A Comparison of Wind Speed and Forest Damage Associated with Tornadoes in Northern Arizona

DAVID O. BLANCHARD

NOAA/National Weather Service, Flagstaff, Arizona

(Manuscript received 26 April 2012, in final form 23 September 2012)

ABSTRACT

Damage surveys in the aftermath of tornadoes occurring in the forested regions of the Mogollon Rim in northern Arizona have been assessed using the enhanced Fujita scale (EF scale) damage indicator (DI) and degree of damage (DOD) tables. These surveys often revealed different DODs within close proximity as well as different spatial patterns and areal extent of tree damage exhibiting the same DOD, making the determination of wind speed and EF-scale ratings challenging. A localized tornado outbreak occurred across northern Arizona on 6 October 2010, producing at least 11 tornadoes and substantial areas of forest damage. Remarkably, one of these tornadoes passed over a three-dimensional sonic anemometer. Wind data from this sensor are compared with tree damage in the adjacent forest to assess the performance of the EF-scale metrics for damage to trees.

1. Introduction

In recent years, there has been an enhanced effort to conduct detailed damage surveys in the aftermath of tornadoes in northern Arizona (Blanchard 2006). Most of these surveys have taken place in the forested regions of the Mogollon Rim (Fig. 1), an escarpment defining the southwestern edge of the Colorado Plateau. The rim ranges in elevation from approximately 2000 to 2500 m (~6500 to 8000 ft) with a few mountainous locations rising above 3500 m (~11 500 ft). Conifers are the dominant type of vegetation, but stands of deciduous trees can also be found.

Although detailed tornado damage surveys in forests are a recent development in northern Arizona, damage surveys and investigations in forests elsewhere have a much longer history. Some of the earliest formal studies were conducted in Europe by Wegener (1917) and later by Letzmann (1923), who examined different combinations of radial, tangential, and forward speeds to develop schematic illustrations of several fundamental wind-field patterns. In this early work, Letzmann suggested that when a tornado moved through a forest, it produced a damage pattern that was related to the sum of vortex winds (radial V_r and tangential V_t velocities) and forward speed (translational velocity V_{trans}). The pioneering results of Letzmann have been discussed at length by Peterson (1992), Holland et al. (2006), Dotzek et al. (2008), and Beck and Dotzek (2010).

Other studies examining the effects of tornadoes in trees can be found in Hall and Brewer (1959), who investigated a cluster of tornadoes that struck forested regions in west-central Wisconsin. They described a variety of damage patterns and compared them with three idealized flow models, which enabled them to account for the different patterns exhibited in the damage paths. Later, Budney (1965) used aerial photographs to produce drawings representing the types of treefall damage patterns from a tornado in Pennsylvania. Fujita (1989) presented an exceptionally detailed analysis of the extensive high-elevation forest damage produced by a severe thunderstorm in Wyoming. He concluded that the damage was caused both by tornadic vortices and microburst outflows based on patterns of treefall and other damage indicators.

Peltola et al. (1997, 1999) developed mechanistic tree models to predict the thresholds necessary to break the stems of trees. This required different tree models for different species. They found, for example, as crown size grows with greater tree spacing, the wind force on the tree increases and the critical wind speed for damage decreases.

Corresponding author address: David O. Blanchard, NOAA/National Weather Service, P.O. Box 16057, Bellemont, AZ 86001.
E-mail: david.o.blanchard@noaa.gov

DOI: 10.1175/WAF-D-12-00046.1

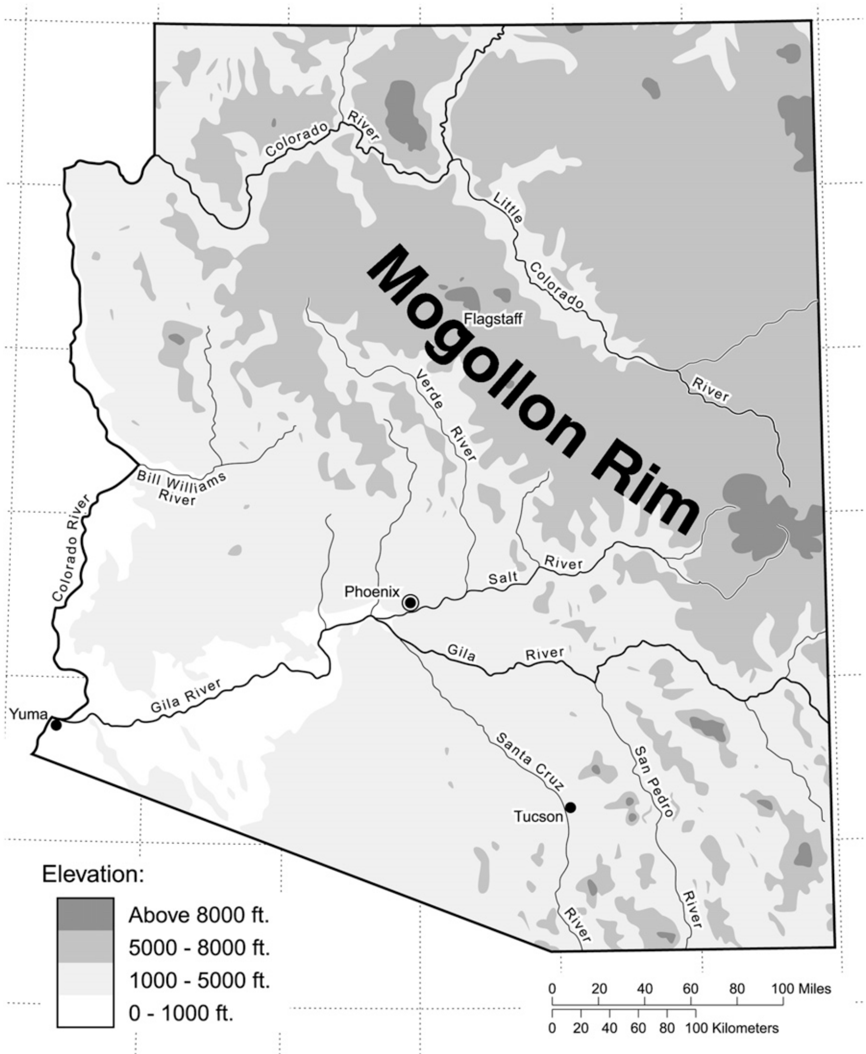

FIG. 1. Map showing major geographic features over the state of AZ. The Mogollon Rim is noted.

