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Assessing a tornado climatology from global tornado intensity distributions

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Abstract

Recent work demonstrated that the shape of tornado intensity distributions from various regions worldwide is well described by Weibull functions. This statistical modeling revealed a strong correlation between the fit parameters *c* for shape and *b* for scale regardless of the data source. In the present work it is shown that the quality of the Weibull fits is optimized if only tornado reports of F1 and higher intensity are used, and that the *c,b* correlation does indeed reflect a universal feature of the observed tornado intensity distributions. For regions with likely supercell tornado dominance, this feature is the number ratio of F4 to F3 tornado reports R(F4/F3) = 0.238. The *c,b* diagram for the Weibull shape and scale parameters is used as a climatological chart which allows to distinguish different types of tornado climatology, presumably arising from supercell vs. non-supercell tornadogenesis. Assuming temporal invariance of the climatology and using a detection efficiency function for tornado observations, a stationary climatological probability distribution from large tornado records (US decadal data 1950–1999) is extracted. This can be used for risk assessment, comparative studies on tornado intensity distributions worldwide, and estimates of the degree of underreporting for areas with poor databases. For the 1990s USA data, a likely tornado underreporting of the weak events (F0, F1) by a factor of two can be diagnosed, as well as asymptotic climatological *c,b* values of $c = 1.79$ and $b = 2.13$, to which a convergence in the 1950-1999 US decadal data is verified.

Keywords: Tornado; Intensity Distribution; Statistical Climatology

1 Introduction

Tornadic storms are a prominent form of severe weather causing significant to devastating damage to man-made structures, forests etc. They occur in all regions worldwide from which thunderstorms are known. Thus, knowledge about tornado intensity distributions is important for both basic climatology research and practical issues like risk assessment (Brooks and Doswell 2001a) and the insurance industry (Dotzek, 2002). Intensity of tornadoes is measured either by the Fujita scale (F-scale, Fujita and Pearson, 1973; Fujita, 1981) or the twice-as-fine TORRO scale (T-scale, Meaden, 1976). The F-scale, which will be used throughout this paper, distinguishes two intensity classes at a time for weak (F0, F1), strong (F2, F3) and violent (F4, F5) tornadoes (Kelly et al., 1978). In the original definition by Fujita and Pearson (1973) and the review by Fujita (1981) the Fujita (F) scale is defined formally equal to the Beaufort[1] (B) scale as (v in m s^{-1})

$$v(B) = 0.84\, B^{3/2}\,, \qquad v(F) = 6.30\, (F + 2)^{3/2}\,. \tag{1}$$

It defines $F = 1$ as the low end of hurricane force winds (33 m s^{-1}) and $F = 12$ as Mach 1 (330 m s^{-1}). In practice, the useful range goes from $F = 0$ to $F = 6$. Note that the Fujita scale classes (F0, F1, … F5) are discrete, while the italicized F denotes a continuous variable. So with the windspeed-based definition given above, $F = -2$ corresponds to $v = 0$, the F-classes comprise integer intervals in F, e.g. F0 ranges from $0 \le F < 1$, and the central value of cass Fn is $F = n + 0.5$.

However, due to a lack of direct windspeed information, in practice F-scale rating is almost exclusively based on observed maximum damage at a given point. This issue has been, and is still under discussion (Doswell and Burgess, 1988; Brooks and Doswell, 2001b;

[1] The original description of the Beaufort scale considers the effect of a 10-minute average windspeed over sea, while the Fujita and TORRO scales are related to the peak windspeeds. However, the *velocity-based* definition of the Beaufort scale in Eq. (1) is applied to both, average *and* peak windspeeds as e.g. for weather forecasts.

McDonald, 2002) and preliminary concepts to include information on strength of man-made structures (Fujita, 1992; Dotzek et al., 2000; Dotzek, 2001) as well as tree damage (Hubrig, 2002, 2004) have been developed.

Recent studies revealed that tornado intensity distributions for the USA and many countries in Europe, South America and other regions worldwide show a similar, quasi-exponential behavior (Brooks, 2000; Brooks and Doswell, 2001b; Dotzek, 2001, 2002). Nevertheless, it remained unclear whether an exponential distribution is indeed an appropriate description for tornado intensities. In their previous work, Dotzek et al. (2003) applied a new statistical modeling in a comprehensive manner to observed intensity distributions from various regions worldwide. It turned out that present tornado intensity distributions seem not to be described properly by exponentials, as they show curvature to the right in lin-log plots even for large databases. Besides, exponentials do not fulfill the physical boundary condition of zero tornadoes with zero windspeed, and cannot reflect the presence of an upper limit to tornado intensities near the F5-F6 threshold following from energy budget calculations. Both can be satisfied by Weibull distributions, which still encompass exponentials as a special case. A Weibull distribution, which is often used with extreme values, "ordinary" windspeeds and even for distributions of tornado path length and width (Brooks, 2004), is given in the following three-parameter form for the probability density $p(x)$ and probability $P(x) = \int_a^x p(x')\,dx'$:

$$p(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} \exp\left(-\left(\frac{x-a}{b}\right)^{c}\right), \quad \forall\ x > a\ ; \tag{2a}$$

$$P(x) = 1 - \exp\left(-\left(\frac{x-a}{b}\right)^{c}\right), \quad \forall\ x > a\ . \tag{2b}$$

Here, a denotes the lower boundary in the variable x (either v or F); b is a scaling factor and c a shape parameter. For $c = 1$, Eq. (2a) reduces to an exponential distribution. Physical and statistical considerations suggest to include negative F-scale values in the intensity analysis, i.e. to apply the scales down to $v = 0$ m/s, as originally proposed by Fujita and Pearson (1973). Using Fujita's $v(F)$ relation from Eq. (1), this leads to $a = -2$ for a Weibull distribution in F. Dotzek et al. (2003) demonstrated that Weibull fits in either v or F reproduce the observations significantly better than exponentials. For each region and time frame under investigation the estimated parameters b and c of the Weibull fit were plotted in a c,b diagram. Therefore each data source is represented by a corresponding point. Structures within this diagram provide information about tornado climatology, e.g. a random distribution of c,b points would indicate that there is neither a temporal nor a spatial relation between different databases. The occurrence of clusters would reveal different groups with similar properties of the tornado intensity distributions. However, Dotzek et al. (2003) have found a strong correlation between the c and b values indicating a "universal" climatological property. For the large (>70 years) US database, the temporal evolution of the c and b values was investigated over several decades. This revealed a convergence towards an asymptotic climatological intensity distribution.

The latter issues were the main motivation for the present paper. In Sec. 2, we address the question how the observed c,b correlation is related to a climatological invariant. Using the large US database, and by introducing a detection efficiency function for tornadoes, a climatological Weibull intensity distribution for presumably supercell-dominated tornadogenesis is derived. Sec. 3 considers the problem of F0 underreporting and rating problems and how the fitting procedure can be optimized. In Sec. 4, the previously proposed characterization of intensity distributions via analyzing the average slope in lin-log plots is extended to an analysis of the neighboring F class occurrence ratio. This suggests using the

c,b diagram for an identification of climatologically distinct areas (e.g. supercell vs. non-supercell tornadoes). Sec. 5 and 6 present discussion and conclusions.

2 Correlation of the Weibull parameters *b* and *c* for tornado intensity distributions

2.1 An invariant property of the distributions

Fig. 1 shows a diagram for the Weibull parameters *c* (shape) and *b* (scale) derived from a fitting procedure to individual tornado intensity data sets from various regions worldwide (cf. figure 6 and tables 5 and 6 from Dotzek et al., 2003). A more detailed discussion of the fitting procedure is given in Sec. 3 of this work.

Part of the F-scale data for this analysis were extracted from Goliger et al. (1997), Peterson (2000), and Teittinen (2000). Updated numbers of the Japanese tornado climatology (cf. Niino et al., 1997), for Ireland, and the United Kingdom were kindly provided for this study within the European Severe Storms Laboratory (ESSL) network[2]. The sources for remaining countries were already given by Brooks and Doswell (2001b). For large databases like from the U.S., splitting the data into individual decades was possible. For most non-U.S. countries having smaller databases, all data from the whole time period with rated tornadoes had to be included to yield a reasonable sample size. The data records, their time periods, and their sample sizes are given in Table 1.

