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Estimating Wind Speeds in Tornadoes and other Windstorms: Development of an ASCE Standard

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1 INTRODUCTION

Estimation of near-surface wind fields in tornadoes has important applications in both structural engineering and meteorology. Estimated near-surface wind speeds are used in the design of nuclear power plants, safe rooms, storm shelters, and could be used in tornado-resistant design for other buildings and residential structures [1-3]. A better understanding of the near-surface wind field is also important for identifying possible changes in the tornado record due to climate change and for assessing likelihood and intensity of tornadoes given certain atmospheric conditions [4]. However, assessing the near-surface wind speeds in tornadoes is difficult due to complex flow in time and space [5-7], and challenges obtaining in-situ measurements [7, 8]. Radar measurements have provided useful insight into tornadic wind flow, however they typically cannot sample the near-surface winds. Because of these difficulties, meteorologists and engineers have turned to damage-based methods to estimate near-surface wind speeds in tornadoes such as the Fujita (F) Scale [9] and the subsequent Enhanced Fujita (EF) Scale [10]. However, damage-based estimates of near-surface wind speeds have not been validated and their accuracy has been questioned [11, 12], spurring other methods to reconstruct near-surface tornado wind fields such as assessing tree fall patterns [13]. This paper will discuss the background of and state of the science with regard to near-surface wind speed estimation methods (e.g., in-situ, radar, damage-based). To improve and standardize these methods, the American Society of Civil Engineers (ASCE) has formed a committee in 2015 to develop a standard for wind speed estimation in tornadoes and other windstorms. Sub-committees were created to advance each of the different wind speed estimation methods. The initiation, development and current status of the standard will be also discussed in the paper.

2 STATE OF THE SCIENCE: NEAR-SURFACE WIND SPEED ESTIMATION

This section will discuss the different methodologies, both old and new, that exist for estimating near-surface wind speeds. The discussion will revolve around methods planned for inclusion in the new ASCE standard. These include the EF Scale (with discussion of the original F Scale), remote sensing, in-situ measurements, radar, forensic engineering and tree-fall patterns. Each of the methods discussed here will be addressed by sub-committees of the main ASCE standards committee, the structure of which is discussed in Section 3.

2.1 F Scale

The original Fujita (F) Scale was developed in 1971 by the late Dr. Ted Fujita, to provide a scale to rate the intensity of tornadoes and hurricanes using damage as a proxy, since wind speed measurements were rare [10]. It has received widespread use in rating tornadoes [14]. Fujita established ranges of wind speeds, and fitted them into categories from F0 to F12, corresponding to speeds of 40 mph up to Mach 1. Only F0 to F5 were practical for windstorms. He described the type of damage that could be expected in each F Scale category. This scale served as the primary method for rating tornado intensity for more than three decades. Some of its shortcomings included 1) not accounting for differences in construction type and quality; 2) wind speeds were merely estimates and had never been validated; 3) lack of sufficient guidance which led users of the scale to inconsistently rate damage from the same storm; and 4) damage levels at the upper end of the F Scale could occur at lower wind speeds [14].

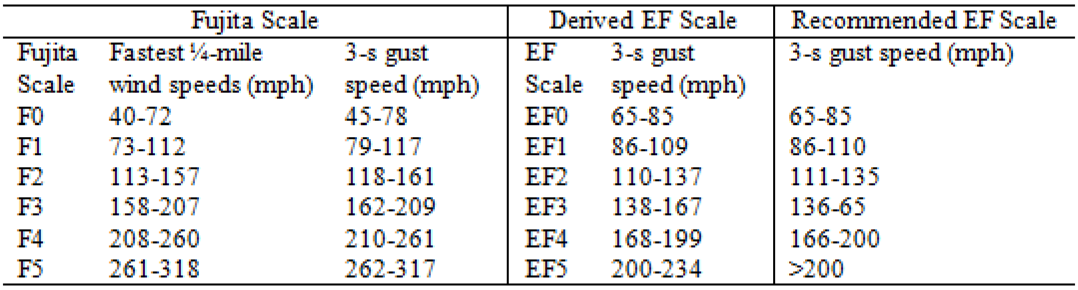
2.2 EF Scale

Researchers at the National Institute of Standards and Technology [15] and Texas Tech University spearheaded efforts to improve the F Scale [16]. A steering committee of meteorologists and engineers, and a forum of F Scale users recommended the following strategies for improving upon the F Scale:

