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Tornadoes in Germany

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Abstract

A climatology of tornadoes in Germany using the TorDACH database up to the year 2000 is presented. The total number of tornadoes is 517 and the number of reports has increased substantially after 1870. Tornado activity is at maximum in July, and at minimum from November to February. The daily distribution peaks in the afternoon and early evening with a weak secondary morning maximum due to waterspout outbreaks. In general both daily and seasonal trends follow the variation of thunderstorm activity. The highest F–scale rating so far is F4 and in the range from F1 to F4 a nearly lin–log distribution of tornado intensity is found. The low number of reported F0 tornadoes indicates that perhaps only every third tornado in Germany is reported. Also the geographical distribution shows that many cases from east Germany are missing. However, three different regions of typical tornado activity can be inferred: the northern coastal region, the hilly terrain of mid and southern Germany, and a zone influenced by Mediterranean air in summer and an orogenic low–level wind shear in the south–west. For the latter an example of a tornado alley is given. From a conservative estimate of tornadic activity in Germany a number of 4 to 7 tornadoes per year and a recurrence density of about 0.1 to 0.2 a^{-1} 10^{-4} km^{-2} is deduced, in accordance with earlier work. However, both extrapolation based on statistical arguments and the more detailed records of recent years suggest values a factor of 3 to 4 higher.

Keywords: Tornado; Climatology, Germany

1 Introduction

Tornadoes present a violent threat to society even in central Europe where their number is smaller than in the U. S. tornado belt. Extremely high values of windspeed and shear inside the funnel yield a high damage potential even for strong buildings. Therefore it is desirable to obtain a complete statistical record of the spatial and temporal distribution of tornadoes to be able to better estimate the regional tornado risk.

The European tornado climatology presented by Wegener (1917) still is an outstanding report of tornado research in the early twentieth century. As far as Germany is concerned, Wegener's book was by far not the only work devoted to tornadoes: already in the mid–nineteenth century public interest and scientific research on tornadoes began to intensify. Martins (1850) provided a catalogue of guidelines for the observation of tornadoes (*Tromben* or *Wind- / Wasserhosen* in German). But only about twenty years later, Reye (1872) published a longer and still valuable monograph on tornadoes and hurricanes and took into account both events in Germany and around the world. After World War I, tornado research was continued by Wegener (1928) and, for example, by Letzmann (1937) who published guidelines for tornado research which are still valid (cf. Peterson, 1992a,b; Dotzek et al., 2000) and Koschmieder (1940). Considering the time up to World War II Peterson (1992b, p. 166) stated that tornado research in Europe was probably more widespread than in the U. S. A. (cf. also the closing remarks of Wegener, 1928).

In the 1950s and 1960s, however, tornadoes were more often referred to as strange and rare phenomena even though the 1950s had a very large number of tornado reports. As a consequence, fewer scientists published their work on tornado theory and case studies (e. g. Roßmann, 1959; Markgraf, 1961). However, triggered by some strong tornadoes in the late 1960s and early 1970s (e. g. Nestle, 1969; Franz, 1969; Wippermann et al., 1969; Euteneuer, 1970; Szillinsky, 1970; Werner, 1973), interest of meteorologists and the German weather service DWD was drawn to tornadoes again. Related to the danger potential of tornadoes to nuclear power plants (Jurksch & Cappel, 1976), low–flying aircraft (Fuchs, 1981), on the occasion of a case study (Fuchs & Bock, 1989), and in a general investigation of low–level wind field characteristics in Germany (Christoffer & Ulbricht–Eissing, 1989), climatological data on tornadoes in Germany since 1945 have been published. Also, Berz (1980) re–evaluated Wegener's results to estimate tornado risk from the view of reinsurance companies (cf. Munich Re, 1998, 1999). All these studies and also more recent damage surveys (e. g. Kühnel, 1994; Hubrig, 1999), however, suffered from being scattered within the scientific literature of different fields such as meteorology, wind engineering, and forest sciences. Besides, many of these articles and reports were published in German and thus often overlooked in foreign countries. This impression is supported by Goliger & Milford (1997), who remarked that Wegener's and contemporary official statements by the DWD on tornado frequency in Germany surprisingly contradict each other. Similarly, Reynolds (1999) attempted to elaborate a revised tornado climatology for Europe. Without taking into account at least the climatological statistics cited above, his analysis was based on inadequate data and gave misleading results for Germany.

In order to provide a modern and reliable data record for tornadoes in Germany, Austria, and Switzerland (D, A, CH) the network TorDACH (http://www.op.dlr.de/˜pa4p/TorDACH/) was initiated in 1997. It aims at a complete tornado record for each of these countries also including case studies (cf. Dotzek et al., 1998; Hannesen, 1998; Hannesen et al., 1998, 2000; Dotzek, 1999, 2000; Schmid et al., 2000a,b; Holzer, 2000a,b).

This paper focuses on the German TorDACH data as of spring 2000. It is organized as follows: after this brief review of tornado research in Germany from Wegener (1917) to the present time, the climatological data are evaluated in Sec. 2. Decadal, monthly and daily distributions of tornado activity are given as well as the preliminary intensity distribution of tornadoes. The general geographical distribution is addressed in Sec. 3, supplemented by an example of a well–defined tornado alley in south–west Germany. The results are discussed in Sec. 4 and Sec. 5 presents the conclusions.

2 Statistical results

Figs. 1–4 show statistical information on the presently known 517 tornado cases recorded from 1587 to 1999. Only cases which occurred within the borders of present–day Germany have been taken into account. Generally speaking, in the twentieth century the record is not yet complete for the periods of World War I and II and for eastern regions of Germany during the cold war era. Also, additional late reports from the 1990s can be expected within the next few years. Nevertheless, the TorDACH database is now large enough to perform a revised analysis of tornadoes in Germany.

2.1 Decadal distribution

As Fig. 1 a shows, only scattered tornado reports are known from the time between 1587 and 1780. After that about 3 to 7 tornadoes per decade were reported. Since approximately 1870 the number of observations has strongly increased in Germany due to greater public interest in and publications on tornadoes (Fig. 1 b). In addition the 1890s had a number of significant tornado outbreaks. A decadal average starting in 1870 (and neglecting the 1940s due to World War II) yields a value of 39 tornadoes with a large standard deviation of ± 25 per decade. For Germany as a whole (356 984 km^2) a recurrence density for tornadic thunderstorms of 0.1 to 0.2 $\mathrm{a}^{-1}\,10^{-4}\,\mathrm{km}^{-2}$ is found, similar to the values for Switzerland and Austria and roughly 20 times less than for the U. S. tornado belt. It should be emphasized that this time series also takes into account decades in which a large number of tornadoes most likely remained unreported, so the present estimate must rather be considered a lower bound on tornado activity in Germany.

To be able to judge on the reliablity and completeness of the time series, it is instructive to compare it to that of Germany's westerly neighbor France. Brooks & Doswell (2000, cf. their Fig. 2) show a bar chart with both French (Dessens & Snow, 1989, 1993; Paul, 2000) and the German TorDACH tornado data presented here. Due to climatological similarities between Germany and at least northern regions of France one would expect a clear positive correlation between their decadal trends of tornado activity. But even though both time series show an increase in tornado reports after 1950 and a minimum in the 1940s, the correlation of the two time series is very weak, leading to a correlation coefficient of only $r = 0.28$ for the period 1800 to 1999.

