8B.5 DERIVATION OF PHYSICALLY MOTIVATED WIND SPEED SCALES

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1. INTRODUCTION

A class of new wind speed scales is proposed which rely on physically relevant quantities like mass flux density, kinetic energy density (pressure), or kinetic energy flux density. These so-called Energy- or E-scales can be applied to wind speeds of any intensity. Full details are provided by Dotzek (2008).

Development of wind speed scales has long been a subject of research. Fujita (1981) has provided a review of the field focusing on those scales which were designed to describe the most intense wind phenomena on earth: Tornadoes, downbursts, and tropical cyclones. Inherently, devising scales for high wind events can be tackled from two sides:

(i) wind speed-based, and
(ii) damage-based.

The former approach is usually taken by the atmospheric sciences, while the latter reflects more the standpoint of wind engineering. However, the conceptual difference and partial incompatibility of both approaches has led to considerable controversy and confusion, primarily because even wind speed-based scales must usually rely on post-event damage surveys, due to the scarcity of in situ wind measurements, at least in tornadoes and downbursts.

The difference between approaches (i) and (ii) above can be substantial, as *wind speed-based scales* are in general concerned about the maximum winds that can physically occur for a given wind phenomenon, and in particular about what its maximum (local) intensity (wind speed) was.

Damage-based scales, however, aim to determine the minimum wind speed necessary to cause the observed damage to individual man-made structures or vegetation. Also, a likely upper bound of wind speeds can be estimated in those cases in which undamaged structures remain, for which apparently their critical damaging wind speed level had not been attained in the storm.

Three wind speed scales are frequently used in meteorology, wind engineering and related sciences: the Beaufort (B), Fujita (F), and TORRO (T) scales. The relationship between velocity v, prefactor v_*, and the scale value X, with offset X_0, in these scales is

$$v(X) = v_* \, (X - X_0)^{3/2} \quad , \qquad (1)$$

and may also be used for an approximation of the Saffir-Simpson (S) scale mainly applied to hurricane winds over the Atlantic basin. For the Fujita scale, Eq. (1) becomes

$$v(F) = 6.302 \text{ m s}^{-1} \, (F+2)^{3/2} \quad . \qquad (2)$$

The F, T, and S-scales classify the physically possible velocity range for tornadoes, downbursts, and tropical cyclones. This makes them applicable worldwide in a consistent way – an important point in climatological analysis (cf. Dotzek et al., 2005, 2008). Yet, the question if the exponent 3/2 in Eq. (1) is the best possible choice was often raised.

To include the variation in building strength in different regions of the world, local descriptions of typical damage for each scale class are needed. Fujita (1981, 1992) and NOAA-NWS (2003) have provided this with growing detail for the USA. Dotzek et al. (2000) and Hubrig (2004) present a damage description for central Europe over F- and T-scale which was developed with input by Munich Re and also describes vegetation damage, traditionally taken into account in European wind damage ratings. The description is available online in German at www.tordach.org/pdf/FT_scales.pdf. An updated English version is currently being prepared and will appear on the ESSL website under www.essl.org/-research/scales/.

This paper aims to develop velocity scaling laws which avoid the flaws of the scales characterised by Eq. (1) and also allow for a calibration to findings from statistical modelling, wind engineering, damage analyses or mobile Doppler radar measurements. In Sec. 2, the E-scale resulting from these requirements is developed and related to the physical variables mass flux density, energy density and energy flux density. Conversion of, for instance, existing Fujita-scale data to the E-scale is an issue of great practical importance and also exemplified there. Secs. 3 and 4 present discussion and conclusions.

2. THE E-SCALE

The E-scale derivation will start from the most widely accepted high wind speed scale, the F-scale from Eq. (2), and then proceed via the related Kelly et al. (1978) scaling, here designated as the K-scale. The velocity ranges and number of scale classes of these well-accepted scales will serve as an exemplary frame of reference for the development of the new scales. Note that the F- and K-scales, as well as the S- and the new E-scales give the class boundaries in wind speed: integer scale values denote the threshold from a lower scale class to the next higher one.