Holland et al. (2006) presented a quantitative physical model to describe patterns of downed trees produced by tornadic winds. Their model was based on a simple Rankine vortex and a modified tree model designed by Peltola et al. (1999). The resulting treefall patterns were shown to depend on translational velocity, radial velocity, and tree resistance. Dotzek et al. (2008) noted that the computer results produced by Holland et al. (2006) supported the analytical hand-drawn analysis produced by Letzmann (1923), as the underlying model was the same.

Bech et al. (2009) compared tree fall in a forest with the results from a combined Rankine vortex model that varied the rotational (i.e., both the tangential and radial) and the translational components of the wind, the ratio $G_{\max}$ between the rotational and translational components of the wind vector, and the deflection angle α (the angle between the radial component vector and total wind vector). Their methodology helped to confirm the tornadic character of the damage, while discarding microbursts as a cause, and gave a reasonable estimate of vortex strength.

Beck and Dotzek (2010) also used a Letzmann-type model for treefall patterns and concluded that the model allows for ‘‘a more accurate classification of tornado intensity in comparison with the classification based on pure damage analysis. . .’’ They further noted that an advantage of the Letzmann-type model is its independence of tree species and other tree parameters such as those described by Peltola et al. (1997, 1999) and Peterson (2003). Most importantly, they stated that the damage pattern completely determines the wind field and its intensity in the Letzmann model if the tornado translation speed is known and an average critical velocity for stem breakage is used. They noted, however, that additional factors including slope and terrain might influence the treefall pattern.

The inherent difficulties of performing a damage survey were discussed by Doswell and Burgess (1988), who pointed out that tornadoes that occur in open country (or forests) often do not damage structures, hence making a Fujita scale (Fujita and Pearson 1973) rating more difficult. Similarly, Bech et al. (2009) noted that while the newer enhanced Fujita scale (EF scale; WSEC 2006) describes the effects on trees and vegetation in more detail than the original Fujita scale, it does so much less precisely than for artificial structures.

It is evident that the research and observations of damage to forests and trees by tornadoes has an extensive history. Yet, the recently adopted EF scale has a limited selection of damage indicators (DIs) and degrees of damage (DODs) from which to assess tornadic tree damage and assign an EF-scale rating. Nor does it consider treefall pattern even though it has played an essential part of the analyses by Fujita (1989) and others.

The intent of this presentation is to examine and discuss the EF-scale DIs and DODs for assessing tree damage in a forest during recent tornado events in northern Arizona. As part of the discussion, damage surveys and meteorological data from a localized tornado outbreak that occurred across northern Arizona on 6 October 2010 and produced at least 11 tornadoes are examined. One of these tornadoes—a long-track event that was 42 km in pathlength—passed over a three-dimensional sonic anemometer in its later stages. Wind data from this sensor are compared with nearby tree damage to assess the EF scale for damage to trees and whether modifications might be considered for forest damage.

2. Results of northern Arizona damage surveys

The more recent tornado damage surveys of the primarily coniferous trees in northern Arizona were assessed using EF-scale DI and DOD tables (WSEC 2006). Earlier surveys used the original *F* scale (Fujita and Pearson 1973).

It was frequently observed that DODs 1 and 2 (DOD1: small limbs broken, up to 1-in. diameter; DOD2: large branches broken, 1–3-in. diameter) were rarely encountered without also having DOD3 and DOD4 present (DOD3: trees uprooted; DOD4: trunks snapped); that is, surveys were rarely able to find damage consisting of only DOD1 and DOD2. Evidence of DOD5 (debarking of trees) has not been found in these forest surveys. This is consistent with the findings of Ladue and Ortega (2008), who found little debarking in areas devoid of artificial structures.

Equally challenging was that DOD3 and DOD4 were often present in the same area and even side by side (i.e., within a few meters or less of each other), resulting in some uncertainty in determining the appropriate DOD and wind speed causing the damage. Both DOD3 and DOD4, however, have expected wind speeds (EXP) that are in the same EF rating (EF1); thus, this may have little practical implication.

Consequently, in natural forests, we are likely limited to DOD1–DOD4 representing a range of EXP from 60 to 104 mi h^{-1} ($\sim$27–46.5 m s^{-1}) and which corresponds to sub-EF0 to upper-end EF1 storms. The EF scale includes, in addition to the EXP, a lower bound wind speed (LB) and upper bound wind speed (UB). Including the full range from LB to UB for DOD1–DOD4 corresponds to sub-EF0 to midrange EF2 events [48–128 mi h^{-1} ($\sim$21.5–57 m s^{-1})].

As currently implemented, there are no DODs in the EF scale available for assessing EF4 or EF5 damage in trees and EF3 is only available if debarking of trees (DOD5) is present. Beck and Dotzek (2010) noted that while damaged objects provide an estimate of the lower limit of wind speeds, inference of an upper limit of wind speeds requires objects strong enough to remain undamaged by the storm. Peterson (2003) had previously suggested that "the existing tree damage metrics are overly simplistic, and that their application is likely to be vague, and perhaps even misleading."

Figure 2 shows a damage swath through a ponderosa pine forest. This damage path, which occurred during the morning hours of 14 October 2006, was $\sim$15 km in length, but rarely more than 25–50 m wide. In the damage path are numerous trees with snapped trunks and crowns (DOD4) at a variety of heights as well as standing trees with removed branches (DOD1 and DOD2). Figure 3 shows a patchwork damage pattern from the same event with snapped trunks (DOD4), uprooted trees (DOD3), broken branches (DOD1 and DOD2), and undamaged trees all within a few tens of meters of each other. Assigning a reasonable and appropriate DOD is challenging and the result could be a rating of anywhere from low-end EF0 to upper-end EF1. In these locations, the EXP for the most prevalent DOD was used to assign a representative EF value.

