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Abstract

We address the issue to determine an appropriate general functional shape of observed tornado intensity distributions. Recently, it was suggested that in the limit of long and large tornado records, exponential distributions over all positive Fujita or TORRO scale classes would result. Yet our analysis shows that even for large databases observations contradict the validity of exponential distributions for weak (F0) and violent (F5) tornadoes. We show that observed tornado intensities can be much better described by Weibull distributions, for which an exponential remains a special case. Weibull fits in either v or F scale reproduce the observations significantly better than exponentials. In addition, we suggest to apply the original definition of negative intensity scales down to F-2 and T-4 (corresponding to $v = 0\ \mathrm{m\,s^{-1}}$) at least for climatological analyses. Weibull distributions allow for an improved risk assessment of violent tornadoes up to F6, and better estimates of total tornado occurrence, degree of underreporting, and existence of subcritical tornadic circulations below damaging intensity. Therefore, our results are relevant for climatologists and risk assessment managers alike.

Keywords: Tornado; Intensity Distribution; Statistical Climatology; Risk Assessment

1 Introduction

Intensity of tornadic storms, measured either by Fujita's F scale or its twice–as–fine counterpart, TORRO's T scale (Fujita and Pearson, 1973; Meaden, 1976; Fujita, 1981, cf. also Table 1), is a quantity of great practical importance. This holds from both the point of view of individual tornado victims, the insurance industry, and the climatologist evaluating statistical properties of tornado intensity distributions. To know what percentage of reported tornadoes is weak (F0, F1), strong (F2, F3) or violent (F4, F5) is necessary to estimate tornado risk at a given spot (e. g. Thom, 1963) or for a whole country (e. g. Kelly et al., 1978; Schaefer et al., 1986).

The issue of the actual shape of an average tornado intensity distribution is even more important. If there is some universal shape of the distribution, at least for large enough data samples, then this would allow not only for an estimate of risk, but also for an assessment of tornado underreporting depending on F or T scale, and an estimate of total tornado number to be expected in a given country or region.

Since the European Conference on Tornadoes and Severe Storms, ETSS 2000 in Toulouse (Snow and Dessens, 2001), it has become apparent that for the USA and many countries in Europe, South America, and other parts of the world, very similar–looking intensity distributions were found (Brooks and Doswell, 2001; Dotzek, 2001). These distributions showed a nearly exponential distribution in the intensity range from F2 to F4 (T4 to T9). Only for F5, and the weak F0 and F1 tornadoes, the distribution shape deviated from the exponential form. As discussed by Brooks (2000), Brooks and Doswell (2001), Dotzek (2002), and shown in Fig. 1, with ongoing augmentation of tornado databases, the observed intensity distributions should approach the exponential for all F or T scale classes. As Fig. 2a shows, the tornado data for the whole USA followed this trend over the last decades. Nevertheless, the question remained if exponential distributions do indeed present the natural or physical limit for any growing national tornado record, or if other distribution shapes were more appropriate. As mentioned above, finding the right shape of intensity distributions is highly relevant for risk assessment and climatology.

These issues are addressed in our paper. Sec. 2 reviews data from the USA and many other countries worldwide, with a special analysis for Germany. Sec. 3 develops the statistical modeling procedure for tornado intensity distributions and evaluates it with data from various countries worldwide. Secs. 4 and 5 present discussion and conclusions. The Appendix gives the raw F scale database used in our investigation.

2 Intensity distribution data

Due to the formal equivalence of the Fujita and TORRO intensity scales, we will apply them interchangeably in our paper. Fig. 1 and Table 1 illustrate the interrelation between the two scales. In particular, we will usually depict intensity distributions with F scale on a T scale abscissa in Figs. 2–4 as this enables simultaneous plotting of data based on either F or T scale.

2.1 USA data

Looking at the USA data record first, Fig. 2a shows the historical evolution of the USA tornado intensity distribution functions, averaged over the decades from 1920 up to 1999. From F2 to F4 intensity, all curves do indeed fall into a distinct range with uniform slope in this lin–log diagram. Further, it becomes evident that the older distributions are much more curved to the right (low number of weak tornadoes, super–exponential decay for violent tornadoes), and biased to the stronger tornadoes, than the ones from about 1950 on. The 1990s with the largest number of reports, and also the best infrastructure to detect tornadic storms, display only very slight curvature to the right and seem to provide evidence for a temporal transition to an exponential disribution as schematically illustrated in Fig. 1.

When looking at regional data on a state–sized level for the 1990s in Fig. 2b, compared to the distribution for the whole USA, obviously significant curvature to the right and also a variety of slopes in the F2 to F4 range remains. As depicted in Fig. 2c, Brooks and Doswell (2001) were able to show that the average slope apparently is an indicator for dominance of supercell over non–supercell tornadoes. Regions like Florida, the Front Range or the West Coast states California (CA), Oregon (OR), and Washington (WA) experience many non–supercell tornadoes. Accordingly, their intensity distribution has a much steeper slope than for the storms in the socalled “tornado alley” comprising Oklahoma (OK), Kansas (KS), and Nebraska (NE). So, while the slopes could be assigned physical meaning, the curvature to the right present in these different distributions remained unresolved.

To clarify this further, and to make the data more comparable to European countries, Fig. 3a shows the decadal tornado intensity data only for the state of Oklahoma from 1950 to 1999. Being in the heart of tornado alley, and comparable to the size of typical European countries, it is better–suited for comparisons than the whole USA. Again, we have plotted the distribution as a probabiliy density function $p(\mathrm{F})$ over T scale, with the data given for F scale only. Apparently, the slope of the curves in the intermediate intensity range is roughly equal, but even the data for the 1990s still display considerable curvature to the right, especially for strong and violent tornadoes.

The question may be raised if, contrary to prior assumptions, this curvature does indeed represent the real climatological conditions, and if the nearly exponential shape of the 1990s intensity data for the whole USA is a mere smoothing artifact coming from the merger of data from regions with distinct tornado climatologies.

2.2 International data

When data from countries worldwide are concerned, there is usually a much smaller database available than for the USA (e. g. Dotzek, 2003). Yet, some countries do have long and homogeneous tornado records of a size comparable to the numbers from Oklahoma shown in Fig. 3a (cf. Wegener, 1917; Niino et al., 1997; Brooks and Doswell, 2001; Dotzek, 2001).

For a selection of nine countries from both hemispheres and encompassing all continents except Antarctica, Fig. 3b gives their intensity distributions $p(\mathrm{F})$. Aside from the extreme curves for France and the United Kingdom, the other distributions are similar in shape and close together, resembling the functions found for Oklahoma. And common to all distributions is a more or less pronounced curvature to the right.

As a further continental European example, we looked at the German TorDACH tornado record from 1453 to 2001 (cf. Dotzek, 2001, for an overview) in greater detail, provided by the European Severe Storms Laboratory ESSL. Fig. 4a gives the German tornado intensity distribution for all intensity–rated tornadoes in the TorDACH data (about 50% of all). The $+$–symbols give the distribution $p(\mathrm{F})$, while the $\times$–symbols denote the same distribution with T scale, $p(\mathrm{T})$. Especially for the F scale, there is an almost constant slope from F1 to F4 intensity, a significantly lower number of F0 tornadoes and also a slight drop at the F5 tornadoes (which have a very small sample size in Germany). So also in Germany, being almost exactly twice as large as Oklahoma, curvature to the right is found in the current intensity distribution.

The same holds in principle when looking at Germany's historical data $p(\mathrm{F})$ in Fig. 4b for dinstinct sampling periods. These periods were chosen to reflect the sampling by Alfred Wegener (1917), Johannes Letzmann from 1917 to 1939 (cf. Peterson, 1992a,b; Dotzek et al., 2000), two intermediate periods with little tornado research, yet with (1940 to 1979) and without (1980 to 1996) strong and violent tornadoes. The last chosen period is from 1997 until present, starting with the foundation of the TorDACH network and increased tornado reporting via the internet.

We see that the last phase from 1997 on has indeed seen a higher percentage of weak tornadoes, supporting the concept depicted in Fig. 1. What's more, the early period up to 1916 has a very large contribution from strong and violent tornadoes, likely because mainly these have made it into historical archives and chronicles. But in general, all these probability density functions show some degree of curvature to the right.

With this evidence from many different countries worldwide, we will proceed by investigating physical arguments which might support a lower number of very weak and violent tornadoes as compared to an exponential intensity distribution.

3 Statistical modeling

3.1 Observational issues

3.1.1 The F0 problem

There is a problem related to application of the Fujita and TORRO scales for very weak tornadoes. The original definitions by Fujita and Pearson (1973), Meaden (1976), and the review by Fujita (1981) defined the F and T scales formally equal to the Beaufort scale as (v in $\mathrm{m\,s^{-1}}$)

$$v(\mathrm{F}) = 6.30\,(\mathrm{F}+2)^{3/2}\,, \quad v(\mathrm{T}) = 2.36\,(\mathrm{T}+4)^{3/2}\,, \quad v(\mathrm{B}) = 0.84\,(\mathrm{B}+0)^{3/2}\,. \qquad (1)$$

The resulting slight velocity differences between the F and the T scale class boundaries were eliminated in the tabulation by Dotzek et al. (2000). In practice, T0, T1 corresponds to F0; T2, T3 corresponds to F1, and so forth. While Eq. (1) shows that wind velocity $v = 0\ \mathrm{m\,s^{-1}}$ is only attained for negative values of the F and T scales, namely F-2 and T-4, common application imposes a lower limit at F0 = T0 $\approx 18\ \mathrm{m\,s^{-1}}$.

This choice is appropriate in the sense that at about this windspeed corresponding to Beaufort 8 the first, very light damage could be caused by a tornado. This is also reflected in Table 1 showing typical loss ratios

$$\bar{S}\ \text{in}\ \% = 100\,\frac{\text{Damage in EUR or US\$}}{\text{Reinstatement value in EUR or US\$}}\,. \qquad (2)$$

for light ($\bar{S}_{-}$) and strong ($\bar{S}_{+}$) buildings in Central Europe (cf. Dotzek et al., 2000). Near F0 or T0 intensity, the loss ratios first attain nonzero values. Table 1 also depicts velocity ranges for negative F and T scales values as originally designed by Fujita and Pearson (1973) but never seriously exploited afterwards.