One flaw of, for instance, the current F- and T-scales is that they distinguish more than one sub-

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critical class (so, $X_0 < -1$). Therefore, the first step is to require $X_0 = -1$ as default for any new high wind speed scale in order to avoid unwanted detail with sub-critical winds (note that scales considering any wind speed relevant, like the B-scale, have $X_0 = 0$).

This has interesting implications for the relation of the F-scale to the coarser scaling apparently first described in the scientific literature by Kelly et al. (1978). They grouped two F-scale classes together, yet devised only a verbal description for their scale: [F0, F1] events were termed "weak", [F2, F3] "strong", and [F4, F5] "violent". The one remaining group, [F-2, F-1], was named "sub-critical" by Dotzek et al. (2003). This verbal K-scale can readily be quantified using the above requirement $X_0 = -1$:

$$v(\mathrm{K}) = v_* \, (\mathrm{K} + 1)^{3/2} \,, \quad v_* = v(\mathrm{F}{=}0) = 17.825 \text{ m s}^{-1} \,. \quad (3)$$

Eq. (3) exactly reproduces the F-scale thresholds F-2, F0, F2, F4, F6 for K-scale values K-1, K0, K1, K2, and K3. This is illustrated in Fig. 1, showing that Eqs. (2) and (3) describe the same non-dimensional curve v/v_*.

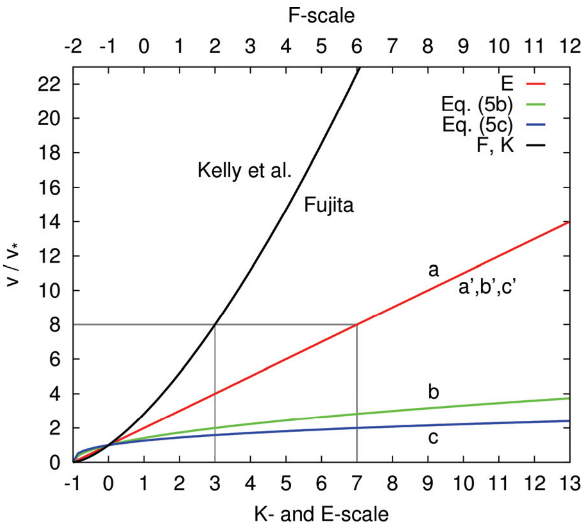

Figure 1: Non-dimensional velocity relations as a function of different wind speed scales. The upper curve represents both Fujita's F-scale definition and the present K-scale alluded to by Kelly et al. (1978). Curves (b) and (c) represent scaling laws from Eqs. (5b,c) with constant steps in energy density (pressure) and energy flux density, respectively. The linear curves (a), (a') have constant steps in mass flux density, and are congruent to (b') and (c'), also in the final form of the E-scale. The lower left rectangles mark the relevant region of application for the E- and K-scales.

Yet, aside from being too coarse, for instance, for statistical modelling of tornado intensity distributions, the K-scale still shows the empirical and arbitrary exponent 3/2, the scaling is not linked to physical quantities, and the width of scale classes strongly grows with increasing K (cf. Fig. 1). The latter is a fact sometimes criticised already in the F-scale context by insurers and wind engineers.

To meet the full set of requirements for the new scales (Dotzek, 2008), any formulation should be based on physical observables, like maximum horizontal wind speed v (or momentum density), maximum values of kinetic energy ($\propto v^2$) or kinetic energy-flux density ($\propto v^3$). They bear more physical relevance than a formal scale variable X and, depending on structural characteristics, v^2 or v^3 are directly related to wind load and damage (cf. Emanuel, 2005; Webster et al., 2005; Dotzek et al., 2005):

$$M = \rho \; v \;, \quad [M] = \text{kg m}^{-2}\,\text{s}^{-1}, \text{ mass flux density}, \quad (4a)$$

$$E = \rho/2 \; v^2 \;, \quad [E] = \text{J m}^{-3} = \text{Pa} \;, \text{ energy density}, \quad (4b)$$

$$P = \rho/2 \; v^3 \;, \quad [P] = \text{W m}^{-2} \;, \text{ energy flux density}. \quad (4c)$$

