8B.6 **EXPERIENCES USING THE EF-SCALE SINCE ITS INCEPTION**

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1. INTRODUCTION

Since the beginning of 2007, the EF-Scale has become the standard by which the NWS rates tornado intensity. Over this time period, numerous damage surveys have been completed by surveyors, including the authors, creating an experience base from which an assessment can be made of, its value, issues resulting from its inadequacies, needed improvements.

As the adoption of the F-Scale has become widespread from the 1970's to the 1990's, engineers have become increasingly concerned that the wind speeds at the high end of the F-Scale were too high. The Enhanced Fujita Scale (EF-Scale) was designed primarily to lower the wind speeds associated with the high ratings and to add more Damage Indicators (DIs) (McDonald et al. 2003 and WSEC, 2004). The steering committee involved in creating the EF-Scale desired a climatological continuity in tornado ratings as the new scale became adopted. Therefore, the only choice was to change the relationship between wind speed and Degree of Damage (DOD) while attempting to maintain the relationship between DOD and rating. As will be mentioned later in this paper, this strategy creates problems when building construction standards change within a DI.

The EF-Scale brings to surveyors a more comprehensive set of damage descriptions to 28 DIs vs a few DIs associated with the F-Scale. Damage surveyors identify the DI, then the DOD, to derive an expected wind speed. Adjustments to the wind speed estimate are made based on the surveyor's estimate of the DI's structural integrity. The final rating comes out of the wind speed estimate. Ideally, there should be less subjectivity concerning the derivation of an EF-Scale rating, and there should be many more data points from which to construct a more precise map of tornado intensity. In reality, the experience gained by multiple surveys indicates that while the EF-Scale provides many more points for wind speed estimation, there is still just as much subjectivity in determining wind speed estimates as with the F-Scale.

This paper describes the advantages the EF-Scale brings to damage surveyors, issues with the chosen DODs, and then suggestions for improvements to the EF-Scale including consideration of an evolution to a superior wind speed/energy scale.

2. ADVANTAGES OF THE EF-SCALE

A convergence of the EF-Scale with a large number of DIs and the widespread adoption of GIS-based skills amongst a broader population of surveyors has created an opportunity to develop highly detailed tornado damage path data capable of being combined with radar, demographic, and other mapping information.

Camp, 2008 used helicopter-based aerial imagery and GPS information shot by several surveyors (including the lead author) to generate a detailed GIS-based damage survey of the Enterprise, AL tornado of 2007

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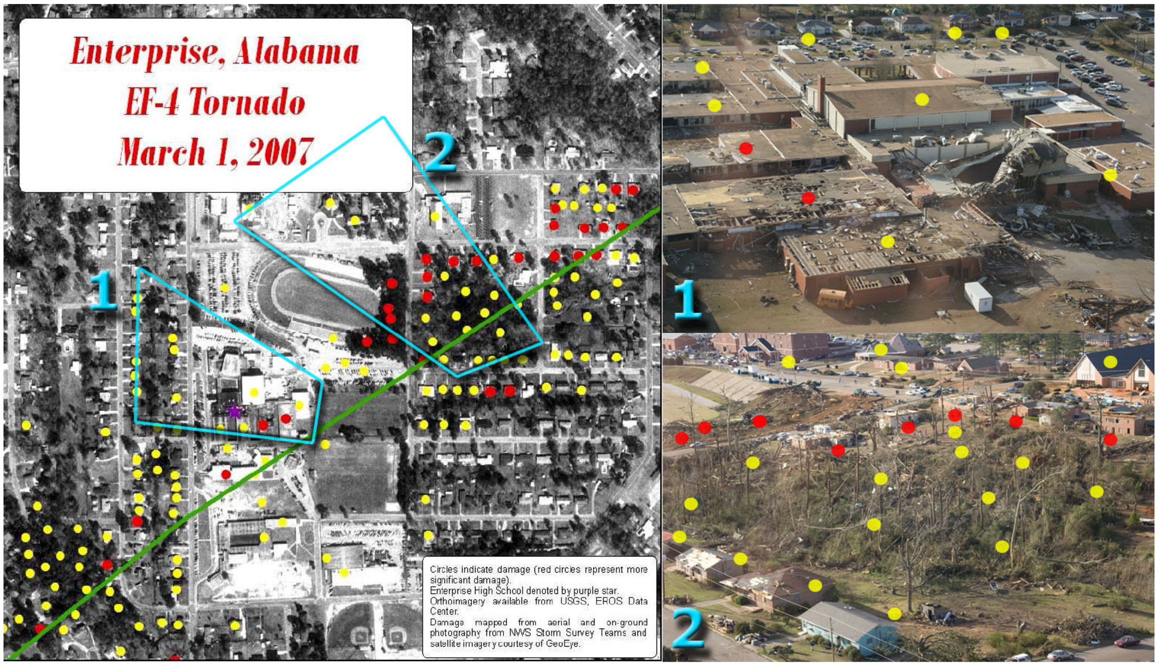

