TORNADO INTENSITY ESTIMATION

Past, Present, and Future

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The enhanced Fujita scale, devised to rate wind damage more precisely, will need accountability and flexibility to keep pace with advances in mapping, documentation, and the growing understanding of structural responses to airflow.

In a conversation over a controversial damage assessment, a friend of one of the authors asked, "Why did we spend so much time rating that tornado?" Among several possible answers to this question, three include to understand the relationship between the strength of tornadic wind and building performance, to satisfy a strong public interest in the maximum intensity of a tornado, and to develop a long-term assessment of the risk tornadoes present to our population and infrastructure. Damage assessors require an accurate method of relating building damage to wind speed as they perform detailed surveys from a small subset of high-impact tornadoes (e.g., Prevatt et al. 2011; FEMA 2007). To serve the public interest and the National Climatic Data Center (NCDC) storm data record, the National Weather Service (NWS) documents the path length, width, and maximum damage rating for every tornado county segment (NOAA 2007).[1] Such data are used in meteorological and climatological research, as well as in determining construction standards for critical infrastructure such as high-tension electric lines and nuclear power plants (e.g., Ramsdell et al. 2007).

The 2007 adoption of the enhanced Fujita (EF) scale (WSEC 2006) by all practicing wind damage surveyors in the United States was intended to improve the accuracy and precision of damage surveys by providing more guidance than was available through the original Fujita (F) scale (e.g., Fujita 1971). After three years of tornadoes and other wind events were surveyed using the EF scale, a consensus of the authors and other interested scientists and engineers was that it was time to assess its performance. An EF scale

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The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-11-00006.1

In final form 25 September 2012

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stakeholders' group was convened in March 2010 to evaluate the EF scale, to understand new techniques in estimating damaging wind strength, and to map out a plan for future improvements. This article documents the important findings of that meeting, summarizes key experiences since, and suggests how estimating tornado and damaging wind strength may evolve into the future.

Because of the historic lack of direct measurements and remotely sensed tornado wind speeds at or near ground level, damage surveying has remained the most common method for indicating tornado strength. Interrogation of Storm Prediction Center (SPC) whole-tornado data (via www.spc.noaa.gov/wcm) indicates the total land-path areas of tornadoes in the United States covers only ~10^3 km^2 yr^{-1} (vs. nearly 9×10^6 km^2 for the nation's conterminous land area). As such, the occurrence of a direct tornado strike upon a fixed, sufficiently sturdy, and well-calibrated wind measuring station is quite rare. Only 31 direct in situ tornado observations are evident between 1894 and 2011. From Karstens et al. (2010), 26 observations are documented. Additional observations include the following: a single tornado's strike on both a Texas Department of Transportation meteorological tower and a West Texas Mesonet site on 28 March 2007 (NCDC 2011); a hit on the El Reno station of the Oklahoma Mesonet by a violent tornado (rated EF5 nearby; NCDC 2011) on 24 May 2011; a mesonet station near Tipton, Oklahoma, demolished by a tornado-thrown trailer on 7 November 2011 (NCDC 2011); and a strike on the Fort Cobb, Oklahoma, mesonet site by a later tornado from the same supercell (NCDC 2011).

Even though ~10^2 central U.S. tornadoes have been sampled near ground by mobile radar [for a climatology thereof, see Alexander and Wurman (2008)], combined with fortuitous, in situ surface encounters of either the deliberate (Karstens et al. 2010) or inadvertent (Blair et al. 2008) variety, direct observations still only account for a tiny minority of events out of >1,000 tornadoes recorded annually in the Weather Surveillance Radar-1988 Doppler (WSR-88D) radar era. Instead, in situ observations provide a slowly building database from which to correlate measured winds with proximal damage. Given these factors, the representativeness of brief, in situ observations of some tornado events with regard to tornadoes at large is uncertain at best. These rare in situ observations do provide an alternate source of wind speed estimations and points of comparison to the traditional damage-based survey methods (e.g., Wurman and Alexander 2005).

For the foreseeable future, damage assessments likely will remain the principal means for estimating tornado intensity in most events, to the extent that cost and staffing availability permit NWS meteorologists to assess impacts in person. When in-person NWS surveys are not possible soon after an event, areas affected are remote or poorly accessible, and/or other logistics prevent timely and complete surveys, alternate sources of information must be relied upon exclusively. Such sources include field researchers, storm spotters and chasers, the news media, damage accounts from emergency management and law enforcement officials, and remote photos and video from any reliable source. Occasionally, for events of extreme damage or human impact, assessment teams may be used that include non-NWS experts. Independent assessments from such experts (e.g., Marshall 2002) are used to finalize event mapping and rating.

BACKGROUND.