This could indicate that the tornado climatologies in the two countries are systematically different. A more plausible explanation, however, would be the conclusion that in each country, still many cases of tornadic storms are overlooked. So although in each country by itself the recorded cases presumably represent valid statistical subsets of the total number of tornadoes, the detection efficiency as a function of time is highly different between France and Germany. Probable causes are different population density and differently varying public scrutiny towards tornadoes. In addition, a peculiarity of the political situation after World War II might have led to the very large number of detected tornadoes in the 1950s in Germany: the presence of many meteorologists in the U. S. armed forces who were familiar with tornadic storms. Similarly the rise in tornado reports from 1970 to 1999 is likely to be caused by a greater public awareness than due to climatological changes.

One should also be aware that most statistics on wind damage in forests have not been evaluated yet for traces of tornadic storms. So all these probable effects on tornado detection efficiencies indicate that the total number of tornadoes are likely to substantially exceed the number of reports presently known.

2.2 Monthly distribution

For 496 of the 517 tornadoes recorded in Germany the exact date or at least the month of occurrence is known. The monthly distribution is shown in Fig. 2. A mid–summer maximum in July (27 %) is found, and more than 2/3 of all cases occur from June to August. Only a few cases have been recorded in winter.

As already analyzed by Wegener (1917) this kind of distribution is quite representative for continental regions of central Europe where the the maximum values from June to August follow the annual trend of thunderstorm activity (Finke & Hauf, 1996; Hagen et al., 1999). The winter cases, on the other hand, are often linked to the passage of strong cold fronts within storm cyclones and preferably occur over the plain and homogeneous terrain of northern Germany.

The months July and August also represent the most probable time for waterspout outbreaks. Not only are these found over the North or Baltic Sea, but over greater lakes as well. Lake Constance at the German–Swiss–Austrian border is a prominent example. In this time of year the water surface temperatures are at their highest and even rapid cumulus congestus development may suffice to initiate waterspout formation in otherwise calm weather.

Compared to the time series presented in Sec. 2.1 the monthly distribution appears to be stable and representative for the "real" distribution. The nearly 500 cases available here suffice to form a valid subset of the total number of tornadic storms.

2.3 Daily distribution

Concerning the diurnal cycle of tornado activity, Fig. 3 also shows the resemblance to the trend of thunderstorm activity with a broad maximum of the distribution between 1500 and 1900 LST, i. e. 1400 to 1800 UTC (Wegener, 1917; Finke & Hauf, 1996; Hagen et al., 1999). However, the number of tornado reports which give the time of tornado formation is much smaller compared to the statistics shown before: only 200 of the 517 cases are classified with an exact time. A small ambiguity can arise from the use of different times: UTC, LST (i. e. UTC + 1 h), or the light savings time during summer (UTC + 2 h). In this paper LST is the basic time used, so the two other named alternatives can only introduce a ± 1 h error which may broaden any maximum a bit. Besides, a normalization of time (following Kelly et al., 1978) to account for seasonal effects by mapping the time from sunrise to sunset for each day of the year to 12 normalized "hours" has not been performed. The majority of cases occur during summer when variations of daylength are small, so this simplification appears to be justified.

Nevertheless, from the available cases, the distinct afternoon maximum of tornadic activity is still obvious. More than 1/2 of all cases occur from 1500 to 1900 LST. The rise of tornado activity sets in at about noontime, simultaneous to the begin of thunderstorm formation (Finke & Hauf, 1996). The secondary peak between 0700 and 0800 LST is due to some multiple waterspout outbreaks. It can only be speculated if it reflects a climatological fact or a mere coincidence. A larger number of tornadoes with recorded time of occurrence will show if this maximum will be smeared out or remain in the future. A physical argument supporting an early morning maximum of waterspout activity could be the following: over water, especially over large lakes, the temperature difference between the surface and the atmospheric boundary layer will be largest around sunrise. This unstable moist boundary layer will be highly susceptible to any convective forcing due to cumulus development in higher levels and thus enhance the likelihood of non–supercell tornado genesis.

2.4 Intensity distribution

The probability density function of tornado intensity in Germany is given in Fig. 4 for both the TORRO and Fujita intensity scale ratings (Fujita & Pearson, 1973; Meaden, 1976; Fujita, 1981). On the abscissa, only the T–scale is shown, but as Table 1 indicates, in practice the T–scale is just the F–scale with a spacing twice as fine, so T0 and T1 are F0, T2 and T3 correspond to F1, and so on. The fact that a given T–scale rating is uniquely mapped to an F–scale, but not vice versa, is the reason for the difference in T and F–ratings in the figure. The data presented by Fuchs (1981) have been given a rating roughly corresponding to the Fujita scale, but not to the finer TORRO scale. So the number of F–rated tornadoes presently more than doubles the number of T–ratings.

As in the U. S. A., the majority of tornadoes (65 %) are weak and only 2 to 3 % are violent. The highest observed intensity in Germany was T8 / F4, although among the historical and still unrated tornadoes there may be other violent tornadoes which took place over open fields and therefore caused only weak damage despite their high windspeeds. Note in Fig. 4 the approximate lin–log law for the right tail of the F–scale distribution which is found for north American tornadoes as well: Brooks & Doswell (2000) report a mean number ratio of F$[n+1]$ / F$[n]$ of about 0.36 for supercell and 0.10 for non–supercell events with $n \geq 2$. The TorDACH data for Germany yield F4 / F3 = 0.27, F3 / F2 = 0.34, and F2 / F1 = 0.42. Even though only about a quarter of all German tornadoes have been given an F–rating yet, the slopes agree reasonably with the American distributions and indicate a preference for supercell tornadoes.

Fig. 4 also shows that the finer–resolved T–scale rating presently does not reflect any lin–log law. As mentioned, 69 tornadoes have *only* an F–rating which cannot be unambiguously mapped to the T–scale (cf. Table 1). Therefore here the database of rated tornadoes is about halved. Besides, the fine spacing between consecutive T–scales is sensitive to inaccurate ratings: if for instance many T5 tornadoes are wrongly rated as T4, then any lin–log law in the data is lost except for a very large database, where ± 1–errors in T–scale rating are likely to be evenly distributed over all ranges of scales. So for the T–scale rating we cannot expect a smooth intensity distribution until a much larger number of cases has carefully been given a rating according to the TORRO intensity scale. As the T–distribution involves twelve classes compared to the mere six classes of the Fujita scale it might be argued that in fact more than twice as many T–ratings than F–ratings were necessary to obtain a smooth intensity distribution over the TORRO scale. The reason for that is the need for a representative subset of all tornadoes in each intensity class to make the whole distribution representative. For a certain given number of reliably rated tornadoes in each class, doubling the number of classes means to double the minimum total number of rated events. So by now the situation is contrary to what it should be (twice as many F–ratings than T–ratings) and we cannot expect a smooth probability function for tornadic intensity with T–scale at this time.

3 Geographical distribution

Concerning the geographical distribution of tornado activity, Fig. 5 gives both locations (circles) of recorded tornadoes (cf. Wegener (1917, p. 87), Fuchs (1981, p. 9), and Christoffer & Ulbricht–Eissing (1989, p. 73)) and a sketch of three different regions with more or less uniform climatology.

Most obvious from looking at the distribution of single events is the low data density in east

Germany. Only the Berlin region makes an exception here. While a higher detection efficiency for densely populated areas is a well–known phenomenon with tornado and other significant weather statistics, there is no obvious climatological explanation for the low number of reports in east Germany. Synoptical settings as well as terrain shape or land use are highly similar in the western and eastern part of the country. Instead, most tornadoes in east Germany from 1945 to 1990 are likely to either have been unreported on a national scale, or they have only been published in annual reports of forest authorites or other publications difficult to access. Therefore presently no discussion of regional effects on tornado genesis in the eastern part of the country can be made. It can only be stated again that the 517 tornadoes up to 1999 must be a substantial underestimation of the total number of events as so many cases from east Germany are obviously missing: about 100, assuming the same report density for east and west Germany. This corresponds to 2 to 3 missed cases each year from 1945 to 1990.