2.1 Linear scaling in M, E, P

The first and seemingly natural approach is to apply a linear, uniform scaling in each of the quantities *M, E, P* and to relate this to corresponding velocity relations $v(\mathrm{X})$. However, this intuitive approach will prove to be impracticable.

$$M_* \, (\mathrm{X} + 1) = \rho \, v \quad \Rightarrow \quad v(\mathrm{X}) = v_* \, (\mathrm{X} + 1) \;, \quad (5a)$$
$$v_* = \rho^{-1} M_* \;,$$

$$E_* \, (\mathrm{X} + 1) = \rho/2 \, v^2 \quad \Rightarrow \quad v(\mathrm{X}) = v_* \, (\mathrm{X} + 1)^{1/2} \;, \quad (5b)$$
$$v_* = [2\rho^{-1} E_*]^{1/2} \qquad = v_* \, (\mathrm{X} + 1)^{-1/2} \, (\mathrm{X} + 1), \quad = v_*' \, (\mathrm{X} + 1) \;.$$

$$P_* \, (\mathrm{X} + 1) = \rho/2 \, v^3 \quad \Rightarrow \quad v(\mathrm{X}) = v_* \, (\mathrm{X} + 1)^{1/3} \;, \quad (5c)$$
$$v_* = [2\rho^{-1} P_*]^{1/3} \qquad = v_* \, (\mathrm{X} + 1)^{-2/3} \, (\mathrm{X} + 1), \quad = v_*' \, (\mathrm{X} + 1) \;.$$

Eqs. (5a-c) are shown in Fig. 1 and denoted (a), (b), (c), respectively. The scale increments M_*, E_*, and P_* are the quantities which can be used to calibrate the scales. These will necessarily be in the Form $v(\mathrm{X})$.

Unfortunately, Eqs. (5b,c) and Fig. 1 reveal that uniform linear scaling in quantities *E* and *P* does lead to non-linear increments in v, and only for the mass flux density *M* are both scalings in *M* and v linear. Even if formally linearising the non-linear v(X) relations in the last lines of Eqs. (5b,c), the resulting effective v_*' is a monotonic, decreasing function of scale parameter X. Only Eq. (5a) displays a genuinely constant value of v_* compared to the v_*' functions.

Fig. 1 further reveals the major practical disadvantage of linear scaling in non-linear quantities like in Eqs. (5b,c): The exponents 1/2 and 1/3 lead to very slowly increasing functions $v(\mathrm{X})$. Hence, it is almost impossible to map wind speeds of ~143 m s^{-1} (the upper threshold of the F5 range) like those measured in the most violent tornadoes (cf. Potter, 2007) with a limited number of scale classes, unless an unreasonably large value for v_* is chosen (which would, however, make the scale also very coarse again).

2.2 Non-linear scaling in M, E, P – the E-scale

To circumvent the difficulties encountered with the linear scaling in *E* and *P* from Eqs. (5b,c), it is necessary to introduce a non-linear scaling in which the effective $v_*' = \text{const.} = v_*$. Consequently, I finally propose the following generic type of scaling, henceforth termed the "Energy-scale" or E-scale, as the scaling velocities are related to energy via E* or P*:

$$X_* (X - X_0)^n = a_x v^n \Rightarrow v(X) = v_* (X - X_0) \ , \quad v_* = [a_x^{-1} X_*]^{1/n} \ . \quad (6)$$

The scaling quantity X_*, the air density-dependent prefactor a_x and the exponent n depend on the physical observables (M, E, P) in which the non-linear scaling is performed. Application of this scaling leads to modified forms of Eqs. (5a-c), requiring again $X_0 = -1$:

$$M_* (X + 1) = \rho v \Rightarrow v(X) = v_* (X + 1) \ , \quad v_* = \rho^{-1} M_* \ , \quad (7a)$$

$$E_* (X + 1)^2 = \rho/2\, v^2 \Rightarrow v(X) = v_* (X + 1) \ , \quad v_* = [2\rho^{-1} E_*]^{1/2} \ , \quad (7b)$$

$$P_* (X + 1)^3 = \rho/2\, v^3 \Rightarrow v(X) = v_* (X + 1) \ , \quad v_* = [2\rho^{-1} P_*]^{1/3} \ . \quad (7c)$$