What we call "F0 problem" can be described by the following two points:

- First, F0 tornadoes are likely to be overlooked due to their small damage potential and their sometimes very brief lifetimes (cf. Knupp, 2000). This is one of the explanations for strong F0 underreporting especially in earlier decades or centuries.

- Second, the physical phenomenon "tornado vortex" does not start at F0 in a binary fashion. There are definitely many subcritical tornadic circulations in contact with the ground and with a parent convective storm which simply do not reach damaging windspeeds.

- Third, current F scale rating practice e. g. in the USA rates tornadoes causing no damage to man–made structures as F0, no matter how high the windspeeds actually have been.

On some occasions, the negative–F subcritical circulations may be observed, for instance by whirling dust at the ground or a well–defined funnel cloud in a moist atmospheric boundary layer situation. These subcritical tornado vortices are then wrongly classified as F0 events under the current procedure. This neglect results in an aliasing error from the negative F values to the F0 class, resulting in a higher number of events than realistic there.

Assuming a purely exponential intensity distribution to be valid for all F or T classes would further result in an extremely high number of subcritical events (cf. Table 2), as will be further outlined below.

3.1.2 The apparent F5 limit

From Table 1 we see that the upper limit of the F5 class is assumed at 143 m s^{-1}, resulting in total or near–total destruction of buildings ($\bar{S} \approx 100\%$). There exists a long debate among wind engineers and meteorologists about maximum windspeed in tornadoes. For neither the F or T scale a thorough calibration of damage versus windspeed exists. Many authors have argued that the F and T scale velocities at the high end are too large, and that there should be an upper limit at about 125 m s^{-1} based on radar, thermodynamic and damage analyses (Zrnić et al., 1985; Davies–Jones, 1986; Fiedler and Rotunno, 1986; Bluestein and Golden, 1993; Lewellen, 1993;

Golden, 1999). However, in the 3 May 1999 F5 Bridge Creek tornado in Oklahoma, for the first time radar–observed Doppler velocities at only 30 m AGL have reached 142 $\mathrm{m\,s^{-1}}$ (Monastersky, 1999; Davies–Jones et al., 2001). A later re–evaluation of the radar data lead to a velocity estimate of 135 $\pm$ 10 $\mathrm{m\,s^{-1}}$ (J. Wurman, pers. comm, 2002). These values are close to the upper F5 limit or even slightly within F6 from the scales' definition. In addition, there is ongoing debate coming from the modeling community about small regions with transonic velocities in tornadoes (Lewellen et al., 2002). So, even if clear F6 tornadoes have never been reported during the last decades, they might still be 10 to 100–year events.

The apparent existence of a physically motivated upper limit of windspeeds in tornadoes, lying somewhere near the F5 to F6 boundary has important consequences for the tornado intensity distribution shape for violent tornadoes. As "super–violent", i. e. F6 or T12, T13 tornadoes appear highly improbable for physical reasons, the probability of tornadoes approaching this saturation region of intensity should be significantly lower in a relative sense compared to those tornadoes which are still far away from the highest possible intensities. Otherwise, an extrapolation of an exponential intensity distribution to F6 events would lead to an unrealistically large number, as shown in Table 2 which gives 6.5 F6 tornadoes in the USA per decade, making them a 1.5–year event. We cannot expect a homogeneous slope from an exponential distribution from F2 to F4 to extend beyond the F4 limit then. Instead, probability should decrease quicker towards the high end of intensity.

In summary, the arguments concerning the likely physical reality of reduced numbers of F0 and F5 tornadoes compared to exponential distribution shapes, being well–supported for intermediate tornado intensities, result in the conclusion that the overall shape of intensity distribution should indeed be curved to the right as seen in the observational data.

3.2 Fitting procedure

As outlined above, in a lin–log plot and for an intermediate range of F or T scale values the tornado intensity distributions $p(\mathrm{F})$ or $p(\mathrm{T})$ can be well approximated by an exponential, like

$$p(\mathrm{F}) = \exp\left[b - c\,\mathrm{F}\right] . \tag{3}$$

However, the exponential $p(\mathrm{F})$ does neither model the lack of observed F5 tornadoes, nor the missing F0 properly. Also, the number of extrapolated super–violent F6 tornadoes is far too high, cf. Table 2.

The goal of a fitting procedure is then to find a more adequate distribution in order to better understand and model the occurrence of tornadoes. The observed F scale distribution $p(\mathrm{F})$ in the lin–log plot is usually curved to the right.

Evaluation of a number of candidate functions $p(\mathrm{F})$, however, shows that for instance, the sum of two exponentials is always curved to the left in a lin–log plot and thus not superior to the single exponential. The Gumbel distribution has no lower bound on the abscissa, thus not excluding tornadoes with negative windspeed. Even if a Gumbel distribution would fit the observed data better, it could not model them from a physical point of view. Power–law distributions would be represented by straight lines in the log–log plot and a left–curved distribution in the lin–log plot. Therefore, they are also no candidate to model the observational data.

After testing other options like the Gamma distribution as well, we chose the Weibull distribution to model observed tornado intensities. It is often used with extreme values, "ordinary" windspeeds, and even for distributions of tornado path length and width.

The Weibull distribution has three parameters a, b, c, and is given by the following equations for probability density $p(x)$ and probability $P(x)$:

$$p(x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} \exp\left[-\left(\frac{x-a}{b}\right)^{c}\right] \quad , \quad \forall \quad x > a \; , \tag{4}$$

$$P(x) = 1 - \exp\left[-\left(\frac{x-a}{b}\right)^{c}\right] \quad , \quad \forall \quad x > a \; . \tag{5}$$

Here a denotes the minimum value in x, b is a scaling factor, and c is a shape parameter. Note that for $c = 1$ an exponential distribution follows as a special case. Aside from the existence of a lower bound in x, this makes the Weibull distribution well–suited for our purposes.

To clarify any physical significance of parameters b and c, it is useful to look at the first moments, namely mean μ and variance σ^2, and the mode x_d (location of the $p(x)$–maximum) of the Weibull distribution:

$$\mu = a + b\,\Gamma\left(1 + \frac{1}{c}\right) \; , \tag{6}$$

$$\sigma^2 = b^2\left[\Gamma\left(1 + \frac{2}{c}\right) - \Gamma^2\left(1 + \frac{1}{c}\right)\right] \; , \tag{7}$$

$$x_d = a + b\left(1 - \frac{1}{c}\right)^{1/c} \quad , \quad c \geq 1 \; . \tag{8}$$

In Eqs. (6) and (7), Γ denotes the Gamma function.

Parameter c is an indicator of how close to an exponential the Weibull distribution is, and as we are dealing with right–curved distribution functions, we can expect $c \geq 1$. Parameter b is more closely connected to the moments μ and σ^2 of the distribution, e. g. $a + b$ is a proxy to the mean F scale or windspeed in an observed tornado intensity distribution. Thus, as in historical records mainly significant tornadoes were listed, while nowadays also weak tornadoes are often reported, one should see a general decline in the value of b over time.

After choosing the type of function $p(x)$, we can also investigate what best to choose as the independent variable x. Aside from the F or T scale values, a natural variable in order to characterize tornadoes is the windspeed v itself. This appears attractive, as ordinary non–rotational windspeed distributions are long known to be Weibull–distributed. Thus, a first question to answer is, how the distribution in F scale would look like if the v scale distribution were specified.

Assume the windspeed distribution to be $G(v)$ with the density function $g(v) = dG/dv$ and the continuous F scale distribution to be $P(\mathrm{F})$ with the density function $p(\mathrm{F})$. Recall that F and v are uniquely linked by

$$v(\mathrm{F}) = v_0\,(\mathrm{F}+d)^{3/2}\;, \quad \mathrm{F}(v) = v_0^{-2/3} v^{2/3} - d\;, \quad v_0 = 6.30\,\mathrm{m\,s^{-1}}\;, \quad d = 2 \qquad (9)$$

for the F scale. Corresponding formulas for the T scale would be formally equivalent, as Eq. (1) shows. We then have

$$\frac{dv}{d\mathrm{F}} = v_0 \frac{3}{2} (\mathrm{F}+d)^{1/2} \quad \forall \quad \mathrm{F} \geq -d \quad , \qquad \frac{d\mathrm{F}}{dv} = \frac{2}{3} v_0^{-2/3} v^{-1/3} \quad \forall \quad v > 0\,. \qquad (10)$$

The density functions of each of the distributions can now be converted to the other one by the well–known transformation functions

$$p(\mathrm{F}) = g(v) \left| \frac{dv}{d\mathrm{F}} \right| \qquad \text{and} \qquad g(v) = p(\mathrm{F}) \left| \frac{d\mathrm{F}}{dv} \right| \;. \qquad (11)$$

Assuming a Weibull distribution for the velocity (with $v > a$), the distribution $p(\mathrm{F}) = p[v(\mathrm{F})]$ is

$$p(\mathrm{F}) = \frac{3}{2} v_0 (\mathrm{F}+d)^{1/2}\, \frac{c}{b} \left(\frac{v_0\,(\mathrm{F}+d)^{3/2} - a}{b} \right)^{c-1} \exp\left[- \left(\frac{v_0\,(\mathrm{F}+d)^{3/2} - a}{b} \right)^{c} \right] \;. \qquad (12)$$

If the fit is performed in F (with $\mathrm{F} \geq a$), we can directly use the original Weibull distribution:

$$p(\mathrm{F}) = \frac{c}{b} \left(\frac{\mathrm{F}-a}{b} \right)^{c-1} \exp\left[- \left(\frac{\mathrm{F}-a}{b} \right)^{c} \right] \;. \qquad (13)$$

Both parameters b, c are known as soon as the Weibull distribution is fitted to the observational data $p(\mathrm{F})$. The fitting procedure is performed with the cumulative distribution $P(\mathrm{F})$, instead of $p(\mathrm{F})$ itself, thus leading to a pseudo–linear regression problem.