In west Germany the data density is high enough to allow for a regionalization of tornado outbreaks. Interestingly, aside from the discussion of the main climatologically homogeneous regions below, note that there is also a zone with no tornado reports at all in west Germany. It is the Rothaar–mountain region (approximately at 51° N, 8.5° E) near the letter **b** in Fig. 5. Future research will reveal if this is a statistical artifact or some meteorological truth not yet understood.

Waterspout events near the North and Baltic Sea coast and, most pronounced, over lake Constance are very often multiple funnel tornado outbreaks. While at lake Constance at the German–Swiss–Austrian border most events are detected and reported, waterspouts over the Seas often remain unreported as they usually do no damage. As mentioned in Sec. 2.2 the German waterspout high season is in July and August, and again our statistical record of these events is not complete.

Focusing on tornadoes occurring over land we generally can identify three climatologically uniform regions denoted by **a**, **b**, **c** in Fig. 5. These are from North to South

a the homogeneous and flat terrain of northern Germany, from the coastline to the first hill or mountain ranges,

b the hilly and mountainous terrain farther south towards the Alps,

c the Upper Rhine valley region in south–west Germany with the flat and low–level valley base (100 to 200 m ASL) and the nearby mountain ranges (up to 1500 m ASL).

What appears to be relevant in region **a** is a synoptic setting characterized by frequent passage of deep low–pressure systems, high upper–level winds and, especially in winter, advection of moist and relatively warm low–level air from the North Sea towards the coast. In addition, the boundary layer is subject to the jump in surface roughness from the ocean to the coast, and again from the flat terrain to the first mountain ranges. Increased surface roughness results in higher surface layer vorticity which may be transformed from horizontal to vertical vorticity in the presence of thunderstorm updrafts. As the orography in northern Germany is relatively homogeneous, no preference of certain regions of tornado activity can be found except for the general statement that the north–eastern part of the country seems to be less tornado–prone than the north–west: the former is at greater distance to the North Sea coast. However, due to the low number of reported cases in east Germany this argument cannot yet be verified.

The hilly and mountainous terrain in region **b** shows a more localized distribution of tornado activity. Here regional terrain forcing effects become increasingly important for tornado genesis. The low–level flow patterns and convection are strongly affected by terrain shape, land–use, and surface moisture. As most thunderstorms and tornadoes occur within geostrophic mid–level flow from south to west (Hagen et al., 1999) the orientation of certain valleys and ridges will determine the orographic lift which can lead to tornado funnel formation and touchdown on a day supportive of strong (and probably supercellular) thunderstorms. As local effects have found to be so important in region **b**, a tornado funnel may also dissipate very quickly if the low–level orogenic flow pattern changes. Therefore the majority of tornado path lengths are shorter than 10 km. Another interesting aspect in the south–east part of region **b** is the fact that in central and southern Bavaria near Munich the number of thunderstorm days is quite high (Finke & Hauf, 1996), but the number of reported tornadoes appears to be lower than on average for all of region **b**.

The last region with well–defined climatological tornado characteristics is found in the south–west of Germany and is denoted region **c** in Fig. 5. Here the Upper Rhine valley extends roughly northward along the Swiss–German and French–German border. In fact the synoptic situation in summer is very similar in the Upper Rhine valley, the region of lake Constance, and the Swiss and French Jura mountains (cf. Piaget, 1976; Dessens & Snow, 1993). Here very warm and moist air can be advected directly from the Mediterranean Sea by a south–westerly flow towards region **c**. As a consequence, the Black Forest region in south–west Germany has a very high thunderstorm frequency.

In a part of region **c** shown in Fig. 5 by the small rectangle evidence for the presence of a tornado alley is found: locations and damage swaths of recent and historical tornadoes in that area are depicted in Fig. 6. The tornado alley (Wegener, 1917) is located in a west–east direction in the area Strasbourg–Heidelberg and northern Vosges mountains–northern Black Forest (cf. also Fig. 7 for names of geographical places). In addition a climatological analysis of synoptic situations with deep convection using precipitation accumulation derived from radar data also yields a preference for even non–severe convection in the same area (Gysi, 1998).

An explanation for this apparent accumulation of tornado observations was found through numerical modeling studies using the non–hydrostatic mesoscale model KAMM (Adrian & Fiedler, 1991) in an extensively revised version suitable for simulation of deep convection over complex terrain (Dotzek, 1998, 1999). Hannesen (1998) supported these findings by a climatological evaluation of data from the Karlsruhe Doppler radar, denoted by + in Figs. 6 and 7. The resulting low and mid–level flow characteristics of the Upper Rhine valley region are depicted schematically in Fig. 7 for a synoptic situation with south–westerly geostrophic flow during the summer season. Typically the low–level air in this situation comes from the Mediterranean Sea and is very warm and moist (Ludlam, 1980; Morris, 1986). Two orographic forcing effects are then superposed on this air mass.

On the one hand, southerly flow prevails in the lowest 500 m between Black Forest and Vosges mountains (solid black arrows) advecting a shallow layer of further moistened and heated air induced by the eastern slope of the Vosges mountains (thin open arrows) due to exposure to the sun from the early morning hours on. Northward, between Vosges and Palatinian mountains another westerly flow component enters the Rhine valley between 300 to 1000 m AGL. This leads to the formation of a convergence line (heavy dashed line) where not only lifting is induced but also the low–level supply of moist warm air is at a maximum (thin open arrows). In the region of the tornado alley the necessary orographic effects (veering winds in the lowest kilometers AGL, low–level heat and moisture content, forced lifting) are most pronounced and facilitate the development of supercell storms with hail or tornadoes. The most severe case has been the T8 / F4 Pforzheim tornado (No. 11 b in Fig. 6) in July 1968 leading to over 100 million DM damage within the city of Pforzheim alone (Nestle, 1969; Euteneuer, 1970). Note that since the setup of the Doppler radar in Karlsruhe in 1992 at least four tornadoes have occurred in the operational radar range (Nos. 14 to 16 of Fig. 6 and another one farther north near Pfungstadt on 1 May 1998), two of which (15 and 16) could be studied (Hannesen et al., 1998, 2000).

4 Discussion

The TorDACH data presented here are in good agreement with the results of Wegener (1917). But now the larger number of recorded tornado outbreaks compared to earlier publications also allows for more detailed analyses of the geographical distribution of tornadoes in Germany. Another new result of this investigation is the evidence found for the universality of probability density distribution of tornado intensity versus the F–scale. Similar to the distribution presented by Brooks & Doswell (2000) for the U. S. A. and France (cf. Paul, 2000), the slope of the intensity distribution follows a lin–log law for F–scale values larger than one.