For this E-scaling, characterised by linear $v(X)$ functions denoted (a'), (b'), (c') in Fig. 1, all values v_* in Eqs. (7a-c) are constants (but not necessarily the same). This means that for externally specified critical values of M_*, E_*, or P_*, the scaling velocity v_* can be computed (calibration). Or, for any specification of v_* (like with the present F-, S- or T-scales), the corresponding physical quantities M_*, E_*, or P_* can be evaluated for comparison:

$$v_* = \rho^{-1} M_* = [2\rho^{-1} E_*]^{1/2} = [2\rho^{-1} P_*]^{1/3} \ . \quad (8)$$

Note that the Mach- or M-scale for wind speeds from zero to the supersonic range is a special case of an E-scale with externally specified v_* and can also be named E_M-scale here:

$$v(M) = v_* \ M \ , \quad v_* = [\kappa R T]^{1/2} = [\kappa \rho^{-1} p]^{1/2} \approx 340 \text{ m s}^{-1} \ . \quad E_M\text{-scale} \ (9)$$

In Eq. (9), M denotes the Mach number, v_* is the speed of sound, and $\kappa = c_p/c_v$, $R = c_p - c_v$, T, and p have their usual thermodynamic meanings.

2.3 Evaluation and calibration of the E-scale

Dotzek (2008) started with the E-scale formulation of the E_F-scale, designed for the velocity range of the F-scale:

$$v(E) = v_* (E + 1) \ , \ v_* = 17.825 \text{ m s}^{-1} \ . \quad E_F\text{-scale} \quad (10)$$

No claim is being made that this initial value of v_*, equalling $v(F{=}0)$, is the only possible one, but it is chosen here to facilitate the conversion of existing F-scale-rated tornado and damaging wind reports to the E-scale. Relations like Eqs. (9) or (10) for the B-, T-, and S-scales are given by Dotzek (2008).

As the new E-scale is closely linked to the physical quantities of Eq. (4), the scaling quantities

$$M_* = \rho v_* \ , \quad E_* = \rho/2\, v_*^2 \ , \quad P_* = \rho/2\, v_*^3 \quad (11)$$

can be evaluated. Assuming a standard value of ρ = 1.225 kg m^{-3}, each v_* from Eqs. (9) and (10) leads to the physical scaling quantities M_*, E_*, and P_* given by Dotzek (2008). For completeness, note that the Mach-scale is calibrated even though not M_*, E_*, or P_* but v_* is specified, as the speed of sound constitutes a critical value itself.

Future calibration of the E-scales is possible, provided specific values of either M_*, E_*, or P_* are found to be significant, for example from statistical modelling or wind engineering studies. From the statistical modelling of tornado intensity distributions, Dotzek et al. (2005) showed that tornado intensities are exponentially distributed over mass-specific kinetic energy v^2. An exponential distribution implies the presence of a distinguished scaling law with a characteristic decay rate $\propto v_0^{-2}$. The v_0-values reported by Dotzek et al. (2005) were approximately 40 m s^{-1}, corresponding to $E_* \sim 1000$ J m^{-3} from Eq. (11). Interestingly, virtually the same energy scale of ~1000 J kg^{-1} was derived by Schielicke and Névir (2008) and shown to apply for a wide range of atmospheric vortices from tornadoes to tropical and extratropical cyclones. Further proof of a universal energy scale E_* of about 1000 J kg^{-1} (or J m^{-3}) could also provide a foundation to calibrate the E-scales. Once such scaling values have been identified, the E-scales introduced here could easily be adjusted due to their linear v(E) relation.