Presently, observed tornadoes are rated as F0 or larger. Thus, as a first step, with either F or v as the independent variable x, the cumulative distribution $P(x)$ can be computed. Taking the logarithm twice from Eq. (5), we obtain:

$$\ln[-\ln(1-P(x)] = c\,\ln(x-a) - c\,\ln b\;. \tag{14}$$

This has the form $Y = B\,X + A$, where $X = \ln(x-a)$, and $Y = \ln[-\ln(1-P(x)]$. Linear regression then yields $B = c$, and $A = -c\,\ln b$. The Weibull parameter a is externally specified depending on fit variable and range. For fits starting at F0, this is either $a = 0$ or $a = 17.819 \simeq 18\ \mathrm{m\,s^{-1}}$.

However, to assume that there do not exist any tornadic cirulations with velocities less than $18\ \mathrm{m\,s^{-1}}$ (F = 0) may not be justified. Thus, in the next step we consider that, though tornadoes with windspeeds less than $18\ \mathrm{m\,s^{-1}}$ are not yet regularly recorded, they physically exist: For instance, a large percentage of funnel cloud reports will indeed have been tornado vortices at the ground with negative F or T scale intensity.

Also in this case the cumulative Weibull distribution $P(x)$ can be fitted to the data. Yet, a problem arises: To compute $P(x)$, the presently unknown number of F-2 and F-1 tornadoes is necessary.

This problem is solved by specifying the unknown sum of F-2 and F-1 tornadoes consecutively from $n = 1$ to a large number N to find out for which number of these negative–F tornadoes the Weibull fit attains the largest explained variance r^2. Note, however, that due to the small number of intensity classes in the Fujita scale, this maximum in r^2 can be rather flat in some cases. In practice, this means that the determined optimal parameters of the Weibull function will then have large standard deviations.

In the case of the fit including negative F scale values, the three open fit parameters are the total number N_0 of tornadoes as well as the parameters b and c of the Weibull distribution. The Weibull parameter a (lower bound in x) is then either $a = -2$ or $a = 0\ \mathrm{m\,s^{-1}}$, of which the latter is the natural lower bound for velocity.

Three slightly differing routines were programmed to find the best and most reliable way to model observed tornado intensity distributions. Procedure I iterates the unknown number of negative–F tornadoes without introducing a separate distribution class for these cases. This means that in the cumlative distribution $P(x)$, the iterated number of negative–F tornadoes is added to the observed F0 tornadoes. So, identical to the simple regression problem when starting the fit at F0 and not at F-2, the first class of $P(x)$ contains all tornadoes with intensities less than F1. This is a straightforward generalization of the case without negative–F tornadoes. However, this procedure turned out to have several disadvantages: First, the information contained in the number of observed F0 tornadoes is lost by merging F0 and negative–F trial cases in one distribution class. Second, this procedure puts a disproportional weight on the (for some databases rather low) number of observed strong tornadoes. For some countries, spurious left–curved distributions were then diagnosed. And last, Procedure I proved not to be fully consistent. The iterated best–fit number of negative–F tornadoes was often not reproduced by the Weibull function derived from this fit. As a consequence, Procedure I was not applied for the Weibull fits presented in this paper.

Procedure II works similar as Procedure I, but treats the negative–F tornadoes as a single additional class of the distribution, thereby preserving the information contained in the F0 observations. This, and the higher number of classes led to a consistent scheme to model the observational data. Procedure II further computes quality measures to determine the significance of the fitting results, standard deviations of the fit parameters (Press et al., 1992), and also the moments from Eqs. (6)–(8).

Procedure III is identical to Procedure II except that the negative–F tornadoes are further split into two classes, F-1 and F-2, for each of which the number of cases is iterated independently. Compared to n trial numbers for the negative–F tornadoes in Procedure II, here we have to solve roughly n^2 independent linear regression problems until the best fit is found. For large databases, this leads to a prohibitive amount of computing time. And besides, as no additional information is introduced by separating the unknown F-1 and F-2 classes, the results obtained with Procedure III were virtually identical to those of Procedure II.

Therefore, only results of Procedure II will be discussed in the following. The lin–log plot of Fig. 5 based on the data from Table 2 outlines the capabilities of the different fitting methods. The step function gives the USA tornado intensity distribution from the 1990s, ranging from F0 to F5. The exponential fit (a) results in an overestimation of F5 and F6 tornadoes (6.5 F6 tornadoes per decade), and an even stronger overestimation of F0 tornadoes. Any subcritical tornadic circulations with negative F values are extremely exaggerated. The Weibull fit starting at F0, i. e. 18 m s^{-1} (b), gives a much better representation of the observations in the range F0 to F5, but does not allow for any climatological statement on the frequency of subcritical vortices. And still, about 2 F6 tornadoes per decade are extrapolated. Starting the Weibull fit at F-2 (c), improves the situation further and also gives the lowest number of 1.3 F6 tornadoes per decade.

In the range from F1 to F5, this Weibull fit is almost alike (b) starting at F0. But now, a reasonable estimate of the subcritical tornadic circulations can be made, dropping to zero cases with zero windspeed, a physical boundary value not satisfied by exponential distributions. Nevertheless, even though Fig. 5 and Table 2 show that the fit of the Weibull distribution from F-2 on describes the observations best, it should be kept in mind that the estimated number of F-2 and F-1 tornadoes is still an extrapolation and requires some (difficult) observational evaluation to test its reliabilty. The number of reported funnel clouds appears to be a good proxy for these subcritical circulations at the ground. Also radar–derived climatologies of mesocyclones might be an option to estimate the number of these currently missing cases (cf. Stumpf and Marzban, 2000; Knupp, 2000).

The accuracy of the fit was similarly or even equally good for Weibull distributions in either F or v, especially when including the negative–F classes. From a statistical point of view, v and F both appear adequate as independent variables to fit tornado intensity distributions. Yet, fits in v have the attractive property to generalize the concept of ordinary straight–line windspeed distributions which can well be represented by Weibull functions.

3.3 Fitting results for various regions worldwide

For applications in statistical climatology it would be highly useful to compare the individual Weibull parameters b, c from different countries worldwide, or distinct climatological regions within large countries like the USA, by our proposed Weibull fitting procedure. In addition, where long and reliable tornado records exist, decadal trends of the parameters b, c can indicate if there is evidence for any convergence to an asymptotic or "universal" distribution.

To perform such an analysis, the F scale data given in the Appendix were extracted from e. g. Goliger et al. (1997), Peterson (2000), Teittinnen (2000), and the European Severe Storms Laboratory (ESSL) network. Also, updated numbers of the Japanese tornado climatology (Niino et al., 1997), for Ireland, and the United Kigdom were kindly provided for this study. Other sources for remaining countries were already given by Brooks and Doswell (2001). Where available, different stages of individual F scale databases were also considered, to detect any temporal trends in the Weibull parameters or the fitting quality.

Results for the Weibull fitting Procedure II are presented in Tables 3 and 4. Based on these data, Fig. 6 gives what we name “cb–plots” for the Weibull fits in v and F, respectively. Initially, a clustering of points from regions with similar tornado climatology was expected as a relationship between b and c.

A large number of available tornado intensity datasets was modeled. Tables 3 and 4 show the resulting c, b parameters and the correlation coefficient, which was the same for both fits in v and F when including the negative–F classes.

The fitting procedure shows a convergence with time for c and b in the USA decadal distributions from 1920 to 1999, visible in Table 3. As expected, c approaches 1, and b generally declines also, as more and more weaker tornadoes have been recorded over the decades. Also, Weibull fits in v are always closer to exponentials than those in F, i. e. their c is closer to 1.

Figs. 6a,b illustrate the fitting results in cb–plots for fits in v and F, respectively. Some scatter in the data occurrs, but an apparent asymptotic upper bound is visible in the c, b data, marked by an approximated linear relationship given by the dashed line.

To decide if the scattered points far away from these limiting functions come from countries with very small databases, short tornado records, or those without violent tornadoes, Figs. 6c,d only give those data coming from intensity distributions which contain F5 tornadoes. This still encompasses countries where there have been only 1 or 2 F5 tornadoes reported. We see that now most of the scatter in the data is gone and the remaining points are those closest to the upper limit in the data region. Also, these data points are aligned like a “string of pearls”, and not distributed erratically. Only weak evidence for clustering is found.

Parameters c and b can now also be used to compare tornado intensity distributions from all over the world with those from the large USA database. Taking again Germany as an example, their Weibull parameters are comparable to those from from the USA in the 1950s.

4 Discussion

Our statistical climatological approach stood the test to model the 1990s USA tornado intensity data with a significant improvement compared to a conventional exponential fit. This improvement became most notable for the F5 and probable super–violent F6 tornadoes — those which pose the largest threat to lives and property — and also for the very weak F-2 to F0 tornadoes. The latter usually do not pose any significant threat, but they are important in a climatological sense. First, determination of their number is needed for any estimate of total tornado occurrence or incidence in a given country or region. Second, to know their number enables us to determine the amount of underreporting in current tornado observations. Third, with improved observation of F0 and probably negative–F tornadoes, reliable knowledge of the weak end of tornado intensity spectra helps to obtain a more reliable fit of the violent end also.

It was found to be convenient to use the accumulated distribution function $P(x)$ instead of the probability density function $p(x)$ for the fitting process. The former leads to a much more reliable estimate of the Weibull parameters due to its integral instead of differential character, especially for small databases or those without reports of violent tornadoes.