Adopting the statistical reasoning of Brooks & Doswell (2000) by assuming that for a perfect detection efficiency also the F0 tornadoes would lie on a lin–log probability density function $p(\mathrm{F})$ with slope a of the form

$$p(\mathrm{F}) = \frac{a^{\mathrm{F}}}{\sum\limits_{n=0}^{5} a^n} \quad ,$$

we can extrapolate how many tornadoes are likely to "really" take place in Germany each year. This is certainly somewhat speculative, but nevertheless valuable to approximate the tornado risk in the light of the fact that waiting for a reasonable amount of F0 tornadoes to be reported may take a long period of time. So extrapolation of the points for F2 and F3 tornadoes (which best reproduced the predicted slope $a = 0.36$) in Fig. 4 shows that the number of reported F0 tornadoes should roughly increase by a factor of 20, thereby increasing the total number of all tornadoes by a factor of 3. A similar reasoning concerning the slope of the intensity distribution shows that also violent tornadoes (F4 and F5) are by now slightly underrepresented by the statistical record, but with little effect on the extrapolated total number of tornadoes.

Combined with the already mentioned approximately 2 to 3 unreported tornadoes each year in east Germany from 1945 to 1990, this leads to the conclusion that as an estimate of the "true" number, 15 to 25 tornadoes occur each year in Germany, corresponding to a recurrence density of 0.4 to 0.7 $\mathrm{a}^{-1}\ 10^{-4}\ \mathrm{km}^{-2}$. The TorDACH data from recent years (1997–2000) support these figures. In addition to the extrapolation above one should keep in mind that severe weather damage statistics of forest authorities in Germany lie largely unopened today, and tornadoes over water surfaces generally remain unreported as they seldom cause damage. For this reason a factor of 3 to 4 between total and currently established known number of tornadoes per year does not seem to be unrealistic. It must be stated, however, that the majority of these additional tornadoes are weak and do not imply a damage potential increase of tornadoes by the same magnitude.

Aside from recording preferably all tornadic storms occurring, assigning a proper intensity value to each of them is one of the climatologist's main issues. As Table 1 shows, the frequently used Fujita scale and the TORRO scale are very similar, both in design and usage. Ideally they should depend on windspeed alone. Due to the lack of direct wind measurements in most cases, in practice they are usually applied as damage scales, however. Two aspects are worth to be touched here: first, if evaluation of the TorDACH data yields any preference for one of the two scales and second, if and how ratings from different regions of the world could unambiguously be compared. With the first question, either of the scales has its pros and cons. As became obvious from the intensity distribution in Fig. 4, for a low number of rated tornado reports, the finer–spaced T–scale is more susceptible to errors in rating and to sparsely filled intensity classes, leading to the observed oscillations in the T–scale intensity distribution. Here the F–scale is less ambiguous and further smoothes the intensity distribution due to an integration over two steps in T–scale for one step in F–scale. However, for tornado risk assessment, for example by reinsurance companies a rather precise rating of tornado intensity would be desirable. Furthermore rather densely and homogeneously populated regions like central Europe should more likely allow for such precision of careful damage analyses. For this reason in the present study the T–scale is equally applied as the F–scale, despite its shortcomings concerning the larger minimum required number of recorded events. In addition, due to the perfect compatibilty of the T–scale with the F–scale each T–value can be readily transformed to the appropriate F–value (but not vice versa). So probably even in the U. S. A. where only the Fujita scale is widely used, whenever the precision of available windspeed or damage estimate allows, a tornado should be given a T–rating.

Any such data record, however, will only be suitable for comparison with those from other regions of the world after a universal method of estimating tornado intensity depending on windspeed alone has been developed. Steps to reach this point have been made by Fujita (1992) and, independently Dotzek et al. (2000). Based upon the perception that damage to buildings depends on their structural strength makes it obvious that a worldwide–valid verbal description of damage corresponding to a certain T or F–scale cannot exist. Fujita (1992) introduced the structural strength of buildings to modify the F–scale accordingly, leading to the so called f–scale. However, his approach results in a matrix–like classification scheme which has not yet found widespread use. Dotzek et al. (2000) also introduced a measure of structural building strength, the loss ratio $\bar{S}$. This term from the insurance business denotes the percentage of damage to an object to the reinstatement value of that object:

$$\bar{S} \text{ in } \% \quad = \quad 100 \, \frac{\text{loss occurred in US\$ or €}}{\text{reinstatement value in US\$ or €}} \quad .$$

It is useful here to further discriminate between light and strong building structure and so to introduce $\bar{S}_{\mathrm{light}}$ and $\bar{S}_{\mathrm{strong}}$. These quantities valid for central Europe are also given in Table 1. After definition of these quantities it suffices to modify the verbal description of the intensity scale by consideration of typical architecture in a certain region and to supplement it by the corresponding loss ratios $\bar{S}$. Then in each country separate damage descriptions exist for the windspeed intervals of the T or F–scale (cf. Dotzek et al., 2000, for a description valid for central Europe). In this way the introduction of multidimensional classification schemes is circumvented and the well–known TORRO or Fujita scales are retained. It is only necessary to set up local damage descriptions related to the windspeeds of the intensity scale. Nevertheless, still many problems in this field remain to be solved.

5 Conclusions

This paper has assessed the climatology of tornadic thunderstorms in Germany to bridge the gap between the results of Wegener (1917) and today. Concerning the eastern part of Germany and offshore regions of the North and Baltic Sea the TorDACH data base is still quite sparse. Nevertheless a synopsis of available climatological statistics and Doppler radar as well as mesoscale model case studies showed that

1. as a lower bound, 4 to 7 tornadoes are spawned each year in Germany, leading to a recurrence density of 0.1 to 0.2 $\mathrm{a}^{-1}\ 10^{-4}\ \mathrm{km}^{-2}$,

2. the maximum monthly activity is between May and August, peaking in July (27 %),

3. the maximum daily activity is from 1500 to 1900 LST (1400 to 1800 UTC) with a weak secondary maximum in the early morning hours due to mid–summer waterspout formation,

4. the largest intensity determined was T8, i. e. F4, and the data already indicate a lin–log supercell–dominated intensity distribution with F–scale,

5. the low number of reported weak tornadoes (T0–1, F0), waterspouts, and the low data density in eastern Germany all indicate that still many tornadoes are overlooked or falsely classified as non–tornadic storms,

6. an extrapolation based on statistical arguments indicates that the “true” number of tornadoes is three to four times as high as the lower bound estimate given above, leading to 15 to 25 tornadoes each year, and 0.4 to 0.7 a^{-1} 10^{-4} km^{-2},

7. tornadoes appear to cluster in regions with increasing surface roughness and terrain height; both are factors which enhance the low–level (horizontal) vorticity,

8. three climatologically different regions of tornado activity can be inferred: the coastline and the flat terrain of northern Germany, the hilly terrain of central and southern Germany and the Upper Rhine valley region in south–west Germany where both terrain–induced low–level wind shear and advection of moist, warm Mediterranean air facilitate (severe) thunderstorm formation,

9. only by mere chance, tornadoes have not yet caused many fatalities in Germany, and their damage potential is therefore still underestimated.

The future of tornado research in Germany mainly relies on the point if a professional institution will monitor and analyze tornado outbreaks, open the archives of forest authorities, and eventually issue weather forecasts of potentially tornadic synoptic situations. Such forecasts could be expected to trigger a considerably larger number of tornado reports than before and a greater public awareness of tornadoes in Germany. The first explicit tornado warning issued by the DWD on 2 September 2000 is a promising step in this direction.

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Please check http://www.op.dlr.de/˜pa4p/TorDACH/ for updates of the data presented in this paper.

