Analysis of Tornado-Induced Tree Fall Using Aerial Photography from the Joplin, Missouri, and Tuscaloosa–Birmingham, Alabama, Tornadoes of 2011*

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ABSTRACT

In this study, aerial imagery of tornado damage is used to digitize the falling direction of trees (i.e., tree fall) along the 22 May 2011 Joplin, Missouri, and 27 April 2011 Tuscaloosa–Birmingham, Alabama, tornado tracks. Normalized mean patterns of observed tree fall from each tornado's peak-intensity period are subjectively compared with results from analytical vortex simulations of idealized tornado-induced tree fall to characterize mean properties of the near-surface flow as depicted by the model. A computationally efficient method of simulating tree fall is applied that uses a Gumbel distribution of critical tree-falling wind speeds on the basis of the enhanced Fujita scale. Results from these simulations suggest that both tornadoes had strong radial near-surface winds. A few distinct tree-fall patterns are identified at various locations along the Tuscaloosa–Birmingham tornado track. Concentrated bands of intense tree fall, collocated with and aligned parallel to the axis of underlying valley channels, extend well beyond the primary damage path. These damage patterns are hypothesized to be the result of flow acceleration caused by channeling within valleys. Another distinct pattern of tree fall, likely not linked to the underlying topography, may have been associated with a rear-flank downdraft (RFD) internal surge during the tornado's intensification stage. Here, the wind field was strong enough to produce tornado-strength damage well beyond the visible funnel cloud. This made it difficult to distinguish between tornado- and RFD-related damage and thus illustrates an ambiguity in ascertaining tornado-damage-path width in some locations.

1. Introduction

Aerial oblique photography has been used to document and assess tornado damage for several decades (e.g., Fujita et al. 1967, 1970, 1976; Davies-Jones et al. 1978; Fujita 1981, 1989). This work was pioneered by T. T. Fujita and his colleagues, who used such photographs to remotely observe tornado damage, compose damage paths, and relate scouring patterns to near-surface tornado dynamics. Aerial oblique photographs were critical in identifying cycloidal “suction” marks, or

lines of debris deposition, within the damage paths of many tornadoes. Fujita surmised that these marks were the result of multiple vortices orbiting the parent tornadic circulation, a hypothesis that has been investigated recently by numerical simulation (e.g., Lewellen and Zimmerman 2008).

Aerial analysis of tornado damage has primarily utilized oblique photographs (photographs taken at an angle of greater than 3° from vertical). Although aerial oblique photographs can reveal information that is not easily determined from the ground, their utility in spatial analysis is limited by difficulties in accurately determining distances. In contrast, aerial vertical photographs (photographs taken at an angle of less than 3° from vertical) have an approximately constant scale throughout, allowing measurements to be made from the photograph for subsequent geospatial analysis. The use of aerial vertical photographs for tornado documentation has been limited, however.

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As a rare example in which aerial vertical photography has been used in tornado-damage analysis, Fujita (1989) used aerial vertical photographs and stereo image pairs, in addition to oblique aerial photographs, to document an unusual Fujita-scale magnitude-4 (F4) tornado occurring on 21 July 1987 in Wyoming. This tornado traversed complex terrain on either side of the Continental Divide at elevations that ranged from approximately 2380 to 3270 m above sea level. In addition to objectively determining the tornado's starting point, ending point, length, and spatially varying width, Fujita used the vertical aerial photographs to map the generalized direction of fallen trees (i.e., windfall or tree fall) overlaid on topographic maps. From this analysis, Fujita identified converging and diverging tree-fall patterns within the tornado damage path. Differences in these patterns were primarily attributed to microbursts in close proximity to the tornado. Fujita noted that identifying patterns in tree fall would be difficult, if not impossible, without the aid of aerial photographs.

Fujita's study is one of many to document and analyze patterns in tornado-induced tree fall (e.g., Letzmann 1923; Hall and Brewer 1959; Budney 1965; Fujita 1981; Bluestein 2000; Peterson 2003). As in Fujita (1989), a common theme among these studies is the converging tree fall within the tornado damage path that results from the complex near-surface flow structure in tornadoes. In an attempt to understand the tornadic wind field causing these convergent tree-fall patterns, more recent studies have employed an analytical model of a translating Rankine vortex combined with modeled tree stands to produce composite charts of simulated tornado-induced tree fall (Holland et al. 2006; Bech et al. 2009; Beck and Dotzek 2010). Through an iterative and subjective process, a pattern of tree fall resembling that which occurred in nature is produced, and the resulting pattern of winds in the vortex is estimated.

Although the analytical vortex model may be considered to be simplistic, the results provide an encouraging and alternative means of estimating properties of the near-surface wind field in tornadoes. Prior to 2011, relatively few aerial vertical photographs had been taken of tornado-induced tree fall, especially from strong tornadoes. Consequently, the number of fallen trees that could be used as observations to verify these modeling studies has been limited, and verification attempts have generally relied on small patches of instantaneous tree fall from tornadoes of mostly weak to moderate strength.

The purpose of this study is to utilize high-resolution aerial vertical photographs of the 2011 Tuscaloosa–Birmingham, Alabama, [category 4 on the enhanced Fujita scale (EF4)] and Joplin, Missouri, (EF5) tornado

tracks to document tornado-induced forest damage and to better understand the behavior of near-surface winds in and near strong tornadoes. Two approaches are taken to accomplish this goal. First, mean cross sections of normalized observed tree fall during the peak-intensity period from each tornado are compared with results from analytical vortex simulations of idealized tornado-induced tree fall. These simulations are performed using a Gumbel distribution (Gumbel 1958) of critical tree-falling wind speeds that is based on the EF-scale (WSEC 2006) recommendations for tree damage with increasing wind speed. The goal of the analysis presented herein is to provide a method of verifying the simulation results that improves upon methods used in prior studies (e.g., Bech et al. 2009; Beck and Dotzek 2010) by reducing subjectivity when comparing the modeled results and observations. The suggested properties of the near-surface wind field are documented in each case and are compared with findings from damage assessments conducted by the National Weather Service (NWS).

