International Approaches to Tornado Damage and Intensity Classification

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1. Introduction

Tornadoes are one of the most destructive natural hazards on Earth, with occurrences having been observed on every continent except Antarctica. It is difficult to determine worldwide occurrences, or even the fatalities or losses due to tornadoes, because of a lack of systematic observations and widely varying approaches. In many jurisdictions, there is not any tracking of losses from severe storms, let alone the details pertaining to tornado intensity. Table 1 provides a summary estimate of tornado occurrence by continent, with details, where they are available, for countries or regions having more than a few observations per year. Because of the lack of systematic identification of tornadoes, the entries in the Table are a mix of verified tornadoes, reports of tornadoes and climatological estimates. Nevertheless, on average, there appear to be more than 1800 tornadoes per year, worldwide, with about 70% of these occurring in North America. It is estimated that Europe is the second most active continent, with more than 240 per year, and Asia third, with more than 130 tornadoes per year on average. Since these numbers are based on observations, there could be a significant number of un-reported tornadoes in regions with low population density (Cheng et al., 2013), not to mention the lack of systematic analysis and reporting, or the complexity of identifying tornadoes that may occur in tropical cyclones. Table 1 also provides information on the approximate annual fatalities, although these data are unavailable in many jurisdictions and could be unreliable.

Few structures are designed to survive tornadoes, although engineering design for certain critical infrastructure (e.g., nuclear reactors, electrical transmission grids) does consider tornado impacts. To perform such design, as well as to develop risk or loss models, estimates of tornado intensity, i.e., wind speeds, are required along with the occurrence rates. However, wind speeds in tornadoes are rarely measured, particularly in the lower 10 m of the atmosphere where most infrastructure is located. As a result, tornado intensities are assessed based on the indirect evidence of damage observations, as discussed below. Such estimates have significant uncertainty associated with them (Edwards et al., 2013), notwithstanding recent efforts at improving these.

There is a growing recognition for the need to have consistent assessment of the tornado hazard across borders and around the world. For these reasons, the International Association of Wind Engineers (IAWE) formed a working group to examine the issue of international tornado damage classification. The long-term objective of the working group is to develop a common approach to international tornado intensity and damage assessments based on consistent methods and indicators. The objective of this report is to identify the various approaches currently used to classify tornadoes around the world; to identify similarities and differences in the scales used for damage and intensity classification; to identify common international Damage Indicators; and to provide recommendations on how a common scale may be developed.

2. Brief History of Tornado Classification Around the World

Fujita (1971, 1973a,b) was the first to categorize tornadoes by damage and associate the damage to different ranges of wind speeds. In his scale, the wind speeds were an extension of the Beaufort Scale, at the lower end, and the Mach Scale, at the upper end. The Beaufort Scale categorizes wind speeds from calm (Beaufort 0) to the minimum speed for a hurricane (Beaufort 12), and then beyond. The Mach scale is related to the speed of sound, with Mach 1 being the speed of sound. F1 on the Fujita Scale matches Beaufort 12, and is associated with a description of “moderate damage”. Fujita Scale F0 is for the onset of damage, which was matched to Beaufort 11. The Fujita Scale has 12 levels, up to F12, which was equated to Mach 1 in a similar way. The wind speeds in each band of the scale are evenly distributed within the bounds from Beaufort 11 to Mach 1. Since wind speeds in tornadoes could not be directly measured, they were related to damage in an ad-hoc manner; in fact, the United States’ Storm Prediction Center (SPC) states that the “precise wind speed numbers are actually guesses and have never been scientifically verified” (Storm Prediction Center, 2017b). Damage observations in the Fujita Scale were based on wood-frame, single-family houses (called frame houses), mobile homes, trees, cars, trucks, and train cars. Appendix A provides the original Scale.

The Fujita Scale proved to be popular internationally, and has been used without modification in many countries, either formally by governmental meteorological offices or informally by researchers, even though it was based on damage indicators appropriate for the United States (USA). Several countries and regions still use it, although these appear to be mostly informal. Other countries used a modified form of the Fujita Scale, such as Japan, where modifications ranged from additional indicators of damage to modified wind speeds (Fujita, 1973a; EMS, 1998).

Over time, the wind speeds associated with damage in the Fujita Scale were believed to be problematic. For destructive tornadoes, where the primary damage indicators tend to be wood-frame houses, doubts were raised about the wind speeds required to completely destroy such structures (Phan and Simiu, 1998). Several other issues were also raised, but perhaps the most important was the lack of consideration of both the quality and type of construction. Fujita himself recognized these issues and introduced the f-scale, which was a damage scale that provided corrections to wind speeds in order to determine the appropriate F-Scale rating based on the type and quality of construction. Six categories of buildings were introduced, which were weak and strong outbuildings, weak and strong frame houses, brick structures, and concrete buildings (Fujita and Merriam, 1992; see also Storm Prediction Center, 2017a).

The first systematic modification of the Fujita Scale was led by researchers from Texas Tech University, and came to be called the Enhanced Fujita (EF) Scale (WSEC, 2006). Mehta (2013) describes the process used in the development of this scale, which was based on an expert-elicitation. In 2007, the National Weather Service (NWS) in the USA formally adopted the EF-Scale. The EF-Scale brought in a total of 28 Damage Indicators (DI), which included various types of buildings, non-building structures, and trees. These are listed in Appendix A. In addition, for each of these DIs, a series of possible damage states, called Degrees of Damage (DOD), were introduced. Each DOD had a range of estimated wind speeds associated with it, examples of which can be found in Appendix A. Finally, the wind speeds in the scale were modified, based on a linear correlation analysis of DIs common to both scales, for similar degrees of damage. This resulted in significantly reduced wind speeds for the most destructive tornadoes (EF4 and EF5). However, this choice to correlate the new scale to the original Fujita Scale ensured that there was at least a partial connection to the historical record such that EF-Scale-based damage assessments lead to similar ratings as F-Scale assessments (e.g., EF3 damage should be equivalent to F3 damage). However, it can be argued that the changes in the DIs and the various DODs makes this claim somewhat dubious since one of the factors that led to the development of the EF-Scale was the biased use of original scale (Storm Prediction Center, 2017b). In any case, the increased numbers and range of DIs, together with the clarity of the explicit DODs is considered a significant improvement, although the changes to the wind speeds in the intensity scale remain controversial (as discussed below).