The data vary both in the number of observed F-scale intensities and in the total number of tornadoes. Concerning the maximum reported F-scale value for a given region and time frame we distinguish different classes of data sets as indicated by the symbols in Fig. 1 (observations extending to F3, F4 or F5 events, respectively and small databases with poor statistics, i.e. less than total 100 events excluding F0). The *c,b* data points from regions with observed F5 events follow a curved line, whereas in particular those without F4 and F5 events

[2] http://essl.org

lie significantly below this line. The points corresponding to statistically poor databases exhibit an irregular scattering and, thus, will be excluded from the following analysis.

The line of points formed by the F5-including databases suggests an interdependency of the parameters *c* and *b*, which comes unexpected since they are - by definition of the Weibull distribution - independent parameters. Thus, this relation appears to reflect a general, climatologically relevant property of the corresponding intensity distributions. If so, such a property must be invariant, both regionally and temporally. One possible candidate is the occurrence ratio for neighboring F-scale classes $R(\mathrm{F}n/\mathrm{F}n-1) = N(F)/N(F-1)$, where $N(F)$ denotes the number of reported events for an intensity class F. We choose the R(F4/F3) ratio since it possesses a reasonable statistical sample but is, at the same time, not too strongly affected by the F-dependent detection probability. The latter refers to the fact that weak tornadoes are likely often overlooked since they are on average shorter-lived and cause less significant damage (see next subsection for a more detailed discussion).

Considering all data sets from regions with documented F5 events, which are supposed to have a similar climatology and good statistical quality, we find R(F4/F3) = 0.238(13) [3]. Based on the Weibull probability density distribution from Eq. (2a) we approximate the tornado occurrence per F-scale class by

$$N(F) = N_0\, p(F+2) = N_0 \frac{c}{b}\left(\frac{F+2}{b}\right)^{c-1} \exp\left(-\left(\frac{F+2}{b}\right)^{c}\right) . \qquad (3)$$

Here, we use a = –2 and $F = n + 0.5$ for each discrete F-scale class Fn, and N_0 is the total number of events. From Eq. (3) we can derive the occurrence ratio

[3] Throughout this paper, uncertainties (error bars) of numerical values are given in parentheses for the last significant decimals, e.g. 0.238(13) = 0.238±0.013, or 13.8(20) = 13.8±2.0, respectively.

$$\frac{N(F)}{N(F-1)} = \frac{\left(\frac{F+2}{b}\right)^{c-1} \exp\left(-\left(\frac{F+2}{b}\right)^{c}\right)}{\left(\frac{F+1}{b}\right)^{c-1} \exp\left(-\left(\frac{F+1}{b}\right)^{c}\right)} = \left(\frac{F+2}{F+1}\right)^{c-1} \exp\left(-\left(\frac{F+2}{b}\right)^{c} + \left(\frac{F+1}{b}\right)^{c}\right), \qquad (4a)$$

$$\ln\frac{N(F)}{N(F-1)} = (c-1)\ln\frac{F+2}{F+1} - \left(\frac{F+2}{b}\right)^{c} + \left(\frac{F+1}{b}\right)^{c} . \qquad (4b)$$

For a given ratio, this nonlinear equation has to be solved numerically in order to derive the $b(c)$ relation. Using R(F4/F3) = 0.238 from above, we obtain the solid line $b(c)$ shown in Fig. 1 which reproduces the observed correlation in the *c,b* diagram very well. This indicates once more a similar "universal" climatology for the data samples with points close to this line.

2.2 Extracting a climatological Weibull distribution from US decadal data

The c,b points derived from the US decadal data from 1950-1999 as shown in Fig. 1 reveal a monotonous behavior with time. Dotzek et al. (2003) interpreted this as a convergence towards climatological parameters *c* and *b* of a stationary probability density distribution *p**. To assume stationarity of *p** is also supported by the third IPCC Assessment Report (IPCC, 2001). The observed distribution can then be written as the product of *p**(*F*) and a detection efficiency function $p_d(F)$. The latter is defined as the probability to observe *and* classify an event as a tornado of a certain intensity F[4]. Thus, based on this definition a detected, but unclassified tornado will not occur in the observed intensity distribution. This is important, because, e.g. in the US since 1982, observed tornadoes without rated damage to man-made structures have been assigned as F0 events, no matter how high the windspeeds actually have been (Brooks, 2004). Under the assumption of a temporal invariance of the asymptotic

[4] Further, one could introduce a probability distribution for the error width in assigning the appropriate F-scale. This would then lead to a convolution instead of a simple multiplication. For the sake of simplicity, and due to the lack of information about the shape of such an error distribution, we consider the simple product only.

distribution p^*, we can extract p^* and the time-dependent p_d from the US decadal data by a simultaneous fitting of fixed Weibull parameters and variable detection probabilities to the multiple US dataset with respect to five decades starting in 1950. The fit function is defined as follows:

$$N(F) = N_0 \; p^*(F) p_d(F) \; , \tag{5a}$$

$$p_d(F) = 1 - d \exp\left(-\left((F - f)/w\right)^{2.7}\right) \; (F \geq f) \; , \tag{5b}$$

where N_0 is the total number of tornadoes per decade and d, f, and w are the time-dependent fit parameters. $1–d$ is the detection probability at low F, and w is the width of the detection efficiency function. Before the fitting procedure, the decadal data have been normalized with respect to the average number of F4 observations in order to remove fluctuations in the total number of events among the different decades. F0 data for the 1980s and 1990s were excluded from the fit, since they may contain also tornadoes of higher intensity without having rated damage. This requires also an adjustment of the shift parameter f which is chosen to yield a best fit with $f = –0.5$ for 1950s to 1970s and $f = 1.5$ for 1980s and 1990s, respectively. The result of the fitting procedure is given in Table 2. The Weibull parameters c and b as well as the total number of events N_0 were shared by all five data sets as global fit parameters. Fig. 2a shows the US decadal intensity distributions and the stationary intensity distribution $N^* = N_0 p^*$. The corresponding detection efficiency functions $p_d(F)$ are depicted in Fig. 2b in comparison to the ratio of the observed data and $p^*(F)$, which demonstrates the consistency of the fitting procedure. The error bars are deduced from the statistical error $N^{–1/2}$ of the number of observed tornadoes for a given intensity class. The detection efficiency function gives an estimate for the degree of underreporting which is approximately 50% for weak US tornadoes (F0, F1) in the 1990s. As a result of the fit, we obtain from p^* climatological Weibull parameters $c = 1.79(12)$ and $b = 2.13(20)$ (shown as data point with error bars in Fig. 1) which can be attributed to a supercell-dominated case since presence of

violent (F4, F5) tornadoes is apparently an indicator for supercell tornadogenesis (see Secs. 4 and 5 for further discussion). How well this distribution agrees with other data sets is also seen from Fig. 1, which shows the *c*,*b* dependence (dashed curve) for a constant occurrence ratio R(F4/F3) = 0.177 calculated from p^*.

The knowledge of the climatological Weibull parameters allows for a calculation of the relative occurrence of tornado intensities including subcritical (negative-F) and superviolent events (F6), as given in Table 3. Comparing the calculated values with the US data from the 1990s, we find a reasonable agreement. Also, the tentative estimate of F6 tornadoes being roughly a 10-year event in the USA (Dotzek et al., 2003), is reproduced by our present result. These data are useful for both improved tornado risk assessment and a climatological characterization of other regions worldwide (see also Secs. 4 and 5). The largest uncertainty of the fitting result concerns the number of subcritical tornadoes. However, this extrapolation is more academic since such weak vortices will remain very difficult to detect.

3 The F0 problem and subcritical tornadoes

In their previous work Dotzek at al. (2003) used pseudo-linear regression fitting procedures of the cumulated probability from Eq. (2b) in a linearized form:

$$\ln[-\ln(1-P(x))] = c\,\ln(x-a) - c\,\ln b\,, \tag{6}$$

which has been found to be the most stable method. To obtain the Weibull parameters for various regions their “Procedure II” treated the number of subcritical tornadoes (negative-F) as a free fit parameter and included the observed F0 events as a separate class. In several cases, strong underreporting of F0 events forced the fit to comparatively large *c* values which resulted in an underestimation of the stronger tornadoes (F4, F5). Other problems can emerge from events rated as F0 not being distinguished from subcritical vortices or result from

established rating practice (e.g. apparently in the USA) if no damage to man-made structures is reported. In order to circumvent this, "Procedure I" from Dotzek et al. (2003) may be used. In this case, also the number of F0 events is treated as unknown, and the sum of subcritical and F0 tornadoes (F-2 to F0) is a free parameter. In fact, Fig. 3 reveals that Procedures I and II are special cases of our p_d concept: We have $p_d = \theta(-1)$ for Procedure I and $p_d = \theta(0)$ for Procedure II, respectively, where θ is the unit step function $\theta(x) = \{^{1\ x\geq 0}_{0\ x<0}$. In the following, the effects of these special cases of p_d functions will be demonstrated for the German TorDACH[5] database V 1.4.00 as of spring 2004.

