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FOREST DAMAGE ASSOCIATED WITH TORNADOES IN NORTHERN ARIZONA

David O. Blanchard*
NOAA/National Weather Service
Flagstaff, AZ 86015

1. INTRODUCTION

In recent years, there has been an increased effort to conduct damage surveys in the aftermath of tornadoes in northern Arizona (Blanchard 2006). Most of these surveys have been in the forested regions of the Mogollon Rim (Fig. 1). The Mogollon Rim is a crescent-shaped geological feature that arcs between the Kaibab Plateau in north-central Arizona southward through the Flagstaff area, thence eastward to the New Mexico border where it merges with the White Mountains. The Rim plateau ranges in elevation from approximately 6500 to 8000 feet. Conifers are the dominant type of vegetation and the generally dry climate has resulted in a sparseness of deciduous trees.

Tornado damage surveys of trees and forests have a long history. The literature indicates that 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, he suggested that when a tornado moves through a forest it produces a damage pattern that relates to the sum of vortex rotation and forward speed. The results of Letzmann have been discussed at length by Peterson (1992), Holland et al. (2006), and Dotzek (2008).

Other studies examining the effects of tornadoes in trees can be found in Hall and Brewer (1959) and Fujita (1989), who performed a detailed analysis of a high elevation tornado in Wyoming.

Holland et al. (2006) described a quantitative physical model to assess tornadic wind speeds in forested areas based on a simple Rankine vortex and a modified tree model designed by Peltola et al. (1999). Their computer model results supported the analytical hand-drawn results produced by Letzmann (1923).

To facilitate forest damage surveys Bech et al. (2009) used a Rankine vortex to simulate a tornado vortex adjusted with a translational speed. They compared damage patterns to model results indicating that the model got the essential features correct and gave a reasonable estimate of vortex strength.

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

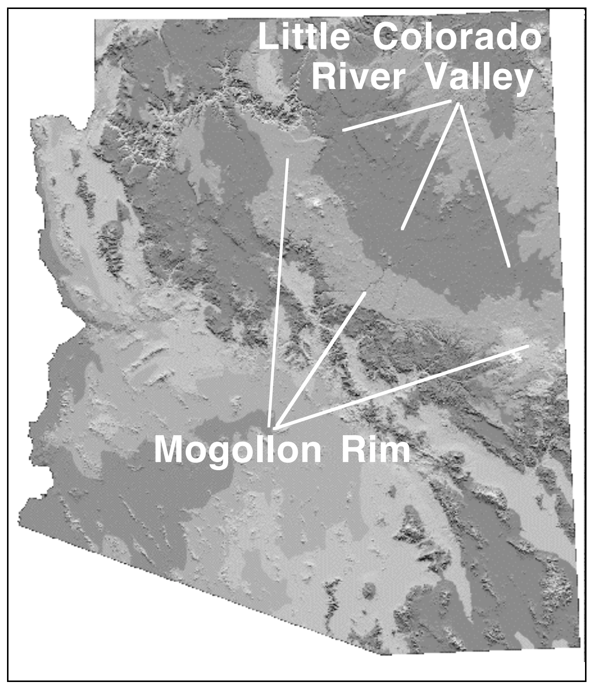

Figure 1. Map showing major geographic features over the state of Arizona. The Mogollon Rim and Little Colorado River valley are noted.

Peltola et al. (1997, 1999) developed mechanistic tree models to predict the thresholds necessary to break the stems of several tree species. This required different models for different species. They found, for example, as crown size grows with greater tree spacing the wind

* *Corresponding author address:* David O. Blanchard, NOAA/NWS, P.O. Box 16057, Flagstaff, AZ 86015; e-mail: david.o.blanchard@noaa.gov.

force on the tree increases and the critical wind speed for damage decreases.

It is clear that the research and observations of damage to trees by tornadoes has an extensive and well-researched history. Yet, the recently adopted EF-scale (TTU 2006) has a limited selection of Damage Indicators (DIs) and Degrees of Damage (DODs) from which to assess tornadic tree damage.

The focus here is to briefly examine and discuss the DIs and DODs for assessing forest damage as well as the difficulties encountered in obtaining detailed information on tornado damage paths in forested and mountainous terrain.

2. RESULTS

Recent tornado damage surveys of the primarily coniferous trees in northern Arizona were assessed using the EF-scale DI and DOD tables (TTU 2006). Earlier surveys used the original F-scale.

It was observed that DODs 1 and 2 (1: small limbs broken, up to 1” diameter; 2: large branches broken, 1–3” diameter) were rarely encountered without also having DODs 3 and 4 present (3: trees uprooted; 4: trunks snapped); that is, surveys were unable to find damage of only DODs 1 and 2. These DODs (1–4) represent a range of expected wind speeds from 60 to 104 mph, which corresponds to sub-EF0 to upper-end EF1.

Equally challenging was that DODs 3 and 4 were often present in the same area and even side-by-side making it difficult to determine the likely wind speed causing the damage (Figs. 2, 3). As noted by Peterson (2003), the patterns of tornado damage to trees in natural forests suggest that the existing tree damage metrics may be overly simplistic. Furthermore, the DI28 (hardwood trees) and DI29 (softwood trees) DOD5 has an expected wind speed value (EXP) of 131 mph with an upper wind speed bound (UB) of 153 mph, limiting this DOD to EF2 for the EXP or EF3 for the UB. No DODs are available for assessing EF4 or EF5 damage.