- identify additional damage indicators
- correlate appearance of damage and wind speed
- preserve the use of the historical database
- seek input from users
- use an expert elicitation process to determine wind speeds since measurements were still not generally available

With these goals in mind, the Enhanced Fujita (EF) Scale was developed [10, 16]. Twenty-eight "damage indicators" (DIs) including buildings, trees, and other structures were defined, with several "degrees of damage" (DODs) defined representing the sequence of progressive damage for a given DI. Progressive damage sequences have been defined for a large number of structures, and have been modeled by many researchers [17, 18, 19, 20]. Each DOD in the EF Scale had an expected (EXP), lower bound (LB) and upper bound (UB) of wind speeds that would likely cause a given level of damage based on expert elicitation. Consistent with current engineering practice, wind speed values are assumed to be three-second gusts. Because of the need to preserve the historical database, a relationship was derived between the F Scale and EF Scale. Expert elicitation was used to determine the F Scale rating of the newly-developed DODs. The F Scale wind speeds were converted from fastest 1/4-mile to three-second gusts and correlated to the expert elicitation wind speed values for the EF Scale. This correlation was used to derive EF Scale wind speed ranges, which still had six categories ranging from EF0 to EF5, but the wind speeds associated with the numerical categories were different from those in the F Scale. The relationship between the F Scale and EF Scale is provided in Table 1, which shows that for the lowest tornado category (F0 or EF0), the EF Scale wind speeds are higher than those of the F Scale. For all other tornado categories, the EF Scale wind speeds are lower than those of the F Scale. The values from the derived relationships were rounded to the nearest 5 mph to develop the final recommended EF Scale wind speed ranges, also shown in Table 1. The derived EF Scale wind speed ranges were modified slightly for operational reasons and show up as "Recommended" EF Scale values in Table 1.

Table 1. Relationship between F Scale and EF Scale [10]



Fujita Scale			Derived EF Scale		Recommended EF Scale
Fujita Scale	Fastest ¼-mile wind speeds (mph)	3-s gust speed (mph)	EF Scale	3-s gust speed (mph)	3-s gust speed (mph)
F0	40-72	45-78	EF0	65-85	65-85
F1	73-112	79-117	EF1	86-109	86-110
F2	113-157	118-161	EF2	110-137	111-135
F3	158-207	162-209	EF3	138-167	136-65
F4	208-260	210-261	EF4	168-199	166-200
F5	261-318	262-317	EF5	200-234	>200

The EF Scale was adopted by the National Weather Service (NWS) in February 2007 as the official way to rate tornado intensity in the U.S. It is applied to individual DIs, and the tornado is rated by "…applying the highest DI, provided there is supporting evidence of similar damage intensity immediately surrounding the DI" [10]. The estimated wind speed based on this assessment is then associated with an EF-number (EF0 through EF5).

After more than seven years in practice a number of issues have arisen with the EF Scale [17]. These include but are not limited to: 1) not accounting for debris associated with tornadoes; 2) observation of a DOD for a given DI only provides lower bound wind speed estimates and higher winds could have occurred later; 3) lack of DIs for use in rural areas); 4) wind speed ranges associated with higher DODs are quite large; 5) Lack of DIs and DODs for violent (EF4 and EF5) tornadoes 6) large gaps in wind speed between DODs for some DIs; 7) missing photographic guidance; and 8) inconsistent wind speeds for certain damage states for DIs with similar construction. These limitations can allow for ratings to be highly subjective, especially for violent tornadoes. As a result, there is considerable interest among both wind engineers and meteorologists to significantly improve the EF Scale [21, 22].

The EF Scale subcommittee of the newly formed ASCE committee will convert the EF Scale into standards language and format, and update and improve the damage-based method of rating tornado intensity. Improvements being considered include: 1) adding or updating photographic guidance; 2) developing new DIs and associated DODs; 3) modifying existing DIs and DODs; and 4) improving tree DIs and DODs. Updates and improvements will rely on new data from forensic surveys, laboratory results, and modeling studies to refine and improve this method. The subcommittee will also evaluate the damage-based practices employed by international groups.