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Tables

Table 1: TORRO and Fujita scales of tornado intensity compiled to an equivalent windspeed v given in $\mathrm{m\,s^{-1}}$ and $\mathrm{km\,h^{-1}}$. The velocity range Δv of each T–scale step and mean loss ratios $\bar{S}_{\mathrm{light}}$ and $\bar{S}_{\mathrm{strong}}$ for central Europe are also shown.

					significant							
	weak				strong				violent			
Fujita	F0		F1		F2		F3		F4		F5	
TORRO	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
v in $\mathrm{m\,s^{-1}}$	17 – 25	25 – 33	33 – 42	42 – 51	51 – 61	61 – 71	71 – 82	82 – 93	93 – 105	105 – 117	117 – 130	130 – 143
v in $\mathrm{km\,h^{-1}}$	76 ± 14	104 ± 14	135 ± 16	167 ± 16	202 ± 18	238 ± 18	275 ± 20	315 ± 20	356 ± 22	400 ± 22	445 ± 23	491 ± 23
Δv in $\mathrm{m\,s^{-1}}$	8	8	9	9	10	10	11	11	12	12	13	13
$\bar{S}_{\mathrm{light}}$ in %	0.05	0.10	0.25	0.80	3.0	10.0	30.0	90.0	100	100	100	100
$\bar{S}_{\mathrm{strong}}$ in %	0.01	0.05	0.10	0.25	0.80	3.0	10.0	30.0	60.0	80.0	90.0	95.0

Figure captions

Figure 1: Tornado reports per decade in Germany, a) from 1550–1849 and b) from 1850–1999. Note the factor 10 change in scale between the two figures.

Figure 2: Monthly variation of tornado activity in Germany until 1999.

Figure 3: Daily variation of tornado activity in Germany until 1999.

Figure 4: T and F–scale probability density functions, 1587–1999. Note that presently the number of F–rated tornadoes roughly doubles the number of T–ratings.

Figure 5: Map of German tornado sites (circles) and regions of uniform climatological characteristics. Zone **a** denotes the northern flatlands, **b** corresponds to hilly or mountainous terrain while region **c** is influenced by Mediterranean air in summer. The small rectangle indicates the region of Fig. 6.

Figure 6: Tornadoes in the Upper Rhine valley region: 1) 29 Jul 1845, 2) 24 May 1878, 3) 4 Jul 1885, 4) 1 Jul 1895, 5) 11 May 1910, 6) End Sep 1913, 7) 7 Jun 1952, 8) 10 Aug 1959, 9) 13 Aug 1952, 10) 27 Apr 1960, 11 a,b) 10 Jul 1968, 12) 8 May 1985, 13 a,b) 23 Jul 1986, 14) 21 Jul 1992, 15) 9 Sep 1995, 16) 23 Jul 1996. Ka = Karlsruhe, Hd = Heidelberg, Sb = Saarbrücken, Str = Strasbourg, Stg = Stuttgart, Pf = Pforzheim. Orography shaded in 200 m steps, white = below 200 m ASL, dark grey = above 600 m ASL. The + denotes the location of Karlsruhe radar, range rings every 30 km.

Figure 7: Boundary–layer flow characteristics in the Upper Rhine valley region for south–westerly geostrophic flow. Bold arrows: channeled southerly flow, bold dashed line: low–level convergence due to westerly cross–flow between the Vosges and Palatinian mountains, light arrows: advection of warm moist air, starting at the eastern slope of the Vosges mountains. Terrain height contours and the + correspond to those of Fig. 6.

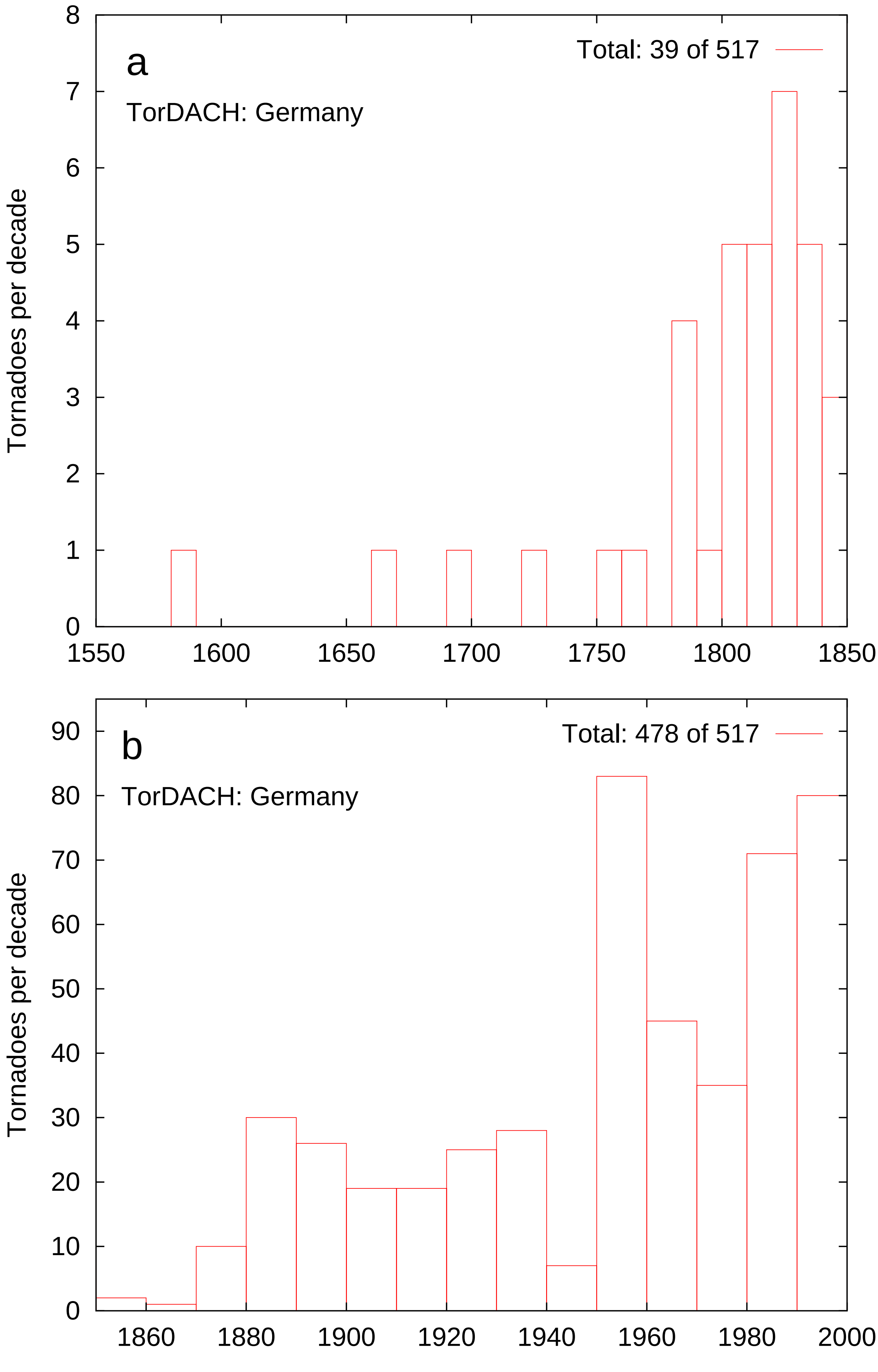

a
TorDACH: Germany
Total: 39 of 517
Tornadoes per decade
0
1
2
3
4
5
6
7
8
1550
1600
1650
1700
1750
1800
1850
b
TorDACH: Germany
Total: 478 of 517
Tornadoes per decade
0
10
20
30
40
50
60
70
80
90
1860
1880
1900
1920
1940
1960
1980
2000