A second approach is taken to document and analyze a few distinct tree-fall patterns identified along the Tuscaloosa–Birmingham tornado track. Concentrated bands of tree fall are observed to extend well beyond the primary damage path, especially in areas of complex topography. These damage patterns are analyzed for possible connections to factors external to the tornado, such as the underlying topography or rear-flank downdraft (RFD) internal surges (RFDIS; e.g., Finley and Lee 2004; Lee et al. 2004, 2012; Marquis et al. 2012). In addition, the spatial extent of the tornado-induced tree fall from the Tuscaloosa–Birmingham tornado is compared with video documentation of the tornado to show that tornado-strength winds can extend well beyond the condensation funnel near the ground.

2. Method

a. Tornado tracks

The National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey (NGS) obtained aerial vertical photographs along many tornado damage paths shortly after the 27 April 2011 tornado outbreak and along the 22 May 2011 Joplin tornado damage path. The photographs were acquired at a nominal altitude ranging from 1524 to 4572 m with a ground sampling distance of 0.25 m per pixel. The photographs were freely available online from the NGS (http://ngs.woc.noaa.gov/storms/apr11_tornado/ and <http://ngs.woc.noaa.gov/storms/joplin/>).

In this study, aerial vertical photographs of the Joplin and Tuscaloosa–Birmingham tornadoes were imported into the Environmental Systems Research Institute, Inc.,

FIG. 1. Digitized tree fall from the (a) Joplin and (b) Tuscaloosa–Birmingham tornadoes. The arrow colors denote track-relative tree-fall direction that has utility in identifying locations of converging or diverging tree-fall patterns. (c),(d) Zoomed-in areas of the damage path where the tree-fall patterns appear to have been strongly influenced by the underlying topography (background DEM). The red arrow in (d) denotes the photograph location of Fig. 11, which is described in section 3c.

(ESRI) ArcGIS software and were spatially referenced using the nearest universal transverse Mercator zone projection. From these photographs, fallen trees were identified and manually digitized as polyline features with the starting and ending points of each line representing the base and tip of each fallen tree, respectively. Approximately 10 300 fallen trees were identified and digitized along the Joplin tornado track, beginning at the tornado starting point and ending where the tornado track crossed Interstate Highway 44 (Fig. 1a). Along a majority of the Tuscaloosa–Birmingham tornado track, approximately 94 500 trees were digitized (Fig. 1b).

Using the spatial extent of the digitized tree fall, damage paths for each tornado were digitized as polygon features. The approximate location of the most intense damage was digitized as a polyline along the direction of translation for each tornado. The translation direction for each tornado was computed using the vertices of the maximum damage line. In addition, base-velocity radar data from the nearest Weather Surveillance Radar-1988 Doppler (WSR-88D) site were used to estimate positions of the tornado vortex signature (TVS; e.g., Brown et al. 1978). The digitized TVS positions were used to estimate the approximate translation speed of each tornado.

FIG. 2. Geospatial evolution of the Joplin tornado including (a) translation speed, (b) elevation, (c) width, and (d) translation direction. The gray-shaded region denotes the portion of the track with digitized tree fall. Vertical dark-gray lines delineate the approximate transition from one tornado life-cycle stage to another. Numbers in (c) are spatially joined EF-scale ratings assigned by the NWS. Aerial imagery provides supporting evidence that EF3 damage occurred in the intensification stage during the period for which the NWS designated an EF2 rating.

A Digital Elevation Model (DEM; USGS 2011) of 30-m horizontal resolution was used to estimate changes in elevation along each damage path through an iterative process by 1) “densifying” the maximum damage line with vertices of 30-m spacing, 2) computing a buffer around each vertex using the damage-path radius, 3) extracting DEM points within each buffer, and 4) computing the mean and standard deviation in elevation within each buffer. The goal of this process was to assess the variation of the underlying topography within each tornado’s damage path. The variation of each tornado’s translation speed, elevation (MSL), damage-path width, and translation direction are presented in Figs. 2 and 3 for the Joplin and Tuscaloosa–Birmingham tornadoes, respectively.

b. Analytical vortex simulation of idealized tornado-induced tree fall

The analytical vortex model described in Holland et al. (2006) was used to simulate a tornado-like vortex traveling through a forest. This model assumes a Rankine velocity distribution using the following set of equations:

$$V_{\text{tan}} = V_{\text{max}} r R_{\text{max}}^{-1} \quad \text{if } r \leq R_{\text{max}}, \quad (1)$$

$$V_{\text{tan}} = V_{\text{max}} r^{-1} R_{\text{max}} \quad \text{if } r > R_{\text{max}}, \quad (2)$$

$$V_r = V_{r-\text{max}} r R_{\text{max}}^{-1} \quad \text{if } r \leq R_{\text{max}}, \quad \text{and} \quad (3)$$

$$V_r = V_{r-\text{max}} r^{-1} R_{\text{max}} \quad \text{if } r > R_{\text{max}}, \quad (4)$$

where V_{max} is the maximum tangential wind velocity, $V_{r-\text{max}}$ is the maximum radial wind velocity, R_{max} is the radius of maximum tangential velocity, r is the radial distance from the geometric center, and V_{tan} and V_r are the tangential velocity and radial velocity at r , respectively. The radial profile of V_{tan} in Eq. (2) is based on the conservation of angular momentum, and, although the radial profile of V_r in Eq. (4) is similar to V_{tan} , its physical basis is uncertain. Cyclostrophic imbalance in the near-surface layer may lead to a faster rate of change in V_r than is given by Eqs. (3) and (4), perhaps approaching r^{-2} rather than r^{-1} in Eq. (4), for example (D. Lewellen 2012, personal communication). Tests performed with this adjustment as compared with

FIG. 3. As in Fig. 2, but for the Tuscaloosa–Birmingham tornado. Sections of the track that are of particular interest are denoted by the dark-gray-shaded regions and their associated labels. The white star in (c) indicates the relative location of a destroyed railroad bridge.

those using Eqs. (1)–(4) produced a narrower vortex, especially as the ratio of V_r to V_{tan} increased. Achieving consistency with observed tree fall required increasing the magnitude of the wind field, with peak wind speeds exceeding 134 m s^{-1} (300 mi h^{-1}) while increasing the ratio of V_r to V_{tan} . Although extreme wind speeds of this approximate magnitude cannot be ruled out, at least for the cases presented herein, the analytical vortex model described in Eqs. (1)–(4) appeared to be more reasonable with respect to vortex width and peak wind speed inferred from damage severity. In addition, the use of this analytical model allowed the results to be comparable with the work of Holland et al. (2006) and Beck and Dotzek (2010).