Prior to World War 2 (WW2), European Scientists were active in the transnational collection of tornado reports and in tornado research (Wegener, 1917). In 1937, guidelines for the optimum damage assessment and classification were adopted by the predecessor of the World Meteorological Organization (WMO), the so-called International Meteorological Organization (IMO) (Letzmann, 1939). After WW2 and until 2000, the British Tornado and Storm Research Organisation (TORRO) was the only organisation collecting tornado reports in a transnational way. TORRO introduced its own damage scale (Meaden, 1976), the so-called T- or TORRO-Scale. Only minor adaptations of the wind speeds were needed (Dotzek et al., 2000; Dotzek et al., 2003) to synchronize the T-scale with the F-scale in a way that two T-classes resemble one F-class, i.e. the T-scale has twice the resolution. The original T-scale uses damage descriptions similar to the original F-scale and does not use the DI-DOD concept. The original T-scale is still used by TORRO and some of its private collaborators in other countries. Around the turn of the millennium, researchers started with additional transnational initiatives, like TorDACH (Dotzek, 2001; Holzer, 2001). In 2006 the European Severe Storms Laboratory (ESSL) was formally founded. One of ESSL's main tasks is to maintain the European Severe Weather Database (ESWD) (Dotzek et al., 2009) that built on private initiatives that emerged earlier (Groenemeijer and Kühne, 2014). Over the past few years, a growing number of National Weather Services have joined ESSL. Within the ESWD, both F- and T-scale ratings are valid, including sub-categories of F-scales (upper or lower bounds of every class). ESSL itself, since 2012 (Feuerstein et al., 2012), uses the DI-DOD approach.

One alternative to the damage-based Fujita, Enhanced-Fujita, and Torro Scales is the E-Scale (Dotzek, 2009), introduced by ESSL founder, Nikolai Dotzek, prior to his sudden passing. The Energy- or "E-Scale" is based on a nonlinear scaling of physical quantities which results in a universal wind speed – scale relation, which is always linear in velocity. This offers the advantage of treating the nonlinear scaling of damage-related physical properties (e.g., wind pressure is proportional to velocity squared, energy is proportional to velocity cubed) separately. No countries or regions use this scale for tornado classification.

3. Current Tornado Classification Approaches

Table 2 summarizes the current approaches to tornado classification used in various jurisdictions around the world. The national weather services in the USA, Canada and Japan all use officially-adopted versions of the EF-Scale, modified for use in their country. In 2013, Canada adopted a modified version of the EF-Scale (Sills et al., 2014), which had 31 DIs and slightly modified wind speeds at the low end of the scale to match warnings (Environment Canada, 2013). In 2016, Japan adopted the Japanese Enhanced Fujita (JEF) Scale (Tamura et al., 2016), which also had slightly different wind speeds (JEF-scale Guidelines, 2015), but also with DIs particular to Japan (see Appendix A). Thus, the differences with the original (US) EF-Scale in Canada and Japan are due to additional and modified DIs, different wind speeds associated with similar DODs, and different wind speeds in the EF-Scale itself.

Every country that has formally adopted a version of the EF-Scale has established different wind speed ranges, while Europe has maintained original F-Scale speeds, citing the lack of scientific evidence supporting changes to the speeds, noted by SPC (2017a). Table 3 provides the official wind speeds used in damage classifications in the USA, Canada, Japan, and Europe (ESSL), along with the original F-Scale speeds. The original (US) EF-Scale arose from an expert elicitation process such that the wind speeds associated with various damage states for the damage indicators were estimated, as described in WSEC (2006) and Mehta (2013). These modified speeds were then plotted against the original Fujita Scale speeds for the same damage state. The revised wind speed ranges were then obtained following linear regression (and some rounding). In Canada, the regression was modified to be non-linear to better fit the original TTU data and so that it would fit through the origin (wind speeds = 0). This resulted in a lower bound speed for EF0, close to the wind speed for which warnings are issued (90 km/h). Finally, the wind speed ranges were rounded off in 5 km/h increments. In Japan, a similar process as for Canada was used.

In Europe, few countries have formally adopted a damage scale or conduct routine damage surveys. However, the ESSL maintains the European Severe Weather Database (ESWD) for all of Europe, which provides a public, internally-consistent database for tornadoes going back more than a century (Antonescu et al. 2016). The ESSL approach to damage classification and assessment of tornado intensity uses a hybrid approach which involves DIs and DODs, similar to those in Fujita’s modified scale, in conjunction with wind speeds based on the Fujita and Torro Scales. In fact, ESSL has continued to use Fujita’s original wind speed ranges, rather than the modified speeds of the EF-Scale providing a significant contrast to the current North American and Japanese approaches.

In the rest of the world, there are no formally-adopted tornado intensity or damage scales. For example, while China tracks and records the numbers of tornadoes, they currently have an informal rating process using either the Fujita or Enhanced Fujita Scale. In Australia there is a blend of F- and EF-Scale used whenever damage surveys are conducted with some tracking of significant events. Informal ratings also occur in South Africa, using the Fujita Scale. In European countries, meteorological offices tend to use the TORRO Scale more often than the Fujita Scale, perhaps because of the more complete descriptions of damage in the former. However, as mentioned above, the ESSL is the organization which records and maintains the database.

In summary, amongst the countries or regions that conduct official damage surveys or maintain official databases, there are no two which use exactly the same classifications. In the rest of the world, there are no officially-adopted, tornado-classification scales and limited regular government-based (i.e., weather-service-based) damage surveys or maintenance of databases. Researchers in these regions tend to use the existing scales in an ad-hoc manner, with detailed damage surveys conducted following significant events (many of which are published – Appendix C contains some references to non-governmental damage survey approaches from different parts of the world). Thus, there is a need to develop a consensus for consistent internationally-focussed tornado damage and intensity scales. As can be seen, to achieve this, issues with respect to both intensity classification and damage classification exist. Section 4 deals with the former, while section 5 deals with the latter.