3.1 Example: Data from Germany 855-2004

Fig. 4 shows the tornado intensity distribution for Germany based on 557 intensity-rated observations between the years 855 and 2004 (about 65% of all reported events, most of which having occurred between 1880 and 2004) in comparison with the Weibull fits using Procedure I (solid curve) and II (dashed curve). Procedure II results in a best fit with $c = 3.592$, $b = 4.089$ and $N_0 = 599$, i.e. N(F-2 to F-1) = 45. The result of Procedure I, however, is $c = 2.174$, $b = 2.924$ and $N_0 = 1338$, i.e. N(F-2 to F0) = 877. In the latter case, exclusion of the F0 tornado reports in the fitting procedure brings the Weibull distribution in much better agreement with the observed F1 to F5 data, and the c,b parameters close to the climatological values obtained from the US decadal data. The fit is also self-consistent, as the "input" of N_{in}(F-2 to F1) = 1140 coincides very well with the corresponding value calculated from the cumulative Weibull distribution N_{out}(F-2 to F1) = 1152.

[5] The TorDACH data can be accessed at http://tordach.org.

3.2 Worldwide results excluding F0 observations

The result of fitting Procedure I for various regions worldwide with sufficiently large databases (more than 100 events above F0 intensity) is given in Table 1 in comparison with the values for *c* and *b* from Dotzek et al. (2003) using Procedure II. As shown in Fig. 5, most of the data for Procedure I (bullets) in the *c,b* diagram are shifted towards lower *c* values indicating a better convergence compared to Procedure II (circles). The self-consistency of the fit can either be measured by the ratio of the input number of weak/subcritical tornadoes and the corresponding output (modeled) number from the cumulative distribution as a consistency parameter

$$r_c = N_{in}(\text{F-2 to F1})/N_{out}(\text{F-2 to F1}) , \qquad \text{F0 reports excluded, Proc. I} \qquad (7a)$$

$$r_c = N_{in}(\text{F-2 to F0})/N_{out}(\text{F-2 to F0}) , \qquad \text{F0 reports included, Proc. II} \qquad (7b)$$

or by the well-known χ^2 parameter (e. g. Press et al., 1992). Treating also the F0 reports as an unknown in the Weibull fit yields a convincing improvement of both the self-consistency r_c (see inset in Fig. 5) and the χ^2 values (see Table 1) demonstrating that Procedure I is superior to Procedure II in this respect.

A few data points (8 out of 44) show an increase in *c* of more than 10% if F0 data are excluded from the fit. The corresponding databases are either quite small (e.g. Australia and Canada) or show a large number of F0 events (N(F0) > N(F1), e.g. Oklahoma 1990s – supposedly caused by subcritical tornadoes or tornadoes without rated damage being assigned as F0) or a strong F2 underreporting (N(F2) < N(F3), e.g. France). However, even after a generally improved convergence, we still find a significant number of data points in the *c,b* diagram below the curve of constant R(F4/F3) = 0.177. Thus, the question arises whether a different climatology is associated with these data points. This is addressed in the following section.

4 Worldwide tornado intensity distributions and corresponding climatology classes

4.1 N(F)/N(F–1) ratios for various regions worldwide

As shown in Sec. 2, the occurrence ratio R(F4/F3) seems to reflect a climatological invariant, which agrees well with the data points in the *c,b* diagram for regions with observed F5 tornadoes. This ratio corresponds to a part of the average slope of the intensity distribution, which has been hypothesized as an indicator for the nature of tornadogenesis processes (Brooks and Doswell, 2001b; Dotzek et al. 2003). In the following, we will extend this analysis from the average slope to the individual $N(F)/N(F-1)$ ratios (F = 2, 3, 4) with respect to those datasets without F5 or F4 events, respectively. Fig. 6 shows the ratios for the data records from various regions worldwide. All datasets including observed F4 events show a comparable $N(4)/N(3)$ ratio. Considering the $N(3)/N(2)$ ratio we get again similar values among the F4-including sets except the data from Eastern Colorado and Florida. The latter show significantly lower ratios like Italy and Japan. The lowest $N(3)/N(2)$ ratios are found for the US West Coast, Front Range and the UK. Based on this analysis, we can distinguish three groups. Group A comprises the regions with F4-including tornado records except Eastern Colorado and Florida. The corresponding average ratios are R_A(F4/F3) = 0.230(12) [6], R_A(F3/F2) = 0.318(11), and R_A(F2/F1) = 0.468(24) [7]. For group C, we find values of R_C(F2/F1) = 0.129(34) and R_C(F3/F2) = 0.048(11). Aside from the absence of F4 events this indicates a difference in the climatology compared to group A. Group B likely is an intermediate case with a possibly bimodal $p^*(F)$. A tentative assignment for the climatology of the various regions being of type A, B or C is given in Table 1.

[6] Compare to R(F4/F3) = 0.238(13) from the F5-including subset of group A (Sec. 2).

[7] Excluding the US decadal data before 1950 and the French data since they show a strong underreporting for weak tornadoes.

4.2 The c,b diagram as a chart for tornado climatology

In order to discuss these indications in more detail, we will consider the behavior of the various regions and apparent invariants in the *c,b* diagram. Fig. 7 shows the *b*(c) curves of constant $N(F)/N(F-1)$ ratios corresponding to group A and C and *c,b* data pairs from selected regions. For each of these regions, the fitting results with F0 data included and excluded are given (cf. Table 1) in order to demonstrate their convergence behavior. The shaded areas cover those parts of the *c,b* diagram associated with invariant $N(F)/N(F-1)$ ratios of group A (upper area, $F = 2, 3, 4$) and group C (lower area, $F = 2, 3$). For large values ($c > 4$), these areas start to overlap whereas at lower *c* values we find two well-separated bands. All data points of group A and C, respectively, fit nicely to the corresponding areas in the *c,b* diagram and are also clearly separated by their convergence behavior (exclusion of F0 in the Weibull fit). This consistency again gives a strong indication, if not even evidence, for the existence of at least two different types of tornado climatology and proves the *c,b* diagram to be a useful climatological chart. In Sec. 5 we will give an interpretation within the context of the previously discussed relation of the average slope of intensity distributions to the physical processes for tornadogenesis.

5 Discussion

In the following, we consider our present assessment of tornado climatology through global tornado intensity distributions in the context of previous studies. Brooks and Doswell (2001b) presented a first comparative study of intensity distributions from various regions worldwide. Their analysis revealed an exponential-like behavior of the distributions, being characterized by a nearly uniform slope in a lin-log plot. Since exponentials are determined by a single parameter, exponentials can be considered as a "first order" approach. Two distinct distributions, one apparently associated with supercell tornadogenesis processes and the other

with non-supercell processes, were found in both the US data and in other countries. The lack of a physical boundary condition (zero probability at zero windspeed) for exponentials, and the curvature to the right of observed intensity distributions at larger F in lin-log plots due to the inherent upper limit of tornado intensity near the F5-F6 threshold, led to the use of Weibull distributions (Dotzek et al, 2003). A further improvement is the introduction of a detection efficiency function $p_d(F)$. The latter was - in form of two special cases - already included in the fitting Procedures I and II from Dotzek et al. (2003). Here, $p_d(F)$ is approximated by a unit step function at $F = 1$ (Procedure I) or at $F = 0$ (Procedure II), respectively (see Fig. 3). In both cases, we have no (Procedure II) or at least no detailed (Procedure I) information on $p_d(F)$. Whereas Procedure II requires efficient detection of F0 tornadoes, Procedure I gives quite good fitting results even for tornado records with strong F0 underreporting (see Sec. 3). The effect of $p_d(F)$ on the observed distributions was qualitatively discussed by Dotzek et al. (2003) (cf. figure 7 therein). In the present work a continuous detection efficiency function $p_d(F)$ is explicitly introduced for the "global" fit to the US decadal data (1950 to 1999). Although this procedure works only for such large databases, it yields information about the likely stationary intensity distribution $p^*(F)$ in form of the parameters N_0, c and b. The Weibull parameters c and b can be applied to other regions worldwide with similar intensity distributions and help to estimate the detection efficiency $p_d(F)$ there. Further, knowledge of $p^*(F)$ is very useful for risk assessment and analysis, e.g. to estimate the probability of violent tornado occurrences (including hypothetical F6 tornadoes) and recurrence intervals.