To model a moving tornado-like vortex, the translation vector of the vortex $\mathbf{V}_s$ is added to the v component of the velocity vector (meridional component) at r . The resulting vortex translates from south to north. The model uses a grid spacing of 10 m and adheres to the recommended time step given by Beck and Dotzek (2010),

$$\Delta t \leq \Delta y / \mathbf{V}_s, \quad (5)$$

to avoid undersampling the flow. A “tree” is specified at each grid point by using a Gumbel distribution of critical tree-falling wind speeds, V_{crit} (Fig. 4), and the model is

iterated forward by simulating vortex passage through the grid of idealized trees. Visualization of this process is available in the supplemental material that accompanies this paper, in the form of a compressed file that contains an html file (with accompanying readme file) that launches two animation files.

The Gumbel distribution used in this study is based subjectively on the EF-scale recommendations for values of V_{crit} corresponding to both hardwood and softwood tree species and is generated using the Numeric Python (NumPy) module for the Python Software Foundation open-source Python programming language. Note that the range of wind speeds corresponding to each degree of damage for trees on the EF scale was estimated through expert elicitation (WSEC 2006). The distribution is right skewed to represent how a given stand of trees might behave with increasing wind speed. The lower and upper bounds given for uprooting and snapping of trees roughly corresponds to the distribution’s interquartile range. A sharp cutoff in V_{crit} exists below the 25th percentile, with no trees falling in winds below 32.6 m s^{-1} (73 mi h^{-1} ; lower-bound wind speed for uprooting of softwoods). The inclusion of some trees requiring V_{crit} above the 75th percentile suggests that relatively few of the remaining trees left standing (likely well streamlined) will fall, because of factors such as wind or debris

FIG. 4. Gumbel distribution of critical tree-falling wind speeds (light-gray vertical bars; left y axis) used in the analytical vortex simulations of idealized tornado-induced tree fall. The mean μ , median $\tilde{x}$, standard deviation σ , interquartile range ($\mu \pm \sigma$), minimum (min), and maximum (max) of the distribution are given in the top-right corner. The range of lower- and upper-bound wind speeds for the five degrees of damage given on the EF scale is provided for both hardwood and softwood trees (horizontal lines; right y axis).

loading. This is based on a common observation of many trees left standing (albeit largely debranched/denuded) in violent tornadoes (i.e., EF4+).

The computation of idealized treefall presented herein differs greatly from methods used in prior studies. Both Holland et al. (2006) and Beck and Dotzek (2010) used a tree model, with some minor differences, to iteratively compute the lateral force induced on individual trees

by the wind and to record the wind direction when the tree's bending moment exceeds the tree's resistance. The method presented herein represents a considerable computational simplification to this established method; the goal of both methods is essentially the same, however. Figure 5 presents a comparison of the idealized tornado-induced tree-fall patterns produced with the EF-scale-based Gumbel distribution to a set of results

FIG. 6. (a) Vortex simulation corresponding to the tree-fall patterns produced in Fig. 5, and (b) cross section of maximum along-track wind speeds from (a).

from Holland et al. (2006) and Beck and Dotzek (2010) using an identical vortex simulation. In this case, $V_{tan} = 49 \text{ m s}^{-1}$, $V_r = 40 \text{ m s}^{-1}$, the magnitude of $V_s = 18 \text{ m s}^{-1}$, and $R_{max} = 75 \text{ m}$.

Our simulations compare best to those from Beck and Dotzek (2010), as evidenced by the agreement in the tree-fall patterns in Fig. 5 and the presence of two convergence lines in Figs. 5b and 5c. A convergence line is defined as an area where trees fell in a converging pattern at a consistent tornado-relative location (vertical gray lines in Fig. 5). A lack of tree fall is present on the left side of Fig. 5c, relative to what is seen in Fig. 5b. To investigate this matter, Fig. 6a was created to show the simulated vortex responsible for producing the tree-fall patterns in Fig. 5, along with the cross section of maximum along-track wind speeds for the translating vortex (Fig. 6b). Winds on the left side of the vortex beyond a radius of 150 m do not exceed $27\text{--}29 \text{ m s}^{-1}$ ($60\text{--}65 \text{ mi h}^{-1}$), thus implying that Beck and Dotzek (2010) assume some trees will fall in winds at and below these values. Likewise, Fig. 6 can be used to diagnose why many trees do not fall beyond a radius of 150 m on the right side of Fig. 5a. Figures 6a and 6b show that winds on the right side of the vortex beyond a radius of 150 m are at or below approximately 49 m s^{-1} (110 mi h^{-1} ; i.e., EF2). Beck and Dotzek (2010) argued that the values of V_{crit} used by Holland et al. were too high, and the analysis of Fig. 6 supports this notion. Given the

similarity of our results to those from Beck and Dotzek (2010), we believe our proposed method is suitable for reproducing tornado-induced tree-fall patterns in a computationally efficient manner that is directly related to the EF scale.

c. Tree-fall verification

The method of reproducing observed tornado-induced tree fall that was established in Bech et al. (2009) and Beck and Dotzek (2010) involves performing simulations until subjectively identified agreement is reached between a modeled tree-fall pattern or modeled wind field and a selected portion of the observed tree fall along the tornado track. This method assumes that the tornado is in a quasi steady state while producing the instantaneous pattern of tree fall and that the distribution of critical tree-falling wind speeds is properly represented. In addition, this method may work well in instances in which the observed tree fall is well organized and is somewhat easy to interpret.