When making an assessment, it is useful to recognize that there may be only partial damage within the swath. Surveys of northern Arizona tornado damage[1] have revealed the extent of damage to typically range from

[1] Twelve surveyed damage paths were considered for this study: 21 February 2000 (1), 9 September 2003 (1), 4 September 2004 (1), 18 October 2005 (2), 14 October 2006 (1), and 6 October 2010 (6).

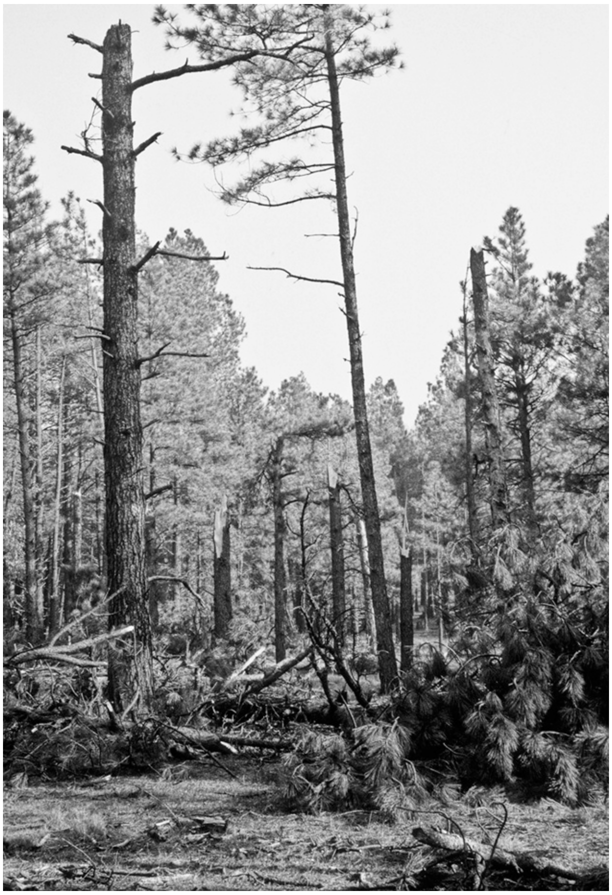

FIG. 2. Portion of the damage path from the 14 Oct 2006 tornado in northern AZ. Note the variation in damage, with trees with snapped trunks next to uprooted trees and all in proximity to undamaged trees.

only a few percent of the trees up to about one-half of the trees within the swath; most swaths exhibited damage at the lower end of this range. By comparison, four of the 6 October 2010 swaths included extensive areas of nearly complete and total damage. The current implementation of the EF scale does not provide a way to distinguish tornado intensity using the extent or completeness of damage and relies, instead, on the presence or absence of the various DODs.

An additional consideration in the assessment was the larger-scale treefall pattern in many of the northern Arizona surveys. Uprooted trees and snapped trunks usually displayed an asymmetric damage pattern. Modeling and analytic studies have noted that, for a given vortex strength, as the forward speed increases, the damage area moves to the right side[2] of the track and

[2] This is for a Northern Hemisphere cyclonic vortex.

FIG. 3. Portion of the damage path from the 14 Oct 2006 tornado in northern AZ. Note the variation in damage to trees with snapped trunks next to undamaged trees.

individual trees align increasingly in the direction of the storm motion (Letzmann 1923; Hall and Brewer 1959; Holland et al. 2006; Beck and Dotzek 2010). This is a result of the additive speeds to the right of the vortex (i.e., $V_r + V_t + V_{trans}$) with subtractive speeds to the left ($V_r + V_t - V_{trans}$). This suggests that some of the surveyed tornado damage paths in northern Arizona may be the result of a weak vortex (small $V_r + V_t$) traveling with a large translational speed (large V_{trans}).

Conversely, the 6 October 2010 damage swaths showed much more symmetry over significant portions of the path. These storms were moving at speeds of $\sim$20 m s^{-1}, which is comparable to other recent cool-season tornadoes in northern Arizona. Thus, the combination of high translation speed and greater treefall symmetry supports stronger vortex speeds (Letzmann 1923; Hall and Brewer 1959; Holland et al. 2006; Beck and Dotzek 2010).

The EF scale only allows for the presence or absence of the various DODs; there is no provision within the EF scale to account for the treefall patterns even though substantial research indicates its importance (Ladue and Ortega 2008; Bech et al. 2009; Beck and Dotzek 2010).

From the preceding discussion it becomes a concern that the EF-scale damage metrics for trees in forests may be too simplistic: the degrees of damage are restricted to too narrow a range, they ignore different tree species (except hardwood versus softwood), pathlength–width metrics are unused, and do not consider treefall patterns. Tree damage from tornadoes can provide substantial information and evidence to determine a rating, but most of this information is unused in the current implementation of the EF scale. With these limitations, the admonition of Beck and Dotzek (2010) that "damaged objects provide an estimate of the lower limit of the wind speed but the upper limit can remain unknown'' is relevant and a concern.

3. Analysis of the 6 October 2010 tornado outbreak

a. Synoptic and radar overview

Many of the recent tornadic weather events in northern Arizona have exhibited similar synoptic and thermodynamic characteristics. These similarities motivated an investigation of synoptic environments associated with tornadoes in northern Arizona (Blanchard 2008). That analysis indicated that a substantial portion of cool-season tornadoes[3] occurred during the approach of an upper-level closed low embedded in the midlatitude westerlies with northern Arizona located in the warm sector of the surface low. Additionally, the wind in the lower troposphere exhibited a strong southerly component, which likely was necessary for advecting warm and, more importantly, moist subtropical air northward across Arizona.

The upper-level low that impacted northern Arizona during the overnight and early morning hours of 6 October 2010 exhibited these and other characteristics described in Blanchard (2008). In addition to the strong southerly flow in the lower troposphere, other important meteorological features in this event were the large vertical wind shear, strong deep-layer mean winds, low convective inhibition, high relative humidity in the boundary layer, and marginal buoyant instability. These characteristics were also noted by Kis and Straka (2010) in many nocturnal tornadoes in the central United States. A detailed mesoscale and local storm environment analysis for this event is beyond the scope of this paper. Rather, the focus here will be to discuss the forest tree damage and the sonic anemometer wind data within the context of the enhanced Fujita scale.