Figure 1

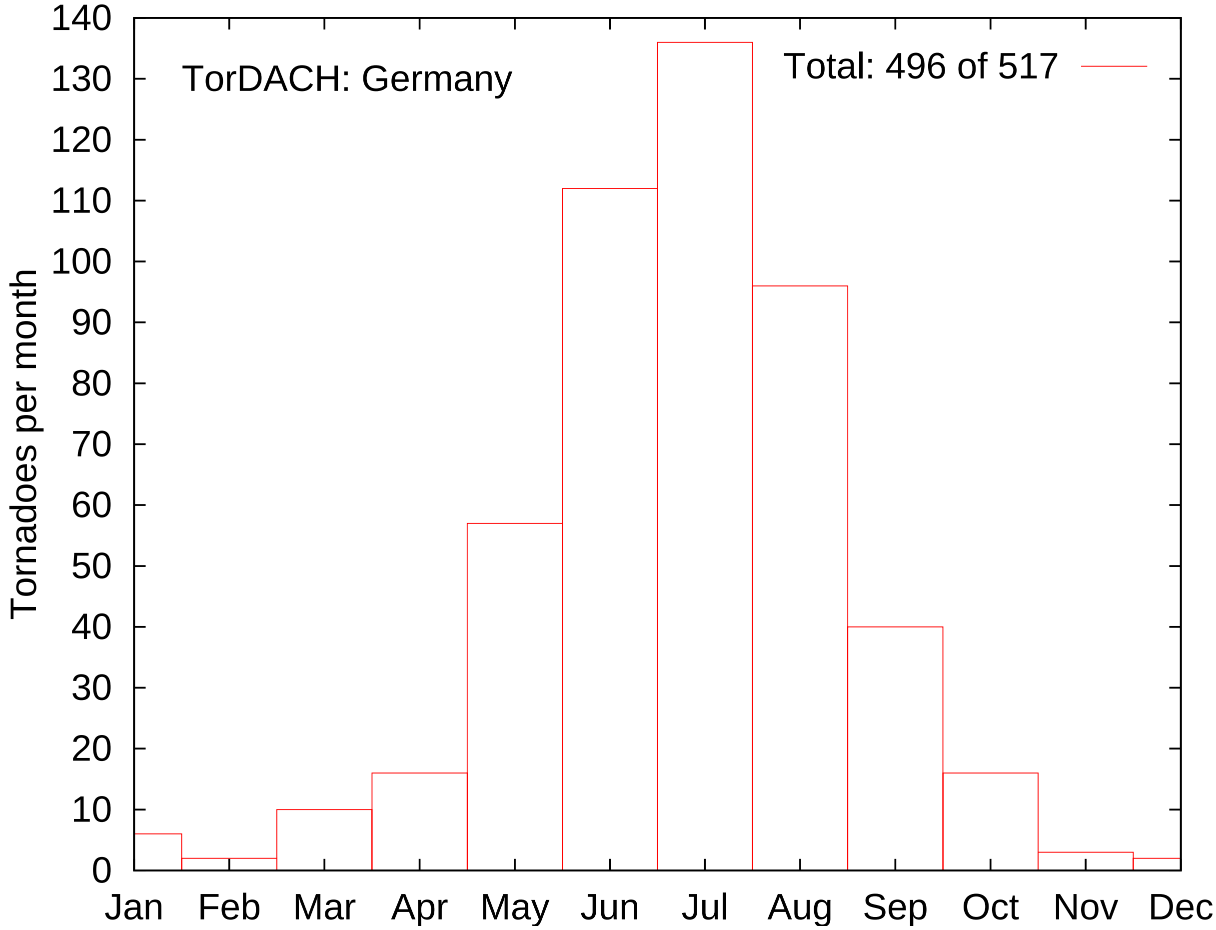
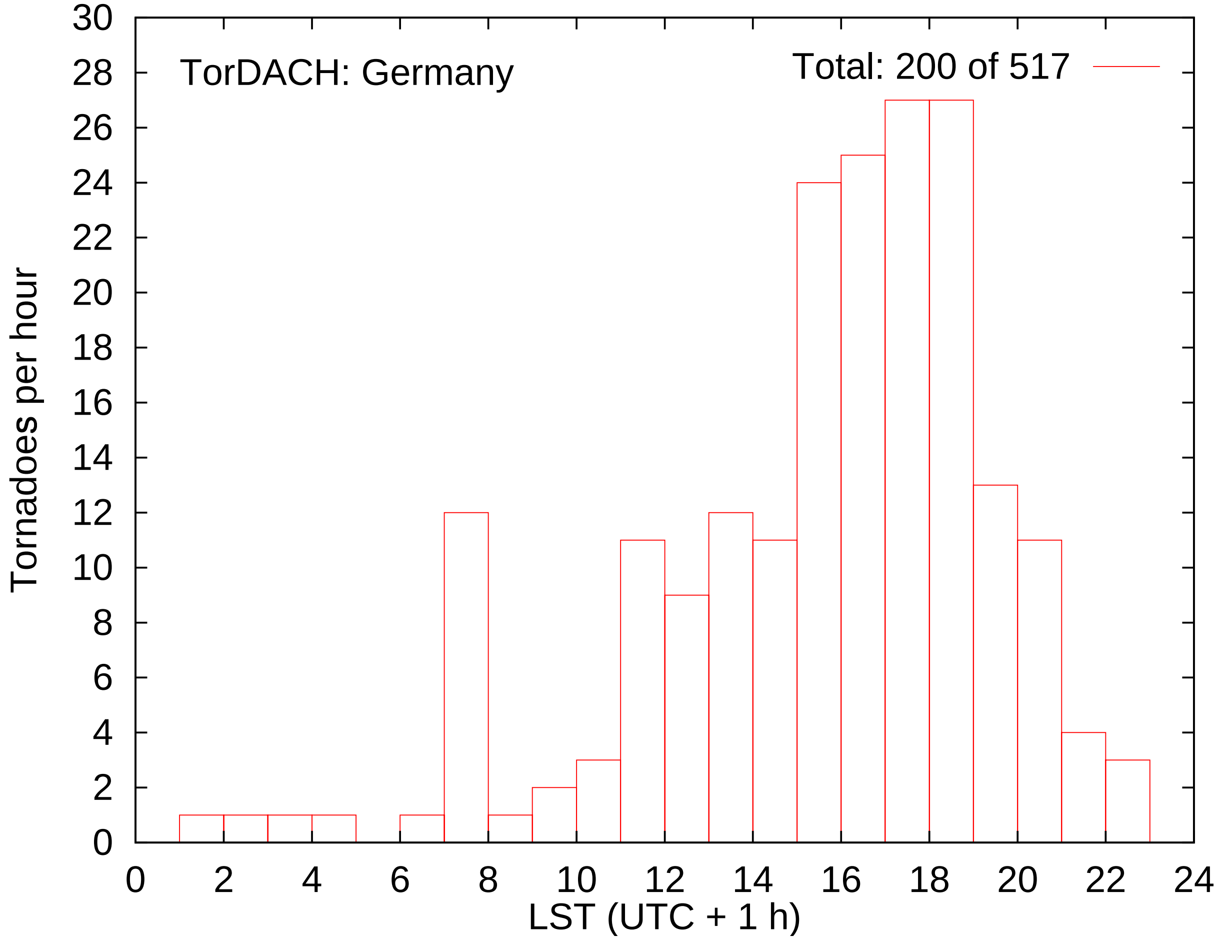

TorDACH: Germany
Total: 496 of 517
Tornadoes per month
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 2



