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Atmospheric Research 56 (2001) 191–201

ATMOSPHERIC RESEARCH

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Some aspects of the international climatology of tornadoes by damage classification

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Accepted 21 November 2000

Abstract

Reports of tornadoes, broken down by damage, from seven countries have been examined. In particular, the long-term relatively high-quality dataset from the US is used to develop distributions which indicate that the number of tornadoes decreases log-linearly with increasing *F*-scale. Two distinct distributions, one apparently associated with supercell tornadogenesis processes and the other with non-supercell processes, are found in both the US data and in other countries. The similarity of the distribution in the US prior to the 1950s, when an official, organized collection effort began, and the French record, suggests that only 15% of French tornadoes are being reported currently. In addition, we can use the simple statistical distributions to estimate the return period of violent tornadoes in France (approximately one every 5–10 years) and the UK (approximately one every 250–300 years). Published by Elsevier Science B.V.

Keywords: International climatology; Tornadoes; *F*-scale

1. Introduction

Tornadoes have been observed on all continents except Antarctica. Prior to the 20th century, most of the reports were anecdotal in nature and systematic evaluation of data was extremely rare. In the 1960s, studies of the damage associated with individual tornadoes in the US led to the development of the Fujita damage scale (Fujita, 1971), a method to classify tornadoes based on the maximum level of damage. Although Fujita estimated windspeeds associated with the different levels of damage,[1] in practice, the

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[1] The formula for the windspeed associated with the different F-levels is $V = 6.30(F+2)^{1.5}$. It defines $F1$ as the low end of hurricane force winds (32 m s^{-1}) and $F12$ as Mach 1 (331 m s^{-1}). In practice, the useful range goes from $F0$ to $F5$.

0169-8095/01/$ - see front matter. Published by Elsevier Science B.V.
PII: S0169-8095(00)00098-3

scale only provides information on damage. Some of the difficulties this leads to have been discussed by Doswell and Burgess (1988) and Grazulis (1993).

All tornadoes in the US have been assigned F-scale values since 1973. It is possible to estimate F-scale values for tornadoes prior to that date if sufficient documentation (e.g., newspaper accounts, photographs) is available. This has been done by Tecson et al. (1977) for all US tornadoes back to 1916 and Grazulis (1993) for US strong and violent tornadoes as far back as 1640, and by other researchers for a number of other countries (e.g., Paul, 1999 for France). Information from many of those countries can be found in this volume (e.g., Reynolds, 2000 for the UK).

The data from the UK were originally given according to the TORRO scale $V = 2.365(T+4)^{1.5}$ (Meaden, 1976), where V is the velocity in m s^{-1} and T is the T-scale number. From the two velocity-based definitions, an F value can be found from a T value by $F = 0.52T + .08$. For simplicity, we have approximated this by $F = 0.5T$ and truncated values to the nearest integer, so that T0 and T1 correspond to $F0$, $T2$ and $T3$ to $F1$, etc., in the manner of Elsom and Meaden (1982). The two scales differ in their assignment of velocity values by 6%. Given the inherent difficulties in assigning F and T values, this is a valid approximation. In operational practice, the two scales differ only in the details of the defining equation. We have chosen to use the scale that is in more widespread use. In addition, the problems associated with damage surveys and uncertainties associated with estimating windspeed from observed damage make highly precise assignments dubious.

Several fundamental questions can be addressed by looking at the results from different countries. Chief among them is: What similarities and differences can be found in the distribution of tornadoes by damage around the world? If tornadoes have similar characteristics in different parts of the world, then it may be possible to use data from areas of relatively high frequency and quality of reports to make estimates of threats in other parts of the world. In addition, it may be possible to develop estimates of the degree of underreporting of tornadoes in different countries.

2. The US record

The longest tornado record collected by an official national agency at the time of the events occurs is that from the US, beginning in 1953 with the creation of the National Severe Storms Project. Through efforts at researching previous events, a relatively high quality record was extended back to 1916 by Tecson et al. (1977). The number of low F-scale tornadoes has increased dramatically since the 1920s (Fig. 1), with approximately 700 $F0$ tornadoes reported annually in the 1990s compared to only seven in the 1920s.