Radar data from the Flagstaff, Arizona (KFSX), WSR-88D radar were collected continuously during the event and the reflectivity and velocity data clearly illustrated the structure of the numerous supercells that moved across the area overnight and during the morning hours.

Figure 4 presents the maximum gate-to-gate differential velocity (ΔV) observed by the KFSX radar at the 0.5° base tilt for three of the surveyed tornadoes. The tornado labeled T1 moved across the area where the wind sensor (discussed below) was located at ~1240 UTC.[4] The results in Fig. 4 indicate that the maximum ΔV for T1 was decreasing from its peak values, which had occurred a few volume scans earlier. Ground surveys in this portion of the path indicated that tree damage was diminishing (i.e., both fewer trees damaged and gaps in the path) but the degree of damage rating was unchanged from what was experienced in the earlier portions of the damage path (i.e., DOD3 and DOD4). Similar results were found for T2 and T3.

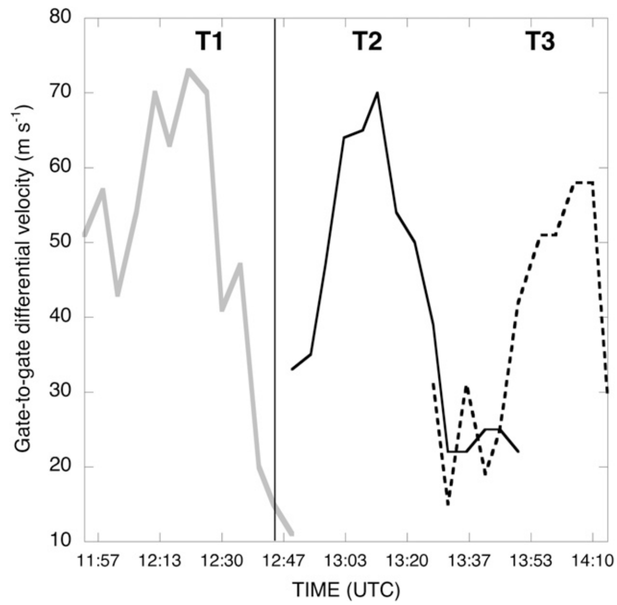

FIG. 4. Time series of the maximum gate-to-gate differential velocity (ΔV, m s^{-1}) observed by the KFSX radar for T1 (thick gray curve), T2 (black curve), and T3 (dashed curve). The thin black vertical bar denotes the time of vortex passage over the sonic anemometer.

b. Analysis of wind data

The School of Forestry at the Northern Arizona University (NAU) in Flagstaff operates three data collection sites in the nearby Coconino National Forest. The goals of their long-term study are to understand the impact of fire and tree thinning on ecosystem fluxes by quantifying the CO_2, H_2O, and energy exchange between the forest and atmosphere. One site is located in an unmanaged, undisturbed forest; a second lies within an area with selective thinning of trees; and the third site—and the one impacted by the tornado—lies within a 10 500-ha area burned by a high-intensity, stand-replacing wildfire (Hochderffer/Horseshoe Fire Complex) in 1996. The ground surface of the third site is covered with sparse grasses, shrubs, and woody debris, along with stands of surviving trees (Dore et al. 2008, 2010).

[3] Cool-season tornadoes (mid-September–May) in northern Arizona are more likely to be associated with supercell thunderstorms than tornadoes occurring during the low-shear warm season (June–early September).

[4] Local time (mountain standard time, MST) is UTC − 7.

Each site included a 3D sonic anemometer (CSAT3; Campbell Scientific, Logan, Utah).[5] The eddy covariance system was positioned at a height of 2.5 m above the ground at the burn site. Data were recorded at 20 Hz by a datalogger and were averaged over 30-min intervals by the on-site equipment. In addition, the full-resolution 20-Hz raw data were postprocessed in the laboratory (Dore et al. 2008, 2010).

The CSAT3 is an ultrasonic anemometer for measuring wind speed in three dimensions. The full-scale wind for the instrument is rated at $\pm$65.535 m s^{-1}. The accuracy is stated to have an offset error less than $\pm$0.004 m s^{-1} and a gain error of between $\pm$2% and $\pm$6% for speeds less than 30 m s^{-1}. No error analysis has been conducted for higher speeds (Campbell Scientific 2012).

The tornado (T1) passed over the instrumented site in the burn area at ~1240 UTC (Fig. 5). The instrument package survived the short-lived but intense winds. A second tornado (T2) passed less than ½ km to the west of the instrumented site at ~1345 UTC. The two damage paths briefly approached each other near the wind site, then separated again. While the first tornado produced significant winds at the CSAT3 site, the second tornado was too distant to have any discernable influence on the winds.

Because this instrumentation is part of a long-term monitoring study, it was not possible to remove it from the field for a postevent calibration. Additionally, two problems were encountered with the wind data from the CSAT3. A brief data gap of 1.6 s (1240:30.10–1240:31.70 UTC) occurred during the transit of the tornadic vortex past the instrumented tower. This was the result of the acquisition software flagging the data quality (e.g., data spikes) and no data were recorded during this interval (S. Dore 2012, personal communication). The second problem was that the u_y-wind component briefly exceeded the maximum value of 65.535 m s^{-1}. No such problem occurred with either the u_x- or u_z-wind components. Consequently, there is a combined 3-s period when the true maximum wind speeds are unknown and likely underestimated. While disappointing that the complete details of the wind remain unknown, the data that are good during the ~4–5-s vortex passage reveal remarkable information and can still be used for a qualitative comparison of wind speed and EF-scale ratings.