Historical tornado ratings and the Fujita scale. T. Theodore Fujita pioneered the concept of organized, detailed tornado damage surveys, doing field examinations and refining his techniques until shortly before his death in 1998. His landmark survey of the Fargo, North Dakota, mesocyclone and tornado of 20 June 1957 (Fujita 1959, 1992) showed that a damage assessment could be performed in a systematic and analytic manner, with the goal of determining airflow characteristics of tornadoes and their immediate surroundings. Numerous surveys by Fujita and his colleagues followed during the ensuing decades, and over time his detailed storm-survey techniques were adopted by other organizations, including the NWS. Those efforts led to the development of the F scale (Fujita 1971; Fujita and Pearson 1973; Abbey 1976), a version of which, named FPP, included Allen Pearson's path width and length ratings on a 0–5 scale.

The F scale assigned levels of destruction to "well built" homes and empirically related those levels to subdivisions of the Beaufort and Mach scales for wind speed estimation. It was officially adopted by the NWS in the late 1970s. In some later cases, Fujita also applied ratings up to F5 based on nonstructural factors: for example, to corn stubble in the Plainfield, Illinois, tornado of 28 August 1990 (Fujita 1993) and the geometry of cycloidal field marks from the Goessel, Kansas, tornado of 13 March 1990 (Fujita 1992). His descriptions of the effects of winds at increasing F levels also included movement of automobiles, an effect not yet addressed by the EF scale.

Meanwhile, engineers at Texas Tech University began studying the effects of tornadoes and other airflows on various types of construction after the F5 Lubbock, Texas, tornado of 11 May 1970. This included occasional collaboration with Fujita, NWS meteorologists, other engineers, and National Severe Storms Laboratory scientists. Those efforts (e.g., Minor et al. 1977) led to advancements in understanding how damage occurs, spurred the development of guidance on "safe rooms" (FEMA 2003), and fostered improvements in home construction and tornado-shelter design.

In the 1970s and 1980s, the Nuclear Regulatory Commission (NRC) funded a project to gauge tornado wind risk to nuclear power facilities, which included the consistent rating of historical tornadoes using the F scale. This ultimately yielded a massive published listing of tornadoes rated F2 or stronger dating back to 1871 and killer tornadoes of any rating since 1680 (Grazulis 1993a, 1997). Grazulis's ratings were based largely on comparison of available historic media accounts to Fujita's descriptions of wind effects at various F scale levels and, in latter decades, NWS ratings. Grazulis (1993a,b) specifically noted anywhere his rating disagreed with that of the NWS.

Multiple tornado climatologies eventually arose, each "aware" of the other but with its own occasionally unique tornado listings and F scale ratings. In addition to Grazulis, the NRC also supported the development of tornado databases at the University of Chicago [Damage Area Per Path Length (DAPPLE); after Abbey and Fujita 1979] and at the National Severe Storms Forecast Center (Kelly et al. 1978). The latter was the predecessor to the SPC tornado dataset, which now comprises the official record of whole-tornado tracks in the conterminous United States. To complicate matters further, NCDC maintains a dataset of tornado county segments, which are stitched together to comprise the SPC data (Schaefer and Edwards 1999) but remain available for research as tornadoes separately from the SPC data. The DAPPLE dataset essentially has vanished, while Grazulis's records often are used to augment the SPC data prior to 1950.

Even in the same database, damage ratings may have been collected inconsistently. To some extent, systematic adjustments in the data constitute "shocks" (Thorne and Vose 2010) to the historical tornado record that, at a minimum, should be acknowledged by researchers using it. For example, the SPC data from the 1950s through the early 1970s contain ratings performed remotely, primarily via archived newspaper accounts and photos, which were prone to emphasis on higher degrees of devastation (Schaefer and Edwards 1999). Once local NWS offices took over ratings from the late 1970s onward, the number of tornado ratings of F2 or greater declined. Grazulis (1993b) suggested that >2,000 F1 tornadoes were rated F2 from 1954 to 1975, a contention consistent with the use of the more temporally stable EF1+ data (instead of EF2+) in the analyses of Verbout et al. (2006). Furthermore, some shifting of tornado ratings toward middle categories may be underway since the 1 February 2007 onset of EF scale ratings (Edwards and Brooks 2010).

Enhanced Fujita scale. Concerns arose about the F scale's accuracy and consistency within a few years of its adoption for U.S. tornado rating. Minor et al. (1977) summarized the consensus among the wind-engineering community that one- and two-family residences often failed for winds considerably less than earlier anticipated by Fujita. In addition, Doswell and Burgess (1988) summarized several critical deficiencies in the F scale, while acknowledging that it was the best available system at the time. They emphasized the F scale's subjective application in practice and the potential unrepresentativeness of damage with respect to tornado intensity, suggesting that F scale ratings might have a margin of error of two or more categories either way. Marshall (2002) discussed the variability of damage ratings from person to person. Doswell (2003) illustrated the practical applications and limitations of the F scale in damage assessment and offered surveying strategies for training purposes. Using the results of live-audience exercises, Edwards (2003) illustrated the subjectivity and interpersonal variation of F scale ratings for any given damage scene among several presented.