Although the mean annual number of $F3$ tornadoes has ranged from about 20 to 60 depending on the decade, it is important to note that there is no long-term secular increase across the length of the record. Indeed, the maximum values (about 50–60 $F3$ tornadoes per year) are found in 1950–1979, with the remainder of the record averaging between 25 and 35 $F3$ tornadoes per year. Changes in the total number of tornado reports in the US are almost entirely the result of changes in the low-end reports. It is

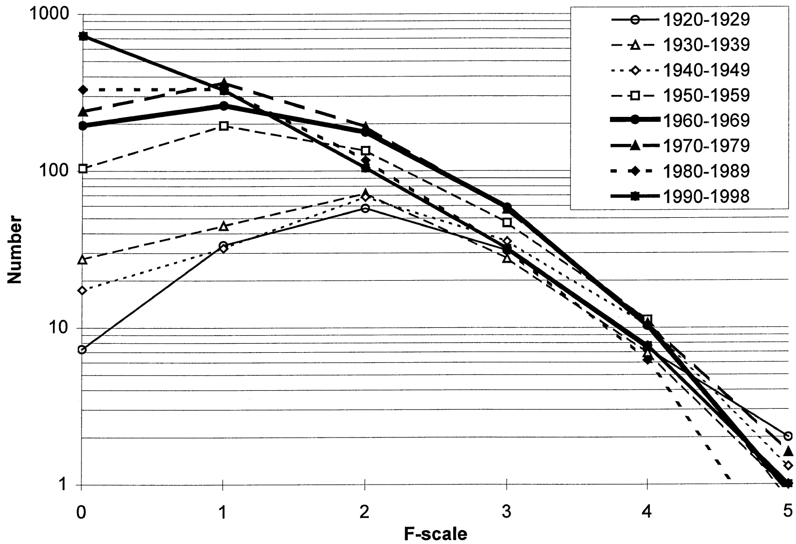

Fig. 1. Annual average of tornado reports by decade in US by F-scale.

also of importance to note that the largest changes between any two decades occurred between the 1940s and 1950s, at a time when it became the responsibility of a governmental weather forecasting and research agency to collect the data when the events occurred. The mean annual number of $F0$–$F2$ tornadoes reported in the US increased from about 150 to 450 from the 1940s to the 1950s.

3. Distributions by *F*-scale

A feature of interest in the US record is that the distribution of tornadoes by F-scale has been approaching log-linear (see Fig. 1). This distribution is consistent with standard statistical distributions of rare events, such as the Gumble distribution, that show a nearly log-linear decline as the intensity of the event increases and the frequency at which it is observed decreases. This log-linear behavior has been seen in other weather records, such as extreme hourly precipitation amounts (Brooks and Stensrud, 2000).

It is important to consider sources of error in the distributions. In general, there are at least four sources of error in the collection of data and classification of tornadoes by damage scale. First of all, there are times when no or very few reports at all are collected. There is evidence of this in periods such as the 1940s in France and Germany, as well as the mid-19th century in Germany (Fig. 2). Similarly, from 1905 to 1995, there were five tornadoes reported in the Eastern Cape province of South Africa. After two well-publicized tornadoes elsewhere in South Africa in the early summer of 1998–1999, there were 10 tornadoes reported in the province the rest of that season (de Coning, personal communication). It seems likely that the total of five reports in the earlier 90 years is an underestimate of the true number of events. In those cases, tornadoes at *all*

