16B.6 IMPLEMENTATION AND APPLICATION OF THE EF-SCALE IN CANADA

David M. L. Sills[1*], Patrick J. McCarthy[2] and Gregory A. Kopp[3]

[1]Cloud Physics and Severe Weather Research Section, Environment Canada, Toronto, ON

[2]Meteorological Service of Canada, EC, Winnipeg, MB

[3]Faculty of Engineering, University of Western Ontario, London, ON

1. INTRODUCTION

Environment Canada began to use the Fujita scale (F-scale, Fujita 1981) to rate the intensity of damage resulting from wind events (primarily tornadoes) in the 1970's following the tornado 'Super Outbreak' in the United States (US) and Canada in April of 1974. It was also applied to past tornadoes in order to establish a tornado climatology for Canada (Newark 1984).

Over subsequent decades, the F-scale was found to have several significant shortcomings. First, as designed, the scale has only a small number of damage indicators (DIs) with which to rate damage. Second, wind engineers have found that the wind speeds associated with F-scale damage ratings for violent tornadoes are unrealistically high (e.g., Phan and Simiu 1998).

Several attempts to improve the F-scale and its use were made. For example, Fujita began to move toward a rating matrix based on types of construction (Fujita 1992). Following on this work by Fujita, Sills et al. (2004) developed an F-scale rating matrix with 20 DIs that was used both operationally and to generate an updated 1980-2009 tornado climatology for Canada (Sills et al. 2012). However, the F-scale wind speed bias was never addressed.

More recently, the development of an enhanced version of the F-scale, called the Enhanced Fujita scale or EF-scale, was spearheaded by Texas Tech University (TTU) in collaboration with a number of prominent US scientists and meteorologists (McDonald and Mehta, 2006). The EF-scale employs 28 different DIs, and wind speeds associated with various levels of damage were recalibrated using an expert elicitation process. The damage ratings were also meant to be backwards compatible with the original F-scale. For the original damage indicators, only the associated wind speeds have changed (e.g., a roof removed from a wood-frame residential home is F/EF2).

The EF-scale was implemented operationally in the US on 1 Feb 2007. After working out some initial problems, it is now used there successfully.

There has been international interest in the use of the EF-Scale, and both Canada and France have now adopted it. The implementation and application of the EF-scale in Canada will be described in the following sections.

2. EVALUATION AND PARALLEL TESTING

Progress with the implementation and use of the EF-scale in the US was monitored by the authors with an eye toward eventual implementation in Canada.

In 2011, the F-scale and the US implementation of the EF-scale were used in parallel to rate tornado damage in Ontario and the Prairie provinces. Unfortunately (or fortunately depending on one's perspective), only two weak tornadoes were verified on the Prairies that year, and they were remotely surveyed due to their distance from the nearest forecast office. It was, however, a relatively busy year in Ontario with 17 tornadoes rated between F0 and F3.

Results from the parallel test included the following:

- Many F/EF-scale ratings were the same,
- Tornado damage near Watford, ON, including downed metal truss hydro towers was rated F2 versus EF3,
- Double-brick houses with roofs and some external walls removed by a tornado in Goderich, ON, were rated F3 versus EF2,

* Corresponding author address: David M. L. Sills, Cloud Physics and Severe Weather Research Section, Environment Canada, 14780 Jane Street, King City, Ontario, Canada, L7B 1A3, David.Sills@ec.gc.ca

- Tornado damage in Shaunavon, SK, including snapped power poles was rated F1 versus EF2,
- There were major differences in tree damage ratings,
- A number of common damage indictors in Canada were not included with the EF-scale, including farm silos / grain bins, heritage churches, and sheds.