4. Wind Speeds in Tornado Intensity Scales

For an international tornado intensity scale, it is important to come to agreement about the actual wind speed ranges in the scale. As shown above, this is not currently the case. There are at least four issues to be addressed: (i) the upper and lower bounds for tornadic wind speeds, (ii) resolution within the intensity scale, (iii) wind speed definition in the scale, and (iv) historical considerations.

Regarding the wind speeds used for the scale, the differences are relatively small between the EF-Scale implementations in the USA and Canada, with the most significant difference being the lower bound of EF0 being decreased to 25 m/s in Canada to better reflect the onset of significant tree damage (see Frelich & Ostuno, 2012) and match operational warning thresholds (Table 3). Japan also chose to decrease the lower bound of EF0 to 25 m/s, but above EF0 wind speeds are generally 3-6 m/s higher than those in the US EF-scale. Differences are even greater when comparing the speeds in the US and Europe, particularly with the most destructive tornadoes at the upper ends of the scales, since Europe’s damage – wind speed relationship is still directly connected to Fujita’s original scale.

Current differences at the upper ends of the scales will likely only be solved via additional research. The most convincing method would be by obtaining direct wind speed measurements simultaneously with observed damage for common DIs and particular DODs. Such measurements are rare, but not impossible, with modern technologies such as radar. The second, perhaps less convincing, approach is to come to agreement on analytical and/or experimental methods for determining wind speeds from observed damage states, such as use of fragility curves (e.g., Kashani et al., 2016) along with correlated observations for multiple DIs (e.g., Kopp et al., 2016). A recent example of this is the use of a treefall model, correlated to wood-frame house damage by Lombardo et al. (2015) and Roueche et al. (2016). Again, field observations can help by providing validation data, as has been done for hurricanes, typhoons and tropical cyclones. In any case, improved scientific proof of the wind speeds at the high end of the scale is needed. (This should begin with a detailed examination of the scientific literature on this topic, which is beyond the scope of the current review.)

The second issue is related to the resolution of the intensity scale, i.e., how many levels to include within the overall wind speed bounds. Both the F-Scale and EF-Scale use six, while the current scale used by ESSL has 10 (see Appendix A). There are two particular points to consider with respect to this issue. The first is related to the precision with which the damage can be assessed and the second is related to the range of wind speeds that are possible for any particular DOD. The first point is related to damage survey practice and the issue as to whether differences in the damage indicators that cause significant differences in performance can be (routinely) identified in the post-event damage surveys. Examples of this may include quality of construction for any actual building, or the sizes, types, quality or quantity of fasteners for a building component. When such details can be easily and routinely identified, the uncertainty in the resulting wind speed estimate is reduced. When such details cannot be accounted for, it would suggest the resolution of the scale be reduced. The second point relates to the inherent variability in performance for certain types of failures and fragility concepts. When the variability is small, say for a concrete traffic barrier blowing over, the resolution can be better. When the variability is over a wide range of wind speeds, the resolution is effectively reduced. The appropriate choices as to resolution are controlled by variability of the most common damage indicators.

The third issue is related to the definition of the wind speed in the intensity scale. The original EF-Scale report uses a 3-sec gust speed at the height (i.e., point) of damage. However, this is in fact a difficult point to establish rigorously. There are three issues that need consideration. First, establishing the wind speed definition involves knowledge of what any particular measurement device actually measures in terms of both spatial and temporal resolution. For example, to use radar, one needs to establish what a radar measurement actually represents since it considers spatial volumes, rather than the temporal responses of traditional anemometers. Second, the duration of high winds in fast-moving or small tornadoes or near the core of larger tornadoes may be less than the prescribed duration (such as 3 seconds). Third, many DIs respond to gusts of relatively short durations (e.g., failures of panels or nailed connections, Morrison et al., 2012), while DODs involving movement of a DI (e.g., vehicles lifting off the ground) may involve longer (and variable) durations. The JEF-Scale deals with these issues in a pragmatic way by stating that the wind speeds in the scale are “equivalent, stationary, straight-line wind speeds”, i.e., not necessarily wind speeds associated with a tornado.

Finally, historic database issues may affect the choices in the intensity scale. As noted above, the original Fujita Scale wind speeds were arbitrarily chosen to connect the Beaufort Scale with the Mach Scale. Since the group that established the original EF-Scale decided that the connection to the historical databases was important, the resulting wind speed ranges depended on the new wind speed to damage relationships and mapping these onto the old scale. This provides a significant constraint, which may or may not be desirable, depending on other factors. It is also worth pointing out that, with a DI/DOD approach which includes wind speed estimates, the actual intensity scale is unnecessary if the desire is only to report wind speeds.

5. Damage Indicators (DIs) and Degrees-of-Damage (DODs)

One of the significant improvements brought by the EF-Scale was improved clarity and methodologies with respect to the damage observations. In all regions with regular and formal damage surveys, the DI/DOD approach is being implemented. In this section, we discuss the issues associated with developing consistent DIs and DODs for an international damage classification approach. Three points are addressed: (i) the range and categories of DIs, (ii) recommendations for processes used to modify or develop new DIs and DODs, and (iii) recommendations for approaches to DIs so that they will be useful from an international perspective.

Appendix A lists all DIs for the US, Canadian and Japanese EF-Scales, along with those used by ESSL. Table 4 provides a summary of these with the DIs categorized into five groups: (i) Buildings, (ii) Non-Building Structures, (iii) Vehicles, (iv) Natural, and (v) Other. Examining the DIs categorized as Buildings, it is notable that the three versions of the EF-Scale all define the buildings by their usage, e.g., farm outbuildings, motels, automobile showroom, etc. In contrast, ESSL follows the modified Fujita Scale with six simple, generic building categories. One can see advantages to both approaches, but interpretation will have a significant dependence on local knowledge. Detailed description of the DIs as presented in WSEC (2006) help to clarify the structural details to some extent (with the example for one- and two-family residences, FR12 in Appendix A). In other cases, these are less transparent in terms of the important structural details that may affect performance under extreme wind loads.