Further contributing to the margin of error in damage assessment, the maximum degree of damage (DoD) available for a damage indicator (DI) in any rating system implies that the wind speed could be stronger than that estimated by surveyors. Doswell and Burgess (1988) succinctly elucidated this quandary, which formed a fundamental motivator for development of more DIs than available in the F scale and ultimately the EF scale. Another motivator was the long-known tendency to underestimate tornado intensity due to a lack of rural DIs (e.g., Schaefer and Galway 1982; Doswell and Burgess 1988; Doswell et al. 2009). Furthermore, wind engineers had ascertained that high-end wind speed estimates from the F scale generally are too strong (e.g., McDonald et al. 2003), even though one mobile-radar measurement existed from the 3 May 1999 Bridge Creek, Oklahoma, tornado of 135 m s^{-1} (302 mph; F5 range). That sampling was made at 32 m AGL (Wurman et al. 2007), well within the height range of a few EF scale DIs. Given these concerns, by the turn of the twenty-first century the need for an upgrade to the F scale had become clear to meteorologists and wind engineers dealing with tornadoes.

A steering committee, composed of meteorologists and engineers from academia, NWS, and NSSL and led by J. McDonald and K. Mehta of Texas Tech University, convened in March 2001 (McDonald and Mehta 2002) to discuss these concerns and incorporate an engineering-based understanding on the wind speeds leading to common failure levels of various potential DIs (WSEC 2006). This led to the 28-DI EF scale currently in use (Table 1), where each DI is layered into DoDs in order to assign a more precise range of probable winds responsible for a given level of damage. Suggestions for an automotive inclusion and for keeping the top F5 speed of 142 m s^{-1} (318 mph) were documented (McDonald and Mehta 2002) but did not become part of the EF scale. So was a suggestion for overlapping DoD wind speeds, critiqued originally by Abbey (1976). Minor wind speed recalibration was incorporated into the initial (derived) EF scale for operational use (Table 2), in order to make the EF and F scales more compatible, and to provide a better transition in tornado climatology. Ideally, F and EF scale ratings equate as closely as possible. This way, an extremely time- and labor-intensive review of tens of thousands of historical tornadoes would not be necessary in order to revise their EF ratings in a systematic manner. Essentially, the F and EF scales should be equivalent for recordkeeping's sake.

Table 1. Summary of damage indicators for the EF scale. In the electronic version of this article, DI numbers link to web pages with DoD numbers, text descriptions, and wind speed thresholds for each DI.

DI No. with hyperlink to DoDs	Damage indicator	DI acronym
1	Small barns, farm outbuildings	SBO
2	One- or two-family residences	FR12
3	Single-wide mobile home	MHSW
4	Double-wide mobile home	MHDW
5	Apartment, condo, townhouse (3 stories or less)	ACT
6	Motel	M
7	Masonry apartment or motel	MAM
8	Small retail building (fast food)	SRB
9	Small professional (doctor office, branch bank)	SPB
10	Strip mall	SM
11	Large shopping mall	LSM
12	Large, isolated ("big box") retail building	LIRB
13	Automobile showroom	ASR
14	Automotive service building	ASB
15	School: 1-story elementary (interior or exterior halls)	ES
16	School: junior or senior high school	JHSH
17	Low-rise (1–4 stories) building	LRB
18	Mid-rise (5–20 stories) building	MRB
19	High-rise (over 20 stories) building	HRB
20	Institutional building (hospital, government, or university)	IB
21	Metal building system	MBS
22	Service station canopy	SSC
23	Warehouse (tilt-up walls or heavy timber)	WHB
24	Transmission line tower	TLT
25	Free-standing tower	FST
26	Free-standing pole (light, flag, luminary)	FSP
27	Tree: hardwood	TH
28	Tree: softwood	TS

In the field, NWS assessors aim to survey a tornado as soon as possible, preferably within a day, before substantial bulldozing and other debris removal and damage repairs have been undertaken by residents and local officials. Surveyors apply the EF scale by matching the observed damaged structure to the appropriate DI and then selecting the closest DoD. Within a DoD one then has the leeway to fine tune

Table 2. Comparison of wind speed ranges assigned to F and EF scale levels.

FUJITA SCALE			DERIVED EF SCALE		OPERATIONAL EF SCALE	
F level	Fastest 1/4 mile in mph (m s^{-1})	3-s gust in mph (m s^{-1})	EF level	3-s gust in mph (m s^{-1})	EF level	3-s gust in mph (m s^{-1})
0	40–72 (18–32)	45–78 (20–35)	0	65–85 (29–38)	0	65–85 (29–38)
1	73–112 (33–50)	79–117 (35–52)	1	86–109 (38–49)	1	86–110 (38–49)
2	113–157 (51–70)	118–161 (53–72)	2	110–137 (49–61)	2	111–135 (50–60)
3	158–206 (71–92)	162–209 (72–93)	3	138–167 (62–75)	3	136–165 (61–74)
4	207–260 (93–116)	210–261 (94–117)	4	168–199 (75–89)	4	166–200 (74–89)
5	261–318 (117–142)	262–317 (117–142)	5	200–234 (89–105)	5	>200 (>89)

a DoD level up or down based on a subjective assessment of mitigating factors, such as condition of the immediate surroundings or available knowledge of the structural integrity (anchoring, attachments, construction materials, etc.). This methodology is aided by a choice of guidance available including but not limited to the EF scale document (WSEC 2006), the EF kit (LaDue and Mahoney 2006) as illustrated in Fig. 1, and the Damage Assessment Toolkit (Camp 2008) currently being distributed in the NWS. As such, the aforementioned subjectivity factors on the F scale have not been eliminated but can be applied more consistently.