Figure 1. An aerial image highlights DIs chosen in a survey of the Enterprise, AL tornado. The image on the left shows light to moderately damaged DIs (yellow dots) indicating < EF2 and > EF2 damage (red dots). The blue polygons (labeled 1 and 2) represent the bounds of the photographs (1 and 2 respectively) taken by helicopter. The same DIs are plotted on each photograph in yellow and red. The center of the tornado track is marked by the green line on the left. Adapted by Camp, 2008.

March 01. Surveyors carried the EFkit toolkit (LaDue and Mahoney, 2006), a GPS device for tracking, and digital cameras. The digital image locations were derived by comparing the image time stamps to the GPS timestamps. The process is somewhat labor intensive though it results in a highly detailed GIS-based survey as can be shown in figure 1. Note that Camp, 2008 treated the high school in image 1 as multiple DIs. The EF-Scale is originally intended to treat large Dis as single structure. However, the center of the tornado vortex was quite likely smaller than the high school and it consisted of multiple additions of different construction practices over a period of time making a single evaluation of the DOD for the structure problematic. The number of available Dis provided by the EF-Scale allowed for a detailed, GIS-based survey that is useful for any quantitative post-analysis. The disadvantage of this method of surveying is the lack of detailed DI analysis from the ground. Determining a rating for Dis in a single image limits the precision and accuracy of the survey.

A more preferable method of leveraging the advantages of the EF-Scale and GIS mapping would be to rate Dis directly in the field while a program automatically attaches location, time and other metadata (e.g., images, audio, text) explaining the rating. The authors know of one tool, The Storm Damage Survey Application, built at the NWS, Omaha office that allows a surveyor to geotag rated structures, assign direction of debris, and map the damage in real time (Griffis, 2007 personal communication) using a laptop or PDA. Figure 2 illustrates the user interface of this tool. The amount of time needed for post-processing a survey can be potentially greatly reduced providing an incentive to generate more detailed surveys. The need for such detail is needed now more than ever by users involved in many aspects of societal impacts of tornadoes (e.g., Rae and Stefkovich, 2000). The authors encourage: 1) all NWS surveyors to capture as much detail as the EF-Scale provides, 2) a common survey format be created that is GIS-based and self describing, and 3) that STORMDATA becomes officially a multimedia archive of such data.

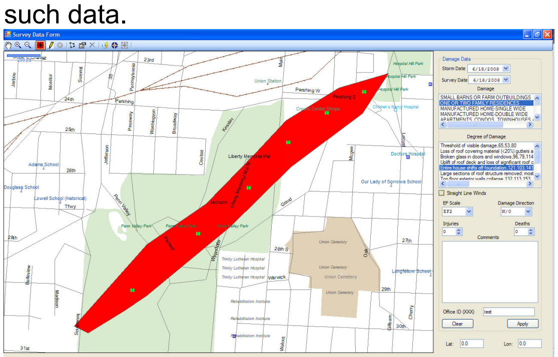

Figure 1. A user interface of a storm survey GPS-based tool.

3. ISSUES WITH THE EF-SCALE DIs

If the EF-Scale provides for greater precision, it is questionable whether the accuracy of the scale has been improved. We identify three sources of challenge in the scale, or the application thereof below, however this list is not meant to be exclusive.