TorDACH: Germany
Total: 200 of 517
Tornadoes per hour
LST (UTC + 1 h)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

Figure 3

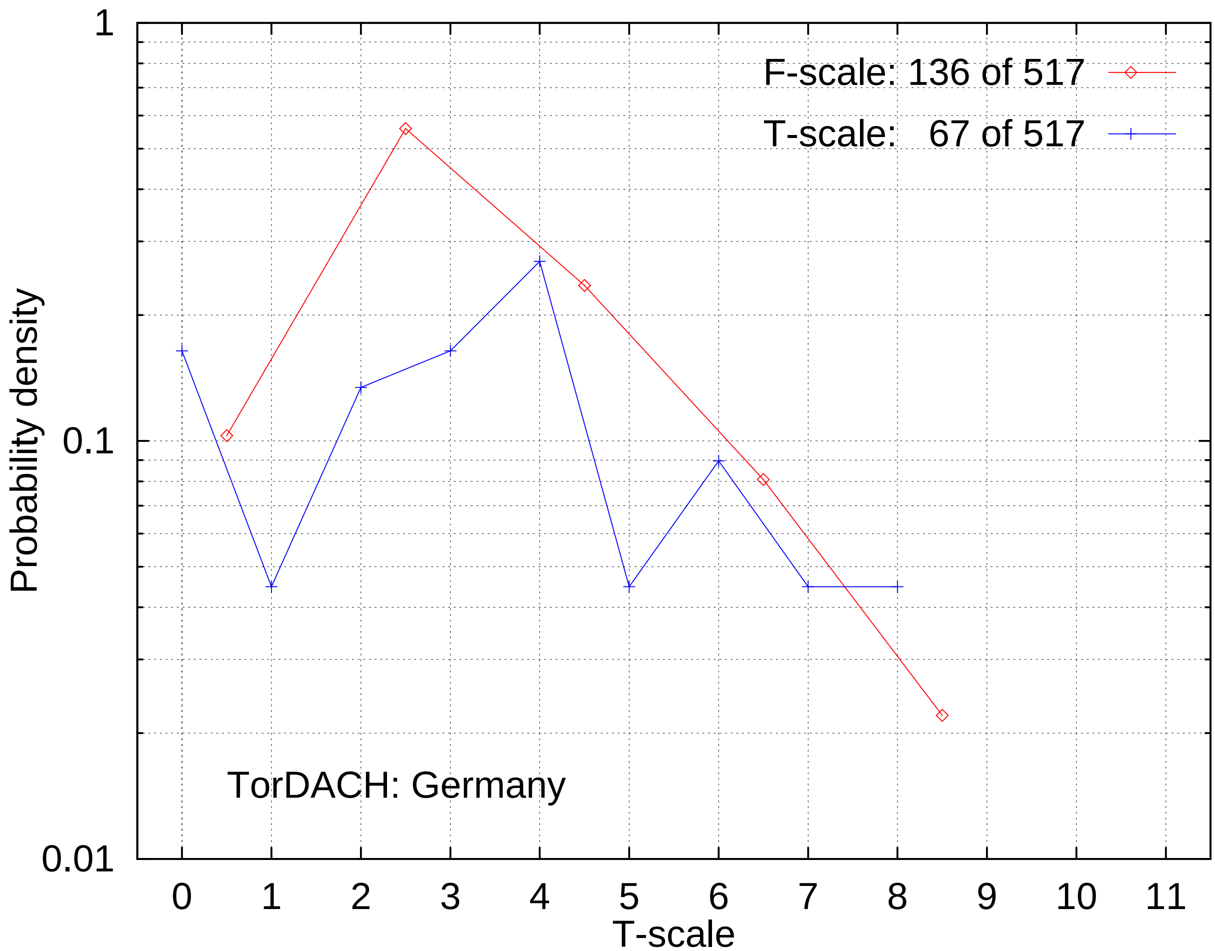

1
0.1
0.01
Probability density
F-scale: 136 of 517
T-scale: 67 of 517
TorDACH: Germany
0
1
2
3
4
5
6
7
8
9
10
11
T-scale