Another problem noted during the parallel test involved the lower bound of EF0, defined to be 65 mph or 105 km h^{-1}. This is substantially higher than the 90 km h^{-1} wind gust threshold typically used with synoptic and thunderstorm wind warnings issued by Environment Canada (Environment Canada 2014a). Even in the US, 58 mph (93 km h^{-1}) is the threshold used for severe thunderstorm warnings. In addition, Frelich and Ostuno (2012) recently confirmed that significant damage to trees begins with wind gusts near 90 km h^{-1}. Thus, implementation in Canada would require an EF0 lower bound near 90 km h^{-1} to eliminate this gap.

3. MODIFICATIONS

To adapt the EF-scale to the Canadian context and address the problems described in the previous section, a number of modifications were made to the EF-scale.

First, two existing EF-scale DIs related to electrical transmission lines and trees were adjusted to better reflect the experience of damage surveyors in Canada. For electrical transmission towers, the wind speeds for Degree of Damage (DOD) 6, 'Collapsed metal truss towers', were lowered so that the expected wind speed value was just below that required for EF3 (Table 1).

For trees, problems with the two existing tree DIs ('Hardwood' and 'Softwood') are widely recognized (e.g. Edwards et al. 2013), including the fact that the differences between the responses of hardwoods and softwoods are less than that between both types of trees in various situations such as saturated ground. Thus, a single tree DI was developed based on both the recent research of Frelich and Ostuno (2012) and the experience of Canadian damage surveyors (Table 2). It employs coverage criteria (e.g., 50% of mature trees snapped and/or uprooted) that were not present in the original tree DIs but have been widely used in Canada. For both of these DIs, more comprehensive notes were added to assist the surveyor with deciding when to use values approaching the upper or lower bounds of each DOD.

Second, four new damage indicators that are frequently encountered in Canada were added. These include:

- Heritage Churches (Table 3),
- Solid Masonry Houses (Table 4),
- Farm Silos / Grain Bins (Table 5),
- Sheds, Fences or Outdoor Furniture (Table 6).

Each was based on the experience of Canadian damage surveyors. However, in the case of 'Heritage Churches', the DODs borrowed heavily from a 'Churches' DI developed in France by KERAUNOS (E. Wesolek, personal communication). Detailed notes including rating guidance were included.

Third, ways in which to eliminate the gap between the lower bound of EF0 (105 km h^{-1}) and the existing damaging wind gust threshold (90 km h^{-1}) were investigated. One solution was to make the lower bound of EF0 open-ended, as is the upper bound of EF5. However, since it is known that significant wind damage begins near 90 km h^{-1}, and tornadoes are defined as being capable of causing damage, it was decided that this option would create more problems than it would solve.

Another solution involved obtaining the original TTU expert elicitation data to better understand the way in which the EF0 lower bound came to be 105 km h^{-1}. It was found that this lower bound resulted from the use of a linear regression fit through the expert elicitation data points. Why a linear fit was used is not explained in the TTU report (McDonald and Mehta, 2006). When a simple power law regression fit was applied instead, not only did it result in a slightly better fit (R^2 of 0.924 vs. R^2 of 0.914)[2] but the lower bound of EF0 was reduced to 92 km h^{-1} (90 km h^{-1} when

[2] It was noted that five pairs of expert elicitation data out of 217 were missing from the TTU regression analysis. Working from the original data, these five pairs were included for both the linear and power law regression analyses presented here. The linear trend line equation is therefore slightly different. Note that none of the 'Service Station Canopy' DI data were included in the TTU analysis, and therefore those data were also not included here.

rounded to the nearest 5 km h^{-1}). This approach had other benefits:

- the regression curve went through the origin,
- the wind speed ranges for each EF-scale category were nearly the same (approx. 43 km h^{-1}) as opposed to the linear regression having wind speed ranges increasing from 33 km h^{-1} for EF0 to 56 km h^{-1} for EF5.

A comparison between the two methods is shown in Fig. 1. Most of the difference exists at the low end of the scale. The two curves are very similar mid-scale, and the power law curve dips down only slightly near the top of the scale. It was decided that the power law solution, making use of the original TTU data, was the most elegant and effective.