The average slope between F2 and F4 in lin-log intensity distributions used by Brooks and Doswell (2001b) for climatological characterization is related to the c,b correlation discussed in our present work. By extension of the average slope (exponential) to individual ratios $R(\mathrm{F}n/\mathrm{F}n-1)$ of neighboring F-class occurrence (Weibull) we are able to associate

distinct areas in the *c,b* diagram to different groups (A, B, C; see Fig. 6 and Sec. 4). Following Brooks and Doswell (2001b) these differences may be a result of the physical processes leading to tornadogenesis in those regimes. Regions belonging to group A as, e.g. the so-called "tornado alley" (OK-KS-NE) appear to be dominated by supercell tornado events. Whereas the occurrence of violent (F4, F5) events is an indicator for supercell tornadogenesis, the situation for group C is less evident. Here, we find regions like the Front Range, West Coast, or the UK. The Front Range of Colorado has many so-called "landspouts" (e.g., Brady and Szoke, 1989), which appear to hardly exceed F2 intensity. However, from several case studies only, we can merely hypothesize that those regions with similar intensity distributions show in fact a dominance of non-supercell tornadogenesis. A few regions (group B) are found in an intermediate situation regarding their location in the *c,b* diagram and their convergence behavior. Florida and Eastern Colorado seem to be closer to group C but show some F4 events from a presumed supercell "background". Japan seems to be close to group A (similar to South Africa), although no violent tornadoes have been reported, probably due to the relatively short sampling time. The latter concerns also Italy in particular, where supercell tornadoes are well-known but violent events are not contained in the short-range database (1990s). Here, an acquisition of historical data is required, as was done e.g. for Germany and France. In general, more systematic analysis is needed in order to prove whether our hypothesis is valid. In this respect our study on intensity distributions and the use of the *c,b* plot for climatological characterization is only a first step. Future work should concern the cross-relation of tornado intensity and tornadogenesis processes.

We have based the Weibull fits exclusively on the F-scale as it has gained the most widespread acceptance worldwide. However, an adaption of our procedure to derive the *c,b* values from tornado reports based on the T-scale is straightforward. We have also successfully applied the Weibull fits to downburst reports as a function of F-scale. Yet, as

downburst intensity is limited to F3 at most, the fits are then based on four F-scale classes only. So especially for downburst reports, but also for tornadoes, the doubled number of T-scale intensity classes compared to the F-scale appears attractive in principle from a statistical climatological point of view. Unfortunately, quite large databases are required to fill the larger number of T-scale classes with statistically representative data samples, and besides, reports based on T-scale are only available from relatively few countries in the world and often do not show adequate sample sizes. Currently, performing the Weibull fits with T-scale reports cannot provide the global perspective offered by the much more widely used F-scale.

The present analysis is still based on a "practical" (damage-related) measure of intensity. From the climatological viewpoint, a velocity-based analysis would be more appropriate. In fact, the original definition of the F-scale is related *physically* to the windspeed and *not* related *phenomenologically* to the observed damage, i.e. we have the defining relation $v(\mathrm{F})$ given by Eq. (1). The damage "D" follows then from a much more complex relation $\mathrm{D}[v(\mathrm{F})]$ which is strongly variable for different regions. Thus, the simple inversion, which treats $v(\mathrm{F})$ as a function of a damage-related F-scale for a specific region (e.g. USA) will not provide a sensible solution to this dilemma (cf. Doswell and Burgess, 1988; Brooks and Doswell, 2001). A much better way, which at the same time keeps the physical foundation of the (v-related) F-scale, is the use of regionalized damage descriptions in form of a damage-related f-scale as suggested by Fujita (1992). The conversion of the phenomenological f-scale into the physical F-scale (which should be exclusively used for climatological considerations) is achieved by means of a regional "f-scale matrix" individually defined for each specific region worldwide. This, of course, demands a more profound knowledge of the windspeed/damage relation, i.e. to find typical, observable damage. For buildings in Central Europe, Dotzek et al. (2000) introduced typical loss ratios (defined for any damaged object as occured loss divided by reinstatement value) as a measure of observed damage related to the

T- and F-scales (cf. table 1 from Dotzek et al., 2003). Further information can be obtained from an analysis of wind damage to trees, presumably showing less variation all over the world. Recent studies on this topic demonstrated that at least up to T5 (i.e. high F2) intensity it is possible to distinguish even between separate T-scale values (Hubrig, 2002, 2004).

However, even with these recent improvements of the tornado intensity rating procedures, the ratings still remain subjective judgements based on the amount of available information. The maximum intensity of a tornado might have occurred in a place where no adequate structures for a reliable damage estimation have been present, e.g. over open rural terrain. Or a slow-moving and relatively weak tornado may lead to high damage comparable to a stronger tornado moving at a more typical translational speed, simply due to its longer local impact time. Another bias with damage-based intensity ratings can arise if the rating is mainly done by one or only very few individuals in a given country. Here, a systematic under- or overrating might result, which can only be avoided if the responsibility for the ratings relies on a larger group of trained experts. While we are aware of these shortcomings of the present tornado intensity rating procedure worldwide, we have nevertheless shown evidence for the usefulness of the Weibull fitting of global tornado intensity distributions: its climatological signal is physically consistent and contributes to our understanding of tornadoes worldwide.

6 Conclusions

Extending recent work on statistical modeling of tornado intensity distributions by Dotzek et al. (2003), we analyzed the outcome of Weibull fits to the observed data from various regions worldwide with respect to climatologically relevant properties. The present study has revealed the following:

- A correlation of the Weibull parameters c and b found in particular for databases including F5 tornadoes indicates the presence of a globally invariant property of these

distributions. It can be attributed to a fixed ratio of the numbers of tornadoes for neighboring F-classes $R = N(F)/N(F-1)$. The observed correlation in the *c*,*b* diagram is well reproduced by a ratio $R(\mathrm{F4/F3}) = 0.238$ extracted from databases with F5 observations.

- Large tornado records like the US decadal data 1950–1999 show a convergence with time along this $b(c)$ curve. Assuming temporal invariance of the climatology and using a detection efficiency function $p_d(F)$ for tornado observations, we extracted a stationary probability distribution $p^*(F)$ from the US decadal data with Weibull parameters $c = 1.79(12)$ and $b = 2.13(20)$. These can be used for risk assessment and comparative studies on tornado intensity distributions worldwide.
- The detection efficiency function $p_d(F)$ also gives an estimate for the degree of underreporting which appears to be approximately 50% for weak US tornadoes (F0, F1) in the 1990s.
- The number of observed F0 tornadoes can give significant uncertainty to a Weibull fit due to likely inherent strong underreporting, difficult segregation from subcritical vortices and current rating practice (e.g. USA). We demonstrated that excluding F0-report data from our analysis improves the quality of the Weibull fits significantly.
- Extending previous considerations on the average slope of intensity distributions, based on the individual $N(F)/N(F-1)$ ratios ($F = 2, 3, 4$), at least two types of intensity distributions (and bimodal cases) can be distinguished, which may be related to a dominance of supercell and non-supercell tornadogenesis, respectively. In the *c*,*b* diagram, constant $N(F)/N(F-1)$ ratios define separate areas, which are consistent with the Weibull parameters extracted from observations. Thus, the *c*,*b* diagram represents a useful chart for worldwide tornado climatology and characterization of intensity distributions.