The horizontal wind speeds are shown in Fig. 6 for the period 1230–1300 UTC. The 20-Hz winds have been filtered using a moving average to produce 1-s winds. Prior to the passage of the vortex at 1240 UTC, wind speeds were generally 3–5 m s^{-1}. For the few minutes prior to passage, there was a gradual increase

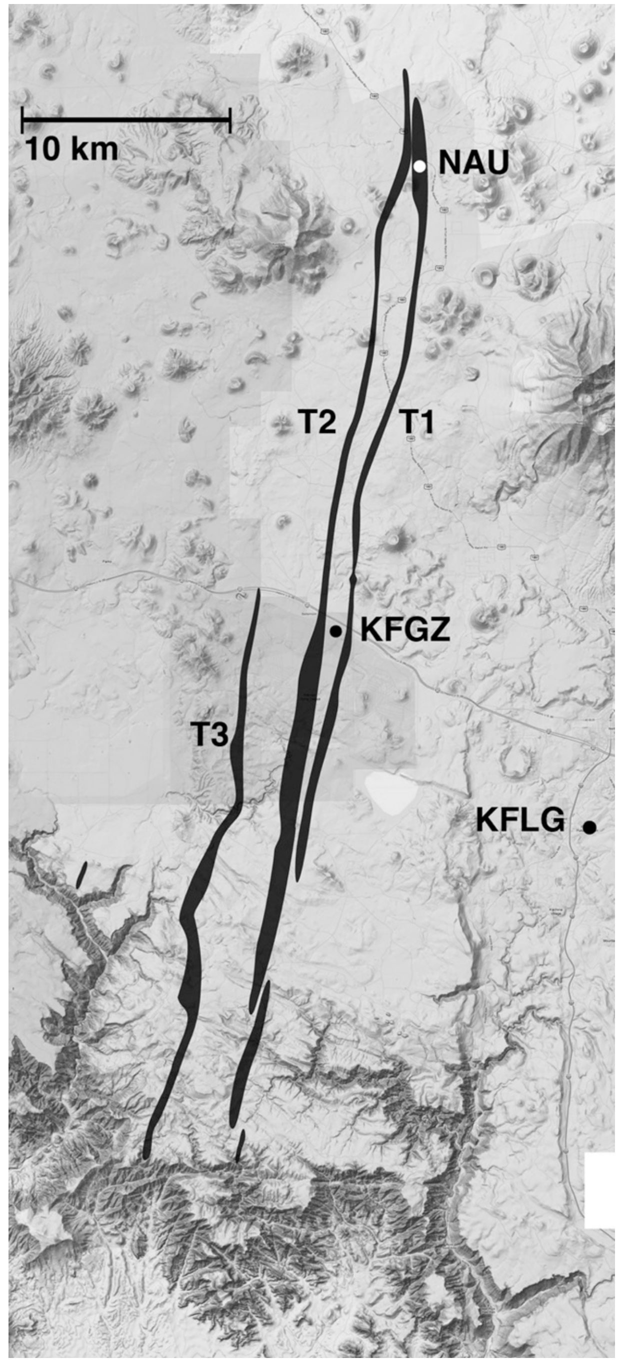

FIG. 5. Map of the damage paths from a few of the major tornadoes on 6 Oct 2010. Tornadoes discussed in the text are labeled T1, T2, and T3. KFLG is Flagstaff Pulliam Airport, KFGZ is the NWS office in Flagstaff, and NAU is the site of the Northern Arizona University sonic anemometer. Background map shows the major terrain features.

[5] Disclaimer: The National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS) does not approve, recommend, or endorse any proprietary product or proprietary material mentioned in this publication.

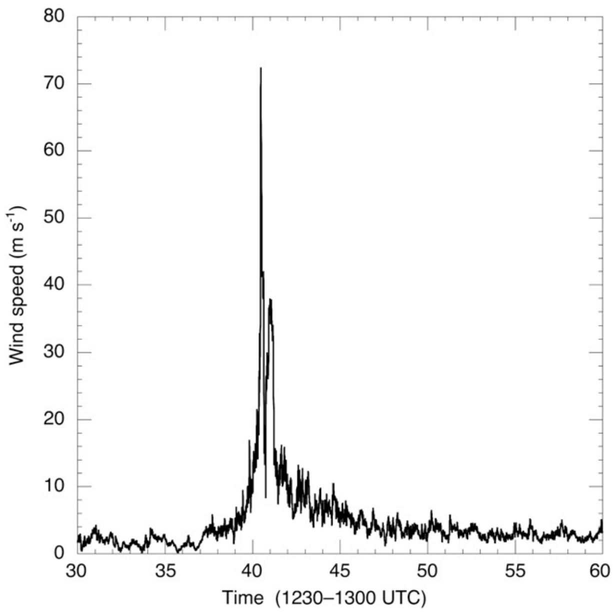

FIG. 6. Horizontal wind speed (m s^{-1}) from 1230 to 1300 UTC recorded by the NAU CSAT3 sonic anemometer. Horizontal tick marks every 1 min; vertical tick marks every 2 m s^{-1}.

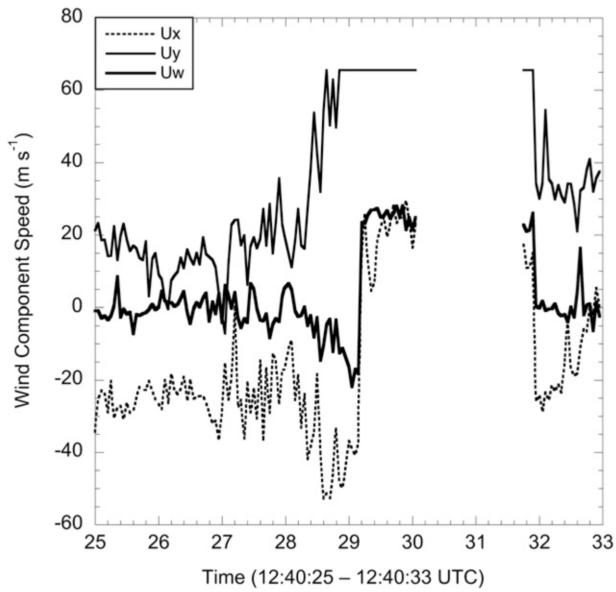

FIG. 7. Wind components recorded by the NAU CSAT3 sonic anemometer. Data are missing from approximately 1240:30.05 to 1240:31.70 UTC. Vertical axis tick marks every 5 m s^{-1}; horizontal tick marks every 0.2 s.

to about 6–10 m s^{-1}. During passage of the tornadic vortex, peak 1-s winds were greater than 70 m s^{-1}, then decreased quickly but remained slightly elevated compared to the prevortex environment.