For some databases the problem of a rather flat maximum in explained variance r^2 of the Weibull fit exists. This means that for a wide range of parameters around the optimum values c and b, qualitatively almost equal fits can be realized. To circumvent this and reduce the parameters' standard deviation, large numbers of observed tornadoes are necessary. Also, a large number of intensity classes is helpful, at best up to F5 or some day even F6. To include the negative intensity classes of F scale into the fitting procedure further increases the number of classes and the support for fitting algorithms. Finally, should the T scale ever receive wider acceptance, its doubled number of intensity classes might also improve the situation from a statistical point of view.

One finding of our study is that it makes little difference technically if the Weibull distribution function is formulated with windspeed v, expressed via the $v(\mathrm{F})$ relationship, or with F scale directly as the independent variable. When fits start at zero windspeed, i. e. $\mathrm{F} = -2$, the fit results are even identical. Fits starting at F0 or $v \simeq 18\ \mathrm{m\,s^{-1}}$ appear to be slighly improved when the fit is performed in v instead of F. And as ordinary windspeeds are well–known to be Weibull–distributed, we conclude that v should be the variable of choice.

Fits should in any case include the presently neglected negative F scale classes: From our experience, Weibull distributions starting with zero value at the origin (either $v = 0$ or F-2, or for large datasets probably also at T-4) appear to be the most fruitful way to gain internationally comparable intensity distribution parameter sets for statistical climatological analysis.

Negative F or T scale values represent subcritical tornadic circulations which are definitly present in nature, but in most cases hard to detect. While the numbers extrapolated for these classes should of course not be considered as rigorously accurate values, they certainly give an order–of–magnitude impression of what is going on beneath convective storms at intensities lower than the wind damage threshold.

Even though many reported funnel clouds likely were indeed negative F scale tornadoes, obtaining a climatological estimate of their total number from scattered available reports is certainly hopeless. Besides, under the present intensity rating practice, those F-1 or F-2 tornadoes which were luckily being detected due to special meteorological circumstances are wrongly rated as F0 events. Only wide–range remote sensing techniques, like radar–derived climatologies of mesocyclonic thunderstorms might provide a solution to this problem.

Both the exponential distribution and the Weibull fit starting at F0 or T0 intensity fail to model these subcritical vortices. While the Weibull fit starting at F0 by definition cannot provide information here (although giving a very good fit to the observations from F0 to F5 intensity), the exponential certainly overestimates the subcritical circulations. Fig. 5 and Table 2 show that already the F0 class is exaggerated by a factor of about 2 by the exponential, leading to an estimate of total tornado number from F0 to F5 almost 70% higher than observed. Including the F-1 and F-2 data would lead to the conclusion that 246 365 F-1 and F-2 subcritical vortices occur each year in the USA. These numbers do not appear to be reasonable. Instead, the physical boundary value "zero tornadoes with zero windspeed" certainly holds, generally contradicting the idea of a perfectly exponential tornado intensity distribution.

Concerning our choice of Weibull functions to model tornado intensity distributions, Fig. 7 gives a schematic explanation of the relation between "real" and observed tornado intensity distributions. Here we have depicted the loss ratios $\bar{S}$ for Central Europe from Table 1 as well as two different probabilities over F scale. First, the normalized p^* represents the "real" tornado intensity distribution with F scale — that what the climatologist or the risk assessment manager wants to know. The curve p_D, however, gives the probability of detection and classification of a tornadic event. To detect a subcritical vortex with negative F scale has a very small probability, and only from about F3 intensity almost all tornadoes will be detected and correctly classified as tornadoes. Note that this schematic p_D–function closely resembles the shape of the loss ratio curves, especially for $\bar{S}_+$, loss ratios for strong buildings.

What we have as the observed tornado intensity distribution $p(\mathrm{F})$, however, is not $p^*(\mathrm{F})$, but rather a multiplication of p^* and p_D over F scale. Note that one could further 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. So apparently only for strong and violent tornadoes can we expect to observe a good approximation to the real distribution p^*.

The F scale does not end at F5 (e. g. Fujita, 1981). Even though F6 *damage* might hardly be distinguished from F5 damage, F6 *intensity*, i. e. windspeed might be identified in some rare cases by mobile Doppler radars. Windspeeds (or rather velocity of debris particles in the tornado vortex) at the F5–F6 threshold have been observed by radar on 3 May 1999 in the Bridge Creek tornado near Oklahoma City.

Our analysis shows that to upgrade the Bridge Creek tornado from F5 to F6 in the USA data for the 1990s would at least not contradict our Weibull fit result: It extrapolated 1.3 F6 tornadoes in the USA for this time period, making them a roughly 10–year event.

Of course, extrapolations like these again raise the old question on how the F scale should be perceived and applied. The literature on this subject is extensive, and problematic issues of the Fujita scale have been discussed e. g. by Doswell and Burgess (1988), aside from the already mentioned subject of maximum windspeeds in tornadoes. Parallel to an initiative to improve the F scale (McDonald et al., 2002), 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, 2001) have been developed.

One criticism of the F scale (and all F scale criticisms equally apply to the T scale) is that there has never been a thorough calibration of the windspeeds in the F scale definition to the damage description therein. Therefore one might be tempted to say that our Weibull fits in F model damage, while the fits in v model intensity, i. e. inherently uncalibrated windspeeds. In practice, however, such a distinction might be academic. Presently, one should keep to the scales' definitions and equate F scale damage description to the prescribed velocities. That is, it appears most sensible to use the $v(\mathrm{F})$–law as a definition and to try to calibrate any expected damage to the velocity intervals of the F scale. Intensity scales could then be applied to both damage and windspeed information. Yet, should any revised $v(\mathrm{F})$–law ever be determined in an effort to improve the Fujita scale (cf. McDonald et al., 2002), it can readily be implemented into our fitting procedure, and all historic F scale data can immediately be re–evaluated.

Apparently, there is a different perception of tornado intensity scales in the USA and Europe: In the USA, the F scale rating with all its shortcomings is almost exclusively determined from damage to man–made structures, whereas in Europe, either damage to man–made structures and trees, or any available, quality–controlled windspeed measurements are evaluated. In addition, ratings are given only when substantial damage or windspeed data is available. Dubious ratings, i. e. to rate an obviously strong tornado passing over open field without damage as F0, are therefore avoided. Such a case would simply remain unrated in Europe.

We have not yet done the fitting with T scale or the $v(\mathrm{T})$–law as the independent variable. This would be attractive from a statistical point of view due to its doubled number of intensity classes compared to the Fujita scale. But as our experience with plotting intensity over T scale shows (compare Fig. 4 from Dotzek, 2001, with Fig. 4 in the present paper), the fine T scale spacing requires extremely large databases before smooth distribution functions suitable for fitting can be expected. Taking the large USA datasets from the 1950s to the 1990s would be a very good test of the T scale's applicability for such intensity distribution fitting. But unfortunately, USA tornado records do not give T scale, and T scale cannot be uniquely inferred from F scale (although the opposite is true).

5 Conclusions

Our study on statistical modeling of tornado intensity distributions has revealed the following:

- 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, a physical boundary condition requires zero tornadoes with zero windspeed. Both can be satisfied by Weibull distributions which still encompass exponentials as a special case.

- Large databases merging tornado reports from various climatologically distinct regions, such as for the USA, are closest to exponential distributions, and show a trend towards convergence to an asymptotic climatological intensity distribution over the past decades.

- Weibull parameters b, c from countries with larger databases and including F5 observations, come close to an approximately linear relationship in the cb–plot.

- Similar to ordinary windspeed distributions, tornado intensity distributions can best be modeled by Weibull functions in $v(\mathrm{F})$. But using the F scale directly is also practicable.

- From physical and statistical considerations, it is highly advisable to include negative F or T scale values in the intensity analysis, i. e. to apply the scales down to $v = 0\ \mathrm{m\,s^{-1}}$.

Such fits from F-2 or T-4 upward both model subcritical circulations and the risk of F6 tornadoes in the most plausible way.

- Approval of the existence of super–violent F6 tornadoes depends on F scale rating practice. In some countries like the USA, F scale is solely determined by damage, ignoring any available windspeed observations. Yet our statistical modeling suggests F6 tornadoes in the USA to be 10–year events, supported by recent Doppler velocity radar data.

- Total number of tornadic circulations can be estimated when including the negative–F cases: For the USA, this leads to $N_0 = 29\,887$ compared to 12 139 currently observed tornadoes per decade.

- Comparison of Weibull parameters b, c with those from the USA reveals that e. g. the current German tornado data are statistically comparable to the 1950s USA data.

Future work will be devoted to clarify the form and basis of the apparent asymptotic relationship between Weibull parameters b and c. If it holds, it could perhaps be exploited to decide upon the conclusiveness of tornado climatologies of individual regions or countries.

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A F scale data

Tables 5 and 6 give the observational data of tornado reports from various regions and time periods used for our study. The data vary both in the number of observed F scale intensities, and in the total number of tornadoes with F scale rating.

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Tables

Table 1: Generalized Fujita and TORRO intensity scales (Fujita and Pearson, 1973; Meaden, 1976) with terminology following Kelly et al. (1978) and Fujita (1981). Beaufort scale and typical loss ratios for light ($\bar{S}_-$) and strong ($\bar{S}_+$) buildings in Central Europe are also given.