Future work should focus on an improvement of the databases, e.g. review of historical events and enhancement of probabilities of detection for the weaker cases. For the latter also more systematic investigation on their genesis is desirable. Here, the regions from group C are of particular interest. If it can be proven that non-supercell tornadogenesis is in general responsible for this type, and provided a sufficiently large data base will be available allowing for detailed analysis like for the US decadal data, the stationary intensity distribution for non-supercell tornadoes could be extracted. This would be very helpful for the analysis of intensity distributions from regions that may significantly experience both types of tornadoes, i.e. have a bimodal $p^*(F)$.

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Table captions

Table 1: Weibull parameters *c* and *b* for fits in *F* starting from F-2 ($v > 0$ m/s) using data from various regions worldwide and two fitting procedures (including and excluding F0 data, respectively). Sample size *N*, maximum observed F-scale intensity and χ^2 values are also shown. The last column gives a tentative assignment for the climatology being of type A, B or C (see Fig. 6 and text).

Table 2: Result for a multiple dataset least squares fit of a climatological Weibull distribution modified with a detection efficiency function from Eqs. (5a,b) to the US decadal data 1950-1999. Uncertainties of free fit parameters are given in parentheses.

Table 3: Absolute 10-year numbers and percentage of tornado occurrence calculated for the USA using the climatological Weibull parameters given in Table 1 compared to the US 1990s data. The variability of calculated values emerging from the uncertainty in the parameters is given in parentheses.

Tables

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Data			Weibull fit in *F* (F0 incl.)			Weibull fit in *F* (F0 excl.)			
Region, time	*N*	F_{max}	*c*	*b*	χ^2	*c*	*b*	χ^2	
USA 1950–1999	39929	5	2.508	3.224	0.0027	2.416	3.124	0.0021	A
USA 1950–1982	20993	5	3.239	3.854	0.0277	2.645	3.389	0.0034	A
USA 1990s	12139	5	1.735	2.151	0.0027	1.927	2.467	0.0020	A
USA 1980s	8192	5	2.658	3.185	0.0097	2.407	2.924	0.0048	A
USA 1970s	8652	5	3.029	3.695	0.0245	2.412	3.136	0.0004	A
USA 1960s	7031	5	3.191	3.814	0.0021	3.028	3.698	0.0003	A
USA 1950s	4915	5	3.485	4.054	0.0168	3.064	3.787	0.0015	A
USA 1940s	1649	5	4.373	4.831	0.0364	4.629	4.903	0.0348	A
USA 1930s	1792	5	3.947	4.516	0.0289	4.024	4.548	0.0296	A
USA 1920s	1391	5	5.025	5.005	0.1570	4.046	4.755	0.0348	A
Oklahoma 1950–1999	2893	5	2.678	3.595	0.0029	2.742	3.652	0.0028	A
Oklahoma 1990s	720	5	1.810	2.452	0.0250	2.605	3.504	0.0095	A
Oklahoma 1980s	515	5	2.409	3.337	0.0052	2.208	3.100	0.0031	A
Oklahoma 1970s	474	5	3.884	4.349	0.0466	3.314	4.062	0.0090	A
Oklahoma 1960s	604	5	3.073	3.915	0.0080	2.923	3.805	0.0062	A
Oklahoma 1950s	580	5	3.182	3.973	0.0407	2.555	3.473	0.0094	A
OK-KS-NE 1950–1999	6755	5	2.566	3.509	0.0077	2.276	3.193	0.0023	A
USA East of CO 1990–2000	10375	5	1.867	2.386	0.0025	1.987	2.572	0.0022	A
Eastern USA 1950–1995	17327	5	3.278	4.061	0.0403	2.646	3.588	0.0053	A
NYNEX 1950–1999	688	4	3.798	3.850	0.0833	2.277	2.820	0.0009	A
Eastern Colorado 1950–1999	871	4	2.738	2.891	0.0127	2.017	2.140	0.0007	B
Florida 1950–1995	2168	4	2.884	3.071	0.0070	2.563	2.803	0.0041	B
Florida 1990–2000	798	3	1.309	1.099	0.0001	1.235	0.971	0.0000	B
CA-OR-WA 1950-1999	327	3	3.473	3.162	0.0001	3.362	3.106	0.0000	C
Front Range 1950–1999	304	3	3.756	3.171	0.0191	2.123	2.042	0.0000	C
Frt Rg / W Coast 1950–1995	631	3	3.595	3.165	0.0046	2.791	2.703	0.0000	C
Argentina 1930–1979	368	5	1.719	2.264	0.0076	1.191	1.196	0.0008	A
France 1680–2000	312	5	4.507	4.796	0.0485	4.785	4.875	0.0454	A
France 1680–1999	294	5	4.588	4.839	0.0633	4.934	4.933	0.0559	A
Germany 855–2004	557	5	3.561	4.077	0.1570	2.174	2.924	0.0031	A
Germany 1453–2003	417	5	3.400	4.017	0.2304	1.658	2.188	0.0001	A
Germany 1453–2002	325	5	3.564	4.011	0.3101	1.612	2.010	0.0008	A
Germany 1453–2001	272	5	3.655	4.093	0.3381	1.650	2.120	0.0014	A
Germany 1453–2000	223	5	3.799	4.186	0.3747	1.689	2.223	0.0003	A
Australia 1795–1999	239	4	2.751	3.253	0.0236	3.821	3.896	0.0000	A
Canada 1950–1998	625	4	2.110	2.641	0.0091	2.932	3.433	0.0003	A
Soviet Union 1795–1986	221	4	3.179	3.547	0.0236	2.282	2.822	0.0033	A
South Africa 1905–2002	204	4	4.294	4.056	0.0261	3.854	3.902	0.0143	A
South Africa 1905–1995	195	4	4.485	4.107	0.0426	3.747	3.844	0.0093	A
South Africa 1905–1990	174	3	5.567	4.171	0.0787	3.240	3.607	0.0000	A
Italy 1990–1999	158	3	5.816	3.949	0.0611	3.592	3.422	0.0000	B
Japan 1961–2000	334	3	4.099	3.83	0.0003	4.236	3.871	0.0000	B
United Kingdom 1950–2002	1047	3	5.750	3.513	0.1397	2.298	1.960	0.0000	C
United Kingdom 1950–1997	944	3	5.968	3.560	0.1617	2.287	1.961	0.0000	C

Table 2: Result for a multiple dataset least squares fit of a climatological Weibull distribution modified with a detection efficiency function from Eqs. (5a,b) to the US decadal data 1950-1999. Uncertainties of free fit parameters are given in parentheses.

		1950s	1960s	1970s	1980s	1990s
	N_0			69400(26150)		
p^*	c			1.79(12)		
	b			2.13(20)		
	f		–0.5		1.5	
p_d	d	0.982(11)	0.946(23)	0.944(24)	0.32(13)	0.49(10)
	w	3.46(25)	2.95(25)	2.61(26)	1.54(36)	2.34(39)

Table 3: Absolute 10-year numbers and percentage of tornado occurrence calculated for the USA using the climatological Weibull parameters given in Table 1 compared to the US 1990s data. The variability of calculated values emerging from the uncertainty in the parameters is given in parentheses.

F-scale	Climatological Weibull fit in *F*			US 1990s	
	N	% (total)	% (F0–F6)	N	%
F-2	15800(9917)	59.1	22.8	–	–
F-1	25197(12277)		36.3	–	–
F0	17448(4508)		25.1	61.4	7370	60.7
F1	7796(1190)		11.2	27.5	3274	27.0
F2	2466(213)		3.55	8.68	1065	8.77
F3	576.0(349)	40.9	0.83	2.03	339	2.79
F4	101.8(81)		0.147	0.358	81	0.667
F5	13.8(20)		0.02	0.049	10/9 [8]	0.082/0.0074
F6	1.4(4)		0.002	0.005	0/1 [4]	0.0/0.0008
Σ F0 to F6	28403(5956)				12139	
N_0	69400(26150)				–	

[8] In the official US tornado database, the Bridge Creek Tornado (OK, 3 May 1999) is rated as F5. Yet, Doppler radar measured near-surface windspeeds (or rather debris particle velocities) at the F5-F6 threshold. An F6 classification of this event would still match the extrapolated probability based on the climatological Weibull fit.

Figure captions

Fig. 1: *c,b* diagram of Weibull parameters *c* and *b* for fits in *F* starting at F-2, i.e. $v = 0$ m/s (from Dotzek et al., 2003). Maximal observed tornado intensity: X, F5; 8, F4; ∀, F3. –, databases with poor statistics. Curves of constant F4/F3 occurrence ratio: solid line, $R = 0.238$ (from regions with F5); dashed line, $R = 0.177$ (from US decadal fit).