In this study, an alternative method of comparing modeled versus observed tree fall was developed by computing a mean cross section of normalized observed tree fall that is oriented perpendicular to the tornado path within a user-specified section of the track. The goal of this method was to reproduce a mean state of the tornado through analysis of the mean tree-fall patterns. This method aims to reduce the impact of heterogeneities that may result in disagreement when trying to compare instantaneous tree fall. Also, this proposed method may work better for long-tracked tornadoes and in sections of the track for which dense coverage of digitized tree fall with widely varying fall directions makes the pattern difficult to interpret. In this study, this method was applied to a section of each track corresponding to the tornado's peak intensity to highlight a potentially useful way for future damage assessments to determine or confirm a tornado's assigned maximum EF-scale rating, especially in regions that lack nonvegetative damage indicators. An example is given in Fig. 7 for the Joplin tornado.

Tree-fall directions were determined by using the beginning and ending points of each digitized polyline representing a fallen tree. The tornado translation direction was assigned to each fallen tree by performing a spatial join (i.e., joining two datasets using nearest distance). This method provides an objective way of conducting tree-fall normalization (Fig. 7a). It is important to note that knowing the precise tornado translation direction when each tree fell is impossible, but we believe that this method is reasonably accurate on the basis of the relative consistency of each tornado's translation directions evident in Figs. 2d and 3d. The

FIG. 7. Visualized overview showing how the best-fit pattern of simulated tornado-induced tree fall was selected for the Joplin tornado. (a) Observed tree fall was normalized using the translation direction and distance from the line of maximum damage. (b) The mean fall direction in 100-m-wide along-track bins was computed to reveal (c) the mean cross section of normalized tree fall. (d) The cross section in (c) was plotted in the y direction for reference. A similar process was carried out in (e)–(h), except using the simulated pattern of instantaneous tree fall from (e). Numerous renditions of (h) were generated until subjective agreement could be identified between (d) and (h). Note that (a) shows only a portion of the observed tree fall that was used in (b)–(d).

normalization was performed by subtracting the tornado's estimated translation direction from each tree's digitized falling direction. This results in a tornado moving due north (i.e., normalized reference frame; Fig. 7a), as is done in the vortex simulations (Fig. 7e), and allows for direct comparison between the modeled results and observations (Figs. 7d and 7h). Both the modeled and the observed tree fall were partitioned into 100-m-wide bins on the basis of the distance from the

line of maximum damage (observed; Fig. 7b) or the zero line (modeled; Fig. 7f), and a mean, normalized falling direction was computed for all tree fall residing in each bin (Figs. 7c and 7g). The mean cross section of normalized observed tree fall was plotted along the x axis (from west to east) and was extended into the y -grid dimension for reference (Figs. 7d and 7h). Many renditions of simulated tree-fall patterns (as shown in Fig. 7h for the Joplin tornado) were generated by fixing $R_{\max}$

and $\mathbf{V}_s$ and adjusting V_r and $V_{\tan}$ until subjective agreement could be identified (i.e., “best fit”) between the simulated and observed tree-fall patterns.

It is important to acknowledge a key assumption in this process. The observed line of maximum damage and the model zero line are assumed to roughly coincide with the same approximate tornado-relative location when vortex translation is accounted for in the analytical vortex model. As can be seen in Fig. 6a, adding $\mathbf{V}_s$ to the v component of the velocity vector causes the vortex center to shift left of the geometric center. Because the track of maximum damage will be related to $R_{\max}$ but may also be associated with other factors, the location with respect to $R_{\max}$ is not known with certainty. For the Spencer, South Dakota, F4 tornado that is described in Wurman and Alexander (2005), the most intense damage occurred at a distance of approximately 66% of $R_{\max}$ from the centerline, and they speculated that this dislocation could be the result of radar effects (debris centrifuging or tapering of the vortex with height). These authors also suggested that, in addition to the peak wind gust, the duration of intense winds, directional variability, and upstream debris may be important factors influencing damage. Thus, while the model geometric center (with vortex translation) likely does not specifically lie along the line of maximum damage, we believe it is close enough to allow this simplifying assumption in the observations–model comparison method.

In some areas, the aerial view of tree fall was obscured by debris or forest canopy. Thus, higher-resolution aerial imagery (Joplin tornado) or ground survey documentation (Tuscaloosa–Birmingham tornado) was used to confirm the location and falling direction of some trees, where possible. Trees with unclear fall directions were not digitized. In addition, the direction of a fallen tree is assumed to represent the instantaneous wind direction when the flow reached a critical speed necessary to cause the tree to fall. This may not be exactly true for every fallen tree, especially for trees that may have become completely airborne. Such trees, however, were a small percentage of the digitized tree fall, with the vast majority observed to have fallen with part of their root or stem structures remaining connected to their original location, allowing the original assumption to remain valid in most instances.

3. Results

a. Joplin tornado

The Joplin tornado formed on the southwestern side of the city at approximately 2235 UTC and lasted until about 2305 UTC (Fig. 2). At the beginning of its life

cycle, the tornado underwent a rapid intensification. The tornado’s damage path grew to a width of nearly 2 km in a span of about 5 min while the tornado traveled east-northeast at approximately 15 m s^{-1} . At that point, the tornado entered its mature stage and was at peak intensity as indicated by the NWS damage-indicator ratings in Fig. 2c. At this time the tornado began to slow from an approximate translation speed of 15 m s^{-1} to a speed of 11 m s^{-1} while the damage-path width remained between 1.7 and 1.9 km. Upon entering its decay stage, the tornado began to turn toward the southeast while its translation speed increased. The remainder of the decay stage was marked by a steady decrease in the damage-path width while the tornado traveled toward the east-southeast at $14\text{--}15 \text{ m s}^{-1}$. The underlying topography shows no significant undulations, with a maximum variation of approximately 20 m within any given buffered region along the track and total relief of about 50 m from beginning to end (Fig. 2b).