Finally, the methods for rounding were revised. The US EF-scale rating thresholds are said to be rounded to the nearest 5 mph to indicate uncertainty. However, the EF-scale speed ranges begin with numbers that are not rounded to the nearest 5 mph (e.g., 86, 111, 136, 166 mph). Thus, accuracy to 1 mph is still implied. Such accuracy is also implied for DI/DOD wind speed values.

For the Canadian implementation, all speed scale and DI/DOD values are rounded to the nearest 5 km h^{-1}. Rounding to the nearest 10 km h^{-1} is probably a better representation of the uncertainty, but its use creates markedly uneven intervals in the speed scale.

The EF-Scale and proposed modifications were approved internally at Environment Canada in 2012 and implemented operationally on 1 April 2013. The approved wind speeds are shown in Table 7. The original F-scale wind speeds are also shown for comparison. The 31 DIs now being used in Canada are shown in Table 8.

4. RESULTS AND CONTINUING WORK

Since its implementation in 2013, more than 70 tornadoes (and several downbursts) have been rated by Environment Canada using the EF-scale, so far ranging from EF0 to EF2. The first tornado rated using the new scale, an EF1 at Shelburne, ON, occurred on April 18, 2013.

Some slight modifications were made for the 2014 season (known as ‘Revision 1’). Future changes are possible and will be made annually as necessary. The latest version can found online (Environment Canada, 2014b). It was decided to not apply the EF-scale to historical events since this has not been done for tornadoes in the US. F-scale ratings will be retained for all tornadoes before 2013.

Tools for improved use of the EF-scale during damage surveys are being developed and annual damage survey training will continue.

Kopp and co-workers at the University of Western Ontario are continuing to work toward better wind speed / damage relationships for trees and vehicles (no current DI) via wind tunnel simulations, and for wood-frame houses using full-scale testing and wind tunnel studies.

Lastly, once an international EF-scale ‘standard’ is established (work has recently begun on this initiative, Sills and Kopp are involved), it is anticipated that Environment Canada’s implementation of the EF-scale will be revisited.

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Table 1. Notes and Degree of Damage (DOD) information for the revised ‘Electrical Transmission Lines’ damage indicator. Wind values listed are expected (EXP), lower bound (LB) and upper bound (UB) and are rounded to the nearest 5 km h^{-1}.

C-1. ELECTRICAL TRANSMISSION LINES (C-ETL)

Typical Construction:

- Single wood poles with wood cross arms, 7-35 m in height and 15-60 cm in diameter (at 2 m above ground)
- Single steel or concrete poles with metal cross arms
- Metal trussed towers

Notes:

- Whether poles go down or not is related to size, composition (wood / concrete / steel) and load (wire tension, number of transformers)
- For small diameter (~15-20 cm) or very old wood poles, decrease toward lower-bound wind speed; for large diameter (~45-60 cm) wood poles, increase toward upper-bound wind speed
- Keep in mind – one weak or overloaded pole going down can cause other poles along the line to break due to wire tension
- Trees falling on lines can bring down poles – *do not use this DI if this is the case*
- Metal truss towers where lines change direction are often more strongly reinforced, increase toward upper-bound wind speed

DOD	Damage Description	EXP	LB	UB
1	Threshold of visible damage	130	110	155
2	Broken wood cross member	155	125	175
3	Wood poles leaning	175	135	200
4	Broken wood poles	195	145	220
5	Broken or bent steel or concrete poles	210	180	240
6	Collapsed metal truss towers	220	185	255

Table 2. Notes and Degree of Damage (DOD) information for revised the 'Trees' damage indicator. Wind values listed are expected (EXP), lower bound (LB) and upper bound (UB) and are rounded to the nearest 5 km h^{-1}.