For a more complete discussion on the historical succession from F to EF scales, advantages, disadvantages, and commentary about their utility, see Doswell et al. (2009). For more details on NWS implementation, experiences, issues, and examples of operational EF scale use, see LaDue and Mahoney (2006) and LaDue and Ortega (2008).

EF SCALE STAKEHOLDERS' MEETING.

In 2010, three years had passed since the adoption of the EF scale. The time had come to reflect upon the success of the EF scale and to discuss its evolution. On 2–3 March 2010, one of the authors (J. G. LaDue) led the effort to convene an EF Scale Stakeholders' Meeting (EFSSM) in Norman, Oklahoma. Participants diversely consisted of all the authors, research and operational meteorologists, wind engineers, NWS policymakers, and a forest biologist serving as a subject-matter expert on wind impacts on vegetation. The purposes were to review the EF scale's background and progress (see introductory section), assess its state, deliberate its future, and set at least preliminary foundations for its management and evolution. EFSSM participants viewed presentations

MHDW DOD 7 Unit slides off CMU block piers

Wind Speed (mph) 94

EF1

Fig. 1. Screen example of EFkit PC software used in many NWS damage surveys as of this writing. Defaults of both values and photographic example are shown for a double-wide mobile home (MHDW; per Table 1) at DoD 7. Users can select the DI (right) and DoD (middle) while sliding the "fine tune" bar up and down to allow for some subjectively assessed leeway in rating: for example, reducing the wind speed if much weaker or no adjacent damage is evident.

on impacts to tornado climatology, possible problems with existing DIs, areas of potential refinement of DIs, new data sources to document DIs, additional methodologies for estimating wind speeds (e.g., tree blow-down patterns, mobile radars, and in situ instruments), a proposed new complimentary wind speed scale, and comparisons of surveys among our international partners. The meeting included free-form discussions on issues such as the inconsistency and subjectivity of EF scale ratings, variations in expertise and experience of surveyors from one event to another, staffing and resource restrictions, and the effects of present and future tornado-rating capabilities on the tornado climatology. We elaborate on these topics starting with a summary of present EF scale concerns (this section), followed by discussion of damage versus wind speed and considerations for damage assessment outside the United States.

Impact of the EF scale upon climatology. The much finer granularity of the EF scale, in terms of specific DIs, allows for a more complete rating of tornadoes away from dense concentrations of structural targets (i.e., population centers). However, the extent to which the EF scale has ameliorated long-standing issues with population biases in the tornado climatology (e.g., Schaefer and Galway 1982) still is unclear. Challenges also linger in mapping probable tornado intensity across areas devoid of current DIs (primarily in treeless areas such as grasslands, deserts, and large stretches of open cropland). Even the utility of EF scale for trees (DIs 27 and 28; Table 1) remains in question, especially for solitary trees whose damage cannot be viewed in context of a surrounding forest or other DIs.

The total impact of the EF scale on the tornado-rating climatology remains ambiguous, in light of previous shocks to the dataset and given the limited sampling time since its February 2007 implementation. Early results indicate the effects are small but still consequential, mainly focused around shifts in relative distributions of strong (EF2–EF3) tornadoes (Edwards and Brooks 2010). In fact, Alexander and Wurman (2008) have illustrated a low bias in tornado intensity estimations from a sample of mesocyclonic tornadoes observed by mobile radar. In light of these concerns, an EF-unknown category is an approved addition to the choices of ratings, to enable surveyors to avoid the troubling process of assigning a numerical rating where no guidance is available.

Fig. 2. Site of the fatal destruction of a mobile home near Fulton, Missouri, by a rain-wrapped, F1-rated tornado on 10 Apr 2001 (for meteorological documentation, see Glass and Britt 2002). At DoD 9 (complete destruction of unit), anywhere from EF1 to EF3 can be assigned for this DI in EFkit. The lack of damage to surrounding trees and to the adjacent satellite TV receiver may indicate either weaker winds than apparent (rating potentially as low as EF0) or the presence of a small-scale subvortex with winds at or above the EFkit default level of EF2. Uncertainty therefore yields a four-category margin of error in this scene alone. (Photo courtesy of NWS St. Louis.)