2.3 Remote Sensing

With improvements in imaging technology, researchers have recently used georeferenced, high spatial resolution remote-sensing data (both satellite- and aircraft-based) to assess damage, and hence wind speeds, following windstorms. Spatial resolution generally needs to be less than approximately 1 m to detect major damage to individual buildings (with even finer spatial resolutions required to discern minor damage) [23]. Commercially available imagery currently has spatial resolutions as fine as 8 cm from some fixed-wing aircraft platforms. Unmanned aircraft systems (UASs) have the potential to provide imagery with an order of magnitude or more improvement in spatial resolution, as demonstrated by UAS flights in 2012 following an EF-3 tornado in Alabama [24]. Remote sensing has been used in addition to, or instead of employing the older methods of walking house-to-house for surveys, or photographing individual buildings from an airplane [25-27]. Quantitative relationships have been established between ground-based and remotely-sensed wind damage states for individual site-built one- or two-family residences (DI: FR12) [26-27], which can be used to predict the ground-level damage state from remote-sensing imagery, significantly decreasing the time and expense required to assess the damage. Figure 1 illustrates an example of this method, where two houses were assigned a DOD value from a ground survey using the EF Scale, and an Enhanced Remote-Sensing Scale (ERS) value – the use of remote sensing to predict damage levels from residential structures – from Luo et al. [27]. Pairs of survey data (ground-based and remotely-sensed) such as these were used to develop the models proposed by Brown et al. [26] and Luo et al. [27]. These methods could be expanded in the future to include other types of DIs. The Remote-Sensing subcommittee of the newly formed ASCE committee will work to define standards addressing the use of remotely-sensed imagery to rate tornado strength and wind speeds. These will likely include spatial and spectral resolution requirements as well as error ranges associated with them.


Example pair 1

Example pair 2

DOD = 4

DOD = 6

ERS = C 1% to 25% B 51% to 75%

ERS = D 1% to 25% C >75% B >75%

Figure 1. Example of paired images from ground and remote-sensing surveys which were used to develop the models relating the two damage states. From Luo et al. [27].

2.4 In-Situ

Measurements from fixed observing stations (e.g., anemometers) in tornadic environments are rare, mainly because the distance between stations is typically large compared to tornado scale [28]. This is also a problem for portable systems [7, 29]. Even if a measurement system happens to be in the path of a tornado, it is at risk of being damaged by high winds and/or debris [30] or not sampling the core flow of the tornadic vortex.

A summary of near-surface wind and pressure (atmospheric) measurements from both fixed and portable systems in the literature is described in [8], including nine such measurements taken using portable platforms, as well as an approximately 100 mb pressure drop measured with a pressure probe from a tornado in 2003 Anemometry attached to “mobile mesonets” at heights of 3.5 m was able to measure wind speeds in tornadic environments in Wyoming [7] and Kansas [31] in 2009 and 2012 respectively. Other, more serendipitous measurements from fixed platforms have occurred in the last few years, including three from the Oklahoma Mesonet in 2011, one of which was from the El Reno tornado (67. 5 m/s gust) [32] and at least two from the West Texas Mesonet. Two of the measurements from the Oklahoma Mesonet were much lower (≈ 40 m/s) due to the measuring system being damaged by debris. A 43.4 m/s, 3-s gust believed to be in a near-tornadic environment was recorded from the Automated Surface Observing System (ASOS) station (10 m) at Denver International Airport in 2013. Other measurements are also likely to exist over the history of ASOS stations and other meteorological networks that may serve other purposes. One such near-surface measurement of a possible multi-vortex tornado was collected by a sonic anemometer in Arizona [30] at a height of approximately 2.5 m. This anemometer was primarily used for carbon flux measurements. Peak (known) instantaneous wind speeds exceeded 80 m/s for this particular record. In addition to the difficulty in actually capturing measurements in-situ, questions still remain over standardizing measurements (e.g., 3-s gust, atypical vertical wind profiles of horizontal winds, comparison with radar measurements) for wind engineering use as they display a markedly different character than wind events considered in codes and standards [33].Include a concise list of key words (not more than ten), for example: Bridge Aerodynamics; Pedestrian Comfort; Wind Energy; Tall Buildings. Key words should be capitalized and separated by semicolons and the list should be terminated by a period.