From an international perspective, it would be useful provide descriptions of the details that significantly affect the performance under extreme wind conditions. This would allow more common indicators to be found around the world than are currently available. For example, almost all regions around the world utilize similar roofs systems, but this fact is not apparent by examining the lists of Building DIs in Appendix A.

The second most common DIs are Non-Building Structures. While the American EF-Scale has three of these, the Canadian has six and the Japanese has 12. In Europe, there are not currently any listed. Many of these have the potential to be useful internationally, such as signs, billboards, fences and free-standing poles. It seems that many of the Japanese DIs could be used in many regions. The JEF-Scale also has vehicles as DIs, as did the original Fujita Scale, while the two North American EF-Scales do not consider vehicles of any kind. While there is clearly a great deal of variability in the movements of parked vehicles during the passage of tornadoes, Paulikas et al. (2016) have provided a detailed analysis of vehicles behaviours, correlated with performance of nearby buildings, viz., roofs of wood-frame houses. Since the resistance of vehicles to wind is controlled by their shape (which can be easily categorized), weight, and the friction between tires and roadways, vehicles represent a possible DI that could be useful internationally, particularly since many of them are identical.

Another common Damage Indicator during tornadoes is natural vegetation such as trees. While there are a wide variety of types, and significant variability for vegetation in urban environments, these indicators would provide a useful possibility for common international DIs. Currently, there are large differences in these DIs/DODs, which may reflect uncertainty with the wind speed models. The Natural DIs in the original EF-Scale, which has two – hardwood and softwood trees – is limited, while the European approach of separating branches, trees in stands, hedges, etc., seems practical. Incorporating recent research, and perhaps developing new research, will be required to fully utilize Natural DIs in an international damage scale.

One of the strengths of the DOD approach is that the correct failure sequence with increasing wind speeds can be established. This is helpful to damage surveyors, particularly with respect to identifying issues of quality of construction of individual buildings, while yielding more accurate results. The larger issue with DODs is with the wind speed estimates, which is discussed in the section above. As pointed out, further work is required to bring agreement about wind speeds, or perhaps simply agreement with respect to the approaches used to estimate wind speeds.

6. Conclusions and Recommendations

The current approaches to tornado intensity and damage characterization around the world have been reviewed. It is observed that no two countries or regions that officially conduct damage surveys and track tornado damage data use the same scale. There are relatively small differences between the countries that use the EF-Scale, while some regions still use the wind speeds associated with the Fujita Scale. This leads to large differences in the intensity scale at the level of destructive tornadoes (EF4/5 or F4/5). This is an issue that needs resolution, which may be obtained through agreement in the development of common methods to assess wind speeds from damage.

The DI/DOD approach implemented in the EF-Scale is useful for characterizing damage and is the common approach used in all countries/regions where tornado characterization has a formal, systematic process. DIs can be characterized as (i) Buildings, (ii) Non-Building Structures, (iii) Vehicles, (iv) Natural, and (v) Other. From an international perspective, it would be useful provide descriptions of the structural and geometric details that significantly affect the performance of buildings under extreme wind conditions, rather than using descriptions of their usage. Many other DIs could be used, particularly Non-Building Structures, Vehicles and Natural (Vegetation) DIs. The JEF-Scale for Non-Building Structures and the European scale for Natural DIs provide examples that could be used, although further work may be required. DODs for each DI should provide sequential failure progressions associated with increasing wind speeds (except in those cases where only “failed” or “not-failed” can be observed, and there are no failure-progression states). Correlations of different DIs and DODs will help with establishing common values using methods, like, e.g., Paulikas et al. (2016) for vehicle movements with wood-frame houses, in the different settings that exist around the world.

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Table 1 Annual Tornado Occurrences, Fatalities, and Casualties Around the World

Continent/Country	Approx. Average # of Tornadoes per year	Approx. Average # of Fatalities/Injuries per year
North America	1358	91/1145
USA (2000-2014)	1297	89/1115
Canada (1980-2009)	61	2/30
Europe[1] (2000-2014)	242	n/a
Asia	>135	>37/ >672
China (1961-2010)	85	35/634
Japan (2006-2015; not including waterspouts)	26	2/48
Philippines	12 – 16	
Bangladesh	n/a[2]	n/a[2]
Vietnam	2	3/32
Taiwan	2	1 or less fatalities/ 1
Malaysia	5	
Indonesia	n/a[3]	
India	< 1	
Sri Lanka	>1	
Australia	77	n/a
Australia	60	< 1 fatalities/ 30-50
New Zealand	17	
South America[4]	> 10	
Argentina	10	
Africa[5]	> 3	
South Africa	3-5	< 5 fatalities/ ~100
Global Totals	>1800	>100

1. Data source is Antonescu et al. (2016) and includes 30 countries, from Portugal and Iceland in the west to Russia and Turley in the east.
2. As discussed in Table 2(b), tornadoes are known to occur, although tornadoes have not been analyzed
3. Tornadoes occur in Indonesia, but no statistics exist
4. Goliger and Milford (1998) report about 10 tornadoes per year in Argentina, but they are also observed in Brazil, Chile, and Uruguay.
5. Goliger and Milford (1998) report 3 – 5 tornadoes per year in South Africa, with tornadoes also having been observed in Botswana, Swaziland, and Namibia.

Table 2(a) Damage scales used in different countries with official governmental-based scales and/or databases

Country	Scale used	Description

USA	EF-Scale	**Brief description of scale:** The EF scale is used to rate the strength of tornadoes and estimate associated wind speeds based on damage (not measurements). The scale is a six-level numerical, damage-based classification of estimated wind speeds (AMS 2014). Users associate the observed Degrees of Damage (DOD) to available guidance in order to estimate three-second wind gusts at impacted structures or vegetation, known as Damage Indicators (DI). As of 2016 the EF scale has 28 DIs.
		