	Subcritical				Weak			
Fujita	F–2		F–1		F0		F1	
TORRO	T–4	T–3	T–2	T–1	T0	T1	T2	T3
Beaufort	0	2	4	6	8	10	12	14
v in m s^{-1}	0 – 3	3 – 7	7 – 12	12 – 18	18 – 25	25 – 33	33 – 42	42 – 51
Δv in m s^{-1}	3	4	5	6	7	8	9	9
v in km h^{-1}	4 ± 4	16 ± 8	34 ± 10	56 ± 12	76 ± 14	104 ± 14	135 ± 16	167 ± 16
$\bar{S}_-$ in %	0.0	0.0	0.0	0.01	0.05	0.10	0.25	0.80
$\bar{S}_+$ in %	0.0	0.0	0.0	0.0	0.01	0.05	0.10	0.25
	Significant							
	Strong				Violent			
Fujita	F2		F3		F4		F5	
TORRO	T4	T5	T6	T7	T8	T9	T10	T11
Beaufort	16	18	20	22	24	26	28	30
v in m s^{-1}	51 – 61	61 – 71	71 – 82	82 – 93	93 – 105	105 – 117	117 – 130	130 – 143
Δv in m s^{-1}	10	10	11	11	12	12	13	13
v in km h^{-1}	202 ± 18	238 ± 18	275 ± 20	315 ± 20	356 ± 22	400 ± 22	445 ± 23	491 ± 23
$\bar{S}_-$ in %	3.0	10.0	30.0	90.0	100	100	100	100
$\bar{S}_+$ in %	0.80	3.0	10.0	30.0	60.0	80.0	90.0	95.0

Table 2: Comparison of tornado reports with F scale in the USA during the 1990s versus exponential and Weibull fits starting at F0 ($v > 18\ \mathrm{m\,s^{-1}}$) or F-2 ($v > 0\ \mathrm{m\,s^{-1}}$), respectively. Numbers for non–negative F scale classes and total tornado number N_0 are also given.

F scale	Observation	Exponential fit in F	Weibull fit in v		Weibull fit in F	
			$v > 18\ \mathrm{m\,s^{-1}}$	$v > 0\ \mathrm{m\,s^{-1}}$	$\mathrm{F} \geq 0$	$\mathrm{F} \geq -2$
F-2	—	193107.1	—	7422.7	—	7422.7
F-1	—	53263.2	—	10556.1	—	10556.1
F0	7370	14691.1	7441.2	7166.2	7856.4	7166.2
F1	3274	4052.1	3256.8	3280.1	3356.8	3280.1
F2	1065	1117.7	1059.9	1106.3	1014.6	1106.3
F3	339	308.3	275.2	286.5	257.2	286.5
F4	81	85.0	58.8	58.4	57.6	58.4
F5	10	23.5	10.6	9.5	11.7	9.5
F6	0	6.5	1.6	1.3	2.2	1.3
Σ F0–F6	12139	20278	12104	11908	12557	11908
N_0	—	266643	—	29887	—	29887

Table 3: Weibull parameters c and b for fits in v and F starting from F-2 ($v > 0\ \mathrm{m\,s^{-1}}$), using USA data. Number of observed F scale classes n and correlation coefficients r are also shown.

Data		Weibull fit in v		Weibull fit in F		
Region	n	c	b in $\mathrm{m\,s^{-1}}$	c	b	r
USA 1950-1999	6	1.672	36.464	2.508	3.224	0.9998
USA 1950-1982	6	2.159	47.670	3.239	3.854	0.9988
USA 1990s	6	1.157	19.880	1.735	2.151	0.9996
USA 1980s	6	1.772	35.810	2.658	3.185	0.9994
USA 1970s	6	2.020	44.752	3.029	3.695	0.9988
USA 1960s	6	2.128	46.928	3.191	3.814	0.9999
USA 1950s	6	2.323	51.432	3.485	4.054	0.9994
USA 1940s	6	2.915	66.901	4.373	4.831	0.9991
USA 1930s	6	2.632	60.455	3.947	4.516	0.9991
USA 1920s	6	3.350	70.537	5.025	5.005	0.9971
Oklahoma 50–99	6	1.786	42.935	2.678	3.595	0.9998
Oklahoma 1990s	6	1.207	24.189	1.810	2.452	0.9965
Oklahoma 1980s	6	1.606	38.401	2.409	3.337	0.9996
Oklahoma 1970s	6	2.589	57.129	3.884	4.349	0.9986
Oklahoma 1960s	6	2.049	48.793	3.073	3.915	0.9996
Oklahoma 1950s	6	2.121	49.883	3.182	3.973	0.9982
CA–OR–WA 90–00	4	2.175	24.709	3.263	2.487	0.9999
CA–OR–WA 50–99	4	2.315	35.418	3.473	3.162	0.9999
E CO 50–99	5	1.825	30.975	2.738	2.891	0.9989
Florida 90–00	4	1.259	15.998	1.889	1.861	0.9974
Florida 50–95	5	1.923	33.902	2.884	3.071	0.9994
Front Rg. 50–99	4	2.504	35.577	3.756	3.171	0.9986
Frt Rg. CO 90–00	4	1.446	16.050	2.169	1.865	0.9876
FrtRg/WCst 50–95	5	2.397	35.470	3.595	3.165	0.9996
NYNEX 50–99	5	2.532	47.583	3.798	3.850	0.9962
OK–KS–NE 50–99	6	1.711	41.409	2.566	3.509	0.9995
USA E 50–95	6	1.245	23.226	1.867	2.386	0.9997
USA E CO 90–00	6	2.186	51.561	3.278	4.061	0.9983

Table 4: As Table 3, but for countries worldwide.

Data		Weibull fit in v		Weibull fit in F		
Region	n	c	b in m s^{-1}	c	b	r
Argentina 30–79	6	1.146	21.461	1.719	2.264	0.9988
Australia 1795–99	5	1.834	36.964	2.751	3.253	0.9979
Austria 10–02	4	3.772	55.731	5.658	4.277	0.9904
Austria 10–01	4	3.041	53.490	4.562	4.162	0.9972
Canada 50–98	5	1.407	27.036	2.110	2.641	0.9986
Finland 97–99	4	3.374	48.307	5.061	3.888	0.9935
France 1680–00	6	3.005	66.178	4.507	4.796	0.9989
France 1680–99	6	3.058	67.057	4.588	4.838	0.9986
Germany 1453–03	6	2.267	50.720	3.400	4.017	0.9909
Germany 1453–02	6	2.376	50.603	3.564	4.011	0.9889
Germany 1453–01	6	2.436	52.175	3.655	4.093	0.9885
Germany 1453–00	6	2.533	53.946	3.799	4.186	0.9882
Ireland 50–01	4	2.597	41.594	3.895	3.519	0.9999
Italy 90–99	4	3.877	49.434	5.816	3.949	0.9981
Japan 61–00	4	2.733	47.240	4.099	3.831	0.9999
Japan 50–69	4	2.160	38.758	3.241	3.357	0.9999
S Africa 05–02	5	2.862	51.465	4.294	4.056	0.9991
S Africa 05–95	5	2.990	52.430	4.485	4.107	0.9986
S Africa Inkanyamba*	4	3.369	52.086	5.053	4.089	0.9980
S Africa Inkanyamba	4	3.289	52.621	4.934	4.117	0.9983
S Africa 05–90	4	3.711	53.669	5.567	4.171	0.9973
Soviet Union 1795–86	5	2.119	42.090	3.179	3.547	0.9985
Switzerland 50–02	4	1.925	43.665	2.887	3.635	0.9991
United Kingdom 50–02	4	3.833	41.489	5.750	3.513	0.9955
United Kingdom 50–97	4	3.979	42.323	5.968	3.560	0.9952

Table 5: Number of F scale–rated tornadoes from regions and time periods in the USA.

Region, time	F0	F1	F2	F3	F4	F5
USA, 1950-1999	16068	14816	6262	2272	465	46
USA, 1950-1982	5212	8466	5559	1388	330	38
USA, 1990s	7370	3274	1065	339	81	10
USA, 1980s	3313	3329	1172	313	62	3
USA, 1970s	2396	3653	1910	570	107	16
USA, 1960s	1951	2615	1769	584	103	9
USA, 1950s	1038	1945	1346	466	112	8
USA, 1940s	174	322	682	355	103	13
USA, 1930s	274	447	717	276	69	9
USA, 1920s	73	336	578	311	73	20
Oklahoma, 1950-1999	981	960	652	219	73	8
Oklahoma, 1990s	428	166	77	37	11	1
Oklahoma, 1980s	192	173	109	29	10	2
Oklahoma, 1970s	70	190	132	63	18	1
Oklahoma, 1960s	160	202	173	51	16	2
Oklahoma, 1950s	131	229	161	39	18	2
CA–OR–WA, 1990–2000	152	50	3	0	0	0
CA–OR–WA, 1950–1999	152	134	38	3	0	0
Eastern Colorado, 1950–1999	425	357	75	13	1	0
Florida, 1990–2000	625	142	26	5	0	0
Florida, 1950–1995	1009	817	305	33	4	0
Front Range, 1950–1999	136	143	23	2	0	0
Front Range of Colorado, 1990–2000	183	20	5	0	0	0
Front Range/West Coast, 1950–1995	288	277	61	5	0	0
NYNEX, 1950–1999	153	358	131	40	6	0
OK–KS–NE, 1950–1999	2211	2590	1280	487	163	24
USA East of Colorado, 1990–2000	5849	3061	1030	343	82	10
Eastern USA, 1950–1995	3547	7142	4463	1523	591	61

Table 6: As Table 5, but for countries worldwide. For South Africa, the *Inkanyamba* data given by Goliger et al. (1997) were evaluated both excluding and including less reliable ratings. The latter is indicated by the asterisk.

Region, time	F0	F1	F2	F3	F4	F5
Argentina, 1930–1979	191	120	44	9	3	1
Australia, 1795–1999	111	67	47	13	1	0
Austria, 1910–2002	4	30	21	5	0	0
Austria, 1910–2001	5	13	7	4	0	0
Canada, 1950–1998	355	161	82	24	3	0
Finland, 1997–1999	4	16	5	1	0	0
France, 1680–2000	33	62	128	74	13	2
France, 1680–1999	30	54	123	72	13	2
Germany, 1453–2003	69	221	91	27	7	2
Germany, 1453–2002	51	183	69	16	5	1
Germany, 1453–2001	39	151	62	14	5	1
Germany, 1453–2000	29	123	52	14	4	1
Ireland, 1950–2001	15	19	8	1	0	0
Italy, 1990–1999	25	90	38	5	0	0
Japan, 1961–2000	87	137	92	18	0	0
Japan, 1950–1969	62	62	27	5	0	0
South Africa, 1905–2002	39	92	51	21	1	0
South Africa, 1905–1995	32	92	51	19	1	0
South Africa, Inkanyamba*	29	91	49	16	0	0
South Africa, Inkanyamba	26	82	48	16	0	0
South Africa, 1905–1990	20	88	51	15	0	0
Soviet Union, 1795–1986	71	95	45	8	2	0
Switzerland, 1950–2002	3	4	2	1	0	0
United Kingdom, 1950–2002	292	693	60	2	0	0
United Kingdom, 1950–1997	240	644	58	2	0	0

Figure captions

Figure 1: Schematic diagram of most contemporary European tornado intensity distributions over T and F scale (solid, also valid for the USA before 1960) and requird future changes (arrows) to an earlier–proposed climatological exponential distribution (dashed).