Mean cross sections of observed normalized tree fall from the three life-cycle stages, as indicated in Fig. 2, show distinctive characteristics (Fig. 8). A gradual transition of V_{crit} from a southeast to easterly (to southeasterly in Fig. 8a, northeasterly in Figs. 8b and 8c) direction (relative to the normalized reference frame) occurs as the maximum damage line is approached from the right side (looking downstream along the tornado track). A convergence line is evident very near the maximum damage line in all three cases. Near the convergence line, an abrupt transition of V_{crit} occurs toward a northwesterly direction and extends to the left edge of the track. Also, the patterns exhibit differences in radial extent and symmetry about the maximum damage line. Tree fall from the intensification and mature stages is skewed toward the right side of the maximum damage line; in the decay stage, tree fall is skewed toward the left side.

It is important to note that the patterns from the intensification (Fig. 8a) and decay (Fig. 8c) stages are likely partially skewed by a significant amount of tree fall that took place near the part of the path considered to be the mature stage (Fig. 8b). To investigate how much skewing might be occurring, an analysis was performed using the first 2-km section of the track (not shown). This analysis showed a reversal in the orientation of the central convergence line evident in Fig. 8, suggesting that the wind field was weaker here relative to other parts of the track (discussed further below), as might be expected with a developing tornado. Thus, ascertaining a representative mean state of a tornado during periods encompassing significant changes in intensity is problematic.

Another notable difference in the observed tree-fall plots in Fig. 8 is a divergent signature present on the

FIG. 8. Mean cross sections of observed normalized tree fall from the (a) intensification, (b) mature, and (c) decay stages of the Joplin tornado, as indicated in Fig. 2.

far-right side in Fig. 8b and, to a lesser extent, in Fig. 8a. This signature is marked with mean V_{crit} winds that are making a transition from a south to southeasterly direction. This stands out because it is not present in any of

the model results from Holland et al. (2006), Beck and Dotzek (2010), or any of the other model results produced for or shown in this study. The lack of this signature in any of the model results likely implies that the mechanism responsible for producing this pattern of damage is beyond the capability of the analytical vortex model. Beck and Dotzek (2010) note a similar pattern of divergence in their Fig. 7b and suggest that this type of signature may be the result of falling-tree interaction or terrain effects. As noted in Fujita (1989), however, a divergent pattern of tree fall may be attributable to strong downdraft winds. Thus, it is also possible that this type of signature could be the result of strong RFD winds closely bounding the tornado on its right flank. The location of tree fall contributing to this signature can be seen on the southern side of the track in Fig. 1a between the intensification and mature periods. Further discussion regarding RFD winds as a possible influence on some tree fall is given in section 3c.

Numerous simulations were performed with the analytical vortex model in an attempt to reproduce the mean pattern of normalized observed tree fall shown in Fig. 8b. This section of the track was selected to characterize the tree-fall pattern while the tornado was most intense. An intriguing aspect of the observed tree fall is the central convergence line that is oriented with a component of tree fall to the south. If one assumes a vortex translation speed of 11 m s^{-1} , the observed pattern of damage can be reproduced using a variety of model configurations. For example, if one assumes a wide R_{max} (i.e., 400 m), the vortex must be configured with a small ratio of V_{tan} to V_r in order to centralize the convergence line. In addition, the vortex must be near EF4 strength (74 m s^{-1}) to reproduce the southward orientation of the convergence line and radial extent of tree fall. As the intensity of the vortex weakens, the orientation of the convergence line reverses owing to a reduction of trees falling on the upwind side of the vortex. To maintain proper positioning and orientation of the convergence line while increasing the ratio of V_{tan} to V_r , R_{max} must decrease and the magnitude of winds must increase. Having an estimate of R_{max} from a ground-based or aerial damage survey greatly simplifies this procedure.

The best-fit pattern of idealized tree fall is shown in Fig. 9a along with a snapshot of the simulated vortex in Fig. 9b. As mentioned previously, an animation of the simulated tree fall for this case is available in the supplemental material that accompanies this paper. In these figures, R_{max} was chosen to coincide with an approximate radius of damage of EF3 and greater of 300 m as shown in Fig. 2c. The use of these parameters resulted in a vortex with $V_{\text{tan}} = 43 \text{ m s}^{-1}$, $V_r = 86 \text{ m s}^{-1}$,

FIG. 9. Best-fit simulations of idealized tornado-induced tree fall and the resulting analytical vortex wind field corresponding to the peak-intensity period for (a),(b) the Joplin tornado (observations shown in Fig. 8b) and the (c),(d) Tuscaloosa–Birmingham tornado (observations shown in Fig. 10b, below).

and peak winds near 104 m s^{-1} . These results support the EF5 rating assigned by the NWS. A low ratio of V_{tan} to V_r was not expected on the basis of visual observations that showed a wide tornado, supported by the wide damage path, and from documentation of tornadoes by mobile Doppler radars that suggests stronger tangential winds than radial winds on the lowest elevations scans (e.g., Wurman and Alexander 2005; Bluestein et al. 2007). It is important to note that mobile radar observations seldom adequately resolve the near-surface inflow layer, where the influence of friction is strong. The inference for the case herein was for a two-cell vortex structure (Davies-Jones 1986) with the implication that near-surface winds had larger tangential components than radial components. A comparison of Figs. 1a and 1b from Lewellen et al. (2000), however, shows that a larger radial-to-tangential wind relationship can exist in the near-surface layer while the overall vortex structure remains two celled (D. Lewellen 2012, personal communication). In addition, a correction for the centrifuging of hydrometeors performed in Wakimoto

et al. (2012) for the LaGrange, Wyoming, tornado suggests that mobile Doppler radar data could be significantly biased, such that the magnitude of radial velocity near the tornado core is significantly underrepresented. The importance of the radial velocity in the near-surface layer is supported, in part, by the presence of large surface roughness in Joplin owing to the high density of buildings and well-established trees. Thus, significant surface roughness may increase the likelihood of a vortex occurring that is similar to the one documented in Lewellen et al. (2000) or, less likely, a low-swirl-ratio vortex. Without detailed near-surface flow measurements, it is impossible to know the tornado's true structure. Nonetheless, we feel it is important to document the model results while acknowledging that uncertainty exists.