Fig. 2: (a) Multiple dataset fit to the US decadal data 1950-1999 using a Weibull distribution $p^*(F)$ multiplied with a detection efficiency function $p_d(F)$. Thick line: climatological distribution $p^*(F)$. Thin lines: individual distributions including $p_d(F)$. (b) Detection efficiency functions $p_d(F)$ (lines) and ratio of observed ratio of the observed data and $p^*(F)$ (symbols) for the individual datasets. For the resulting fit parameters see Table 2.

Fig. 3: Detection efficiency functions $p_d(F)$ (schematic) for fitting Procedures I and II (step functions) and derived from the multiple US decadal dataset fit (continuous function).

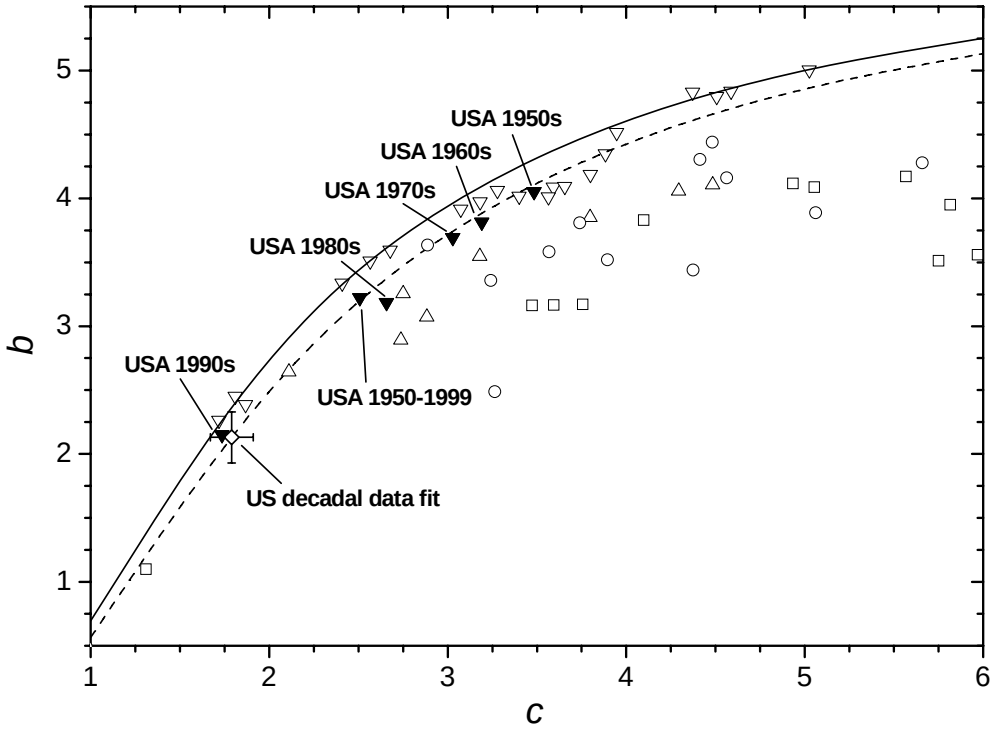
Fig. 4: German tornado intensity data from 855 to 2004. Solid line shows Weibull fit in *F* excluding F0 data; dashed line indicates Weibull fit in *F* including F0 data. See also text and Table 1.

Fig. 5: *c,b* diagram of Weibull parameters *c* and *b*. „ results from Weibull fit in *F* excluding F0 data (Procedure I); –, results from Weibull fit in *F* including F0 data (Procedure II, from Dotzek et al., 2003). Dashed line, curve of constant occurrence ratio R(F4/F3) = 0.177 (from US decadal fit). The inset shows values of the consistency parameter r_c as defined in Eq. (7a,b). See also text and Table 1.

Fig. 6: Occurrence ratios $N(F)/N(F-1)$ (F = 2, 3, 4) for various regions worldwide. Groups with similar ratios: A (presumably supercell dominated); C (presumably non-supercell dominated); B (bimodal case). Group-specific mean ratios are shown as horizontal lines: solid, R(F2/F1); dashed, R(F3/F2); chain, R(F4/F3).

Fig. 7: c,b diagram of Weibull parameters c and b as climatological chart. Areas (shaded) of invariant ratios $R = N(F)/N(F-1)$ for group A (upper area, F = 2, 3, 4) and group C (lower area, F = 2, 3) and corresponding curves of constant R (see also Fig. 6). c,b data for selected regions showing their convergence behavior under exclusion of F0 observations from the fit: full symbols, Procedure I (F0 data excluded); open symbols, Procedure II (F0 data included).

Figures



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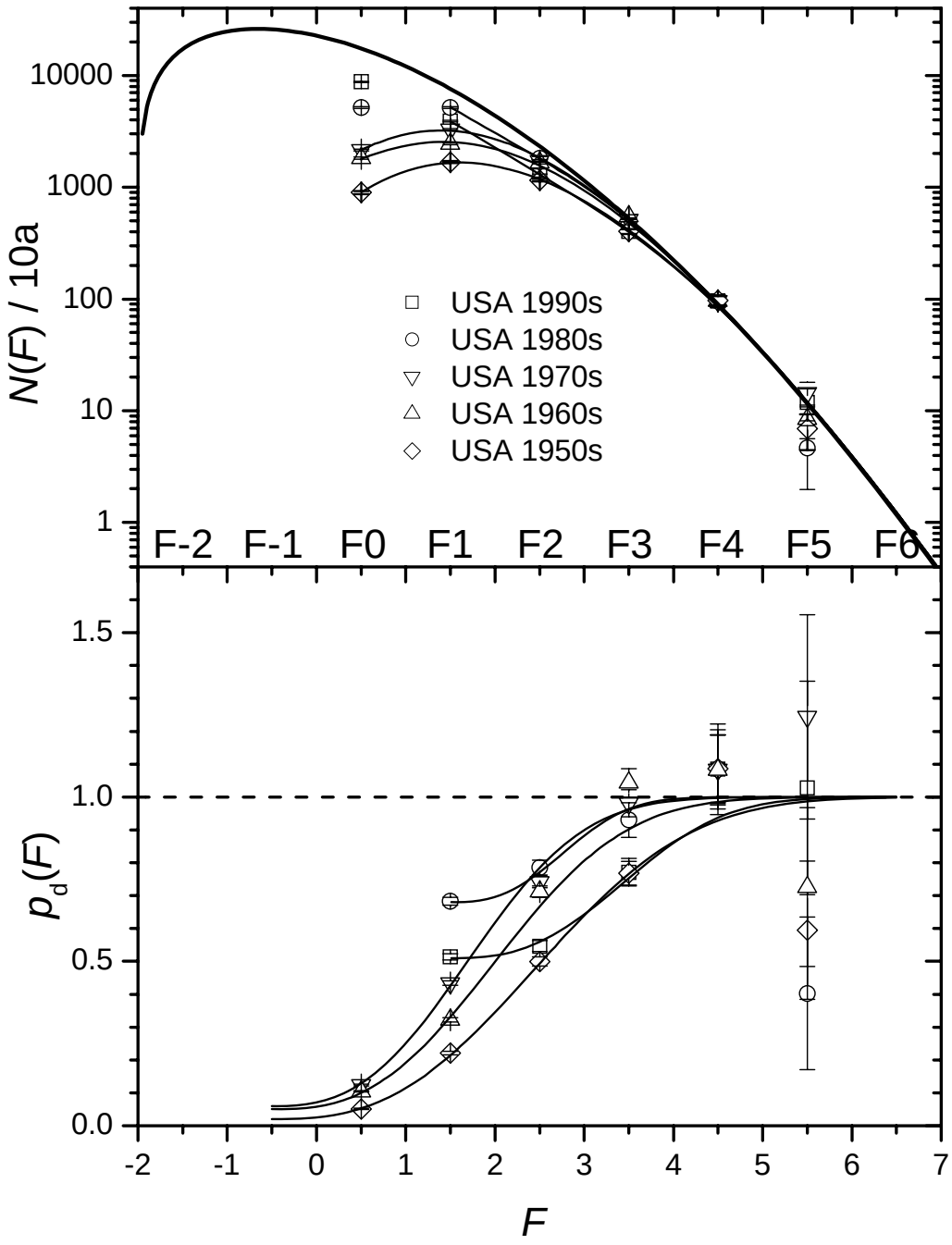