3.1 Variability in Construction Practices Exceed that Accounted for in a DI

We start with the second issue introduced; whether or not any deviations in construction habit of a DI would be large enough for it to be considered a new DI? This question represents a significant issue in the ability for this, or any other, DI to be adopted in different countries (Dotzek, 2008). This same question could be asked within even within the same country.

The following picture shows four houses in Lady Lakes, FL exhibiting loss of roof covering (DOD=4), and broken windows corresponding to a DOD=3 in the EF-Scale (fig. 3). This damage would typically yield an expected (maximum) wind speed of 43 m/s (51 m/s) respectively, or a standard EF1 rating with a possibility of going 2 m/s into the EF2 range. However, vehicles were rolled and moved in each of the photographs. Both Schmidlin, et al. 2002 and Marshall et al. 2008 found that only ~17% of typical passenger vehicles were rolled or lofted in EF3 and EF4 tornadoes while the number drops to ~ 2% for EF1 and 2 tornadoes. Unfortunately, the authors did not have access to a similar survey from Lady Lakes, and therefore no definitive conclusion can be made about the strength of the Lady Lakes, FL tornado based on the percentage of vehicles upset. However, it is from the author's experience that upset vehicles are typically associated with at least an EF2 tornado. These houses performed extremely well in this tornado and represent an upper-bound to the construction quality allowed for this DI in the EF-Scale. They were constructed to post hurricane Andrew building codes with unreinforced masonry concrete block walls, and wood-frame roofs connected with rafter clips to the walls. Had these houses been built with reinforced concrete walls, the standard one- and two-family house DI would certainly not be applicable.

Changing construction codes may also impact the sequence of DODs for any particular DI. An example of this problem may have been found in a mobile home park east of Lady Lakes, FL near Lake Mack. Several homes (both MHSW and MHDW) experienced complete destruction and yet their frames remained anchored to the ground (fig. 4). The mobile home at B agrees well with DOD=9 for a MHDW (Complete destruction of roof and walls leaving undercarriage in place) which corresponds to a lower end EF2. Inspection of mobile home B appeared to indicate that sidewall and frame ties may have been separated by less than 1.5 m, and provided anchoring that exceeded requirements required by the state of Florida's 1994 update (DHSMV, 2005). Surrounding tree damage is consistent with an EF2 as well. Mobile home A, a MHSW, had its walls and roof swept away with a DOD=6 being the closest description (Destruction of roof and walls leaving floor and undercarriage in place). An EF1 results from the expected wind speed; however the upper-bound wind speed corresponds to an EF2. Nearby tree damage indicates that EF2 would represent a lower bound rating, however. The weak point in the mobile home was likely associated with the 2X3" wall stud to base plate connections. Realizing the higher DODs for this DI may not be possible if there is a diversity in construction quality between various components.

Figure 3. Four houses (DI=FR12) with displaced vehicles taken from Lady Lakes, FL (Photographs courtesy of NWS Tampa).

Figure 4. Photographs of two mobile homes A and B, taken from the air and ground. The arrows in the aerial picture indicate the direction of the phototograph. Images by Jim LaDue

3.2 Discriminating Problems between Exposure and/or Wind Speed Variability

The question arises: Can adjacent DIs be used to validate each other? The rationale behind this question is that a surveyor needs to make sure that the primary DI is representative of that described in the EF-Scale (WSEC, 2007). If surrounding DIs show representative damage, then the confidence in the primary DI is increased, and so is likely the confidence of the tornado intensity rating. However, if the structure shows markedly different amount of damage that would correspond to a significantly different wind speed estimate than its surrounding DIs, then the primary DI should be rejected. This type of survey practice was borne out of the results from the LaPlata, MD tornado in which numerous weakly constructed homes were swept off their foundations while vehicles, trees, even mailboxes remained standing (Marshall, 2003). The house in figure 5 stands as an example where a small difference in construction, a dormer window or a weak garage door, may have resulted in a catastrophic roof loss (DOD=6) while surrounding homes experienced more minor roof damage (DOD=4). Standard practice would have a surveyor discount this particular house in the final tornado rating.