2.5 Radar

High-resolution mobile radar wind speed measurements have brought useful insight into the structure of complex wind fields associated with tornadoes [34-37]. In contrast with anemometry, a single wind estimate is typically derived from the power weighted return average motion toward or away from the radar of scatterers (called radial velocity) in a time-integrated period within a three-dimensional resolution volume [38]. These scatterers may be representative of the true wind should they have reached an equilibrium of forces with respect to the moving air in which they are embedded. However, in strongly accelerating flow typical of severe boundary layer winds or small-scale severe wind phenomena, the motion of large scatterers may deviate strongly from the surrounding air [34] and must be corrected [31]. It is also possible to account for debris-induced errors by recording the Doppler radar spectra of power as a function of radial velocity and choosing the maximum values containing enough power to exceed the signal to noise threshold [39]. Other challenges to extracting an accurate wind speed when high winds exceeding the maximum unambiguous velocity associated with a radar must be dealiased [38], a process that can be time consuming to complete manually, or done by algorithm [40], and risks significant error.

Even with a corrected wind speed, the ability of a radar system to measure the near-surface radial velocity is limited due to physical constraints and/or the presence of highly reflective objects such as terrain, or obstructions (e.g., buildings, trees). To mitigate the likelihood of obstructions, successful mobile radar measurements of tornadoes [7, 29, 30, 38] and hurricanes [41] have been confined to relatively open terrain.

Even with a clear view of tornadoes, radar-based wind measurements must be converted to the 10 m, 3-s standard speeds for comparisons with wind speed estimates derived from other methods. While various techniques for smoothing radial velocity data can yield a close estimate of a 3-s wind [36], safety concerns for field teams [34] typically prevent direct sampling as low as 10 m above ground level (AGL). Typically the wind speed at high altitudes is reduced to the 10 m level using a logarithmic profile. However combined radar and in-situ anemometer deployments in tornado boundary layers reveal that wind speeds may remain the same or even increase as altitude decreases from radar sampling altitudes to the 10 m, and even the 3.5 m level [7, 29, 42] as Figure 2 shows from an accidentally close radar deployment. Given the uncertainty as to the vertical profile of horizontal winds in a tornado environment, typically no adjustments are made to the 10 m level. However, there is strong motivation to determine if there is a relationship between tornado structure and the vertical profile of horizontal winds.

Since the first mobile radar deployments, over 100 tornadoes have been sampled with adequate quality and spatiotemporal resolution to create a mobile radar-based climatology of tornado intensity. The findings reveal a biased relation between the wind speeds estimated by radar versus those derived from damage-based surveys [43]. The mode of tornadoes rated by mobile radar was EF2, whereas the mode of the same tornadoes rated by damage survey was EF0. This finding may have significant implications for tornado intensity climatology in general if a standard is created that includes mobile radar data.

As a target increases its range from the nearest Doppler radar, any attempt to estimate the 10 m AGL wind suffers as the lowest available beams become increasingly elevated due to Earth’s and atmospheric refraction [44]. Radar beam broadening further degrades sampling of tornadoes as range increases [45] to the point where tornadoes are not resolved. Instead, any vortex signature is referred to as a tornado vortex signature (TVS) as the effective beam width becomes larger than its core diameter [46]. At these scales the radar is no longer directly sampling the tornado but instead is sampling larger scale flows, sometimes called the tornado cyclone or the larger scale parent circulation identified as a mesocyclone. Any attempt to estimate tornado intensity at the 10 m level via radar-based TVS or mesocyclone signature strength [47] requires a relationship between these scales. Recent research has found there exists a statistical relationship between the vortex signature strength and the EF Scale rating [47, 48]. The uncertainty inherent in this relationship is likely greater than when radar is directly resolving a tornado, and increases with increasing range. The type of storm also affects this relationship, with supercell (squall line) induced tornadoes providing the best relationship and squall line tornadoes providing the worst.