		Key references and source documents:
		• A Recommendation for an Enhanced Fujita Scale (EF scale), Revision 2, by the Wind Science and Engineering Center, Texas Tech University, Lubbock, Texas, USA
		  ○ Updated October 10, 2006
		  ○ http://www.depts.ttu.edu/nwi/Pubs/FScale/EFScale.pdf
		• *NWSI 10-1605, Storm Data Preparation* by the National Weather Service, Silver Spring, Maryland, United States of America
		  ○ Updated March 23, 2016
		  ○ http://www.nws.noaa.gov/directives/sym/pd01016005curr.pdf
		
		Date officially adopted: January 1, 2007
		
		Who maintains scale: National Weather Service's Performance and Evaluation Branch through NWSI 10-1605, Storm Data Preparation

Canada	EF-Scale	**Brief description of scale:** The Canadian version of the EF-Scale is a slightly modified version of the original US EF-Scale, which has 31 DIs, 26 of which are un-modified from the US version. **Key references and source documents:** • Sills, D. M. L., P. J. McCarthy and G. A. Kopp, 2014: Implementa0on and applica0on of the EF- scale in Canada. *Extended Abstracts, 27th AMS Conference on Severe Local Storms,* Madison, WI, Amer. Meteorol. Soc., Paper 16B.6 • Sills, D. M. L., 2013: Enhanced Fujita Scale Damage Indicator / Degree Of Damage Guide. Environment Canada, 19 pp. • https://ec.gc.ca/meteo-weather/default.asp?lang=En&n=1F0BCA63-1 **Date officially adopted:** April 1, 2013 **Who maintains scale:** Science and Technology Branch, Environment and Climate Change Canada

Japan	JEF-Scale	**Brief description of scale:** The EF-Scale approach has been adopted, but with DIs and EF-Scale wind speed ranges specific to Japan. There are 30 DIs. **Key references and source documents:** • JMA Tornado Database, Database on tornadoes and other severe local storms (since 1961, in Japanese), Japan Meteorological Agency (http://www.data.jma.go.jp/obd/stats/data/bosai/tornado/index.html) • JEF-scale Guideline, 2015, Guideline for the Japanese Enhanced Fujita Scale, Japan Meteorological Agency (in Japanese, English version will be issued soon.) **Date officially adopted:** April 1, 2016 **Who maintains scale:** Japan Meteorological Agency
China	EF-Scale/ F-Scale	**Brief description of scale:** Even though Fujita Scale and Enhanced Fujita Scale are both referred to frequently by researchers, there is not an official scale for damage assessment. The China Meteorological Administration is working on drafting a Chinese EF-Scale. **Key references and source documents:** • China Meteorological Administration, 2005-2014, *Yearbooks of Meteorological Disasters in China*, China Meteorological Publishing House (in Chinese). • Wen Kegang, 2006, *The Handbook of China Meteorological Disasters*. China Meteorological Publishing House (in Chinese).
Europe	DI/DOD approach with modified F- and T- Scale	**Brief description of scale:** Government agencies in the individual European countries do not formally document tornado damage or maintain a database. The European Severe Storms Laboratory (ESSL) is the pan-European agency tasked with maintaining a formal database and conducting damage surveys. ESSL uses the DI/DOD approach of the EF-Scale, but the EF-Scale wind speeds are not used; rather, F- and T-Scale wind speeds are used. **Key references and source documents:** • Dotzek et al. (2009) • Feuerstein et al. (2011) • Antonescu et al. (2016) **Who maintains scale:** ESSL

Table 2(b) Damage scales used in different countries <u>without</u> official governmental-based scales and/or databases

Country	Scale used	Description
Australia	n/a	**Brief description of scale:** There is no defined scale used in Australia for rating damage due to tornados or other wind events. Rating is sometimes done for larger events (largely up to and defined by the person or team surveying the damage), but is not systematically or consistently applied. The Bureau of Meteorology's Severe Storm Archive does include F-scale rating for all recorded tornado events, but it is not clear how these were attributed. A field survey was certainly not carried out for most events. More recently the EF-scale appears to have been informally adopted by survey teams, but no work has been carried out to link DODs to Australian structures – so there is significant uncertainty associated with this approach. Considering the points above, there is no source documentation, DODs or owners of the non-existent Australian scale.
South Africa	n/a	**Brief description of scale:** n/a **Key references and source documents:** • Goliger and Milford (1998) **Date adopted:** n/a **Who maintains scale:** n/a
Bangladesh		**Brief description of scale:** There is no formal tracking of tornadoes, but some research is available on occurrence rates. Yamane et al. refer to the occurrence of severe local storms (there are about 145/yr, with 136 fatalities/yr), but tornadoes have not been separated out. **Key references and source documents:** • Yamane et al. (2010) **Date adopted:** n/a **Who maintains scale:** n/a
Malaysia	n/a	**Brief description of scale:** There is no defined scale used in Malaysia for rating damage due to tornados or other wind events. Rating is sometimes done using Beaufort and Fujita Scale but is not methodically or precisely applied. A field survey was certainly not carried out most events. More recently the Beaufort and Fujita scale appears to have been informally adopted by investigator teams. Several initiatives taken by Disaster Research Nexus, School of Civil Engineering, Universiti Sains Malaysia to carried out to and link DODs to Malaysian structures. The Malaysian Meteorological Department currently have their own criteria for wind storm warning systems. There are three categories of strong wind warning/advisory due to TCs that are labelled as First, Second or Third categories.