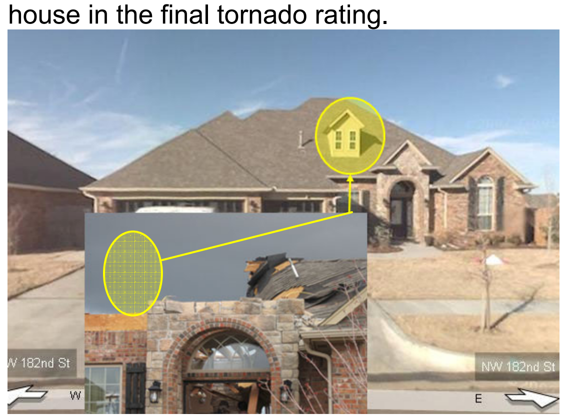

Figure 5. A surveyed house exhibited total failure of its roof on 31 March, 2008. A Dormer window is highlighted by the orange oval in the picture of the house before the damage occurred. The background picture is courtesy of Google while the damage picture was taken by Kiel Ortega.

However, there have been several events which have highlighted the extreme variability of wind in short scales including the video of the small end-wall vortex flipping vehicles in a Leighton, AL parking lot (fig. 6) that have called into question how close adjacent DIs must be in order for one to confirm the other.

Figure 6. A single frame of a small end-wall tornadic vortex crossing the parking lot in Leighton, AL. Two vehicles are being upended in front and just right of the condensation funnel (center). Image courtesy of S and M Equipment and WHNT-TV.

Figure 7. A ground-based survey of structures at a farmstead near Minco, OK from a tornado on 2007 August 19. The red trace represents the path of the surveyor took to investigate the structures. Pictures were geotagged and placed in a KML file to be displayed in Google Earth.

The variability in damage intensity between DIs presents a dilemma for surveyors such as the example shown in fig. 7 where one structure shows damage consistent with an EF2 next to structures showing little or no damage.

In order to determine the cause of the damage variability, surveyors need to step outside the confines of the EF-Scale and look for evidence of wind speed variability in non-DIs. Often, this method requires an aerial view such that the dimensions, orientation and shapes in non-DI and DI damage can be compared. If the damage path is particularly narrow, then there may not be as many qualified DIs available for intercomparison.

3.3 Trees: An Issue with expert elicitation

Soft- and hardwood trees represent the two DIs in which the surveyors (including the authors) had the most difficulty reconciling with the guidance offered by WSEC, 2007. For both the hardwood and softwood trees, increasing DOD number indicates damage caused by a higher expected wind speed. Based on our field experience, we found many deviations from this relationship when comparing tree damage to the behavior of other adjacent DIs. Several examples are provided here to illustrate the issues more clearly.

3.3.1 Tree size and wind resilience

On 28 February 2007, a severe tornado struck a well-built house and removed it from its foundation (figure 8). While remotely consulting with the surveyor, we noticed several saplings that suffered nothing more than snapped branches less than 10 m from the house (DOD=1, see the top two panels) while a grove of nearby trees suffered damage at least DOD=4. It is understandable that a surveyor may not consider saplings as a legitimate DI corresponding to soft- or hardwood trees. However, there have been other situations where even larger, but yet not mature, trees have experienced relatively little damage compared to other DIs in their proximity.

Figure 8. A house (FR12) experienced DOD=10 next to two saplings (TH) experiencing DOD<3. More mature trees experienced DOD=3 to 5 north of the house (bottom two panels). This image is provided courtesy of Evan Bookbinder NWS EAX.

The case from Millers Ferry, AL from a violent tornado on 01 March, 2007 illustrates several Bald Cypress trees within 50 m southwest of two leveled, well built houses that experienced minor tree limb breakage corresponding to a DOD<3 (figure 8). The trees were further to the right of the tornado vortex core than the house but still well within the strong tornadic flow field as evidenced by the pier partially pulled out of the water behind them.

Figure 8. Damage at Millers Ferry, AL from 01 March, 2007. At right is an aerial picture facing northeast. The numbers correspond to photos including #2 (upper left) and #3 (lower right). The aerial photograph is taken courtesy of NWS Mobile. Photograph #2 is taken by Roy Waite. Photograph #3 is taken by Jim LaDue.