2.4 Conversion of the F-scale to the E-scale

To gain acceptance for the new E-scale, existing data based on, for example, F- or T-scale ratings should be readily convertible to the E-scale and also keep the workload for re-rating recorded events manageable. Any existing scale obeying Eq. (1) can be converted into the E-scale of Eq. (6) and vice versa by these transformations between $v(E) = v_* (E - E_0)$ and the $v(X)$ relation, in which the primed variables may be non-integer:

$$E' = X_* / v_* \ (X - X_0)^{3/2} + E_0 \ , \quad (12a)$$

$$X' = [v_* / X_* \ (E - E_0)]^{2/3} + X_0 \ , \quad (12b)$$

wherein E and E_0 denote the E-scale variable and offset. The conversion procedure from F- to E_F-scale is illustrated here (cf. Table 1). In this case, $E_0 = -1$, and the choice of initial v_* values was made for compatibility of the main E_F-scale thresholds to those of the F-scale, to facilitate conversion of ratings based on F-scale to the E-scale definitions.

Table 1 shows that due to the initial choice of v* = v(F=0) in Eq. (10), the E_F-scale thresholds E_F-1, E_F0, and E_F7 correspond to F-2, F0, and F6, respectively. In addition, the E_F3 and F3 thresholds are nearly identical. Thus, the E_F-scale has the same upper "end" as the present F-scale and also comprises the same total number of classes as the F-scale, yet it contains only one sub-critical class and hence one more class in the relevant range of present F0 to F5 ratings. The enhanced resolution mainly sets in above the F4 threshold, that is, the F-scale classes [F4, F5] are mapped to [E_F4, E_F5, E_F6], and the thresholds for these classes are effectively lowered compared to the F-scale. This is also the intensity range for which the Fujita-scale forum (McDonald, 2002, cf. www.-april31974.com/fujita_scale_forum.htm) had claimed the largest demand for improvements in the choice of scale class boundaries.

F	v(F) in m s^{-1}	E_F'	E_F integer
-2	0.0	-1.00	-1
-1	6.3	-0.65	-1
0	17.8	0.00	0
1	32.7	0.84	1
2	50.4	1.83	2
3	70.5	2.95	3
4	92.6	4.20	4, 5
5	116.7	5.55	5, 6
6	142.6	7.00	7

Table 1: Conversion of F- to E_F-scale thresholds using $v_{*,E}$ = 17.825 m s^{-1} and $v_{*,F}$ = 6.302 m s^{-1} according to Eq. (8) Note that only the F4, F5 classes would have to be sub-divided into E4, E5, E6 classes in converting F- to E_F-scale data.

As a conclusion of Table 1, should a conversion of the US tornado intensity data from F- to E_F-scale once come on the agenda in the USA, it would mainly require to review the recorded F5 events, which only amounted to roughly 10 per decade in the 20th century (cf. Dotzek et al., 2003). In the same period, about 80 F4 tornadoes per decade were recorded in the USA, of which only the stronger ones would have to be re-rated to E_F-scale based on the available case information. So even for the world's largest tornado database, the workload involved to adopt the E-scale would indeed remain manageable.

Unfortunately, this effort would be severely hampered by an apparent lack of metadata in the US record of tornado and other severe storm reports based on NCDC's *Storm Data* and derived NOAA-SPC severe weather database files; www.spc.noaa.-gov/wcm/SPC_severe_database_description.pdf. The reports contain quantitative information, yet without metadata on the types or reliability of sources.

3. DISCUSSION

The E-scale concept as presented in this paper is physically straightforward and meets several requirements which had been set up especially in relation to the Fujita scale: (i) the E_F-scale has a finer resolution at the upper end of the possible range of tornadic wind speeds, mapping the two classes F4 and F5 to three new classes E_F4, E_F5, E_F6; (ii) by presently maintaining the upper bound of the F5 class (142.6 m s^{-1}) also for the high end of the E_F6 class, the threshold speeds for present F4 and F5 tornadoes are lowered; (iii) there is only one sub-critical wind speed class with the E_F-scale, but instead one more class in the relevant wind speed range, thus also allowing for improved statistical modelling of tornado intensity distributions (cf. Dotzek et al., 2005).

On the one hand, one additional class in the intensity range of significant (F2 or higher) tornadoes will help to better resolve the far wing of the tornado intensity distribution with its necessary steep decrease towards the apparent upper limit of tornado energy. On the other hand, to have only one class more would not lead to possible implication of too much precision in the high ratings, as sometimes argued with respect to the T-scale with its doubled number of classes compared to the F-scale.