Full-resolution (20 Hz) u_x-, u_y-, and u_z-wind components for the 8-s period from 1240:25 to 1240:33 UTC are shown in Fig. 7. The u_y component peaked at the instrument maximum value of 65.535 m s^{-1} at ~1240:29 UTC while both u_x and u_z remained well within instrument bounds. A gap from the discarded data appears from 1240:30.10 through 1240:31.70 UTC. As winds increased and wind direction began to veer from the south-southeast to south-southwest, there was descending motion (i.e., negative values of u_z) with magnitudes of almost 20 m s^{-1}. This descending motion could be either a rear-flank downdraft (Markowski 2002) or an axial downdraft (Wakimoto et al. 2012; Wurman and Gill 2000). This downward motion quickly reversed, becoming strong ascending motion with magnitudes approaching 30 m s^{-1}. This occurred as the u_x wind changed from a negative value (easterly wind component) to a positive value (westerly wind component), suggesting vortex passage. After the data gap, there was still upward vertical motion on the order of 20 m s^{-1} before it rapidly diminished to near zero.

The maximum 1-s wind was 72 m s^{-1} (161 mi h^{-1}, midrange EF3) while the maximum 3-s wind was substantially lower at 51 m s^{-1} (115 mi h^{-1}, low-end EF2). These were based on the moving mean; the 1-s and 3-s moving median resulted in similar values (Table 1). The instantaneous peak wind observed during the event was 83 m s^{-1} (185 mi h^{-1}, midrange EF4). However, this speed is likely an underestimate because the u_y-wind component was truncated at the instrument maximum value. Note, also, in Fig. 7 that the duration of the entire event was on the order of 4–5 s. It is a reasonable question whether the 3-s wind used by the enhanced Fujita scale (WSEC 2006) is the appropriate metric for a short-duration event such as this.[6] In fact, Doswell et al. (2009) noted that ''no one has conducted any experiments to determine the relationship between duration of the wind and the damage produced....''

Because the sonic anemometer was placed in a location that suffered substantial tree loss in a major wildfire, there were no live trees closer than a few hundred meters.[7]

[6] D. Speheger (2011, personal communication) asked the same question after viewing an Oklahoma tornado in the spring of 2011. He noted ''The tornado was probably 20–30 yards wide and the angular momentum and vertical motion were among the most intense I have witnessed. Any damage-based intensity estimate will likely be underrated given the very short dwell time at any location and any time averaging (even the 3s wind speed estimates of the EF scale) will be significantly lower than the near-instantaneous wind speeds at any point in space with such a small, dynamic tornado.''

[7] Although no live trees were left standing in the vicinity of the sonic anemometer (35.4454°, −111.77184°), there were several dead snags that were toppled. These were used to determine the path and most probable vortex center. Using this information, it was likely that the vortex center passed with a few tens of meters of the instrument.

TABLE 1. Wind speeds (m s^{-1}) recorded at the NAU CSAT3 sonic anemometer site for various averaging periods. Time is from 1240:27.00 to 1240:32.70 UTC. The hours and minutes have been omitted and only the seconds are shown. Data are missing from 1240:30.05 to 12:40:31.70 UTC.

Time	Min	Max	Mean	Median	Averaging period (s)	Comments
27.00–28.00	16.9	45.8	39.5	29.2	1	
27.50–28.50	14.1	54.2	32.2	29.5	1	
28.00–29.00	14.1	83.2	53.4	52.9	1	
28.50–29.50	46.3	83.2	70.5	72.8	1	$u_y > 65.535$
29.00–30.00	65.7	77.2	70.4	69.8	1	$u_y > 65.535$
31.75–32.70	27.7	67.8	44.4	39.3	1	$u_y > 65.535$
25.00–28.00	16.9	45.8	29.7	29.4	3	
26.00–29.00	14.1	83.2	36.5	30.0	3	
27.00–30.00	14.1	83.2	51.2	52.9	3	$u_y > 65.535$

Damage to the nearby live trees using DI28 (softwood) (WSEC 2006) was DOD3/DOD4, but was only partial in extent and affected much less than half of the trees. EXP ratings for DOD3/DOD4 support EF1 winds [87–104 mi h^{-1} (~39–46.5 m s^{-1})], which is considerably lower than the measured winds. The UB ratings support low-end EF2 winds [113–128 mi h^{-1} (~50.5–57 m s^{-1})], which reflect better consistency with the 3-s winds, but not for the 1-s or instantaneous winds. It should also be noted that the winds at the instrument site were taken at 2.5 m while the EF scale is based on 10-m winds. It is unknown what the relationship might be between 2.5- and 10-m winds for this event.

Furthermore, damage to the south of the wind site, while still DOD3/DOD4, was more widespread with larger path width and approaching 100% damage, as well as a more symmetric treefall pattern (Fig. 8). The results of Letzmann (1923), Bech et al. (2009), and Beck and Dotzek (2010) would suggest larger $Vr + V_t$ in the locations with greater symmetry.

c. *Analysis of treefall pattern*

A portion of the damage track from T2 (Fig. 9) indicates that in this location nearly 100% of the trees sustained DOD3/DOD4 damage. With a vector mapping of the tree fall and a Letzmann-type model, an iterative set of experiments could be run to determine the rotational speeds of the vortex using the methodology described by Beck and Dotzek (2010). First, $V_{\rm trans}$ is determined using storm propagation as a proxy for the tornado. Next, downed trees with $\psi = 0°$ and $\psi = 180°$ (fall angle with respect to the direction of translation) are identified. The values of $G_{\max}$ and α can be quantified from the number of convergence and divergence lines in the damage swath. The model is iteratively run by varying the initial estimates of $G_{\max}$, α, and $R_{\max}$ (radius of maximum winds) until the agreement between the simulated and observed treefall patterns is maximized (Beck and Dotzek 2010). This technique allows one to then determine V_r and V_t, and to establish an equivalent EF scale to the damage (Bech et al. 2009; Beck and Dotzek 2010).