C-2. TREES (C-T)

Typical Species:
- Hardwood: Oak, Maple, Birch, Ash, Beech, Cherry, Hickory, Walnut, Aspen, Elm, Poplar
- Softwood: Pine, Spruce, Fir, Hemlock, Cedar, Larch, Redwood, Cypress

Notes:
- General differences in the responses of softwood and hardwood species are less important than other factors
- Decrease toward lower-bound wind speed if trees show evidence of significant rot, or if uprooting occurs with saturated ground or very shallow soil
- In urban / suburban areas, trees broken at base of trunk were likely planted too deeply, had mechanical injury or had girdling roots – decrease toward lower-bound wind speed
- For forests and woodlots composed of even-aged monoculture plantations, decrease toward lower-bound wind speed; for forests or woodlots composed of mature, deep-rooted red oak, red maple, beech, hemlock or white cedar, increase toward upper-bound wind speed
- Increase toward upper-bound wind speed if there are no leaves on trees (e.g., spring or fall)

DOD	Damage Description	EXP	LB	UB
1	Small limbs broken (less than 2 cm diameter)	70	55	85
2	Large branches broken (2-8 cm diameter)	90	65	110
3	Up to 20% of mature trees snapped and/or uprooted	115	80	150
4	More than 20% of mature trees snapped and/or uprooted	150	105	190
5	More than 50% of mature trees snapped and/or uprooted	190	145	230
6	More than 80% of mature trees snapped and/or uprooted; numerous trees may be denuded/debarked by missiles with only stubs of largest branches remaining	235	190	275

Table 3. Notes and Degree of Damage (DOD) information for the new 'Heritage Churches' damage indicator. Wind values listed are expected (EXP), lower bound (LB) and upper bound (UB) and are rounded to the nearest 5 km h^{-1}.

C-3. HERITAGE CHURCHES (C-HC)

Typical Construction:
- Built with bricks and/or stones
- Solidly built roof structure
- May also have one or more bell towers

DOD	Damage Description	EXP	LB	UB
1	Threshold of visible damage	90	70	110
2	Loss of roof covering material (up to 20%)	115	90	140
3	Loss of significant roof covering material (more than 20%); light damage on the bell-tower summit	145	115	175
4	More than 50% of roof structure removed; collapse of the bell-tower summit (spire); walls remain standing	185	150	220
5	More than 80% of roof structure removed; walls partly collapsed; bell-tower structure damaged	225	190	260
6	Roof structure totally removed and blown away; many walls collapsed; bell-tower structure mostly destroyed	270	230	310
7	Complete destruction of building	315	275	355

Table 4. Notes and Degree of Damage (DOD) information for the new 'Solid Masonry Houses' damage indicator. Wind values listed are expected (EXP), lower bound (LB) and upper bound (UB) and are rounded to the nearest 5 km h^{-1}.

C-4. SOLID MASONRY HOUSES (C-SMH)

Typical Construction:

- Asphalt shingles, tile, slate or metal roof covering
- Flat, gable, hip, mansard or mono-sloped roof or combinations thereof
- Plywood/OSB or wood plank roof deck
- All exterior walls are solid masonry construction (e.g. double brick)
- Roof is wood joist and rafter construction

Notes:

- With hip roof, increase toward upper-bound wind speed for DOD4 and DOD5

DOD	Damage Description	EXP	LB	UB
1	Threshold of visible damage	105	85	130
2	Loss of roof covering material (up to 20%), gutters and/or awning; loss of vinyl or metal siding	125	100	155
3	Broken glass in doors and windows	155	125	185
4	Uplift of roof deck and loss of significant roof covering material (more than 20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	155	130	185
5	Large sections of roof structure removed (more than 50%); most walls remain standing	195	165	240
6	Exterior walls collapsed	245	210	285
7	Most walls collapsed, except small interior rooms	285	245	325
8	Complete destruction of building	315	275	355

Table 5. Notes and Degree of Damage (DOD) information for the new 'Farm Silos or Grain Bins' damage indicator. Wind values listed are expected (EXP), lower bound (LB) and upper bound (UB) and are rounded to the nearest 5 km h^{-1}.