Table 3 Damage scale wind speeds used in various countries (in m/s)

F-Scale	USA (EF-Scale)	Canada (EF-Scale; mod.)	Japan (JEF-Scale)	Europe (F-Scale)
(F0) 19-35	(EF0) 29-38	25-37	25-38	(F0-) 25 +/- 7 to (F0+) 30 +/- 9
(F1) 35-53	(EF1) 38-49	38-49	39-52	(F1-) 37 +/- 11 to (F1+) 45 +/- 14
(F2) 53-72	(EF2) 50-60	50-62	53-66	(F2-) 55 +/- 16 to (F2+) 65 +/- 20
(F3) 72-93	(EF3) 61-74	63-74	67-80	(F3-) 75 +/- 22 to (F3+) 90 +/- 27
(F4) 93-117	(EF4) 74-89	75-87	81-94	(F4) 105 +/- 32
(F5) 117-142	(EF5) >89	>88	>95	(F5) 130 +/- 39)

Notes:
USA. original scale in MPH, with a 1 MPH increment at each change in scale
Canada. Original scale in km/hr rounded to 5 km/hr. The lower bound speed for EF0 was chosen to better reflect the onset of damage and match operational warning thresholds.
Japan. Scale is provided in m/s
Europe. Scale is provided in m/s

Table 4 Summary of Damage Indicators (DIs)

	USA	Canada	Japan	Europe
Buildings	DIs 1 – 23 (see WSEC 2006 and Appendix A)	DIs 1 – 23 Same as USA; plus C3, C4 (see Appendix A) C3: Heritage Churches C4: Solid Masonry Houses	DIs 1 – 9 1: Wooden houses and stores 2: Industrialized steel-framed houses (prefabricated) 3: RC apartment buildings 4: Temporary buildings 5: Large eaves 6: Steel-framed warehouses 7: Small non-residential wooden buildings 8: Greenhouses, gardening facilities 9: wooden livestock sheds	A: weakest outbuilding B: outbuilding (huts and barns, anchored lightweight building) C: strong outbuilding, weak frame house (like typical US-midwest houses , if weakly anchored/connected to the foundation) D: weak brick structure/strong frame house E: strong brick structure F: concrete building
Non-Building Structures	DIs 24 – 26 24: Electrical Transmission Lines 25: Free Standing Towers 26: Free Standing Poles	DIs 25, 26, C1, C5, C6 25: same as USA 26: same as USA C1: Electrical Transmission Lines (Canadian) C5: Farm Silos or Grain Bins C6: Sheds, Fences or Outdoor Furniture	10: Small sheds 11: Shipping containers 17: RC utility poles 18: Ground-based billboards 19: Traffic signs 20: Carports 21: Hollow concrete block (HCB) walls 22: Wooden, plastic, aluminium or mesh fences 23: Windbreak or snowbreak fences for roads 24: Net fences 29: Temporary scaffolding (with wall ties) 30: Gantry cranes	
Vehicles			13: Light vehicles 14: Ordinary vehicles 15: Large vehicles 16: Railway vehicles	

Natural	DIs 27 – 28 27: Trees, Hardwood 28: Trees, Softwood	DIs C2 C2: Trees	25: Broad-leaved trees 26: Coniferous trees	G: branches – leafy H: branches- bare I: tree stands – diseased/unstable J: tree stands – strong K: tree stands – edge trees, hedges, underwood
Other			12: Vending machines 27: Gravestones 28: Road surfaces	

Appendix A – Damage Indicators in Officially-Adopted Tornado Damage Classifications

A1. Fujita Scale, as provided in Fujita (1971)

Scale	Wind estimate (fastest ¼ mile, mph)	Typical Damage
F0	< 73	**Light damage**. Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign boards damaged.
F1	73 – 112	**Moderate damage**. Peels surface off roads; mobile homes pushed off foundations or overturned; moving autos blown off roads.
F2	113 – 157	**Considerable damage**. Roofs torn off frame houses; mobile homes demolished; boxcars overturned; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.
F3	158 – 206	**Severe damage**. Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown.
F4	207 – 260	**Devastating damage**. Well-constructed houses leveled; structures with weak foundations blown away some distance; cars thrown and large missiles generated.
F5	261 – 318	**Incredible damage**. Strong frame houses leveled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 meters; trees debarked; incredible phenomena will occur.

A2. United States – EF-Scale

Sources: WSEC (2006) or http://www.spc.noaa.gov/efscale/ef-scale.html

Damage Indicator Class	Description	Label
Building	Small barns, farm outbuildings	1. SBO
Building	One- or two-family residences	2. FR12
Building	Single-wide mobile home	3. MHSW
Building	Double-wide mobile home	4. MHDW
Building	Apartment, condominiums, townhouse (3 stories or less)	5. ACT
Building	Motel	6. M
Building	Masonry apartment or motel	7. MAM
Building	Small retail building (fast food)	8. SRB
Building	Small professional building (doctor office, branch bank)	9. SPB
Building	Strip Mall	10. SM
Building	Large shopping mall	11. LSM
Building	Large, isolated ("big box") retail building	12. LIRB
Building	Automobile showroom	13. ASR
Building	Automotive service building	14. ASB
Building	School, 1-story elementary (interior or exterior halls)	15. ES
Building	School, Junior or Senior High School	16. JHSH
Building	Low-rise (1-4 story) building	17. LRB
Building	Mid-rise (5-20 story) building	18. MRB
Building	High-rise (over 20 stories) building	19. HRB
Building	Institutional building (hospital, government, or university)	20. IB
Building	Metal building system	21. MBS
Building	Service station canopy	22. SSC
Building	Warehouse (tilt-up walls or heavy timber)	23. WHB
Non-Building Structure	Transmission line tower	24. ETL
Non-Building Structure	Free-standing tower	25. FST
Non-Building Structure	Free-standing pole (light, flag luminary)	26. FSP
Natural	Tree – hardwood	27. TH
Natural	Tree – softwood	28. TS

Each DI has a short description and photos which illustrate the details for the various DODs. For example, "one- and two-family residences", FR12 has the following description:

One- and Two-Family Residences (FR12)
(1000 – 5000 sq. ft.)
Typical Construction

- Asphalt shingles, tile, slate or metal roof covering
- Flat, gable, hip, mansard, or mono-sloped roof or combination thereof
- Plywood/OSB or wood plank roof deck

- Prefabricated wood trusses or wood joist and rafter construction
- Brick veneer, wood panels, stucco, EIFS, vinyl or metal siding
- Wood or metal stud walls, concrete blocks or insulating-concrete blocks
- Attached single or double garage

The DOD have a brief description of the damage state with estimates of the lower-bound, upper-bound and expected wind speeds associated with that damage state. For example, the DOD for FR12 are as follows:

DOD*	Damage description	Exp**	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward or outward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed in bottom floor, except small interior rooms	152	127	178
9	All walls collapsed	170	142	198
10	Destruction of engineered and/or well constructed residence: slab swept clean	200	165	220

Source: WSEC (2006). Note that the wind speeds are 3-sec gust at the height of the damage, given in mph.