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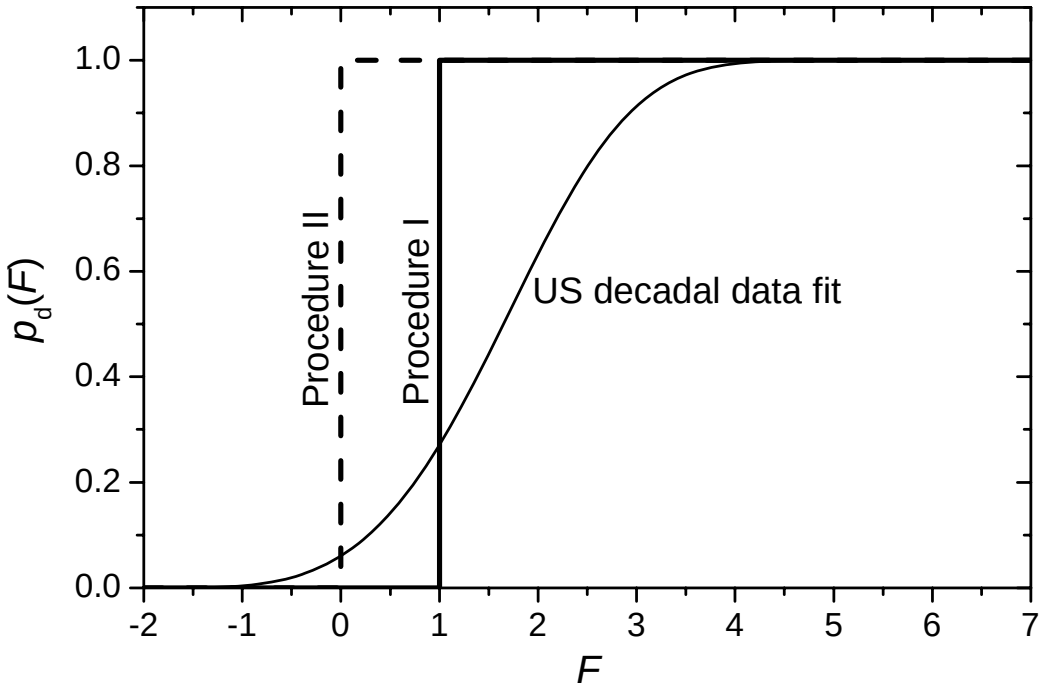

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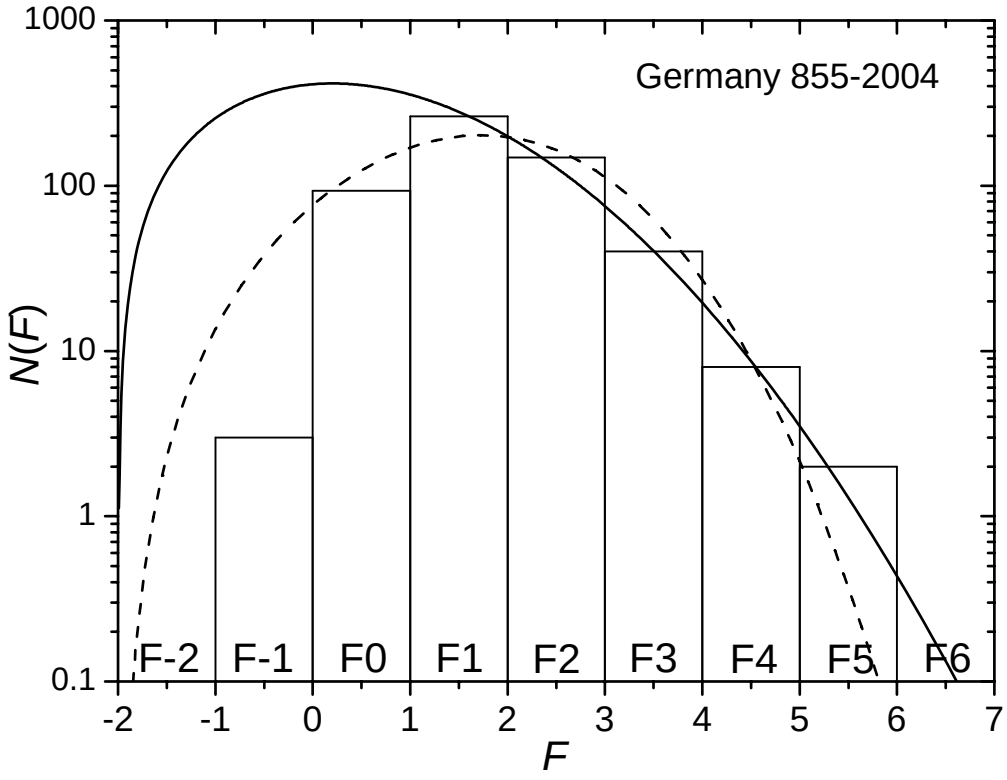

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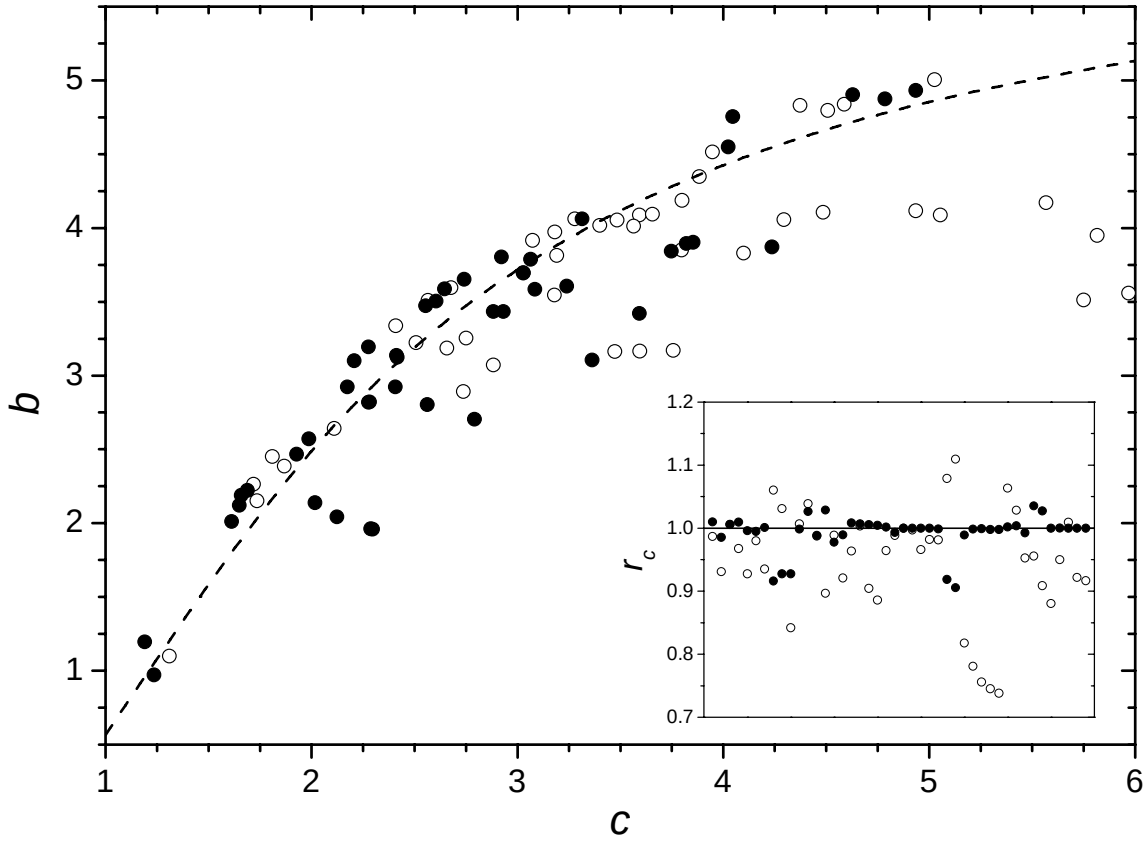