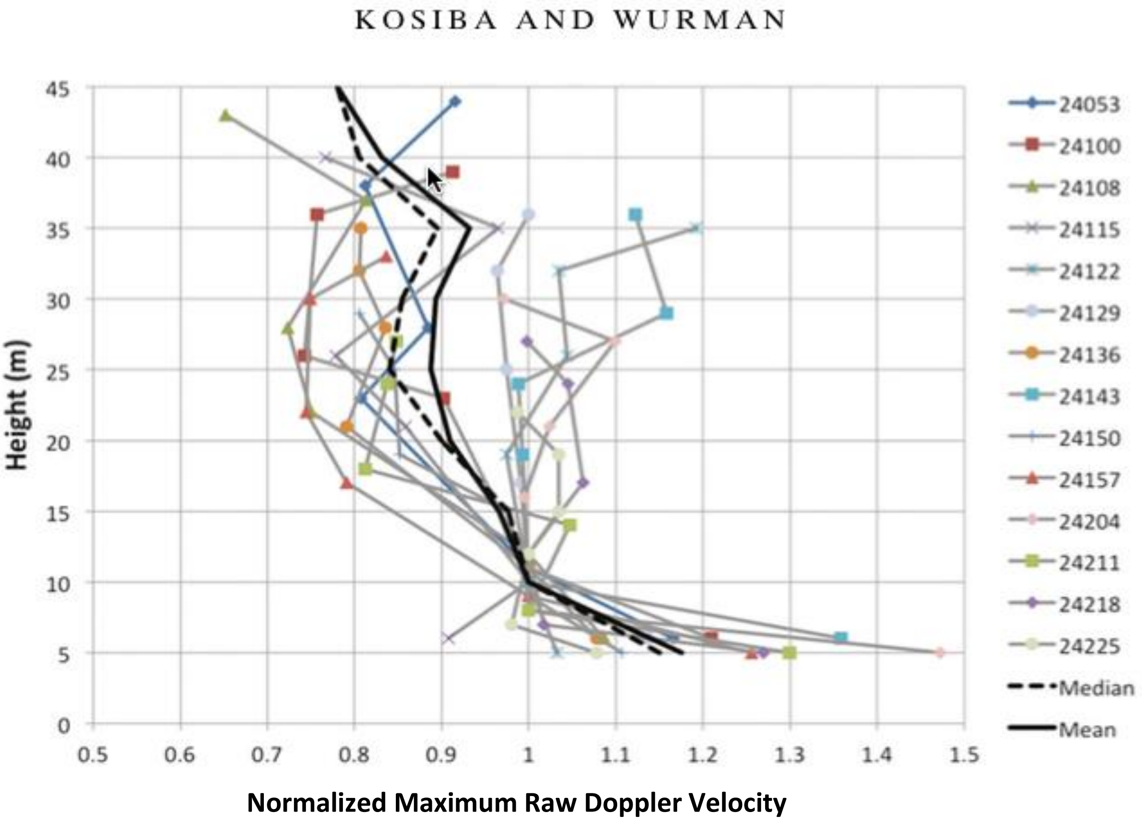


Figure 2. The maximum rapid scan Doppler on Wheels Doppler velocity in the Russell, KS tornado as a function of height normalized by the 10 m AGL value. The time labels represent HMMSS UTC where H represents hours, M minutes, and S seconds. The dashed and solid lines depict the median and the mean for all times respectively. The most intense winds were observed at 5 m AGL. (adapted from [31])

2.6 Forensic Engineering

Of all the recent wind speed estimation methods, tree-fall analysis has gained the most traction recently. Its use has increased after the violent tornadoes that struck highly forested areas such as those in proximity to Joplin, MO and Tuscaloosa, AL. Researchers in [1] and [53] estimated maximum near-surface wind speeds of 78 m/s and 103 m/s respectively for Joplin using tree-fall. Comparisons between tree-fall estimated wind speeds and those based on the EF Scale are underway [64]. Illustrated in Fig. 3 is a comparison of the two methods for FR12. For lower DODs tree-fall wind speed estimates on average are higher than those prescribed in the EF Scale. As the DOD increases, the estimates become closer. A few recent studies [7,31] have tried to combine both in-situ and radar measurements to analyze vertical profiles and compare results between two methods.