Damage to wind speed relationships. Discussion topics included variations in construction practices and structural integrity within any given DI, changes in vulnerability of single DIs based on directional wind angle and vertical velocity, full-scale testing facilities for wind effects on structures, inconsistencies in building codes and enforcement thereof, the effects of flying debris and surrounding surface roughness (buildings and terrain), and the weakest points of structural failure. Glass breakage can introduce internal wind forces that damage some buildings at a lower wind speed than the DoD would indicate, taking advantage of inner structural weaknesses. As illustrated by mobile homes (Fig. 2) and one- or two-family residences in the Greensburg, Kansas, tornado of 4 May 2007 (Marshall et al. 2008), the large range of wind speeds assigned to DoDs caused apparent inconsistencies between damage and wind speed, including with adjacent DIs (Fig. 3). Variations in wind flow characteristics and/or construction in the 1–2-km-wide Greensburg tornado led to a full spectrum of ratings, from EF0 to EF5, in the span of just two city blocks. Duration also adds to the uncertainty in wind speed estimation as physical experiments by Kopp et al. (2010) showed that damage to toe-nail connections progressively increased with the continued application of wind loading over a period of time. Other discussions focused on the inconsistencies in the ascending DoDs within houses (FR12; Table 1) where one DoD covers <20% roof covering but none describes >20% loss in roof covering without damage to roof decking (Brown 2010). The stakeholders discussed other related concerns, elaborated upon by Lombardo et al. (2010).

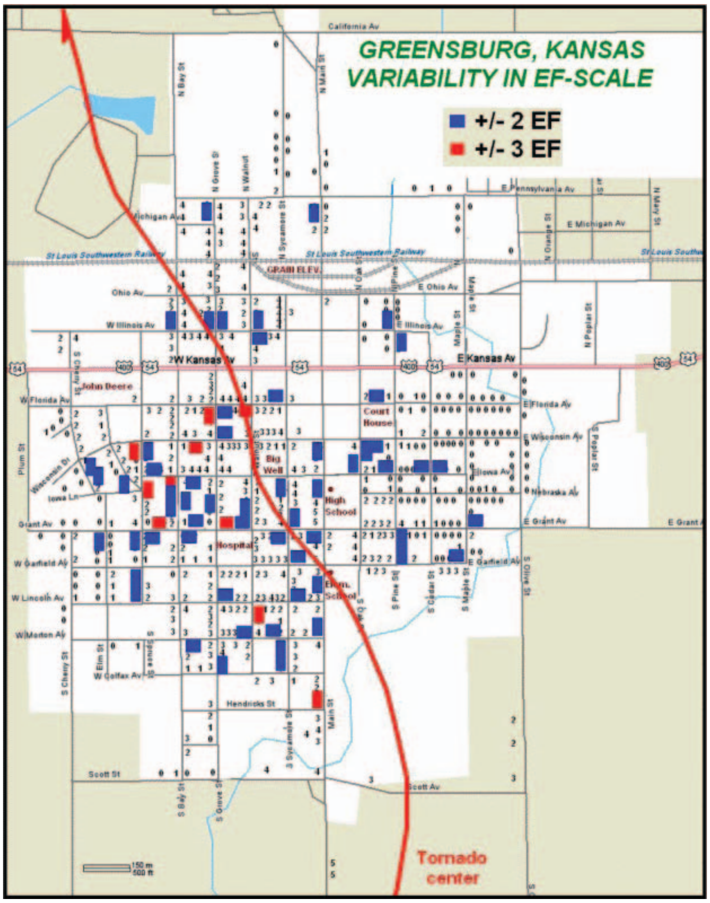


Fig. 3. A map of structure-by-structure EF scale ratings for the Greensburg, Kansas, tornado of 4 May 2007. The blue (red) boxes indicate adjacent structures displaying a rating difference of 2 (3). (From Marshall et al. 2008.)

The EFSSM also covered the damage relationship between wind speed and the two tree-based DIs. The EF scale guidance (WSEC 2006) falls short in correctly identifying softwood and hardwood DIs and assigning higher wind speeds to snapped trunks versus uprooted trees. For example, the guidance includes cedar as softwood and birch as hardwood, despite the available evidence to the contrary (Peterson 2003). In addition, evidence exists that increases in wind speed increases the ratio of uprooted trees to snapped trees in forests (Peterson 2003); this is opposite to the available guidance. The EF scale also fails to account for the positive correlation (regardless of species) that exists between trunk diameter and the risk that a tree will fall, such that the rate of increase of that risk is higher for stronger winds (Fig. 4). In fact, a technique to correlate observed tree fall patterns to the tornado wind field shape and intensity has been under development by Beck and Dotzek (2010). This differs from the methodology currently employed by the EF scale guidance owing to its treatment of trees in large numbers rather than individual DIs. At this time a plan has yet to be developed by the EFSSM participants to fold any vegetation-based techniques into operational practice.