Most of the DIs have DODs which range from “Threshold of visible damage” to “Total destruction” (there are some exceptions, such as MRB and HRB, where the highest DOD is “Permanent structural deformation”). The intermediate DOD provide the expected damage states which could be observed.

A3. Canada – EF-Scale (modified)

Sources: Sills et al. (2014) or https://ec.gc.ca/meteo-weather/default.asp?lang=En&n=41E875DA-1

Canada use the same DIs as the USA does with some small modifications based on Canadian storm damage survey experience, including combining the two tree DIs (TH and TS) into a single tree DI (C-T), and modifying ETL to C-ETL. Four additional DIs not used in the USA are also added. Thus, in Canada 31 DIs are officially used. The modified and additional DIs are:

Damage Indicator Class	Description	Label
Non-Building Structure	Electrical Transmission Lines	24. C-ETL
Natural	Trees	27. C-T
Building	Heritage Churches	C3. C-HC
Building	Solid Masonry Houses	C4. C-SMH
Non-Building Structure	Farm Silos or Grain Bins	C5. C-FSGB
Non-Building Structure	Sheds, Fences or Lawn Furniture	C6. C-SFLF

Here we used the same numbering as for the US EF-Scale, with the four additional DIs using the numbering of C3 – C6). The wind speeds in the EF-Scale are also slightly modified, as shown in Table 3. The remainder of the Canadian EF-Scale is the same as that in the USA. However, additional guidance to surveyors was included in the Notes section for some DIs (e.g., when to adjust speeds toward the upper/lower bound of a particular DOD), again based on Canadian storm damage survey experience.

A4. Japan – JEF-Scale

Sources: JEF-scale Guideline, 2015, Guideline for the Japanese Enhanced Fujita Scale, Japan Meteorological Agency (in Japanese, English version will be issued soon.)

Damage Indicator Class	Description	Label
Building	Wooden houses and stores	J1
Building	Industrialized steel-framed houses (prefabricated)	J2
Building	RC apartment buildings	J3
Building	Temporary buildings	J4
Building	Large eaves	J5
Building	Steel-framed warehouses	J6
Building	Small non-residential wooden buildings	J7
Building	Greenhouses, gardening facilities	J8
Building	Wooden livestock sheds	J9
Non-Building Structure	Small sheds	J10
Non-Building Structure	Shipping containers	J11
Other	Vending machines	J12
Vehicles	Light vehicles	J13
Vehicles	Ordinary vehicles	J14
Vehicles	Large vehicles	J15
Vehicles	Railway vehicles	J16
Non-Building Structure	RC utility poles	J17
Non-Building Structure	Ground-based billboards	J18
Non-Building Structure	Traffic signs	J19
Non-Building Structure	Carports	J20
Non-Building Structure	Hollow concrete block (HCB) walls	J21
Non-Building Structure	Wooden, plastic, aluminium or mesh fences	J22
Non-Building Structure	Windbreak or snowbreak fences for roads	J23
Non-Building Structure	Net fences	J24
Natural	Broad-leaved trees	J25
Natural	Coniferous trees	J26
Other	Gravestones	J27
Other	Road surfaces	J28
Non-Building Structure	Temporary scaffolding (with wall ties)	J29
Non-Building Structure	Gantry cranes	J30

The DIs have brief descriptions to clarify the form of construction. For example, for "Wooden houses and stores", J1, there is an additional description which states "1- 2 story conventional wooden houses (including dwellings combined with stores); 2-story wooden multiple dwellings". Thus, relatively fewer details are given than in the US EF-Scale, even though there are significant variations in the forms of construction.

Each DI has a set of DOD, which are of the same form as the US EF-Scale. Interestingly, they differentiate some damage as due to wind-borne debris. An example of the DODs for J1 is provided below.

DOD	Damage Description		Wind Speed (m/s)		
			Rep.	LB	UB
1	Visible minor damage (breakage of glass)		30	25	35
2	Minor loss (detachment)/ displacement of roofing materials	Clay tile roofing	35	25	50
		Metal sheet roofing	40	30	55
3	Major loss (detachment) of roofing materials	Clay tile roofing	45	30	60
		Metal sheet roofing	50	40	65
4	Destruction/detachment of eaves or sheathing roof boards		50	40	65
5	Damage (deformation, cracking, etc.) to walls from deformation of main frames		55	40	65
6	Loss of metal wall cladding		60	45	70
7	Destruction/detachment of roof frames/ components		65	50	75
8	Major destruction/collapse of main structures and frames		75	55	85

Source: JEF-Scale Guidelines (2015). Wind speeds are 3-sec gust speeds at the height of the damage.

Some of the DIs have limited DODs, such as for vehicles where only overturning is considered. This is likely because much of the JEF-Scale is based on straight-line (boundary layer) wind tunnel testing, and not on observations of damage or correlations between various DIs. (The JEF committee noted that reason is that the estimated critical velocities of lifting and slipping of (isolated) cars were higher than overturning, and a car would be easily blown off once it overturned, because the inclined posture of the car receives larger aerodynamic force. In the study used to develop this, the friction coefficient 0.8 was assumed between tires and road surface and aerodynamic coefficients obtained by normal wind tunnel tests were used. However, it is also true that some damage examples suggest slipping phenomena of cars. Slipping can happen depending upon the road surface condition and surrounding conditions. This may be revised in the near future.)

Ordinary cars

DOD	Damage Description	Wind Speed (m/s)		
		Rep.	LB	UB
1	Overturning	50	45	55

Vans

DOD	Damage Description	Wind Speed (m/s)		
		Rep.	LB	UB
1	Overturning	55	50	60

Source: JEF-Scale Guidelines (2015). Wind speeds are 3-sec gust speeds at the height of the damage.