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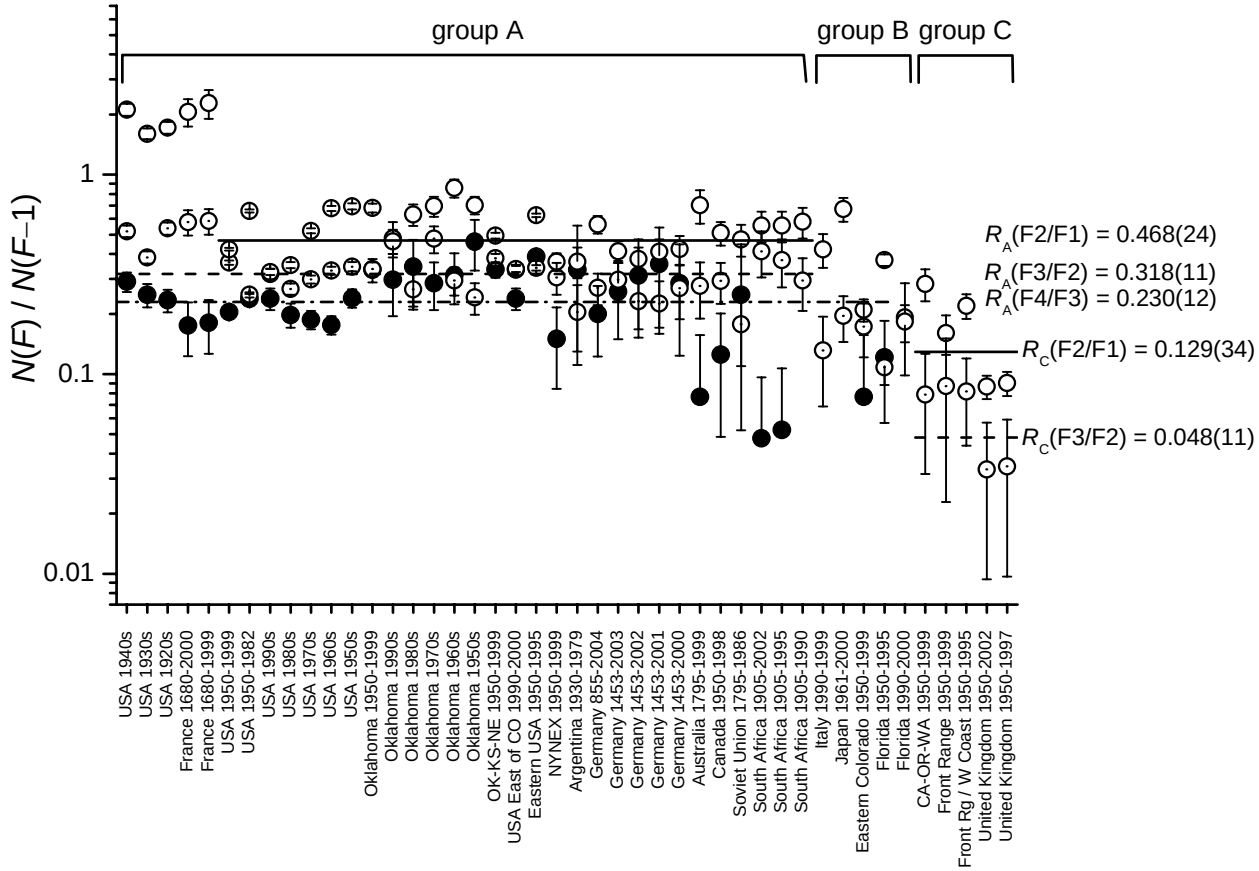

Fig. 6: Occurrence ratios $N(F)/N(F-1)$ ($F = 2, 3, 4$) for various regions worldwide. Groups with similar ratios (see also text): A (presumably supercell dominated); C (presumably non-supercell dominated); B (bimodal case). Group-specific mean ratios are shown as horizontal lines: solid, R(F2/F1); dashed, R(F3/F2); chain, R(F4/F3).

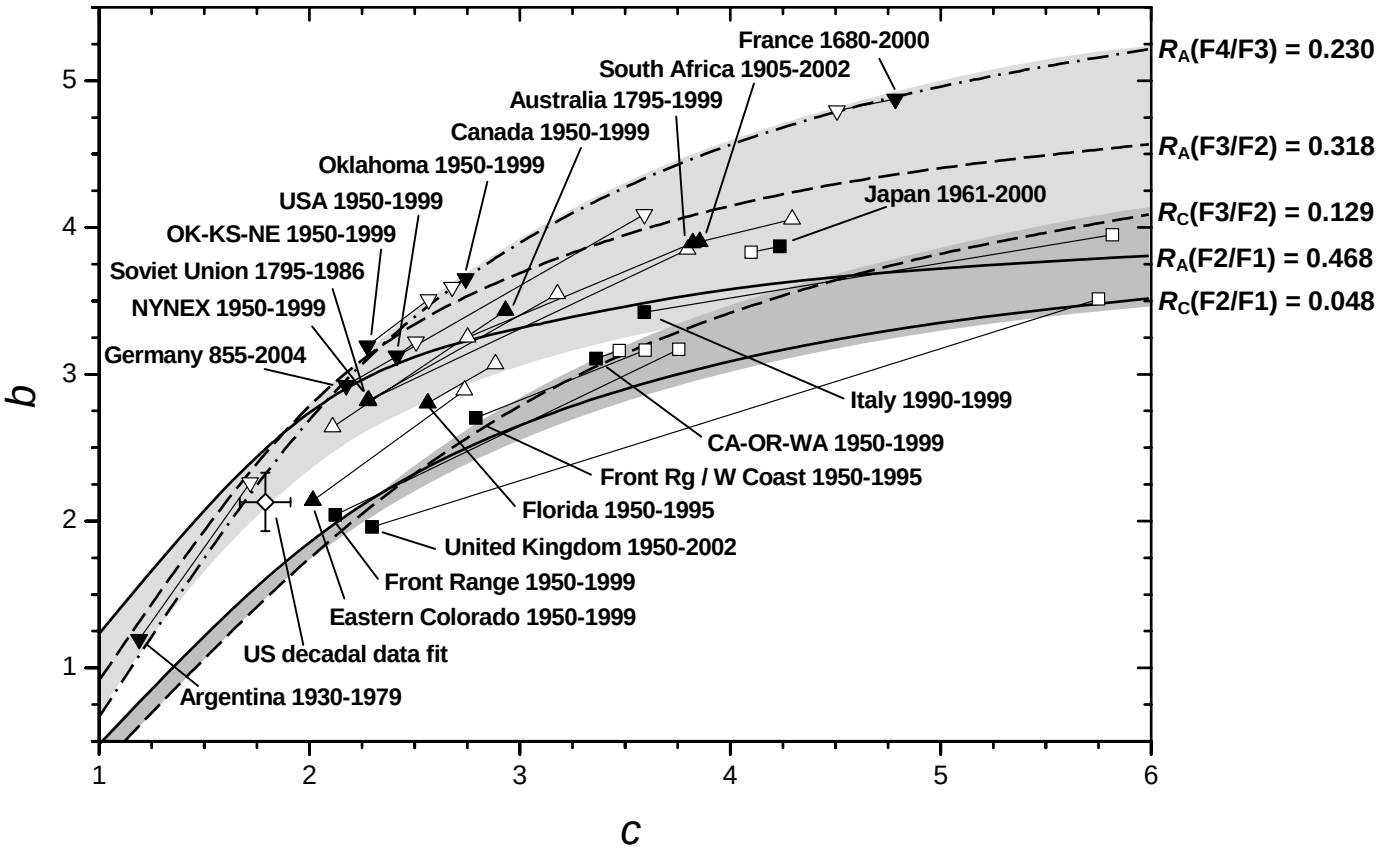

Fig. 7: *c*,*b* diagram of Weibull parameters *c* and *b* as climatological chart. Areas (shaded) of invariant ratios $R = N(F)/N(F-1)$ for group A (upper area, $F = 2, 3, 4$) and group C (lower area, $F = 2, 3$) and corresponding curves of constant *R* (see also Fig. 6). *c*,*b* data for selected regions showing their convergence behavior under exclusion of F0 observations from the fit: full symbols, Procedure I (F0 data excluded); open symbols, Procedure II (F0 data included).