Figure 4

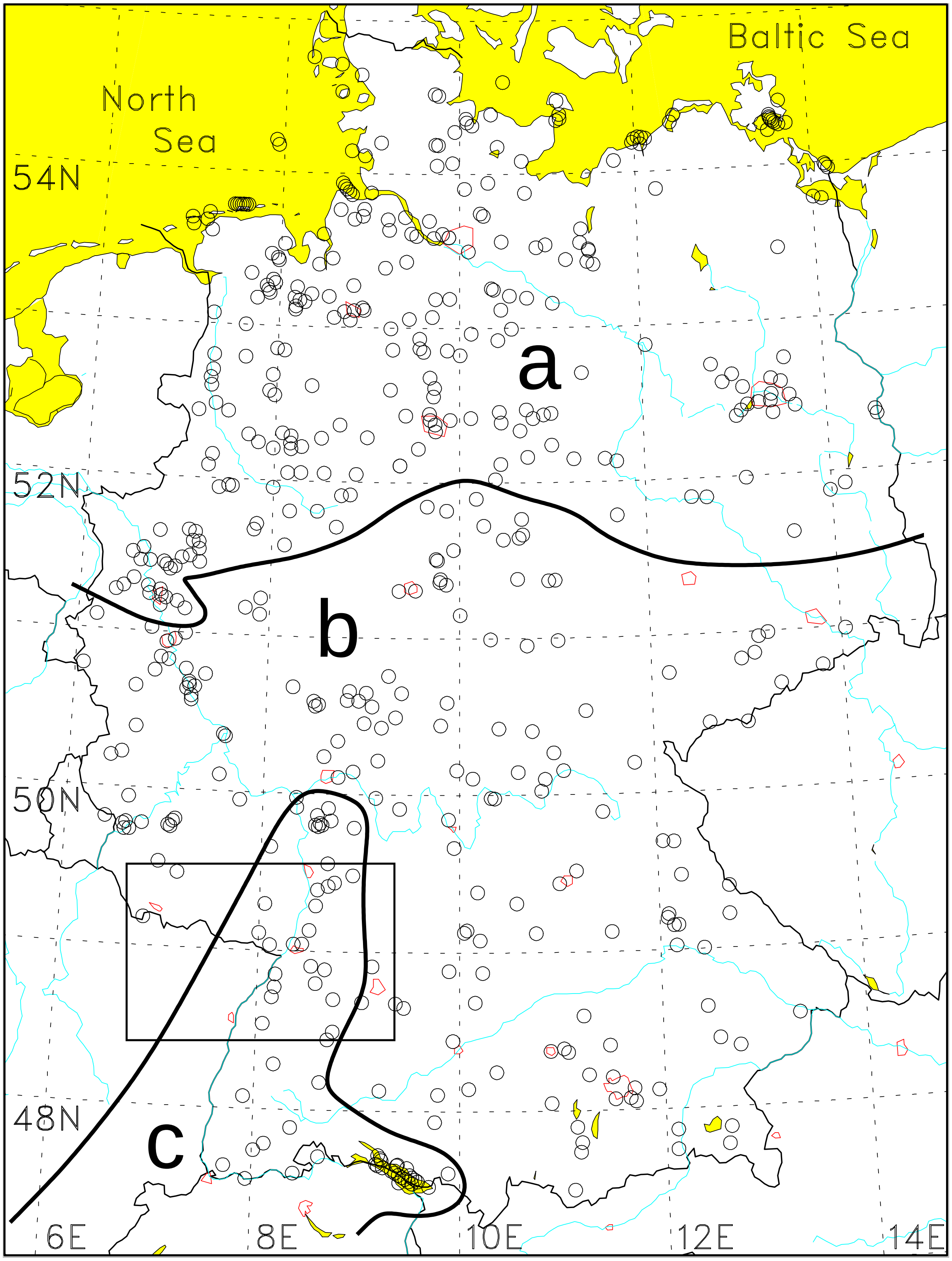


Figure 5

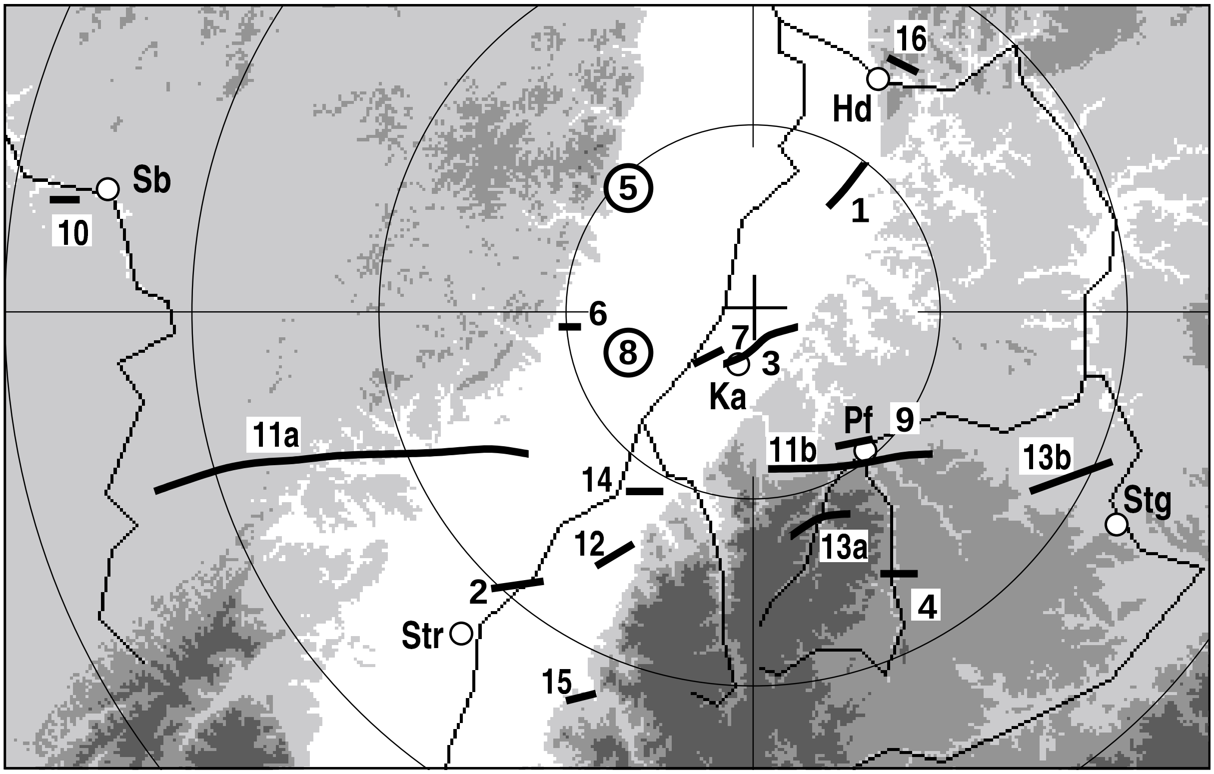


Figure 6

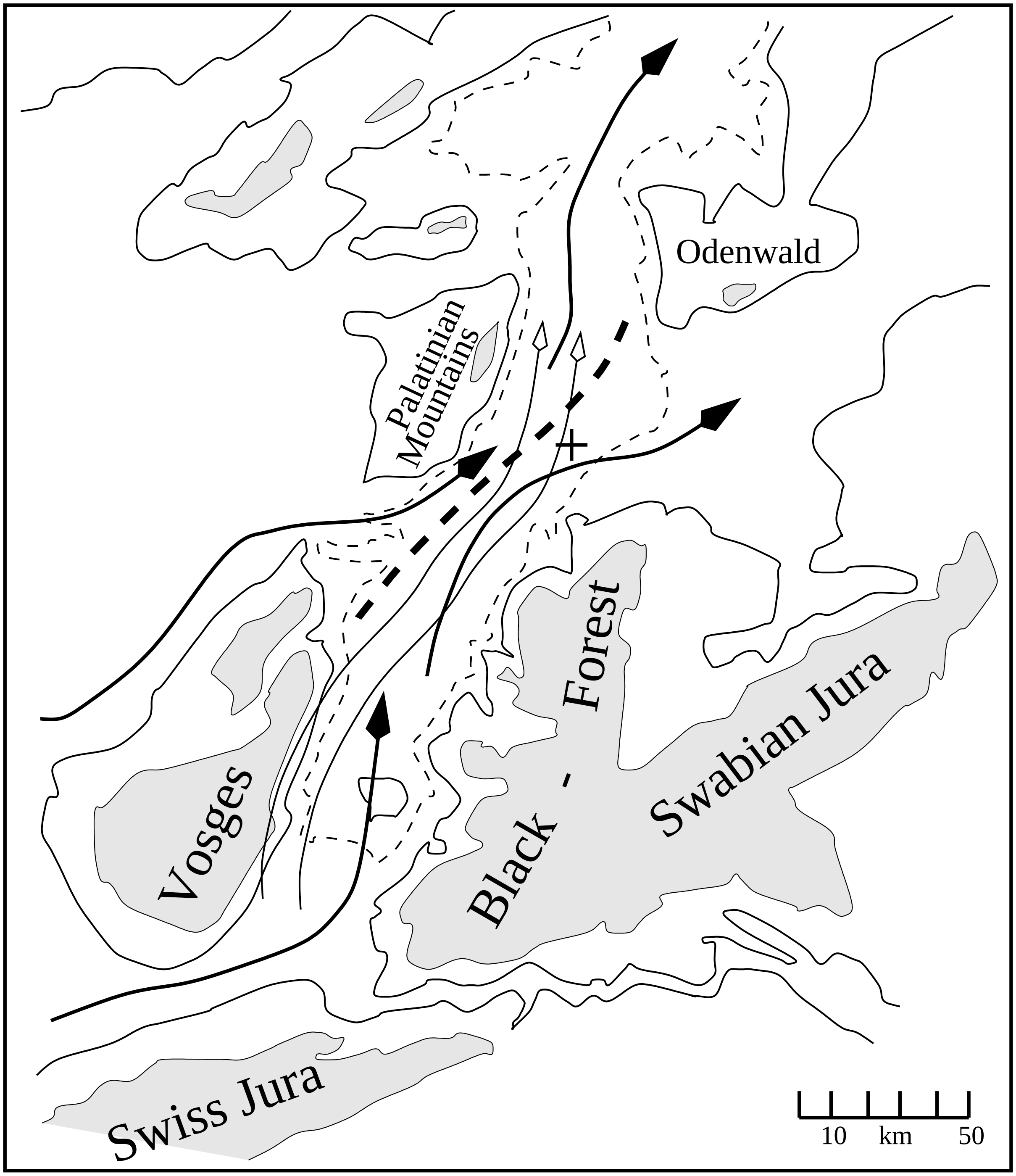

Odenwald
Palatinian Mountains
Vosges
Black - Forest
Swabian Jura
Swiss Jura
10 km 50

Figure 7