C-5. FARM SILOS OR GRAIN BINS (C-FSGB)

Typical Construction:

Farm silos

- Cylindrical structures typically 4-10 m in diameter and 20-50 m in height
- Construction is wood staves, concrete staves, cast concrete, poured concrete or steel panels
- With cast/poured concrete and *Harvestore* steel silos, increase toward upper-bound wind speed

Grain bins

- Cylindrical structures typically 5-20 m in diameter and 5-30 m in height
- Construction is galvanized steel panels and purlins

DOD	Damage Description	EXP	LB	UB
1	Empty unanchored grain bin toppled; anchored grain bin damaged; silo cap damaged	90	70	110
2	Empty unanchored grain bin rolled or carried through air less than 10 m; anchored grain bin toppled; silo cap removed	135	110	160
3	Anchored grain bin rolled or carried less than 10 m; empty portions of silo destroyed	180	150	210
4	Grain bin carried 10-100 m or more; silo destroyed	225	190	260

Table 6. Notes and Degree of Damage (DOD) information for the new 'Sheds, Fences or Outdoor Furniture' damage indicator. Wind values listed are expected (EXP), lower bound (LB) and upper bound (UB) and are rounded to the nearest 5 km h^{-1}.

C-6. SHEDS, FENCES OR OUTDOOR FURNITURE (C-SFOF)

Typical Construction:

Shed
- Single storey and less than 12 m^2
- Wood, metal and/or plastic construction
- Metal, wood, plastic or shingle roof
- May have wood, metal or vinyl siding
- May have one or more windows
- May be unanchored or weakly anchored

Wood fence
- Wood rails, panels and posts (sunk into post holes)

Outdoor furniture
- Light wood, metal and/or plastic construction intended for outdoor use

Notes:
- Increase toward upper-bound wind speed for large and/or well-anchored sheds

DOD	Damage Description	EXP	LB	UB
1	Garden shed overturned; wood fence blown down; outdoor furniture blown over	90	70	110
2	Garden shed rolled or carried through the air less than 10 m; outdoor furniture carried through air	135	110	160
3	Garden shed carried through air 10 m or more	180	150	210