One major strength of the E-scales is to allow for a calibration by specifying relevant critical values for the quantities M_*, E_*, or P_* (or v_* itself as in the special case of the Mach scale E_M). Note that all these quantities depend on air density, so in principle, variations in wind loads from compressibility effects or for tornadoes over high terrain are included in the E-scales.

Relying on physical quantities was also one motivation for Emanuel (2005) to develop the Power Dissipation Index (PDI) for tropical cyclones. It is evident that an E-scale based on the scaling quantity P_* is directly linked to the integral measure PDI. Also, to advance from scales based on observed wind damage to the E-scale would be a similar step forward as switching from the Mercalli to the Gutenberg-Richter earthquake scale in geophysics. Mercalli's scale was based on eyewitness and damage reports, with shortcomings very similar to those encountered in present wind event ratings. The Gutenberg-Richter scale, however, is an energy scale. Adopting the E-scale and applying it to the PDI concept could provide a way to measure the total energy expended in a wind event, and this would be much more meaningful than any present point measurement or damage assessment. Interestingly, the new Environmental Seismic Intensity scale (ESI 2007, see Guerrieri and Vittori, 2007) also takes such an integrative approach and combines the previously applied earthquake scales with a new description of damage indicators from the natural environment without man-made structures.

One big advantage of the E-scales is that they are wind speed scales and bin the physically possible range of peak wind speeds by the v(E) relation. Therefore, the E-scales are applicable worldwide, which is an essential prerequisite for building a homogeneous climatology of high wind events and for studying climate change impacts on severe storms as deemed high on the agenda by IPCC (2007).

Yet, some open points remain, despite the evident improvement in wind speed scale design based on the E-scales: Both national variations in building codes and regional or even local variety in building practice or individual structural strength and maintenance status will lead to a spectrum of observed damage for the same given wind speed value or scale class. In addition, the duration of the high wind speeds acting on a given structure plays a role for the degree of damage. This holds in particular for the long-lived high wind regime in tropical and extratropical cyclones, but less so for the quick passage of tornadoes and damaging wind gusts. These principle problems with their inherent uncertainties will likely persist as long as wind speeds will be estimated from damage for practical reasons. The E-scales are expected to mitigate these problems, as they divide the wind speed range into evenly wide velocity bins compared to the nonlinear increase of wind speed (and degree of damage) intervals known from the presently applied scales.

The f-scale matrix (Fujita, 1992) as shown in Fig. 2 aimed at addressing this for the USA building standards by distinguishing between wind speed (F-scale) and typical damage (f-scale) for a given structure at that wind speed. The f-scale concept is another example of providing national damage descriptions for a universal, worldwide-applicable wind speed scale (cf. the other example for Europe mentioned in the introduction). The f-scale approach provided more detail than the original US damage description over F-scale, and remained at a manageable level of complexity.

Damage: f scale		Little Damage f0	Minor Damage f1	Roof Gone f2	Walls Collapse f3	Blown Down f4	Blown Away f5
Windspeed: F scale		F0 (18–33 m/s; 64–118 km/h)	F1 (33–50 m/s; 118–181 km/h)	F2 (50–70 m/s; 181–254 km/h)	F3 (70–93 m/s; 254–333 km/h)	F4 (93–117 m/s; 333–420 km/h)	F5 (117–143 m/s; 420–513 km/h)
To convert f scale into F scale, add the appropriate number							
Weak Outbuilding	−3	f3	f4	f5	f5	f5	f5
Strong Outbuilding	−2	f2	f3	f4	f5	f5	f5
Weak Framehouse	−1	f1	f2	f3	f4	f5	f5
Strong Framehouse	0	F0	F1	F2	F3	F4	F5
Brick Structure	1	–	f0	f1	f2	f3	f4
Concrete Building	2	–	–	f0	f1	f2	f3

Figure 2: The f-scale matrix (adapted from Fujita, 1992) describing the relation of F-scale wind speeds (intensity) and structure-dependent damage (f-scale). For the building type “strong frame house” in the USA, the F- and f-scale ratings are considered identical.