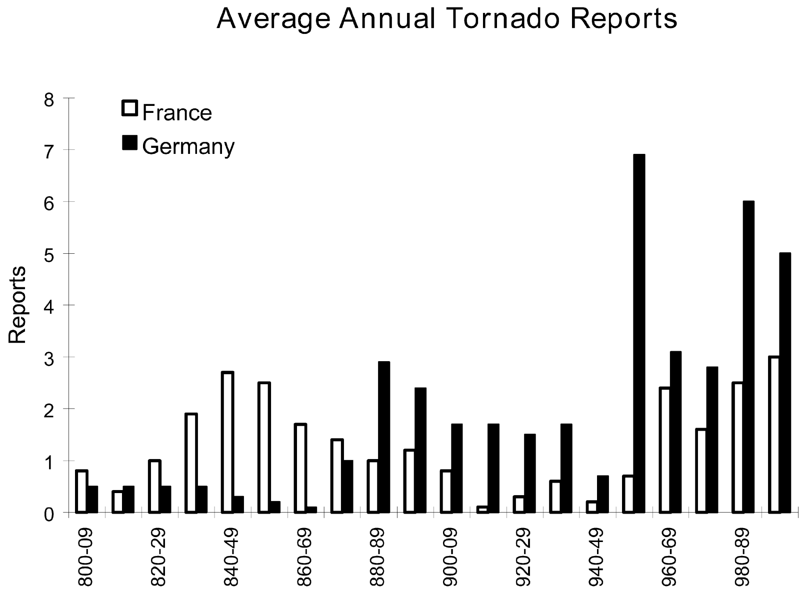

Fig. 2. Annual average of tornado reports by decade since 1800 in France (light bars) and Germany (dark bars).

F-scales are missed. Second, low F-scale tornadoes are likely to be missed in the reporting because they typically have short lifetimes and path lengths. Third, given that the assignment of an F-scale rating depends upon adequate structures being present to be damaged, it is likely that the number of tornadoes at the highest F-scales is underestimated. For example, if there are no structures present in the path of a tornado, it is impossible, in practice, to rate it as a violent tornado. In general, this kind of problem moves tornadoes from higher F-scale values towards lower F-scale values. Finally, there may be random errors in the assignment of F-scale. Interpretation of the exact cause and extent of damage is an extremely difficult task and uncertainties in knowledge of the construction of a building or the debris that struck a building lead to questions about the assignment that are often hard to answer. It is the experience of the authors that damage surveyors may often disagree over the value to assign to event by one F-scale.

The first type of error does not affect the probability distribution function of tornado damage classification, but obviously it will affect the total number of tornadoes. The second and third types of errors “move” tornadoes out of the ends of the distribution towards the middle classes. If there truly are more $F0$ tornadoes than higher classes, random errors actually move tornadoes preferentially out of $F0$ toward higher F-values. A simple hypothetical example illustrates this. Consider the case where there are 1000 “true” $F0$ tornadoes, 400 $F1$ tornadoes, and 160 $F2$ tornadoes. If 10% of tornadoes are misassigned one class too high and 10% are misassigned one class too low, the fact that no tornadoes come into the $F0$ class from “below” means that the distribution of assigned F-scales will be 940 $F0$, 436 $F1$, 168 $F2$, and 16 $F3$ tornadoes.

Since the 1950s, the slope for US tornadoes has been relatively constant for $F2$–$F4$ tornadoes. In the limiting case that the "true" distribution is characterized by a log-linear distribution, it can be shown that, for large numbers of reports, the slope of the line on a log-scale will not be affected by random classification errors except at the ends of the F-scale. Since the other three kinds of errors do not affect the probability distribution function, the slope of the distribution between $F2$ and $F4$ is a basic parameter of the distributions seen in Fig. 1. Between 27 and 35 $F3$ tornadoes have been reported annually in the US, on average, for every 100 $F2$ tornadoes, depending on decade, and between 5 and 8 $F4$ tornadoes have been reported for each 100 $F2$ tornadoes.

Additional insight into the nature of the distribution can be gained by looking at the number of tornadoes in different parts of the US for the period 1950–1995. In the Central Plains (the states of Oklahoma, Kansas, and Nebraska), a region roughly corresponding to an area sometimes called "Tornado Alley", the number of $F3$ tornadoes per 100 $F2$ tornadoes is slightly more than 38, with 13 $F4$ tornadoes per 100 $F2$s (Fig. 3). For the remainder of the US east of that region, except for Florida, the corresponding numbers are 34 and 13. There are almost 7000 tornadoes in the Central Plains region and over 17000 in the Eastern US region over the time period. The Eastern US region is almost 10 times as large as the Central Plains, so that per unit area, there are about four times as many tornadoes in the Central Plains. Nevertheless, the probability of a violent tornado, given that a tornado is reported, is approximately the same in each region. The *unconditional* probability of a violent tornado is much lower in the Eastern US because the overall probability of a tornado is much lower.