b. Tuscaloosa–Birmingham tornado

The Tuscaloosa–Birmingham tornado formed roughly 20 km southwest of Tuscaloosa and dissipated on the north side of Birmingham. Before entering Tuscaloosa,

tornado damage evident in the aerial photographs was sporadic, and the translation direction was not well defined (Fig. 3d), suggesting that the tornado was less organized early in its lifetime. Beginning on the southwestern side of Tuscaloosa, the width of the damage path progressively increased and continued to increase northeast through the city. This period may be characterized as the tornado's intensification stage, with EF4 damage observed in Tuscaloosa (Fig. 3c). The damage path reached a maximum width of nearly 2 km on the northeastern side of the city. Tree fall in this region was extensive, but few damage indicators were available. On the basis of the severity of tree fall evident in the aerial photographs, this part of the track may be characterized as the tornado's peak intensity (Fig. 3c). After sustaining a width near 2 km for about 4 km, the damage path over the next 15 km indicated the tornado made a transition to a more steady-state mature stage with a width of about 1 km that was roughly maintained for 70 km until its demise. The large variation in EF-scale ratings assigned during this period is likely attributable to sparse damage-indicator availability.

Other important features to note include the translation speed of the tornado, which varied between 22 and 28 m s^{-1} throughout its life (Fig. 3a), and the underlying topography, which shows a considerable amount of variation (Fig. 3b). Approximately 175 m of total vertical relief was encountered from beginning to end, along with many localized changes in elevation at various places along the track. The city of Tuscaloosa, located 20–35 km from the start of the track, stands out as having little variation in elevation. Outside of this section of the track, hills and valleys on the order of 25–75 m in vertical relief are fairly common in any given buffered region.

Mean cross sections of observed normalized tree fall from each of the tornado's life-cycle stages, as indicated in Fig. 3c, are shown in Fig. 10. Patterns from the intensification (Fig. 10a) and the approximate steady-state mature (Fig. 10c) stages are surprisingly similar, both in overall appearance and radial extent. The near-neutral orientation of the central convergence lines (i.e., the felled trees were neither oriented northward nor oriented southward) and radial extent of tree fall suggest winds on average were weaker in strength during these periods relative to the peak-intensity stage with a southward-directed convergence line and larger radial extent of tree fall (Fig. 10b). This is supported by analyses performed on smaller sections of the track within the approximate steady-state mature stage, revealing that the orientation of the convergence line becomes northward directed in some places. In addition, the convergence lines in Figs. 10a and 10b are located approximately

FIG. 10. As in Fig. 8, but for the Tuscaloosa–Birmingham tornado during its (a) intensification, (b) peak-intensity, and (c) ~steady-state mature stages as indicated in Fig. 3.

100–150 m to the left of the maximum damage line, whereas in Fig. 10c the convergence line is nearly collocated with the maximum damage line. A more centralized convergence line in Fig. 10c also supports the

notion of weaker flow in this part of the track if the ratio of V_{tan} to V_r is assumed to remain consistent.

Note also that the patterns show similarities to those from the Joplin tornado, especially on the right side of the track, with the exception of the divergent signature noted in Fig. 8b. A key difference exists on the left side of the patterns, however. For example, the peak-intensity stage in Fig. 10b shows primarily west-northwesterly V_{crit} as the centerline is approached from the left side, whereas its counterpart in Fig. 8b indicates primarily northwesterly V_{crit} winds on the left side. This subtle difference is likely attributable to an asymmetry in the near-surface flow field caused by differing translation speeds (11 vs 23 m s^{-1}) for each tornado.

The best-fit pattern of idealized tree fall is shown in Fig. 9c along with its simulated vortex in Fig. 9d. Again, an animation of the simulated tree fall for this case is available in the supplemental material that accompanies this paper. Finding an ideal match proved to be challenging. The asymmetry imposed on the vortex by $\mathbf{V}_s = 23 \text{ m s}^{-1}$ leads to the differences that can be seen on the left side between Figs. 10b and 9c, but little can be done to remedy these differences while maintaining proper tree-fall orientation and extent. Nevertheless, the best-fit vortex is shown with $R_{\text{max}} = 200 \text{ m}$ (estimated from aerial photography), $V_{\text{tan}} = 36 \text{ m s}^{-1}$, $V_r = 76 \text{ m s}^{-1}$, and peak winds near 99 m s^{-1} . The results suggest that the tornado was of EF5 intensity during this stage of its life, despite the EF4 rating assigned by the NWS. The EF4 rating may be attributable to a lack of EF-scale damage indicators in this section of the track, as shown in Fig. 3c. Of interest is that the tornado destroyed a railroad bridge during this period, as noted in Fig. 3c, implying very high wind speeds, but this indicator could not be used in the NWS assessment (K. Laws, NWS Birmingham, 2012, personal communication). Again, strong radial near-surface winds were needed to produce the best-fit tree-fall pattern.

c. Distinct tree-fall patterns

Some distinct treefall patterns were evident in the aerial photographs of the Tuscaloosa–Birmingham tornado damage path. At several locations, concentrated bands of tree fall extended well beyond the primary damage swath. In most cases, these bands of tree fall are collocated with valley channels. Two of the most prominent examples are given in Figs. 1c and 1d. This pattern was observed most frequently on the far left side of the track in valley channels with an approximate orientation that was perpendicular to the tornado translation axis. These observations raise questions about the relationship between near-surface inflow to the tornado and the underlying topography. In particular, to what extent

does the underlying topography influence the direction and speed of near-surface inflow, and what do these conditions imply about vortex structure? It is hypothesized that the pattern of tree fall noted in Figs. 1c and 1d was strongly influenced by, or was the result of, near-surface inflow to the tornado being channeled by the underlying topography.

Prior studies have used observations (e.g., Hannesen et al. 1998, 2000; LaPenta et al. 2005; Bosart et al. 2006) and numerical modeling (e.g., Frame and Markowski 2006; Ćurić et al. 2007, Markowski and Dotzek 2011) to suggest how complex topography may affect the structure and evolution of severe storms and their associated wind flow. For example, Bosart et al. (2006) surmised that southerly inflow to a storm crossing the Hudson River valley (approximately 1-km change in elevation) was channeled parallel to the valley floor. They suspected that this channeling effect significantly modified the low-level vertical wind profile by directing flow parallel to the valley channel, increasing the storm-relative helicity of inflow parcels and enhancing the tornado-genesis potential as the storm crossed the valley. The channeling effect presented herein is similarly thought to have also led to winds increasing above the minimum threshold wind speed necessary to induce uprooting or stem breakage.