No analytical model was available for the work presented here; however, it is reasonable to expect that the application of this method to the treefall vectors in Fig. 9 would result in a different—and higher—wind speed than would the treefall patterns in Figs. 2 and 3, even though both tornadoes produced DOD3/DOD4 damage. This is based on a subjective comparison of the treefall vectors and the various patterns for $G_{\max}$ and α shown by Letzmann (1923, his Fig. 47) and Beck and Dotzek (2010, their Fig. 4).

Comparison of treefall vectors with these schematics is difficult, however, because of the limited values for $G_{\max}$ and α from which to choose. Therefore, it might be useful for future damage surveys if a Letzmann-type model could be run for a range of $G_{\max}$ and α to develop a catalog of damage patterns to which the results of a survey could be compared.

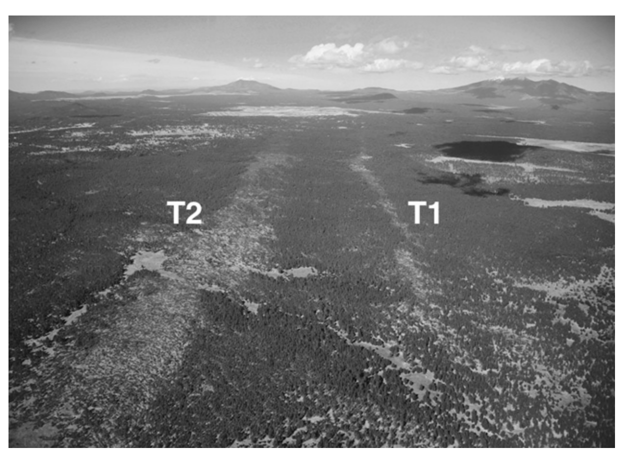

FIG. 8. Aerial photograph looking to the north at a location south of Bellemont, AZ. Both damage paths are from long-track tornadoes. Both exhibited DOD3 and DOD4 damage along their entire lengths. [Photograph courtesy of B. Klimowski, NOAA/NWS.]

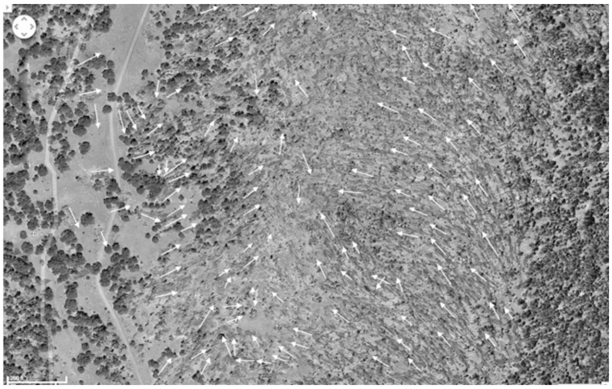

FIG. 9. Aerial photograph showing downed trees in the T2 damage path. Vectors are aligned with individual treefall patterns, allowing a comparison with the schematics developed by Letzmann (1923) and others.

4. Discussion

The results presented here provide a brief examination of some of the potential limitations in the recently adopted enhanced Fujita wind damage scale. In that scale there currently exist 27 damage indicators (DI) for constructed buildings and structures, but only 2 for trees. Furthermore, the 27 DIs for buildings typically have greater granularity with more degrees of damage (DODs) covering a larger range of wind speeds than those for trees.

Recent surveys of tornado damage across northern Arizona and elsewhere have suggested that the EF scale for evaluating damage may be overly simplistic in forests and for trees. It is anticipated, however, that as additional surveys are completed here and elsewhere for tornado damage in forests, that the granularity of DODs can be increased to more accurately portray the damage and assess the EF rating.

A localized tornado outbreak across northern Arizona on 6 October 2010 resulted in at least 11 tornadoes with two long-track events (42 and 50 km). Comparison of these damage paths with those from previous tornadoes resulted in essentially the same degrees of damage (DOD3, uprooted trees; DOD4, snapped tree trunks) occurring along the damage paths, suggesting the same EF rating. In fact, there were considerable differences in the damage ranging from the percentage of trees damaged within the path (i.e., the extent of damage), the pathlength and width, and the treefall patterns within the damage path. The results of Letzmann (1923), Bech et al. (2009), Dotzek et al. (2008), Beck and Dotzek (2010), and Brooks (2004) would suggest that these might have different EF ratings.

It is remarkable that one of the long-track tornadoes from the outbreak passed over a sonic anemometer that recorded u_x-, u_y-, and u_z-wind components at 20 Hz. These data dramatically revealed the rapid increase in both horizontal and vertical wind components as the vortex approached and passed over the observation site. Combining the 20-Hz winds into 1- and 3-s mean winds allowed a comparison between the measured winds at the site and the EF-scale DODs from the nearby tree damage. Examination of the winds and damage suggest the following:

- Comparisons of wind with damage suggest 3-s winds and the EF rating may be too low for the expected (EXP) value but show better consistency with the upper bound (UB).
- The 3-s average wind used for the EF rating may be too long a period for some tornadoes.
- Damage upwind of the sonic anemometer site was much greater in path width, exhibited greater extent of damage, and showed more symmetry in the damage, suggesting the vortex was stronger even though it produced the same DOD3 and DOD4 damage.
- Tree damage indicated the tornado might have been weakening (i.e., diminishing percentage of trees damaged in the swath, less symmetry) when it hit the anemometer site, suggesting the winds recorded at the site might be considered to be a lower range of winds for this type of damage.
- Tornado T2 produced an even more extreme damage pattern, but was also only rated as DOD3 and DOD4.

The enhanced Fujita scale was an effort on the part of many scientists and engineers to provide a better means of assessing the probable wind speed of a tornado or straight-line winds based on the damage to buildings, structures, or trees. The initial version of the EF scale has accomplished this for buildings and structures, but additional work is warranted on how to interpret damage to trees and forests. We look forward to future discussions on this interesting topic.