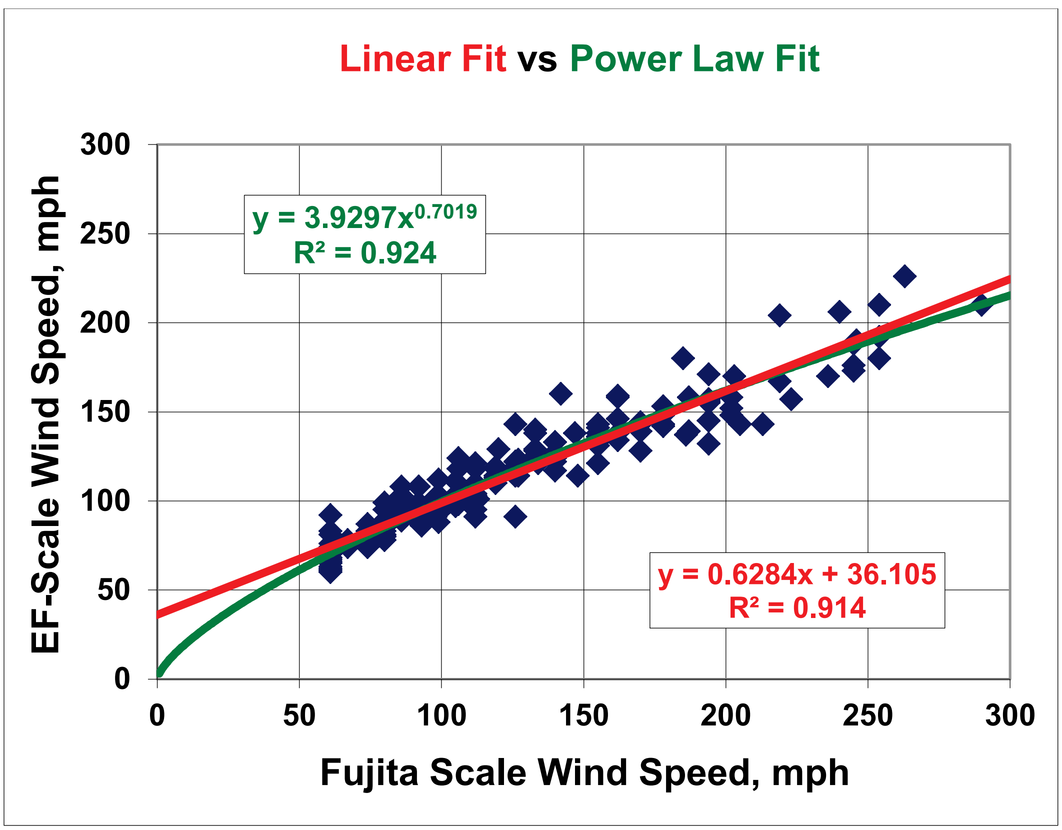

Figure 1. Graph showing data points from the TTU expert elicitations (blue), a linear regression curve (red) and a power law regression curve (green). Resulting equations and R^2 values are also shown.

Table 7. Comparison of F-Scale and EF-Scale wind speeds (as implemented by Environment Canada) associated with damage ratings. Note that for the EF-Scale wind speeds have been increased for lower ratings and decreased for higher ratings. F-scale winds speeds were rounded to the nearest 10 km h^{-1} but that resulted in uneven intervals when applied to the EF-scale results. Therefore, EF-scale wind speeds are rounded to the nearest 5 km h^{-1}.

F/EF Rating	F-Scale Wind Speed Rounded to 10 km/h	EF-Scale Wind Speed Rounded to 5 km/h
0	60 – 110	90 – 130
1	120 – 170	135 – 175
2	180 – 240	180 – 220
3	250 – 320	225 – 265
4	330 – 410	270 – 310
5	420 – 510	315 or more

Table 8. List of 31 Damage Indicators (DIs) and DI codes used with Environment Canada's implementation of the EF-scale. Revised and new DIs are given the prefix 'C' for 'Canadian'.

Number	Damage Indicator (DI)
1	Small Barns or Farm Outbuildings (SBO)
2	One- or Two-Family Residences (FR12)
3	Manufactured Homes: Single Wide (MHSW)
4	Manufactured Homes: Double Wide (MHDW)
5	Apartments, Condos, Townhouses (ACT)
6	Motels (M)
7	Masonry Apartments or Motels (MAM)
8	Small Retail Buildings (SRB)
9	Small Professional Buildings (SPB)
10	Strip Malls (SM)
11	Large Shopping Malls (LSM)
12	Large, Isolated Retail Buildings (LIRB)
13	Automobile Showrooms (ASR)
14	Automobile Service Buildings (ASB)
15	Elementary Schools (ES)
16	Junior or Senior High Schools (JHSH)
17	Low-Rise Buildings: 1 - 4 Storeys (LRB)
18	Mid-Rise Buildings: 5 - 20 Storeys (MRB)
19	High-Rise Buildings: Greater than 20 Storeys (HRB)
20	Institutional Buildings (IB)
21	Metal Building Systems (MBS)
22	Service Station Canopies (SSC)
23	Warehouse Buildings (WHB)
25	Free-Standing Towers (FST)
26	Free-Standing Light Poles, Luminary Poles, Flag Poles (FSP)
C-1	Electrical Transmission Lines (C-ETL)
C-2	Trees (C-T)
C-3	Heritage Churches (C-HC)
C-4	Solid Masonry Houses (C-SMH)
C-5	Farm Silos or Grain Bins (C-FSGB)
C-6	Sheds, Fences or Outdoor Furniture (C-SFOF)