2.7 Tree-Fall Patterns

Of all the recent wind speed estimation methods, tree-fall analysis has gained the most traction recently. Its use has increased after the violent tornadoes that struck highly forested areas such as those in proximity to Joplin, MO and Tuscaloosa, AL. Researchers in [1] and [53] estimated maximum near-surface wind speeds of 78 m/s and 103 m/s respectively for Joplin using tree-fall. Comparisons between tree-fall estimated wind speeds and those based on the EF Scale are underway [64]. Illustrated in Fig. 3 is a comparison of the two methods for FR12. For lower DODs tree-fall wind speed estimates on average are higher

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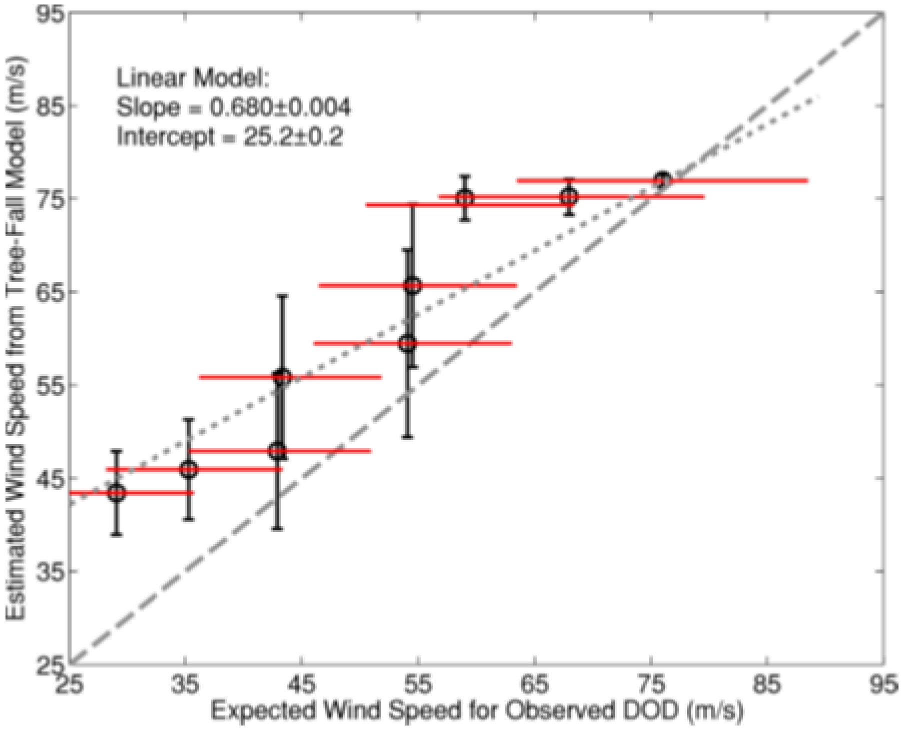

Fig. 3. Comparison of tree-fall estimated wind speeds versus EF Scale estimated wind speeds [62]. Circles are at locations of expected (EXP) wind speed for the EF Scale for a given DOD and median wind speed for tree-fall. Uncertainty (plus/minus one standard deviation) in estimates is also shown.

3 ASCE STANDARDS COMMITTEE

3.1 *Background*

In 2010, three years after adoption of the EF Scale by the NWS, an EF Scale stakeholder's meeting was convened in Norman, OK to reflect upon the history of the EF Scale, to document its current state and deliberate about its future. The participants came from a wide variety of backgrounds, sectors and nations, including operational meteorologists, wind engineers, policy makers, and one forest biologist. At the end of the meeting, the participants expressed a desire to publish the meeting results [20], and develop a formal procedure in which to allow the tornado intensity estimation process to evolve. The members of the stakeholder's meeting formed the EF Scale Stakeholder's Group, whose mission included fostering creation of a formal procedure to improve the EF Scale.

Following violent tornadoes in the southeast US and in Joplin, MO in 2011, disaster investigations by the Federal Emergency Management Agency (FEMA) [65] and the National Institute of Standards and Technology (NIST) [1] documented additional concerns with the existing EF Scale and made recommendations for improvements. The NIST report also called for formalizing a path forward to allow continued improvements to the Scale, and for adoption of the improved Scale by the NWS. A town hall forum on the future of the EF Scale was held in conjunction with the American Meteorological Society's Annual Meeting in early 2014 (http://apps.weather.gov/efscale/presentations.php), further exploring ideas for improvement to the EF Scale and other methods for estimating wind speeds in tornadoes.