Acknowledgments. The author expresses his appreciation to S. Dore and B. Sullivan (NAU School of Forestry) for kindly providing the quality-controlled wind dataset. B. Klimowski (NOAA/NWS) provided the tornado track figures.

REFERENCES

Bech, J., M. Gaya, M. Aran, F. Figuerola, J. Amaro, and J. Arús, 2009: Tornado damage analysis of a forest area using site survey observations, radar data and a simple analytical vortex model. *Atmos. Res.,* **93,** 118–130.

Beck, V., and N. Dotzek, 2010: Reconstruction of near-surface tornado wind fields from forest damage. *J. Appl. Meteor. Climatol.,* **49,** 1517–1537.

Blanchard, D. O., 2006: A cool season severe weather episode in northern Arizona. Preprints, *23rd Conf. on Severe Local Storms,* St. Louis, MO, Amer. Meteor. Soc., P3.4. [Available online at https://ams.confex.com/ams/pdfpapers/115214.pdf.]

——, 2008: Synoptic environments associated with tornadoes in northern Arizona. Preprints, *24th Conf. on Severe Local Storms,* Savannah, GA, Amer. Meteor. Soc., P12.8. [Available online at http://ams.confex.com/ams/pdfpapers/141836.pdf.]

Brooks, H., 2004: On the relationship of tornado path length and width to intensity. *Wea. Forecasting,* **19,** 310–319.

Budney, L. J., 1965: Unique damage patterns caused by a tornado in dense woodlands. *Weatherwise,* **18,** 74–86.

Campbell Scientific, cited 2012: CSAT3 3-D sonic anemometer. [Available online at http://www.campbellsci.com/csat3/.]

Dore, S., and Coauthors, 2008: Long-term impact of a stand-replacing fire on ecosystem CO_2 exchange of a ponderosa forest. *Global Change Biol.,* **14,** 1801–1820.

——, and Coauthors, 2010: Carbon and water fluxes from ponderosa pine forests disturbed by wildfire and thinning. *Ecol. Appl.,* **20,** 663–683.

Doswell, C. A., III, and D. W. Burgess, 1988: On some issues of United States tornado climatology. *Mon. Wea. Rev.,* **116,** 495–501.

——, H. E. Brooks, and N. Dotzek, 2009: On the implementation of the enhanced Fujita scale in the USA. *Atmos. Res.,* **93,** 554–563.

Dotzek, N., R. E. Peterson, B. Feuerstein, and M. Hubrig, 2008: Comments on "A simple model for simulating tornado damage in forests." *J. Appl. Meteor. Climatol.,* **47,** 726–731.

Fujita, T. T., 1989: The Teton–Yellowstone tornado of 21 July 1987. *Mon. Wea. Rev.,* **117,** 1913–1940.

——, and A. D. Pearson, 1973: Results of FPP classification of 1971 and 1972 tornadoes. Preprints, *Eighth Conf. on Severe Local Storms,* Denver, CO, Amer. Meteor. Soc., 142–145.

Hall, F., and R. D. Brewer, 1959: A sequence of tornado damage patterns. *Mon. Wea. Rev.,* **87,** 207–216.

Holland, A. P., A. J. Riordan, and E. C. Franklin, 2006: A simple model for simulating tornado damage in forests. *J. Appl. Meteor. Climatol.,* **45,** 1597–1611.

Kis, A. K., and J. M. Straka, 2010: Nocturnal tornado climatology. *Wea. Forecasting,* **25,** 545–561.

Ladue, J. G., and K. L. Ortega, 2008: Experiences using the EF-scale since its inception. Preprints, *24th Conf. on Severe Local Storms,* St. Louis, MO, Amer. Meteor. Soc., 8B.6. [Available online at http://ams.confex.com/ams/pdfpapers/142166.pdf.]

Letzmann, J. P., 1923: Das Bewegungsfeld im Fuß einer fortschreitenden Wind- oder Wasserhose (The flow field at the base of an advancing tornado). Ph.D. thesis, University of Helsingfors, 136 pp. [Available online at http://essl.org/pdf/Letzmann1923/Letzmann1923.pdf.]

Markowski, P. M., 2002: Hook echoes and rear-flank downdrafts: A review. *Mon. Wea. Rev.,* **130,** 852–876.

Peltola, H., M.-L. Nykänen, and S. Kellomäki, 1997: Model computations on the critical combination of snow loading and windspeed for snow damage of Scots pine, Norway spruce and birch sp. at stand edge. *For. Ecol. Manage.,* **95,** 229–241.

——, S. Kellomäki, H. Välsänen, and V.-P. Ikonen, 1999: A mechanistic model for assessing the risk of wind and snow damage to single trees and stands of Scots pine, Norway spruce and birch. *Can. J. For. Res.,* **29,** 647–661.

Peterson, C. J., 2003: Factors influencing treefall risk in tornadoes in natural forests. Preprints, *Symp. on the F-Scale and Severe Weather Damage Assessment,* Long Beach, CA, Amer. Meteor. Soc., 3.1. [Available online at http://ams.confex.com/ams/pdfpapers/53292.pdf.]

Peterson, R. E., 1992: Johannes Letzmann: A pioneer in the study of tornadoes. *Wea. Forecasting,* **7,** 166–184.

Wakimoto, R. M., P. Stauffer, W.-C. Lee, N. T. Atkins, and J. Wurman, 2012: Finescale structure of the LaGrange, Wyoming, tornado during VORTEX2: GBVTD and photogrammetric analyses. *Mon. Wea. Rev.,* **140,** 3397–3418.

Wegener, A., 1917: *Wind- und Wasserhosen in Europa (Tornadoes in Europe)*. Verlag Friedrich Vieweg und Sohn, 301 pp.

WSEC, 2006: A recommendation for an enhanced Fujita scale (EF-scale). Wind Science and Engineering Center, Texas Tech University, Lubbock, TX, 111 pp. [Available online at http://www.depts.ttu.edu/weweb/Pubs/fscale/EFScale.pdf.]

Wurman, J., and S. Gill, 2000: Finescale radar observations of the Dimmitt, Texas (2 June 1995), tornado. *Mon. Wea. Rev.,* **128,** 2135–2164.