Other regions of the US show a very different distribution. Tornadoes in Florida, the Front Range region of Colorado just east of the Rocky Mountains, and the West Coast

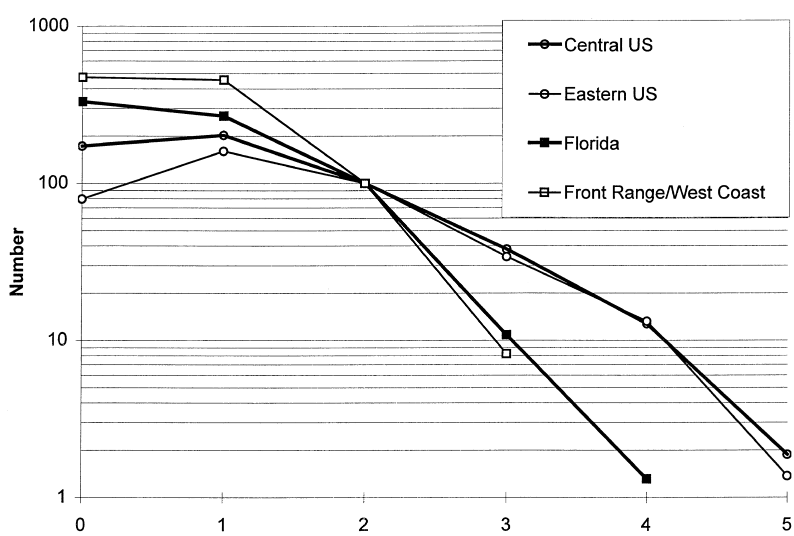

Fig. 3. Tornado reports by F-scale for different regions of US (period of record 1950–1995). Reports have been normalized to 100 $F2$ tornadoes.

states have a much steeper slope as F-scale increases (8–11 $F3$s per 100 $F2$s and 1 $F4$ per 100 $F2$s in Florida, with no $F4$ tornadoes in the 344 $F2$ or greater tornadoes in the Front Range and West Coast) (Fig. 3). Florida, particularly in its southern part, has a tornado record dominated by waterspouts coming on shore, and the Front Range of Colorado has many so-called "landspouts" (e.g., Brady and Szoke, 1989), which are generally considered to be weaker in intensity than supercell-produced tornadoes.

We hypothesize that the difference in the two regimes in the US is a result of the physical processes leading to tornadogenesis in those regimes. The Central Plains and Eastern US regions appear to be dominated by processes associated with supercells, while the other regions are dominated by non-supercell processes. To the extent that the slopes represent the "true" distributions, it appears that there may be two limiting slopes —with the number of tornadoes at $F(n+1)$ being about 36% of the number at $F(n)$ for supercell processes and about 10% for non-supercells. This distribution would imply that about 1 out of every 70 supercell tornadoes is violent ($F4$ or $F5$), and about 1 out of every 7000 reported non-supercell tornadoes in the US is violent.

With the background of the record from the US, we want to look at the distribution of tornadoes in other countries. We have used data from eight countries (Argentina, Australia, Canada, Germany, France, Italy, South Africa, and the UK) with more than 100 tornadoes in each reported by F-scale. The results have been scaled to 100 $F2$ tornadoes as before and plotted in comparison to the US data from the 1990s (Fig. 4).

The Argentine, Australian, Canadian, German, and South African records are all similar to the US records for $F3$ and higher intensity events. The similarity between the Argentine and US records continues below $F2$, with even the $F0$ report frequency being reasonably similar. The Argentine and Canadian $F0$ records lie between the US in the 1980s and 1990s (see Fig. 1). Given the historical underreporting in the US, the apparent