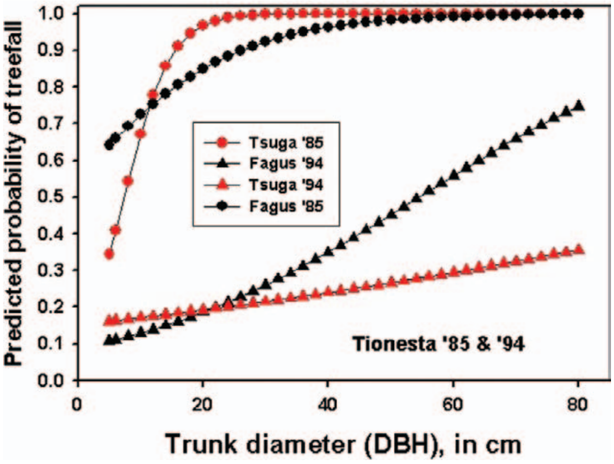


Fig. 4. Risk of tree fall versus size at breast height, predicted from logistic regressions for hemlock (genus *Tsuga*) and beech (genus *Fagus*) trees, from two tornadoes that occurred near Tionesta, Pennsylvania, in 1985 and 1994. The 1985 tornado was estimated to be the stronger of the two. (From Peterson 2003.)

There are many other influences that affect the relationship of wind speed and tree damage, including but not limited to tree species, antecedent soil conditions, and tree exposure (e.g., forest versus residential). The large number of variables provides a significant challenge in providing accurate tree-based DI guidance. However, any guidance that includes what is already known will provide better accuracy than what is currently available. It may be that future tree DI guidance may suggest an assessment of a sample of similar trees in order to account for the diversity of the variables mentioned.

International considerations. Tornadoes long have been recognized as a global phenomenon (e.g., Wegener 1917; Feuerstein et al. 2005), having been recorded in every continent except Antarctica. As such, numerous nations share an interest in improving assessment of their damage. International research and involvement in tornado survey work and damage and intensity scales is well underway. To that end, EFSSM began to realize this imploration by Meaden et al. (2007): "A world meteorological scientific meeting should be held to rule on the most satisfactory tornado scale. No such world meeting—as distinct from U.S.-only meetings which considered only Fujita's scale—has ever been held to discuss the merits of wind-speed scales since the international Beaufort-scale discussions of the 1920s."

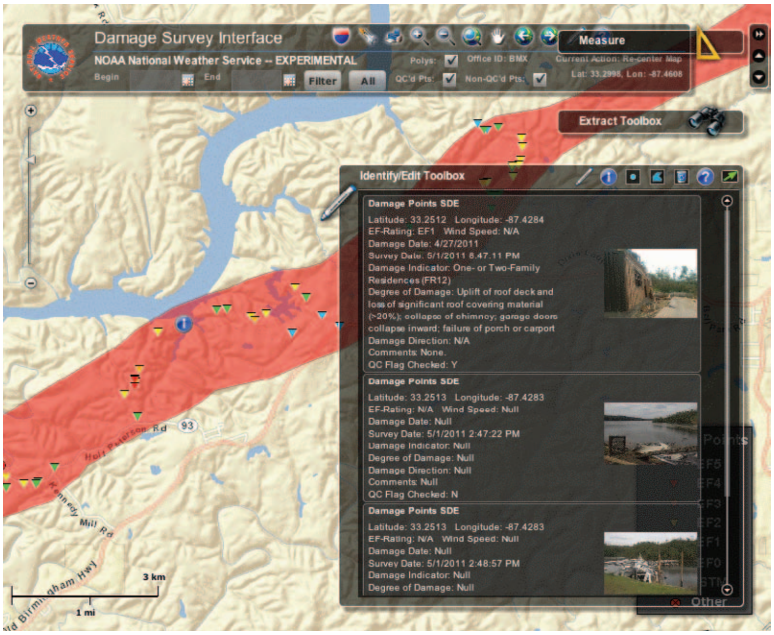
The EFSSM was attended by meteorologists from Canada, Germany, and Finland, where the EF scale was under consideration. Our international colleagues expressed concern that the diversity of construction habits among the DIs would force modifications to the EF scale prior to adoption. Given this diversity, one proposal was forwarded to consider all countries to adopt a more universal, physically derived wind speed scale (E scale; after Dotzek 2009), which could serve as a focus to bind all other wind speed and damage scales.

FUTURE DIRECTIONS AND CONCERNS.

Field use and scale oversight. Documented evidence (e.g., photographic and video), along with laboratory and numerical simulations, has shown great temporal and spatial variability of the fluid characteristics of tornadoes, even on the scale of DIs (singles to tens of meters). Such factors include the presence of multiple suction vortices (Fujita 1970; Fiedler 2009) on scales ranging from nearly a kilometer to as small as ~1 m, along with accelerations related to corner-flow collapse (e.g., Lewellen and Lewellen 2007). These can contribute to tight spatial gradients or rapid temporal changes in tornado intensity, which in turn manifest as extreme variations in damage between adjacent DIs, assuming the tornado encounters a representative density and composition of DIs. Debris also may affect tornadic flow near the surface (Lewellen et al. 2008). The nebulous and complex relationship between actual gradations in damage, debris, and small-scale vortex variability raises two major issues, which for now have no clear answers:

1) *How much damage variation is due to actual effects of vortex dynamics, as opposed to great differences in the structural integrity between nearby DIs (i.e., gradients in damage versus gradients in wind)?* This is a major concern in tornado damage assessment in general, and for EF scale estimation in particular. While perhaps never totally resolvable, this problem may be addressed through additional training of field surveyors in structurally influential concepts of tornado dynamics, in conjunction with greater attention to and metadata documentation of failure modes of DIs (e.g., lack of anchoring). At first, it may seem prudent to fine tune the rating of the scene in Fig. 2 downward as EF scale allows, especially with little evidence of secure attachments or reinforcements. By contrast, how sure can one be that a short-lived suction vortex with winds in the EF3 range did not form, strike a critical part of the structure, and vanish within the confines of the site, especially given a lack of eyewitness information? This is but one example of this subjective challenge that assessors face when considering damage to the immediate surrounding environment.
2) *What can be done to improve DI representativeness? What new DIs should be added, how, and why?* Work will continue to explore new potential DIs, especially for objects and structures more commonly found in rural and remote areas that can "fill in the gaps" in mapping damage paths. Such gaps do still exist, despite the presence of 28 DIs in the current EF scale. Possibilities include center-pivot irrigators (Guyer and Moritz 2003), farm implements, grain bins and silos, rail cars, common oilfield equipment such as pumpjacks, and nonfarm vehicles. Additionally, engineering and botanical studies will continue to reveal insights that could compel revision of wind estimates for existing DIs or even blending of DIs (e.g., hardwood and softwood trees, as discussed above) for which the current distinctions might not be justifiable. How should the EF scale account for variations in tree species, size, symmetry, and soil conditions that can influence their breakage and toppling? How should the EF scale evolve in step with changes in construction practices and codes, both with time and from place to place?

Given the incomplete nature of both the EF scale and knowledge about wind effects, the scale will need to be fluid and evolutionary to some extent. This will allow the accommodation of new DIs and greater understanding of existing ones. Furthermore, an "unknown" category (Doswell et al. 2009) has been added to accommodate those events that still miss DIs. As with the F scale, only a default rating of EF0 has been available for such events, which could misrepresent actual tornado strength grossly.



Damage Points SDE
Latitude: 33.2512 Longitude: -87.4284
EF-Rating: EF1 Wind Speed: N/A
Damage Date: 4/27/2011
Survey Date: 5/1/2011 6:47:11 PM
Damage Indicator: One- or Two-Family Residences (FR12)
Degree of Damage: Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport
Damage Direction: N/A
Comments: None.
QC Flag Checked: Y

Damage Points SDE
Latitude: 33.2513 Longitude: -87.4283
EF-Rating: N/A Wind Speed: Null
Damage Date: Null
Survey Date: 5/1/2011 2:47:22 PM
Damage Indicator: Null
Degree of Damage: Null
Damage Direction: Null
Comments: Null
QC Flag Checked: N

Damage Points SDE
Latitude: 33.2513 Longitude: -87.4283
EF-Rating: N/A Wind Speed: Null
Damage Date: Null
Survey Date: 5/1/2011 2:48:57 PM
Damage Indicator: Null
Degree of Damage: Null

Fig. 5. An example of the damage assessment tool in beta-test mode, taken from a 27 Apr 2011 tornado-track segment northeast of Tuscaloosa, Alabama. Field surveyors with mobile smartphones enter in damage points with DI, DoD, estimated wind speeds, EF scale rating, and pictures. A central server records the information with data in shape file or KML format. (Image courtesy of NWS.)

Any such changes will require a formalized, documented procedure for revision of the EF scale, as advocated by Doswell et al. (2009), but such a process does not exist currently. This issue was discussed at the EFSSM and recognized as necessary for 1) accountability and 2) the integrity and utility of the EF scale in the future. Meeting participants will continue to work to establish an oversight team for the EF scale.[2] At first, this team probably will consist mainly of a subset of EFSSM participants but, like the scale itself, should evolve with time. A key unanswered question is, how will such efforts be supported, financially and logistically, in the face of budgetary and workload uncertainties involving potential participants?

Tornado mapping and climatology. The presence of 28 diverse DIs (with more possible in the future) and geographic information systems (GIS) allows highly textured mapping of tornado damage paths, often at far finer scale than the $10^{-2\circ}$ latitude and longitude resolution of the existing SPC tornado data. GIS-based surveying already has been performed for a few years (e.g., LaDue and Ortega 2008; Camp 2008), supplemented in some cases by digital cameras and video supplying visualized metadata. GIS technology and related software ensure that integrated detailed damage mapping along paths is no longer just the domain of meticulous postmortem research (as in Fujita's work) but can be done rapidly and timely in an operational setting. In fact, the NWS has just fielded a damage assessment tool allowing surveyors to generate high-resolution GIS-based damage maps on the fly using smartphones linked to a central server (Fig. 5; Camp et al. 2010). The inevitable increase in high-resolution mapping of tornadoes, similar to and perhaps even finer in scale than the 3 May 1999 event maps in Speheger et al. (2002), raises important questions, including the following: For both tornado climatology and research, to what extent should digital metadata be affixed to the permanent tornado data, in what way, and under what kind of quality-control process? How can consistency in damage assessment procedures and mapping be ensured from one NWS jurisdiction to another, while allowing flexibility for local constraints in timeliness, staffing, access to expertise, etc.? What are the research implications of grouping relatively coarse historic records, many of which contain little more than a date, time, path length, max path width, rating, and location, with richly textured, metadata-laden tornado maps of the future?