It is important to note a few other factors that could have contributed to the observations documented in Figs. 1c and 1d. Among these factors are inhomogeneity in tree species, age, and type, as well as soil moisture, depth, and type. Perhaps the largest potential factor here is soil moisture. Studies have shown that valleys can have higher soil moisture values than the adjacent ridges, particularly during wet periods (e.g., Western et al. 1999). This might promote a shallower root structure in trees residing in valleys, making them more susceptible to uprooting at lower wind speeds than are needed elsewhere. In this scenario, most if not all fallen trees should be uprooted and no wind-induced snapping should be evident, considering that trees along the adjacent ridges were mostly unharmed. To investigate this scenario, a ground survey was performed on 21–22 January 2012 by the lead author that revealed a cross-channel gradient of tree damage (Fig. 11). Trees along the ridges were mostly unharmed while intense tree fall began about halfway down the side of each ridge and continued to the bottom of the valley, with some snapping evident. From the survey, it was estimated that approximately 66% of fallen trees were uprooted, and the remaining 33% were snapped. It was apparent that a few of the snapped trees were a result of falling-tree interactions. In most cases, however, trees that were snapped appeared to fall as a result of wind loading. These

FIG. 11. Cross-channel gradient in tree fall from the Tuscaloosa–Birmingham tornado. The location of the photograph is indicated by a red arrow in Fig. 1d.

observations support our aforementioned hypothesis of topographically induced flow channeling and acceleration. Further testing of this hypothesis is being conducted with laboratory vortex experiments that will be the subject of future work.

In an attempt to further evaluate potential topographical influences on the near-surface wind field in a broader sense, an analysis of the tree fall was performed

on “rough” and “smooth” subsections of the damage path (Fig. 3b). These subsections correspond to areas with the greatest (± 25 m) and least (± 5 m) variability in topography, respectively, within the approximate steady-state mature stage and have similar values of translation speed, damage-path width, and translation direction (Figs. 3a, 3c, and 3d). It is hypothesized that a positive correlation should exist between topographic

variability and tree-fall variability. The results of our analysis support this hypothesis to some degree.

Standard deviations of the tree fall (Yamartino 1984) within each 100-m-wide bin relative to the line of maximum damage (Fig. 12a) indicate that the rough subsection has, in general, more variability in tree-fall directions relative to the smooth subsection, with an average difference of approximately 15° between comparable bins. A Wilcoxon rank-sum test (Wilcoxon 1945) reveals that 8 of the 11 comparable bins were significantly different using a p value of 0.05 and that 5 of 11 were significantly different using a p value of 0.01. The maximum in the distribution for the smooth subsection is positioned slightly left of the maximum in the rough distribution and is associated with differences in the location of the convergence line relative to the maximum-damage line as shown in Figs. 12b and 12c.

The mean cross sections of normalized tree fall also show slightly different patterns, especially near the line of maximum damage. The rough case shows a near-neutral orientation of the tree fall near the convergence line that is collocated with the line of maximum damage (Fig. 12b), and the smooth case shows a southward-directed orientation of the tree fall near the convergence line located approximately 100 m left of the line of maximum damage (Fig. 12c). This would indicate that the wind speeds may have been slightly stronger over the smooth subsection than over the rough subsection, and this notion is supported by the EF-scale damage ratings within these two sections (Fig. 3c). It is possible that the additional roughness from the topography alone could have led to a reduction in wind speeds, if one assumes that all other variables, such as the tornado and its parent storm, were in an approximate steady state. Support for this steady-state assumption is given by the aforementioned similarities evident in Fig. 3 and by the consistency in base reflectivity from the NWS Doppler radar in Birmingham (KBMX) during these times (Figs. 12d,e). Thus, some evidence suggests that the magnitude and directionality of the near-surface tornado wind field are sensitive to the degree of variability in the underlying topography.

One broad swath of tree fall extending well away from the primary damage path did not appear to be systematically related to the underlying topography. It was located on the right side of the tornado damage path (Fig. 13) and occurred between the intensification and mature stages. In the absence of near-surface observations of the tornado and near-tornado environment during this time, it is difficult to conclusively determine what caused this observed pattern of damage. Evolution of the normalized rotation algorithm (NROT; e.g., Smith and Elmore 2004; Lemon and Umscheid 2008) from

KBMX (Fig. 14) suggests that the TVS was reaching peak intensity near and just downstream of the location of the tree-fall swath. The presence of a strong anticyclonic signature on the southern flank of the track (Fig. 14) along with a sharp increase in inbound radial wind speed within the RFD region noted on KBMX radar at 2215:28 UTC (not shown) suggests that an RFDIS may have occurred. An RFDIS is accompanied by a sharp increase in wind speed and often by changes in thermodynamic characteristics in comparison with the RFD air mass preceding it. Tornado intensification has been temporally associated with RFDISs (e.g., Finley and Lee 2008; Lee et al. 2010, 2012). The placement of the tree-fall swath compares well to observations of an RFDIS in Lee et al. (2012, see their Figs. 11 and 12), particularly near the surge's leading edge. Thus, it seems plausible to establish a connection between the swath of tree fall shown in Fig. 13 and an RFDIS. It is unlikely that a satellite tornado could have produced the damage since trees in this region did not show a convergent pattern and appeared to fall mostly from a consistent direction.