Figure 2: USA tornado intensity distributions $p(\mathrm{F})$ plotted over T scale: a) decadal data from 1920 to 1999, b) normalized regional distributions $N^*(\mathrm{F})$ (1950–1999) compared to total USA in the 1990s, c) categorization of regional $N^*(\mathrm{F})$ distributions into likely supercell or non–supercell storm dominance. For $N^*(\mathrm{F})$ in b),c), the number of F2 tornadoes is fixed to 100.

Figure 3: Distributions $p(\mathrm{F})$ plotted over T scale for a) Oklahoma in the decades from 1950 to 1999, and b) various countries all over the world.

Figure 4: German data from 1453–2001: a) current intensity distributions of all tornadoes over F and T scale, b) the same data over F scale split into characteristic phases of German tornado research.

Figure 5: Comparison of three different fits to the observed USA 1990s decadal intensity distribution with F scale (step function) according to Table 2: a) exponential fit, b) Weibull fit in v starting at F0 intensity (18 $\mathrm{m\,s^{-1}}$), and c) Weibull fit in v starting at F-2 intensity (0 $\mathrm{m\,s^{-1}}$).

Figure 6: Climatological cb–plots of Weibull parameters c and b for fits starting at F-2, i. e. $v = 0\ \mathrm{m\,s^{-1}}$: a),c) fits in v; b),d) fits in F. Data from Tables 3 and 4. In panels c),d) only data from regions with F5 tornadoes are depicted.

Figure 7: Schematic showing a normalized “real” tornado intensity distribution p^* starting at F-2 (0 $\mathrm{m\,s^{-1}}$), an estimate of the probability of detection of a tornado p_D, and the loss ratios $\bar{S}_-$ and $\bar{S}_+$ from Table 1 valid for Central Europe.

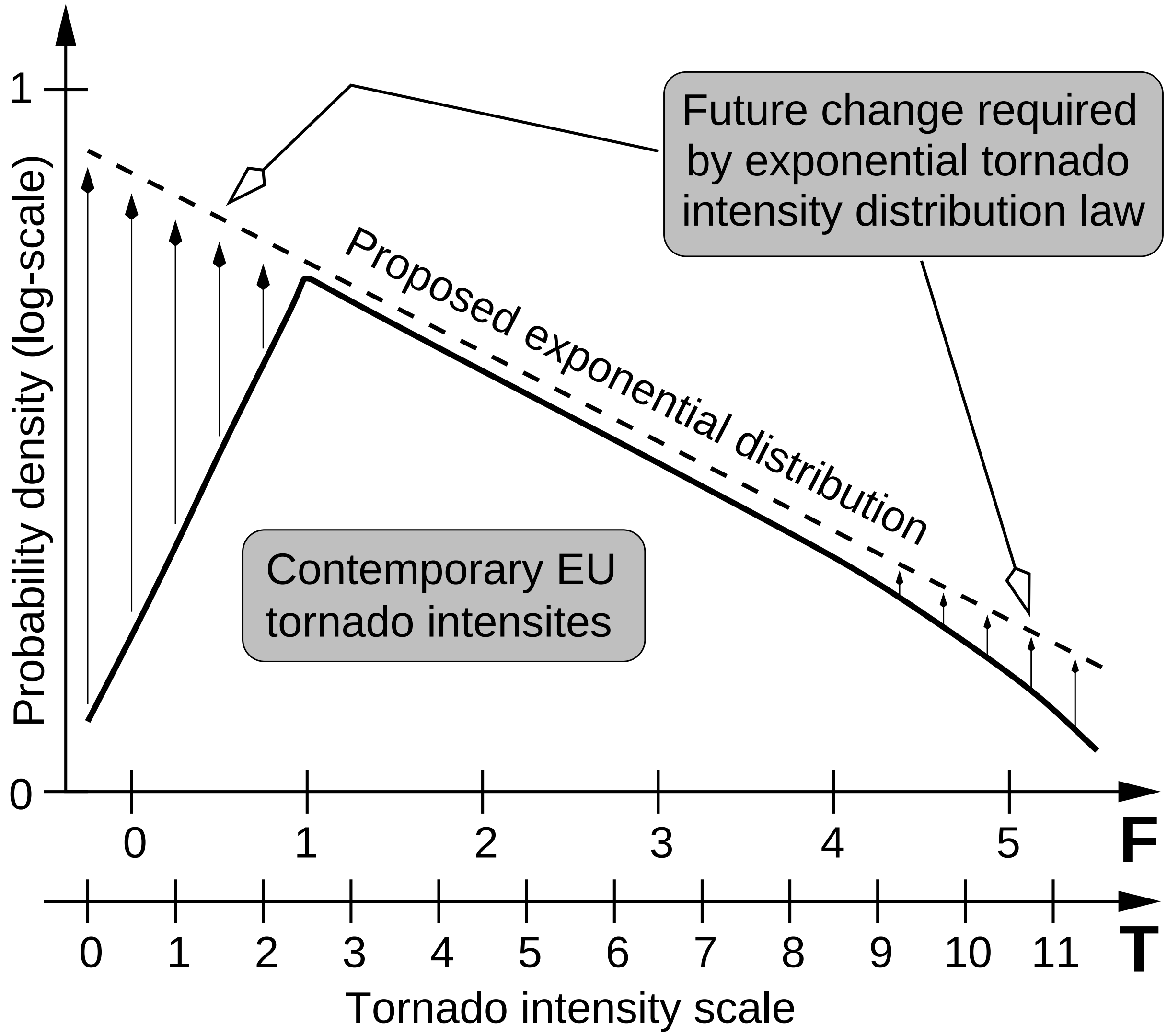
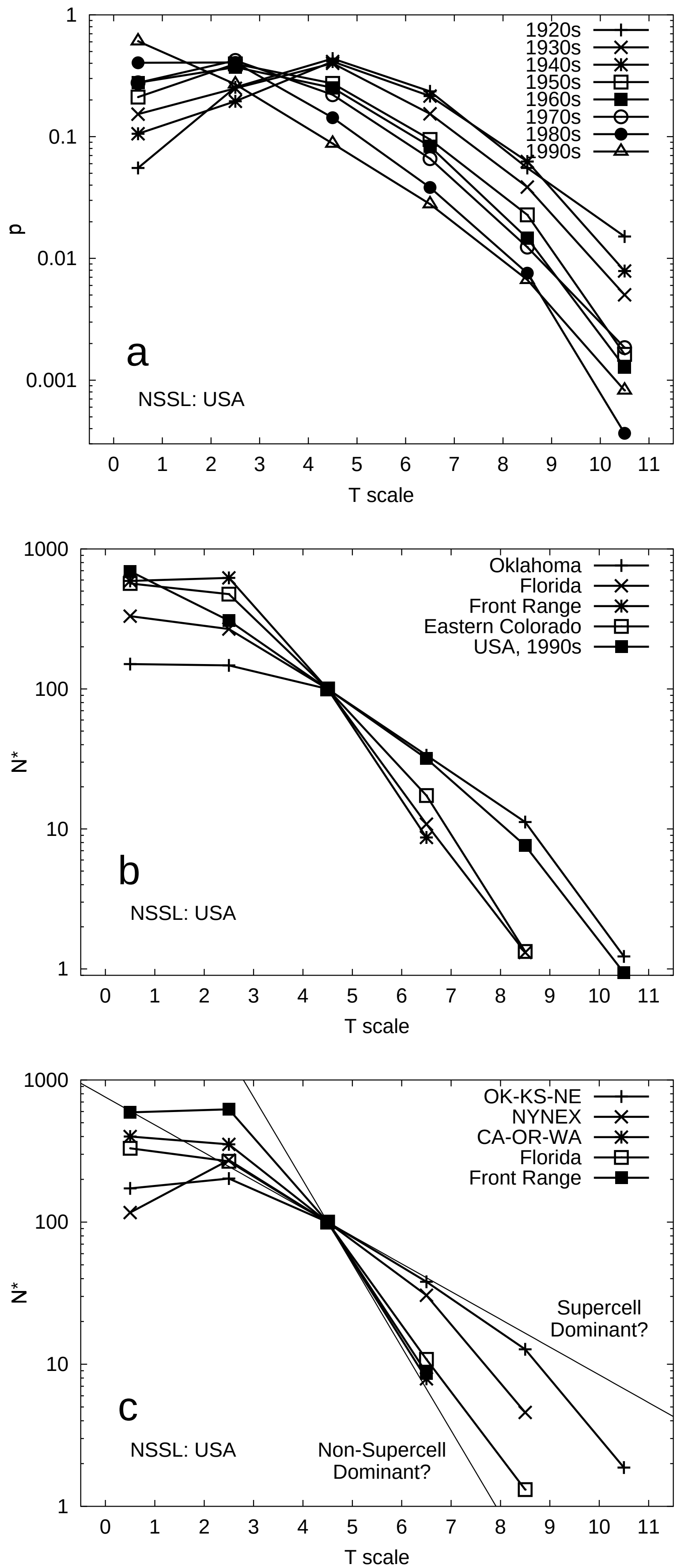