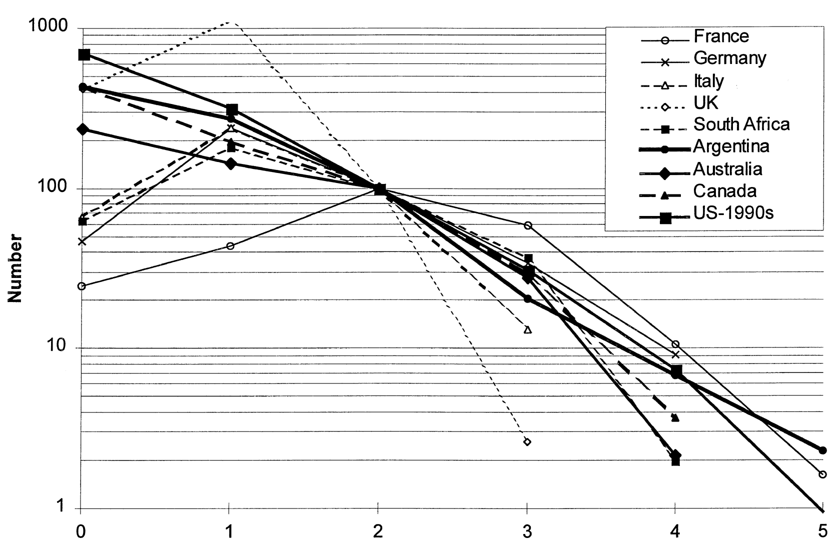

Fig. 4. Same as Fig. 3 except for different countries.

completeness of the their records is remarkable. Although it is likely that tornadoes are missed in the reporting database there, it appears that, if so, they are missed across all ranges of intensity, with only a slight preference for the lowest end of the F-scale. Thus, the records seem to reflect an unbiased sample of the true distribution.

The South African sample shows more apparent underreporting of $F0$ tornadoes than the Argentine, Canadian, or modern American records. Similarly, Italian tornadoes also have a relative lack of weak tornadoes. In addition, the Italian record for $F3$ tornadoes lies between the two limiting distributions in the US record. Although the sample size is relatively small (approximately 18 tornadoes per year), it is not unreasonable to believe that this reflects an important aspect of the Italian climatology. With the long coastline extending into the warm Mediterranean Sea, it seems likely that a large number of Italian tornadoes may be waterspouts that have moved on shore. The geographic distribution of Italian tornadoes supports this notion, particularly in the southern part of Italy and along the Gulf of Genoa (Giovannoni, 1999). Thus, the Italian record may represent both extreme limiting processes-the supercell process seen in the central and eastern US and the non-supercell process that appears to dominate the record in Florida and the Front Range of Colorado.

The UK record, on the other hand, does not resemble any of the records from the US. $F3$ reports are less than 3% of the number of $F2$ reports, in comparison with the 8–11% values seen from Florida, the Colorado Front Range, and the West Coast. Although this implies that the UK record may be dominated by non-supercell processes, the extremely low value is curious. Whether it implies that the apparent limit in the data from the US is too high, or that fundamental differences exist in the basic nature of the datasets, is

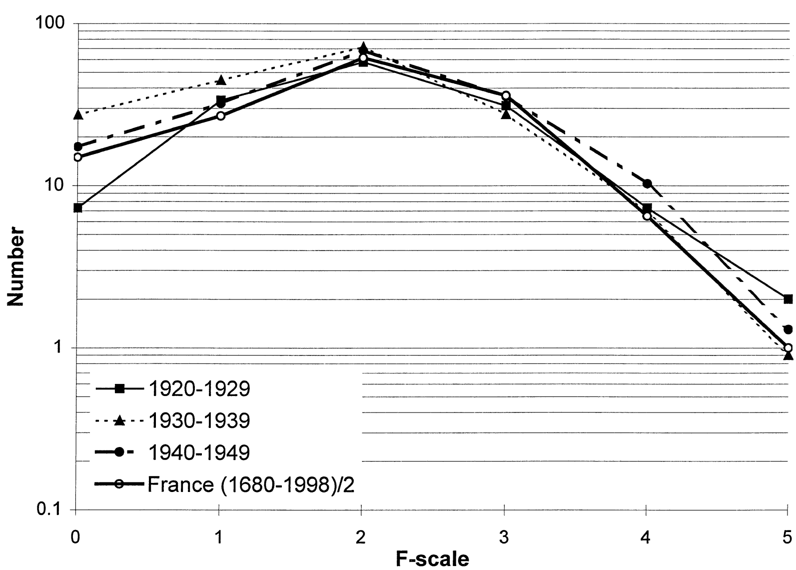

Fig. 5. Annual average of tornado reports by F-scale for US during 1920s (light solid line), 1930s (light short-dashed line), and 1940s (light long-dashed line) and reports from France for 1680–1998 divided by two (heavy solid line).

not clear. Given that procedures for collecting information on tornadic damage are very different in the two countries, it is not obvious that we will ever be able to resolve the reasons for the differences in the records.