These somewhat anecdotal observations have not been made in isolation. Surveys of forest wind damage by Cooper-Ellis et al. 1999 found smaller understory trees were more resilient to wind than trees in the taller canopy. Shirakura et al. 2006 showed a correlation between tree size and damage severity amongst *Q. stellata* (Post Oak) though not as much amongst *Q. marilandica* (Blackjack Oak) in Osage County, OK from a tornado that struck on 08 May 2003. In a review of several forest blowdowns, Peterson, 2003 found tornadoes preferentially damage larger trees although there was no consistency in the strength of that positive relationship amongst the survey sites.

3.3.2 The degree of damage as a function of species

The EF-Scale contains a simplistic discrimination of tree resiliency and wind by discriminating between soft- and hardwood trees. However, the behavior of individual species in high winds shows a much more complicated relationship than is accommodated for by this scale.

A survey of the Newton, GA area tornado track from 01 March 2007 yielded a large majority of the Carya illinoinensis (Pecans) uprooted (TH, DOD=3) with no tree trunks snapped (figure 9a). Conversely, the Pinus palustris (Slash pine) experienced snapped trunks (TS, DOD=4) rather than uprooting (figure 9b). As a caution, these comparisons were made at quite a distance from each other. Yet, each species preferred to suffer two distinct types of catastrophic damage. We did not see a progression of trees uprooted to trees snapped from the periphery to the center of the tornado tracks in either the pine or the pecan groves as one would expect from the corresponding expected wind speed estimates from DOD=3 to DOD=4.

These observations are reflected within studies of tree damage due to tornadoes. Peterson, 2003 observed that the deep rooted Acer saccharum (Sugar Maple) and Quercus alba (White Oak) were relatively wind resistant. However, other deep rooted trees did not show the same tendencies. Shirakura et al. 2006 observed that the whole subgenus Lobatae (Red Oak, Blackjack Oak, and Pin Oak) were weaker than Quercus section Quercus (White, and Post Oaks). More disconcerting is that the ratio of trees uprooted to those snapped appear to increase as the tornado intensity increased (Peterson 2003); a trend opposite to the increase in expected wind speed in between uprooted trees (DOD=3) and snapped trees (DOD=4) within the EF-Scale.

Figure 9. Tree damage observed from the Newton, GA tornado of 01 March 2007. The top image (A) represents snapped Slash pine trunks. The bottom image (B) represents uprooted Pecan trees.

There are more factors to consider than tree size and species when establishing a wind speed estimate. Exposure of trees to nearby gaps appears to have a significant impact on the intensity of tree damage (Holland et al. 2006). The exposure of trees to artificial debris sources (e.g., houses) may cause significantly more damage, including debarking, for lower wind speeds than indicated in the EF-Scale. We found relatively little debarking in areas devoid of artificial structures. Certainly duration of tornadic winds would have an impact on tree damage, even if simply allowing more time for larger gaps to form. Factor in soil type and species' health to all the other variables mentioned suggests that much work needs to be done to produce reliable guidance on trees for surveyors.

A surveyor may not be reasonably expected to investigate all of the factors that led to the damage of a single tree. Instead, the authors suggest that a more statistical approach be done such that the percentage of tree damage is assessed in small blocks where tree density is sufficiently high. In that way, individual variations in tree behavior may not need to be investigated in as much detail.

As an alternative to the single-DI paradigm of estimating tornado intensity, there is hope that bulk treefall patterns across a tornado damage track can be used to assess the strength of the tornado given knowledge of the predominate tree species, tornado motion and basic two-dimensional kinematics. A numerical model of tree fall patterns has already produced relatively realistic treefall patterns using idealized Rankine-combined vortex structures (Holland et al. 2006). This approach would lie outside the traditional EF-Scale

4. DISCUSSION

The purpose of this paper has been to describe the status of the EF-Scale after it has been used for two years. The experiences gained by the authors and other surveyors indicate that the EF-Scale has been beneficial in providing more specific guidance to the NWS surveyors though we offer cautions in accepting such guidance too literally.

The advantages of the scale include its precision by its guidance on numerous damage indicators. The EF-Scale and the coincident widespread adoption of GIS skills throughout the NWS have produced an abundance of detailed surveys that have not been done since Speheger et al. 2002. The implementation of a GPS-based surveyor's tool throughout the NWS should only increase the number of precise surveys available to anyone that may make use of them. We anticipate that the structure of STORMDATA will be enhanced to accept multimedia and GIS-based surveys that are becoming more frequent.