1
0
Probability density (log-scale)
Future change required
by exponential tornado
intensity distribution law
Proposed exponential distribution
Contemporary EU
tornado intensites
0
1
2
3
4
5
F
0
1
2
3
4
5
6
7
8
9
10
11
T
Tornado intensity scale

Figure 1



1920s
1930s
1940s
1950s
1960s
1970s
1980s
1990s
a
NSSL: USA
p
T scale
Oklahoma
Florida
Front Range
Eastern Colorado
USA, 1990s
b
NSSL: USA
N*
T scale
OK-KS-NE
NYNEX
CA-OR-WA
Florida
Front Range
Supercell
Dominant?
c
NSSL: USA
Non-Supercell
Dominant?
N*
T scale

Figure 2

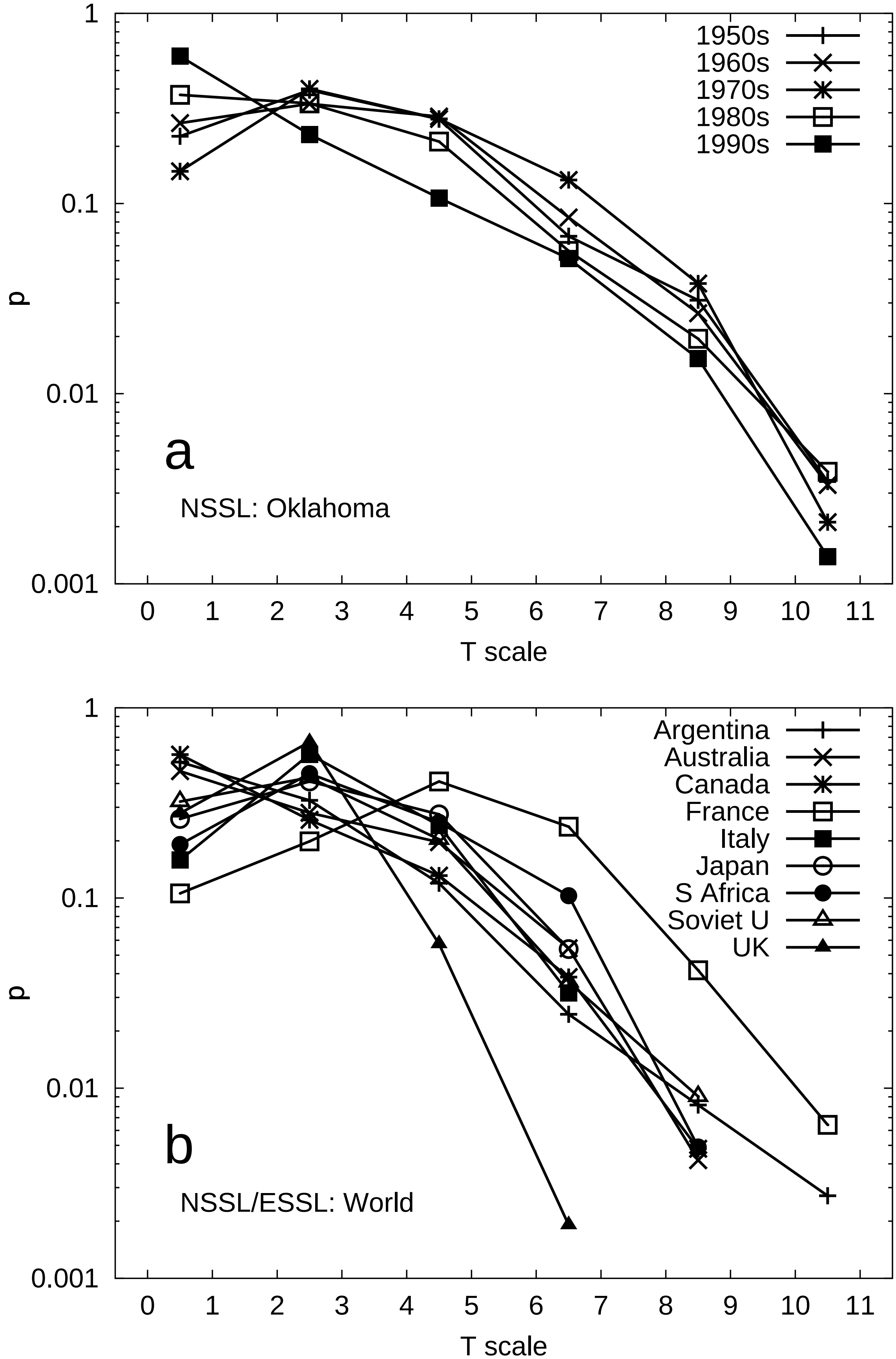
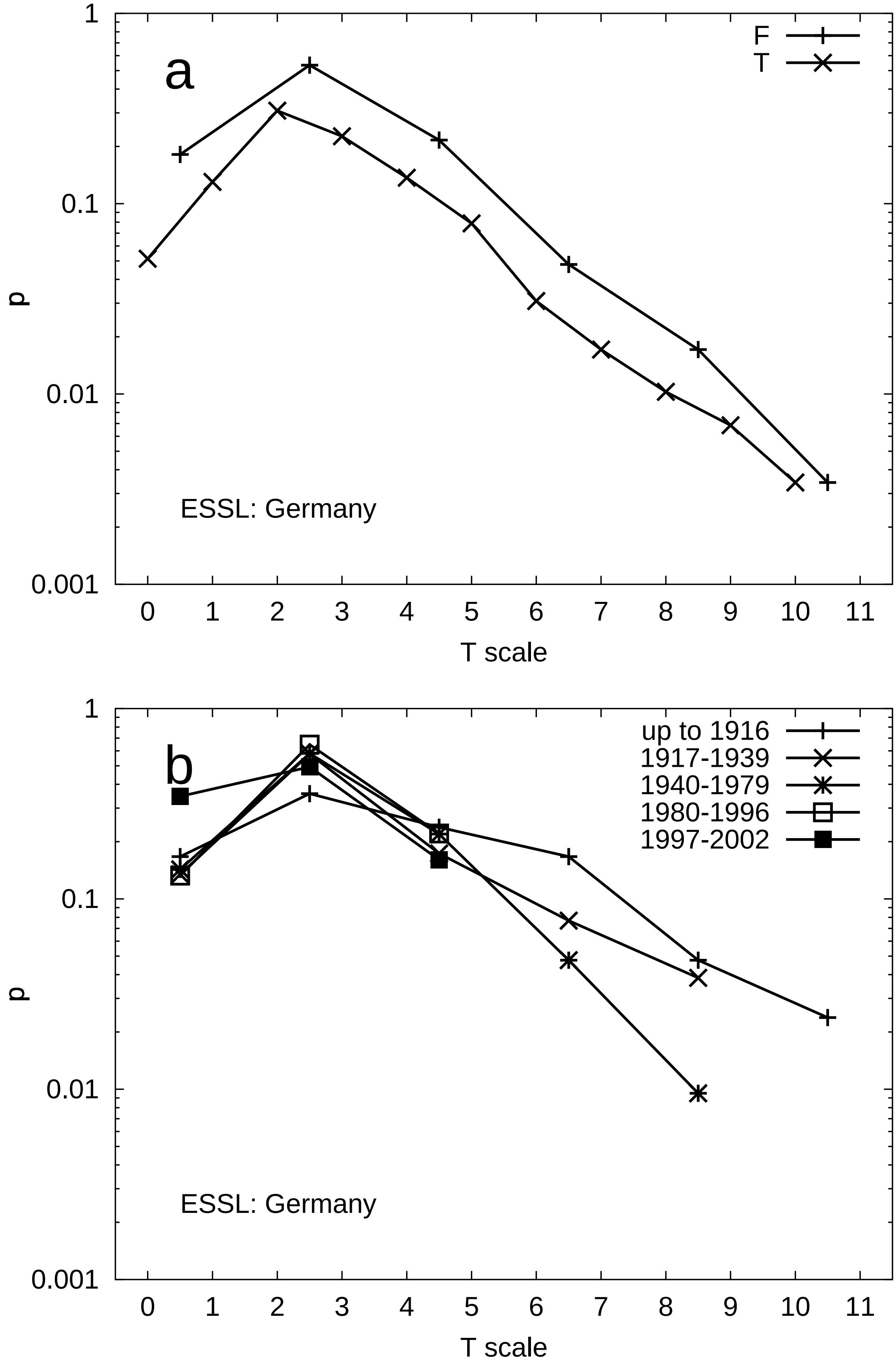
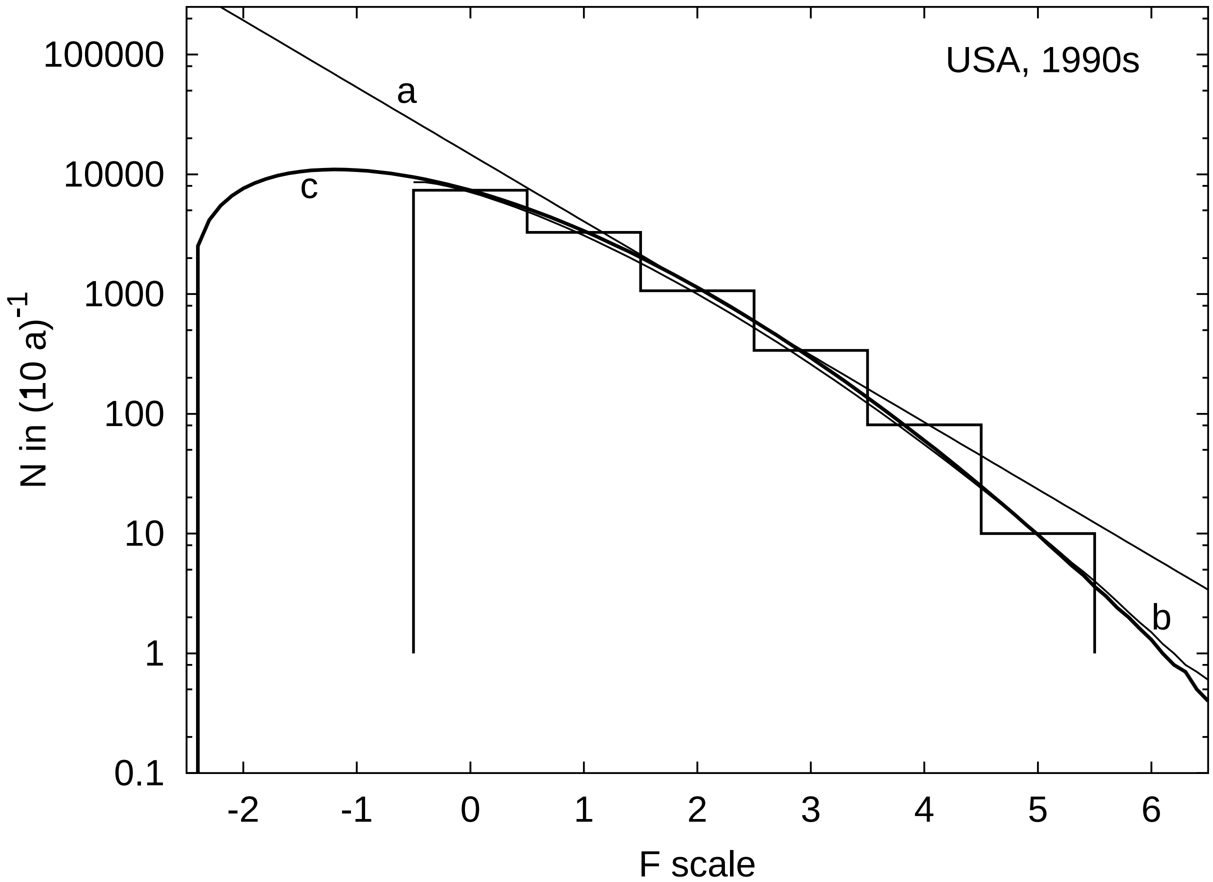