Should purely damage-based EF scale ratings be modulated by output from other methodologies to estimate tornado intensity including mobile radars,[3] fixed instruments, deployable devices, evaluation of engineered structures, and treefall pattern analysis? If so, in what ways and with what designations in the climatological metadata can this be done? Mobile radars provide high-resolution velocity data at the

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[2] The term "ownership of the EF scale" has been proposed, but the EFSSM consensus was that everyone who uses the scale "owns" it. Still, a dedicated team will be needed for its maintenance and oversight.

[3] Final ratings for tornadoes near LaGrange, Wyoming (EF2 on 5 June 2009; Wurman et al. 2013), and El Reno/Piedmont, Oklahoma (EF5 on 24 May 2011; NOAA 2012), were influenced upward by mobile-radar data that suggested higher near-surface wind speeds than estimates available from objects in relatively DI-deprived path segments.

Fig. 6. Methodology to estimate tornado intensity proposed by Beck and Dotzek (2010) involving (a) an observed tree-fall pattern, (b) matching the pattern to the closest modeled pattern, and (c) deriving F or EF scale contours. This damage pattern was derived from a tornado in Milošovice, Czech Republic, on 31 May 2001.

height of the radar beam, and new methods are under development to relate such winds to an estimated 3-s gust at 10 m AGL. However, even with an established relationship, differences still are likely in ratings when compared to that of the damage-based techniques such as Alexander and Wurman (2008) have demonstrated. Another relationship may have to be established between DI-based tree damage rating method and the treefall pattern, consistent with the method discussed by Beck and Dotzek (2010) (see Fig. 6).

How can satellite- and aerial imagery-based damage surveys supplement those from the ground and perhaps even replace them where the latter is not fully possible? There is already supporting evidence that aerial or high-resolution satellite imagery can be used to rate a large number of DIs provided there is ground truth at enough points for proper calibration, as is shown in Fig. 7 (Brown 2010). However, metadata would have to accompany the official record of

Fig. 7. Spatial damage analyses of a 5 Feb 2008 tornado segment in Madison County, Tennessee: (a) EF scale DoDs for houses (FR12; Table 1) by ground survey and (b) RS scale developed by Womble (2005) for damage analysis via aerial imagery. RS values range from RS-B corresponding to roof decking exposed to RS-D representing collapse or removal of roof structure.

any portion of a damage track surveyed in this way to account for the larger uncertainty.

Even without the necessary staffing and other resources to conduct a systematic reanalysis of tornado records, similar to the ongoing hurricane reanalysis project (Landsea et al. 2004), individual events have been and will be reassessed with potential EF scale implications. Studies of past outbreaks can reveal valuable new information about path characteristics and even aspects of tornado structure and behavior (e.g., Ostuno 2008) suitable for forensic reanalysis. This also raises inevitable questions such as the following: How can current understanding of DIs be used to revisit and revise ratings of past events, where sufficiently complete accounting exists of past damage? How should any such changes be reflected with metadata in the existing tornado database? How will such revisions impact the methods and integrity of statistical detrending (e.g., Grazulis 1993b; Doswell et al. 2006; Verbout et al. 2006) necessary to compare tornado records effectively from decade to decade, across major changes in record gathering? What impacts will all this additional information have on risk-reduction and preparedness activities that depend on analyses of the tornado climatology? Should we revisit the notion of classifying tornadoes by their greatest single damage point, and instead invoke an integrated, textured approach? If so, how should tornadoes rated that way be compared to historic, peak-DI-based ratings?

This paper cannot cover all the implications and issues related to the EF scale: some of which may be unforeseen. Still, we hope that the questions and topics discussed, along with a companion paper presented to the wind-engineering community (Lombardo et al. 2010), will stimulate focused, productive, and beneficial discussion that results in ever-improving assessment and documentation of tornadoes worldwide, ultimately leading to better mitigation of the tornado-damage hazard.

ACKNOWLEDGMENTS. We offer thanks to all the attendees of the EF scale meeting, in person and via teleconference, who are too numerous to list here, for their contributions and insights. Additional discussions with the following people helped to focus specific discussion points herein (alphabetically): Ed Calianese, Greg Carbin, Chuck Doswell, Lonnie Fisher, Frank Lombardo, Rich Thompson, and Josh Wurman. For several years, the late Nikolai Dotzek (ESSL) stimulated a great deal of insightful discourse on damage scales, their relationships and analyses, and international involvement in tornado assessment, both before and during the meeting. Nikolai's recent passing was a profound loss in this area of atmospheric science, and his keen, stimulating insights will be missed greatly. Steve Weiss (SPC interval review), along with Tom Grazulis and two other formal reviewers, are recognized for their keen ideas in helping us to improve this article.

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