) (13–17). The numbers next to each complete synthetic tornado path correspond to the synthetic tornado path segment illustrated in Figure 5. The Oklahoma City, OK metropolitan region's interstate system is provided for scale; star indicates downtown Oklahoma City.

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Hybrid (HB), 7.1 Mulhall (MH) and 6.6 km Hybrid Reduced (HR)] are between 50 and 100% wider than the widest tornadoes on record: 2004 Hallam, NE (4.0 km; McCarthy and Schaefer, 2005) and 2013 El Reno, OK (4.2 km; Ashley *et al.,* 2014).

5. Conclusion

Discrepancies between tornado intensity/attribute data necessitate a comprehensive climatology of tornado intensity assessments. The climatology presented in this investigation promotes a more accurate and thorough understanding of the spatial attributes of tornado intensity associated with high-magnitude events by including a variety of data from post-event surveys, modelled/remotely sensed observations and theoretical treatments. By incorporating, for the first time, a national land-use/cover dataset in conjunction with detailed post-event surveyed tornado paths, spatial measures of the damage indicator bias often present in post-event damage surveys and Enhanced Fujita scale (EF) rating procedures were quantified. Additionally, a diverse set of tornado intensity estimation methodologies of noteworthy tornado events led to the development of a set of synthetic tornadoes. Similar to other models used for hazards such as hurricanes, floods and earthquakes, these synthetic tornado paths may serve as a method for estimating possible losses from future tornado disasters. For instance, these paths may be overlaid atop a dataset illustrating components of vulnerability in a geographic information system (GIS) framework to estimate the potential losses to people, structures and insurance policy portfolios. Overall, the research framework and products generated from this investigation will assist both public and private stakeholders in measuring the risk of losses from tornadoes to people and their assets. The results may contribute to outreach initiatives that seek to reduce the gap between perceived and actual risk, and may act to diminish future physical and social vulnerabilities through planning, mitigation and preparedness strategies. Continuous revisions to the tornado climatology, tornado intensity distribution (TID) and resulting synthetics will permit stakeholders to refine the tools used for estimating potential negative tornado effects with the definitive goal of reducing future human casualties and financial losses.

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