1
0.1
0.01
0.001
p
0 1 2 3 4 5 6 7 8 9 10 11
T scale
1950s
1960s
1970s
1980s
1990s
a
NSSL: Oklahoma
1
0.1
0.01
0.001
p
0 1 2 3 4 5 6 7 8 9 10 11
T scale
Argentina
Australia
Canada
France
Italy
Japan
S Africa
Soviet U
UK
b
NSSL/ESSL: World

Figure 3



a
F
T
ESSL: Germany
p
T scale
b
up to 1916
1917-1939
1940-1979
1980-1996
1997-2002
ESSL: Germany
p
T scale

Figure 4



USA, 1990s
a
c
b
100000
10000
1000
100
10
1
0.1
N in (10 a)-1
-2
-1
0
1
2
3
4
5
6
F scale

Figure 5

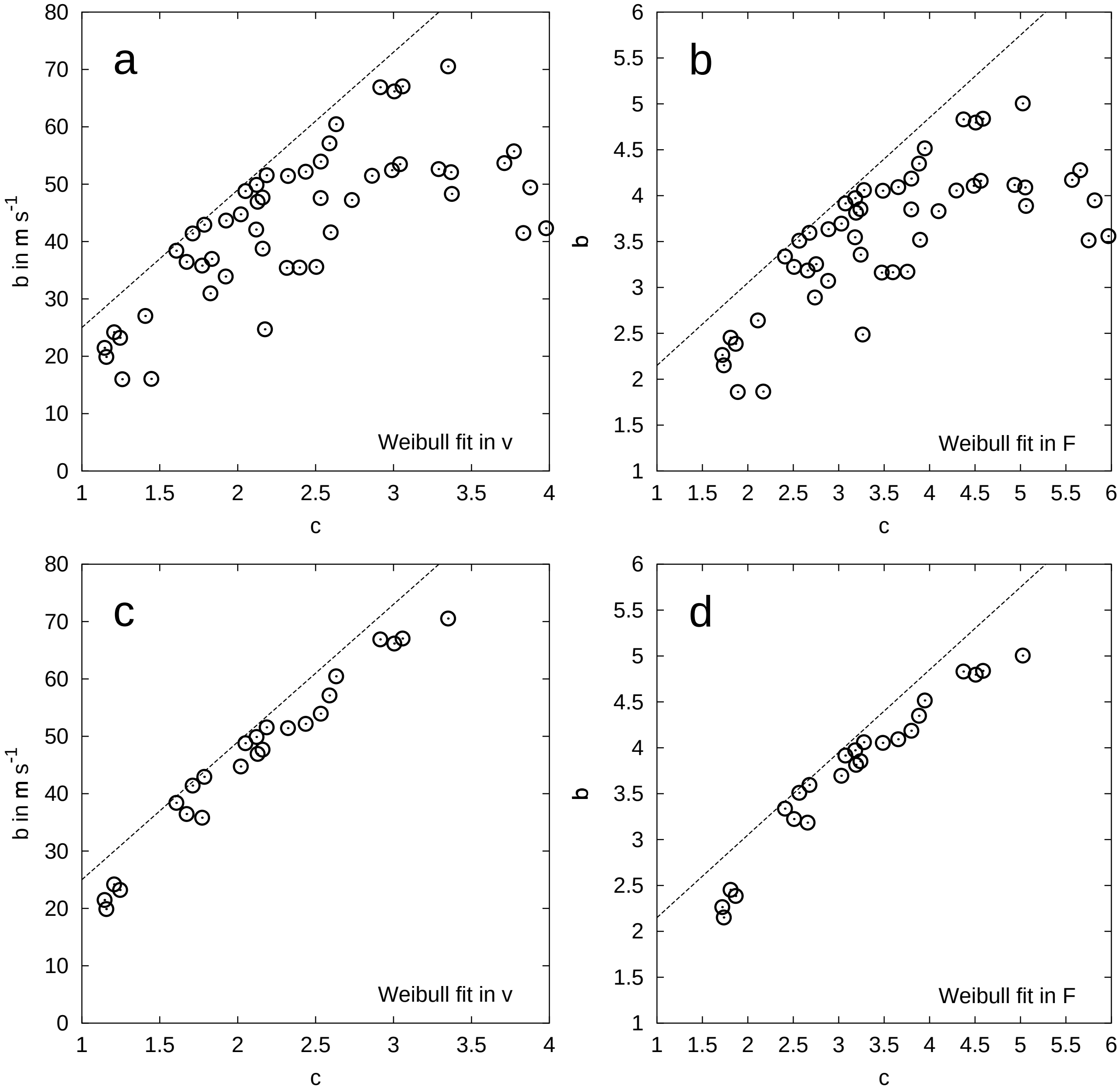


Figure 6

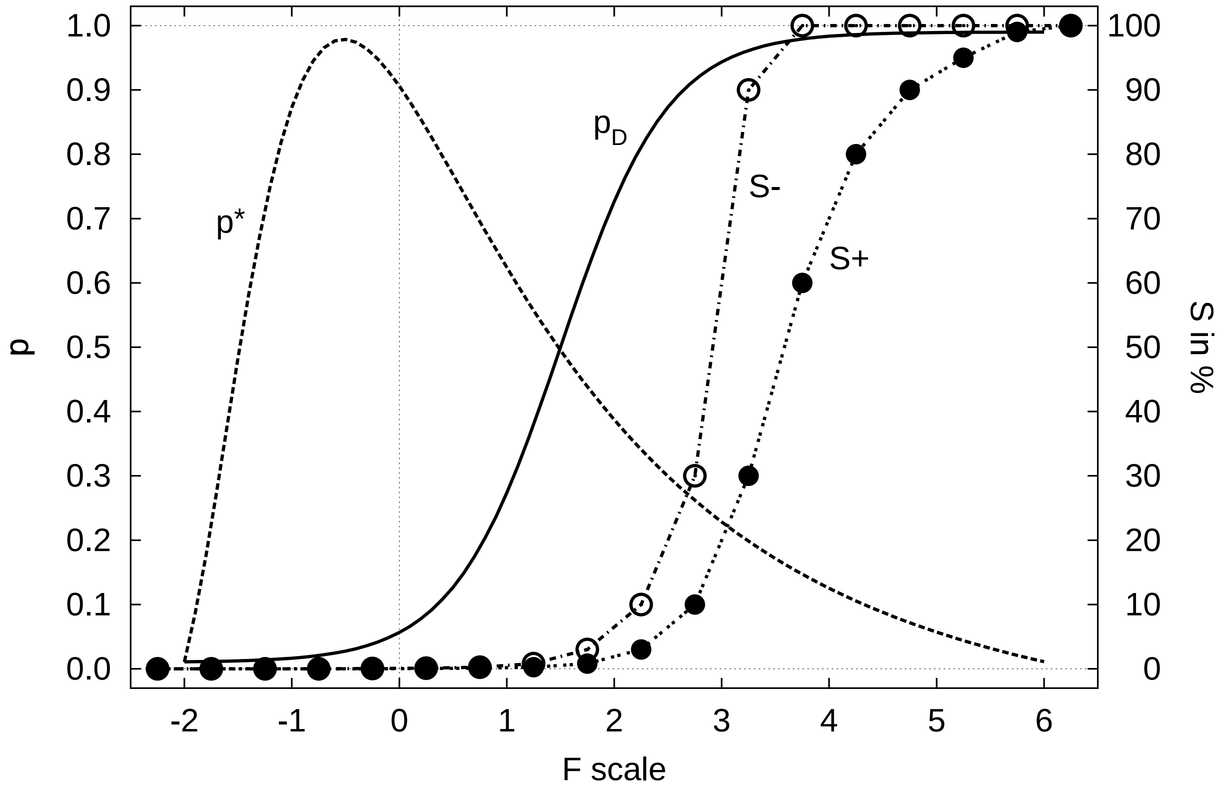

p
S in %
F scale
p*
pD
S-
S+
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
100
90
80
70
60
50
40
30
20
10
0
-2
-1
0
1
2
3
4
5
6

Figure 7