The EF Scale Stakeholder's Group ultimately decided that a standard would be the best structure for a formal procedure and that the American Society of Civil Engineers (ASCE) would be the best 'home' for this standard. The Group submitted a proposal to ASCE to create a national consensus standard for estimating wind speeds in tornadoes and other windstorms, to be housed within ASCE's Structural Engineering Institute (SEI). ASCE approved the proposal in May, 2014, and shortly thereafter issued a call for membership.

3.2 Committee Organization and Activities

The standards committee is comprised of meteorologists, wind engineers, structural engineers, and others in related fields, representing a balance between ‘consumers’ (e.g, NWS personnel that rate tornadoes and other users of the standard), general interest groups (e.g., academic and government scientists and engineers), and producers (e.g., representatives of manufacturers with an interest in this standard, such as construction materials suppliers and storm shelter manufacturers).

This committee will develop standardized methods for estimating the intensity of tornadoes and other windstorms, and then publish the procedures, after ASCE and American National Standards Institute (ANSI) approval, as an ANSI/ASCE/SEI standard. The content of the standard will include the existing EF Scale and improvements to address known problems and limitations, plus additional methods to estimate intensity (such as those in Section 2), and requirements for archiving of the data and metadata used for estimating wind speeds.

The first meeting of the ASCE Committee was held March 12-13, 2015 at ASCE Headquarters in Reston, Virginia. Committee members were provided with an overview of the ASCE standards process, background on formation of the standards activity, and information on Committee organization, operations, and workplan. The Committee is organized with a Main Committee and seven subcommittees: Radar, In-situ, EF Scale, Forensic Engineering, Treefall Pattern Analysis, Remote Sensing, and Data Archival. Each of the subcommittees also met in breakout sessions, to begin the work of assessing the state-of-the-art for each wind speed estimation method, and determining the scope of subcommittee work plans. The subcommittees will develop the specific procedures for wind speed estimation, associated text for the standard, and the corresponding commentary. The Main Committee will then ballot each proposed method according the ASCE’s ANSI-approved consensus process. More information on the ASCE standards process is available at http://www.asce.org/uploadedFiles/Technical_Areas/Codes_and_Standards/Content_Pieces/asce-rules-standards-committees.pdf.

3.3 The Consensus Process and Opportunities for Participation

There are multiple opportunities for involvement in the standards development process by interested individuals and organizations. Interested parties can apply through ASCE for committee membership (membership in ASCE is not required in order to serve on a standards committee). Main Committee meetings are announced at http://www.asce.org/codes-and-standards/codes-and-standards/ and in ASCE, SEI, and AMS newsletters and blogs. These meetings are open to the public. Once the Committee has approved a draft of the entire standard, ASCE will publish the draft and make it available for public comment, for a minimum of 45 days. All public comments must be considered by the Committee before finalization of the standard. Should substantive changes result from consideration of public comments, a second round of public comments must be solicited and then considered.

3.4 The Path Forward

It is anticipated that development of the first edition of the standard will take approximately three years. The second committee meeting is anticipated to be held in McKinney, TX in September 2015. It will be followed by three to four meetings per year for the next few years. Once completed, this new standard’s users will include meteorologists, wind, structural and forensic engineers, climatologists, forest biologists, risk analysts, emergency managers, building and infrastructure designers, and the media. The standard is also intended for adoption by the NWS. Following publication of the first edition, the standard will be reviewed and subject to revision or reaffirmation at intervals not to exceed five years.

4 SUMMARY

Knowledge of near-surface wind speeds in tornadoes is important for many applications. However, obtaining measurements is extremely difficult. Scientists have used damage-based methods to estimate near-surface wind speeds, but these estimates have not been validated. This paper discusses the history and current state of near-surface wind speed estimation and how researchers, scientists and engineers are working toward better estimates and validation of estimates using new methods. To this point, a proposal was accepted by ASCE to create a national consensus standard for estimating near-surface wind speeds in tornadoes and other windstorms. Work toward development of the standard is ongoing.

DISCLAIMER

It is NIST policy to use the International System of Units (metric units) in all its publications. In this paper, however, some information is presented in U.S. Customary Units (inch-pound). Specifically, wind speeds associated with the definition and descriptions of the F and EF Scales are presented in mph, as was done in the original sources defining those two scales.

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