There are numerous issues with the application of the EF-Scale in surveying that can adversely impact the accuracy of assessing the strength of a tornado. Some of these issues may be more general with respect to damage-based surveying while others are directly attributable to the scale itself.

Errors in the wind speed, DOD relationship occur when the construction practices change over time or location of any DI after the elicitation occurred. There is inherent flexibility allowed for a surveyor to adjust an estimated wind speed to account for variability in a DI; however it is not known how far a surveyor can push such an adjustment. At some point, as the Lady Lakes, FL example highlights, construction standards may change so much that a new DI may need to be created. This problem may inhibit the adoption of the EF-Scale to other countries where construction practices of similar structures vary too much from the current DIs.

Surveyors are likely to encounter a large variability in damage amongst similar adjacent DIs that may or may not have much relationship to wind speed. Collateral damage as mentioned in Doswell, 2003, and/or differences in structure exposure and integrity as shown by Marshall, 2008 create large variations in damage. Likewise, small, intense vortices can also produce large damage variations within just a few meters in space. No damage-based scale is going to completely discriminate between the two sources of damage variations. However, we suggest that an aerial and ground survey of the damage track be done to help determine its scale, and therefore contribute to some understanding on the cause of the damage variations. Knowing this may help a surveyor determine how confidently adjacent DIs can be used to confirm each other in a wind speed estimate.

The discrepancy in the progression of DODs for the two tree DIs from what is in the EF-Scale to that found by our surveys and by other studies may represent one of the larger issues in using this scale. As WSEC, 2007 noted, expert elicitation was chosen as an economical method of linking the DOD to the estimated wind speed. This method is critically dependent on the experts being well versed in the behaviors of the DIs as a function of wind speed. In addition, the original choice of DIs depends on an accurate knowledge base. It appears that no one experienced in researching the impact of wind on trees were included to help define the tree DIs, create adequate DODs, and help derive wind speed estimates. The next evolution of the EF-Scale needs to include experts in forestry when vegetation-based DIs are updated in the future.

Now the question remains; how is the EF-Scale going to evolve? The wind speed estimates need to be revisited. New DIs need to be considered and researched. We have heard from NWS surveyors numerous requests for new DIs. The most popular requests include adding vehicles, farm equipment, and unreinforced masonry structures.

We also need to consider the need to employ new scales. More methods than that employed by the EF-Scale can be used to estimate tornado intensity (e.g., Holland et al. 2006; Wurman et al. 2007). In addition, there are too many disparate scales out there that are used to rate wind speeds of phenomena (e.g., EF-, F-, Mach, Saffir Simpson, Torro). A wind speed scale that is coupled to other fundamental properties (e.g., momentum density, kinetic energy density, energy flux density) has been proposed by Dotzek, 2008 that can help bridge the multiple damage-based and wind-speed scales in existence, and place direct ties to these meaningful physical quantities.

Another question remains open at this time about who will facilitate future changes to the EF-Scale? So far, there has been little discussion within the primary users of the scale - the NWS, Texas Tech University, and other critical stakeholders. The NWS should be the entity that facilitates changes to the EF-Scale, primarily because the large majority of the surveyors are employeed there. We have a suggestion that the EF-Scale should be evaluated on an annual time scale. Such an evaluation would include: 1) Incorporating new, well documented images of EF-Scale DIs and DODs in order to assist the surveyor. Identifying current research that may help improve current DIs, identify new DIs in the EF-Scale. 2) Identify issues and research concerning the relationship between wind speed and ratings based on new evidence on the behavior of DIs, and non-EF-Scale-based methods of estimating wind speed. 3) Identify research into estimating damaging winds through other methods outside direct observation and the EF-Scale (e.g., radar, damage patterns). 4) Soliciting calls for concentrating research in areas that would contribute to an improved EF-Scale in as well as to improve tornado intensity estimations through methods other than the EF-Scale. 5) Based on current evidence, make decisions and enacting changes to the EF-Scale including those of DIs, DODs, wind speed estimates vs. ratings. 6) Consider the adoption of alternative rating scales. 7) Plan for additional training, education and outreach.

5. ACKNOWLEDGEMENTS

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