Yet the f-scale never gained widespread acceptance, and mobile Doppler radar measurements of near-surface winds at or slightly above the F6 threshold (cf. Potter, 2007) stoked fears of exaggerated US-media coverage of potential F6-tornadoes. Thus, discussion on improving the F-scale design continued in the Fujita-scale forum (McDonald, 2002, cf. www.april31974.com/fujita_scale_forum.htm) and finally led to the proposition of an “Enhanced Fujita-scale” (EF-scale, McDonald et al., 2004) which became NOAA’s approved tornado wind speed scale from February 2007 on, in spite of ongoing discussion about the new scale (cf. Doswell, 2006; McCarthy et al., 2006; Potter, 2007; Doswell et al., 2008).

In brief, the characteristics of the EF-scale are to retain the numbering of the F-scale classes and in general also the related typical damage, but to specify (based on an “expert elicitation”) significantly lower thresholds for strong and violent tornadoes. Above 200 mi.h^{-1} (89.4 m s^{-1}), no further distinction by the EF-scale is made. The assignment of an EF-scale is based solely on the observed US-type damage, described in much detail by a matrix of 28 Damage Indicators (DI) and a set of Degrees of Damage (DOD) for each DI. The respective merits of the E-scale framework to this EF-scale are further discussed by Dotzek (2008) and Doswell et al. (2008).

In light of the derivation of the E-scales in this paper, in particular the subjective assignment of EF wind speed thresholds corresponding to a certain level of damage seems questionable. In E-scale terminology, one should not adapt v_* to certain national building type or other man-made structures, but proceed the opposite way and provide a world-wide applicable wind speed scale based on physical principles with nationally-adapted damage descriptions – which may well be as detailed as with the EF-scale, should this high level of detail prove feasible.

A key point to be made here again is the importance of defining (and abiding by) an internationally accepted specification of wind speed scales for high wind events like (tropical) cyclones, convective straight-line winds and tornadoes. This paper and Dotzek (2008) substantiate why the E-scale concept is a good candidate to synthesise the present variety of empirical wind speed scales. The effort to identify a large number of damage indicators and to develop detailed degrees of damage for each of them by the EF-scale designers may turn out to be valuable to complement an international E-scale wind speed range by the necessary regional damage descriptions for this range of wind speeds, as advocated here and by Dotzek (2008).

4. CONCLUSIONS

This analysis has led to a new type of wind speed scale, named Energy-scale or E-scale due to the coupling of its scaling quantities to wind energy- or energy flux density. Especially the E_F-scale is proposed to serve as a physics-based alternative to the F-scale. Yet, any scale obeying Eq. (6) is an E-scale and bears the following useful properties:

- The E-scale is based on physical quantities and hence allows for calibration;
- The resulting E-scale versus wind speed relations are always linear;
- The E_F-scale comprises the same number of classes as the F-scale, yet one more class in the relevant range F0 to F5. The enhanced resolution mainly sets in above the F4 threshold, i. e. the classes [F4, F5] are mapped to [E_F4, E_F5, E_F6], so F-scale data would be easy to convert to E_F-scale, if the metadata of US storm databases would only allow for this;
- F-scale thresholds F-2, F0, and F6 are exactly mapped to E_F-1, E_F0, and E_F7, respectively, while the F3 and E_F3 thresholds are nearly identical;

- The E-scale concept can help to unify and reduce the present plethora of different scales for winds from storm to hurricane intensity;
- In the present scientific discussion about appropriate and practicable high wind scales, it will be important to reach an agreement on worldwide standards, in order not to endanger the international comparability of intensity ratings;
- To include variations in building characteristics, one should not adapt the wind speed ranges to national building characteristics. Instead, one worldwide applicable wind speed scale based on physical principles should be complemented by nationally-adapted damage descriptions. The E-scale concept can provide the basis for such a standardised wind speed scale.

To calibrate the E-scales, input from statistical modelling, wind engineering and atmospheric remote sensing is needed to define relevant values of M_*, E_*, or P_* to consistently derive appropriate scaling velocities v_*. Should this be accomplished in the future, conversion among recalibrated E-scales would be easy due to their linear wind speed versus scale relationship.

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