Last, two publicly available videos of the tornado on the YouTube Internet site were geolocated using Google Street View Internet software to mark the approximate location of each video relative to the passage of the tornado and relative to the tree-fall-derived tornado track (Fig. 13). Although these videos were of insufficient quality to allow photogrammetric analysis, in the video frames shown (and the full video), it is clear the condensation funnel did not reach far enough south to impact the observers, yet Fig. 13 depicts the observers immersed within a swath of tree fall. The diameter of the condensation funnel at ground level was, therefore, smaller than the diameter of the swath of tree fall. This result implies that tornado-strength winds extended well beyond the perimeter of the condensation funnel, a finding that has been noted previously in studies that compared Doppler radar velocities with photographs of tornadoes (e.g., Bluestein et al. 1993, 1997; Wakimoto et al. 2011) and in tornado photogrammetric studies (Golden and Purcell 1977, 1978). This finding makes it clear that differences are likely when tornado width is defined visually as compared with using a damage path. Further complexity is added when strong RFD winds topple trees alongside the tornado track, as suggested in Fig. 13. Situations such as this one make distinguishing between tornado- and RFD-related damage difficult.

4. Conclusions

In this study, aerial vertical photographs of tornado damage from the Joplin tornado of 22 May 2011 and the

FIG. 12. (a) Comparison of tree-fall variability within the rough and smooth sections of the Tuscaloosa-Birmingham tornado track, as indicated in Figs. 1b and 3b. White and black stars indicate significant differences using p values of 0.05 and 0.01, respectively. The smooth bars are partially transparent to reveal overlapped regions. Also shown are cross sections of (b),(c) mean normalized observed tree-fall patterns along with (d),(e) contoured 0.5°-tilt KBMX base reflectivity for the (left) rough and (right) smooth subsections.

FIG. 13. Section of the Tuscaloosa–Birmingham tornado damage path encompassing the intensification and peak-intensity stages. Approximate locations of the photographs are indicated by the camera icons. The leftmost photograph was provided through the courtesy of R. Chandler and N. Hughett. The other photograph was provided through the courtesy of J. Rosolowski.

Tuscaloosa–Birmingham tornado of 27 April 2011 were used to

- 1) objectively compose damage tracks for conducting geospatial analysis of each tornado's translation speed, translation direction, width, and underlying topography,
- 2) document tornado-induced tree fall along each tornado's path,
- 3) develop alternative methods of simulating and verifying analytical vortex simulations of idealized tornado-induced tree fall,
- 4) identify tree-fall patterns that were likely induced by external factors, such as RFD winds or underlying topography, and
- 5) geospatially relate the approximate condensation funnel diameter to the width of the damage path as indicated by tree fall.

The use of aerial vertical photographs in tornado-damage surveying has been limited, which is likely attributable to the high costs associated with obtaining such detailed imagery. Yet, as we have shown, these photographs are valuable for objectively identifying the location and geospatial variation of features along a tornado damage path. We recommend continued acquisition of this imagery from future high-end tornado events and from events that present a challenge to

damage surveyors, such as long-track tornadoes, multiple tornadoes occurring over the same areas, and tornadoes occurring in difficult terrain.

In addition to damage-path documentation, the aerial vertical photographs were used to identify and document the location and falling direction of individual trees along the path of each tornado. The falling direction of each tree was normalized using the approximate tornado translation direction. A method was developed to group the tree fall into 100-m bins, relative to the approximate line of maximum damage, and to compute a mean cross section of normalized observed tree fall during the various stages of each tornado. In the future, it would be worthwhile to develop or utilize an image-processing algorithm to automate the tree-fall digitization process so that techniques outlined herein or elsewhere could be used operationally.

The mean cross sections of normalized observed tree fall from each tornado's peak-intensity region were subjectively compared with results from analytical vortex simulations of idealized tornado-induced tree fall that used a Gumbel distribution of tree-falling wind speeds that was based on the EF scale. The best-fit results for the Joplin tornado support the EF5 rating assigned by the NWS. Results for the Tuscaloosa–Birmingham tornado were similar and indicate that winds may have reached EF5 intensity. The presence of large surface

FIG. 14. Evolution of the low-level rotation signature using the NROT algorithm for the Tuscaloosa–Birmingham tornado. Small black lines indicate digitized tree fall along the track.

roughness and a fast translation speed (Tuscaloosa–Birmingham tornado only) during the analysis periods offer support for the strong radial near-surface winds suggested by the model results. The low ratio of V_{tan} to V_r differed from expectations for tornadoes with such large damage-path widths. These results are subject to limitations associated with the analytical vortex model and uncertainties in the assumed EF-scale-based tree-falling wind speed distribution. We encourage further evaluation of our methods and results using a 3D vortex model like those employed by Lewellen et al. (1997) or Le et al. (2008). We also recommend incorporating objective techniques to automate the selection of the best-fit result, such as least squares fitting or self-organizing maps (e.g., Gutowski et al. 2004; Cassano et al. 2006).

The observations were also used to identify a few distinct tree-fall patterns that were caused by possible topographical influences or strong RFD winds, possibly including an RFDIS. For the first of these, concentrated bands of tree fall extending well beyond the primary damage swath and oriented parallel to valley channels were noted at several locations along the track, particularly on the left side. These unique patterns raise some interesting questions about the behavior of near-surface winds in and near tornadoes. On the basis of evidence from aerial photography and from a ground survey, we believe these patterns are the result of topographically

induced flow channeling that is sufficient to increase the speed of the flow above the minimum threshold necessary to induce tree fall. An analysis contrasting two subsections (rough vs smooth topography) from the approximate steady-state portion of the Tuscaloosa–Birmingham tornado damage path showed that the underlying topography was likely influencing the magnitude and local direction of the near-surface wind field.

Evidence for RFD winds in the Joplin tornado was given by a divergent signature on the right side of the mean cross section of normalized tree fall from its mature stage. For the Tuscaloosa–Birmingham tornado, evidence for an RFDIS was given by an extensive swath of tree fall extending well to the right side of the primary damage path that did not appear to be associated with other factors such as the underlying topography. KBMX radar data support the RFDIS at this location. In both cases, the tree fall contributing to these patterns occurred between the intensification and mature stages of the tornadoes.

Last, available video documentation of the Tuscaloosa–Birmingham tornado in Tuscaloosa confirms that the diameter of the condensation funnel was considerably smaller than the tornado diameter that is based on treefall. Differences are likely when tornado width is defined using ground-based visuals versus aerial photographs, especially on the right flank when strong RFD

winds, often evident in an RFDIS, accompany the tornado. Thus, differentiating between tornado and RFD-related damage is difficult and requires careful analysis.

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