Figure 2 shows a well-defined damage swath through a Ponderosa Pine forest. This damage path was ~15 km in length but rarely more than 25–50 m wide. In the damage path are numerous trees with snapped trunks (DOD 4) at a variety of heights as well as standing trees with removed branches (DODs 1 and 2). Figure 3 shows a patchwork damage pattern from the same event with snapped trunks (DOD 4), uprooted trees (DOD3), broken branches (DOD 1 and 2), 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 expected value (EXP) for the most prevalent DOD was used to assign an EF value.

Figure 2. Portion of the damage path from the 14 October 2006 tornado in northern Arizona. Note the variation in damage to trees with snapped trunks next to undamaged trees.

Figure 3. Portion of the damage path from the 14 October 2006 tornado in northern Arizona. Note the variation in damage with trees with snapped trunks next to toppled trees and all in proximity to undamaged trees.

Figure 4 shows an isolated Ponderosa Pine in a large meadow. The survey revealed that tree damage in this meadow was more severe than in the heavily forested locations. In this meadow, trees were not only snapped near ground level but the broken trees were dragged across the ground for a considerable distance. Consequently, the UB was used for this patch of damage resulting in an EF2 rating at this location. However, this may not be the correct interpretation. As noted above, work by Peltola et al. (1997, 1999) showed that as crown size grows with greater tree spacing the wind force increases on the tree and the critical wind speed required for damage decreases.

The log wind profile relationship describes the vertical distribution of the horizontal wind above the ground in the surface layer. It is given by

$$u_z = \frac{u_*}{\kappa}\left[\ln\left(\frac{z-d}{z_0}\right)+\psi\left(z,z_0,L\right)\right]$$

where u_* is the friction velocity, κ is von Karman's constant, d is the zero plane displacement, z_0 is the surface roughness, and ψ is a stability term where L is the Monin-Obukhov stability parameter. Zero-plane displacement (d) is the height in meters above the ground at which zero wind speed is achieved because of flow obstacles such as trees or buildings. It is generally approximated as 2/3 of the average height of the obstacles.

The log wind profile relationship suggests that the greater damage experienced in the open meadow was probably a better approximation of the actual wind associated with the tornado while the lesser damage in the heavily forested areas likely represents a reduction in wind speed owing to the tree canopy and larger zero-plane displacement (d).

Although much of the Mogollon Rim is populated by Ponderosa Pine, occasional stands of hardwood trees are intermixed. Figure 5 shows the damage path as it traversed a location with both softwood (Ponderosa Pine) and hardwood (Gambel Oak) trees. DI29 damage included both DOD3 and DOD4; DI28 damage included one snapped trunk (DOD4) while the remaining oak trees suffered little damage beyond leaning in the direction of the wind. The similar damage (DOD4) lends support to the EXP of ~105 mph (EF1).

Of equal importance was the larger-scale pattern of damage in many of the surveys. Uprooted trees and snapped trunks usually displayed an asymmetric damage pattern. Modeling and analytic studies have

Figure 4. Portion of the damage path from the 14 October 2006 tornado in northern Arizona. This open field was the site of the strongest damage with an EF2 rating.

Figure 5. Portion of the damage path from the 14 October 2006 tornado in northern Arizona. At this location, the damage path went through both softwood and hardwood trees.

Figure 6. A mountain bike was a necessary means of transportation through much of the forest owing to poor quality roads and toppled trees blocking roads.

noted that, for a given vortex strength, as the forward speed increases the damage area moves to the right side of the track and individual trees align increasingly in the direction of the storm motion (Letzmann 1923; Hall and Brewer 1959; Knupp 2000; Holland et al. 2006). This suggests that many of the surveyed tornado damage paths in northern Arizona may be the result of weak vortex strengths traveling with large translational speeds.

Recently, Blanchard (2008) assessed the predominant synoptic-scale patterns associated with cool-season tornadoes in northern Arizona. The results showed a repeatable pattern with a closed low-pressure system approaching Arizona resulting in moderate to strong mean winds and deep-layer shear but only modest buoyant instability. The strong winds and shear are supportive of large translation speeds while the modest instability may contribute to a weaker vortex. Indeed, most damage surveys have assigned damage ratings of EF0, with only small areas of EF1 and EF2.

In addition to the difficulties in assessing and assigning an appropriate DOD were the challenges encountered trying to access the damage path. The Mogollon Rim is densely forested with few paved roads. Access is typically gained via United States Forest Service roads. Although some of these roads are well maintained and passable by passenger vehicles and light-duty trucks, many more are not. Substantial portions of these storm damage surveys were conducted by mountain bike on lesser quality roads and by foot where no roads existed (Fig. 6). Moreover, portions of some damage paths were inaccessible as they were in deep and rugged canyons that did not have trails or were in wilderness areas in which aerial flights were prohibited.

The results presented here provide a brief discussion of the limitations in the recently adopted EF damage scale. There currently exist 27 Damage Indicators (DI) for constructed buildings but only 2 for trees. Furthermore, the 27 DIs for buildings all have greater granularity with more Degrees of Damage (DOD) than those for trees. It is anticipated 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.

REFERENCES

Bech, J., M. Gaya, M. Aran, F. Figuerola, J. Amaro, 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.

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.

——, 2008: Synoptic environments associated with tornadoes in northern Arizona. Preprints, *24th Conf. on Severe Local Storms*, Savannah, GA, Amer. Meteor. Soc.

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

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, enver, 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.

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.]

Peltola, H., 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.

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

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

TTU, 2006: A recommendation for an enhanced Fujita Scale (EF-Scale), Wind Science and Engineering Center, Texas Tech University, Lubbock, Texas 79409-1023, 111pp. [http://www.wind.ttu.edu/EFScale.pdf].

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