A5. Europe – ESSL DIs

Sources:

- Feuerstein et al. (2011)
- ESSL document "Towards an International Fujita-Scale (IF-Scale), ESSLs Current Tornado and Storm Damage Rating Practice", retrieved as of 2 February 2017:
- https://www.essl.org/cms/wp-content/uploads/20150902-Towards-an-International-Fujita-Scale-ESSL-rating-practice.pdf

DI/DOD matrix for Buildings:

	Fujita damage class	f0	f1	f2	f3	f4	f5
	loss ratio (%)	0.1	1	10	50	90	100
	degree of damage → ↓ damage indicator	light roof damage	significant roof damage	roof gone	walls partly collapsed	largely blown down	blown away
A	weakest outbuilding	F0+	F0+	F1-	F1-	F1+	F2-
B	outbuilding	F0+	F1-	F1+	F2-	F2+	F3-
C	strong outbuilding/ weak framehouse	F0+	F1+	F2-	F3-	F3+	F4-
D	weak brick structure/ strong framehouse	F1-	F1+	F2+	F3+	F4-	F5
E	strong brick structure	F1-	F2-	F3-	F4-	F5	F5
F	concrete building	F1-	F2+	F3+	F4+	F5	F5

The Damage Indicators for Buildings are simple, with six distinct, generic, categories. They can be interpreted as:

A … like a doghouse or unanchored light outbuildings

B … like huts and barns, anchored light outbuildings

C … like the typical US-midwest wood-frame houses, if weakly anchored/connected to the foundation

D … like the typical US-midwest wood-frame houses, if well anchored and connected. In Europe, typical single-row brick structures (mainly 2-dimensional single-row brick walls – like garden walls – fall into B or C), which best corresponds to the original Fujita-scale.

E … the typical central European masonry house

F … steel-reinforced concrete buildings. Some historic fort-like buildings (castles) and some Mediterranean-style buildings in wind-prone-areas (like in Dalmatia) also fall into this category with their extremely thick stone-walls (if well-built and kept renovated).

The loss ratio in the table refers to the standard loss ratios used in the insurance industry.

The DOD are also simple and generic, with six categories from “light roof damage” to “blown away”. These are connected to Fujita’s original scale which has an increased resolution using ‘+’ and ‘-‘ on the typical ratings (e.g., F3+ and F3- would represent the upper and lower bounds of the F3 speeds). These ranges can be connected to the T- or TORRO-Scale, which has been historically used in Europe.

Thus, the DI/DOD approach of the EF-Scale is maintained but with a simple set of Damage Indicators and a simplified set of damage states. A similar approach is used for natural DIs, i.e., plants.

DI/DOD matrix for Natural (Plant) DIs:

	Fujita damage class	f0	f1	f2	f3	f4	f5
	loss ratio (%)	0.1	1	10	50	90	100
	damage prevalence → ↓ damage indicator	extremely isolated	isolated	significant	frequent	prevalent	total
G	branches - leafy	**< F0**	**F0+**	**F1-**	**F1+**	**F2-**	**F3-**
H	- bare	**F0-**	**F1-**	**F1+**	**F2-**	**F2-**	**F3-**
I	tree stands - diseased/ unstable	**< F0**	**F0-**	**F0+**	**F0+**	**F1-**	**F1-**
J	- strong	**F0+**	**F1-**	**F1+**	**F1+**	**F2-**	**F2-**
K	edge trees, hedges, underwood	**F1-**	**F1+**	**F2-**	**F2+**	**F3-**	**F3-**

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* This is not a complete list, but reflects papers identified by the committee during its work. See also the list of references from the main body of the document, which are not repeated here.

Appendix D – List of Source of Contributions for Data and Other Information in Report

Australia – Matthew Mason (University of Queensland) and Harald Richter (Bureau of Meteorology, Australia)

Bangladesh – Yosuke Yamane, Taichi Hayashi, and Yukio Tamura (see also Yamane et al., 2010a,b)

Canada – Dave Sills, Gregory Kopp (with data from Environment and Climate Change Canada, 2016; Canadian Tornado Fact Sheet, available via the Government of Canada Open Data Portal, http://open.canada.ca/data/en/dataset/a720afb1-c271-4fbc-b55c-7d242e1701b6.)

China – Qingshang Yang (Beijing Jiaotong University)

Europe – Alois M. Holzer, Pieter Groenemeijer , Thomas M. E. Schreiner, Thomas Krennert, Rainer Kaltenberger (with data from ESSL and Antonescu et al., 2016)

Japan – Yukio Tamura (Tokyo Polytechnic University, with data from Japan Meteorological Agency and JMA Tornado Database, Database on tornadoes and other severe local storms since 1961; in Japanese)

Malaysia – Noram Irwan Ramli (University Malaysia Pahang; Kajian Awal kejadian Puting Beliung Di Malaysia, Malaysian Meteorological Department Research Publication No 11/2015. Available from www.met.gov.my/web/metmalaysia/publications/technicalpaper/fullpapers/document/44762/rp11_2015.pdf [accessed 18 February 2017]; **Malaysia Country Profile** "EM-DAT: The OFDA/CRED International Disaster Database – www.emdat.be – Université Catholique de Louvain – Brussels – Belgium. Available from http://www.emdat.be/database [accessed 18 February 2017].)

New Zealand – from Goliger and Milford (1998), who cite Tomlinson, A.I. and Nicol, B., 1976, Tornado reports in New Zealand 1961 – 1975, Technical Note 229, New Zealand Meteorological Services, Wellington.

Philippines – Jaime Hernandez (University of the Philippines Diliman)

South Africa – Adam Goliger (see also Goliger and Milford, 1998)

South America – from Goliger and Milford (1998)

Sri Lanka - Sujeewa Lewangamage

Taiwan – Yuan-Lung Lo (Tamkang University)

USA –James LaDue and John Robinson (National Weather Service, USA)

Vietnam – Trung Thanh Vu (Vietnam Institute for Building, Science, and Technology)

Report edited by G.A. Kopp (Chair), A. Holzer, Y. Tamura, D. Sills