The French record is also of particular interest, especially when it is considered using the US record as a background. The raw data show a less steep slope from $F2$ to $F4$ than the central and eastern US record, with the peak number of reports in the $F2$ range. A different impression is gathered, however, by comparing the French record to the pre-1950s US record (Fig. 5). The distributions are remarkably similar. Comparing the pre-1950s US record to the 1990s US record shows an increase in the total number of tornado reports by a factor of seven. Thus, it seems reasonable to expect that if an official effort began to collect reports in France, seven times as many reports would be collected as are currently found. Since Paul (1999) has reported three tornadoes per year in modern France, this leads to an estimate that approximately 20 tornadoes per year actually occur in France.

4. Estimating violent tornado occurrence

The existence of what appear to be regular distributions of tornadoes with increasing damage allows us to make estimates of the return periods of extremely rare events such as violent tornadoes. This is important for assessment of the threat of rare, potentially devastating events. Assuming that the "true" distribution of French tornadoes by F-scale would look like the 1990s in the US, we can make an estimate of the return period of violent tornadoes in France. Given that, for the entire US in the 1990s, between 0.5% and 1% of all tornadoes have been violent, a total of 20 tornadoes per year would lead to one violent tornado per every 5–10 years in France. Four were reported in the 33 years from 1967–1999, consistent with that estimate.

We can make a similar estimate for the UK, which appears to be dominated by non-supercell processes. While we do not have the evidence to make a quantitative estimate of the underreporting in the UK, we can provide some bounds on it. Reynolds (2000) reports 33 tornadoes per year in the UK. If we assume that 65–80% of actual tornadoes are reported, then using the non-supercell $F(n+1)/F(n)$ ratio of 0.1 from the US leads to an estimate of one violent tornado every 250–300 years in the UK. TORRO (1997) report two violent tornadoes in the UK historical record, one in 1091 and the other in 1810, both producing $F4$ damage. Given the great antiquity of the reports, caution must be used in their interpretation, but the modern record contains no $F4$ tornadoes and only 1 or 2 $F3$ tornadoes in the UK from 1950 to 1997. The rarity of even $F3$ tornadoes makes it seem likely that the return period of $F4$ tornadoes in the UK must be very long.

5. Discussion

The long and extensive record of tornadoes by damage classification from the US provides a background for reports of tornadoes from other parts of the world. In particular, we have identified two limiting kinds of distributions when the reports are plotted versus F-scale. One, exemplified by the central and eastern US, Argentina, and Canada, is characterized by a ratio of about 36% between reports at a particular F-scale value and the next smaller F-scale value. We hypothesize that this distribution is dominated by processes associated with supercell thunderstorms producing tornadoes. The second distribution, exemplified by Florida, the Front Range of Colorado, and the UK, is characterized by an F-scale ratio of about 10% or less. We hypothesize that this distribution is dominated by processes associated with non-supercell tornadogenesis.

The existence of these two distributions provides a powerful check on the reasonableness of tornado datasets, given that they are of sufficient size. If the observed slope is much steeper or shallower than the "limiting" cases, that may be indicative of certain problems with the dataset. For instance, the relatively low number of $F0$ and $F1$ tornadoes in France are likely the result of underreporting. Comparison with the American record prior to the development of an official, organized collection effort indicates that it is probable that only about 15% of tornadoes are being reported in France. It is not unreasonable to assume that similar (or worse) underreporting problems occur in other countries where we do not have large enough datasets to make the kinds of comparisons that we have made here.

The existence of an official, organized severe weather report collection effort is critical for many reasons. First, it helps identify the true nature of severe weather. The presence of what appear to be consistent distributions in a variety of locations makes it possible even to estimate the likelihood of extremely rare, devastating severe weather events based upon the observed frequency of less rare, but less devastating severe weather events. Thus, data collection is the first step in identifying hazards for groups such as public planning and insurance interests.

On a longer time scale, questions of possible changes in severe weather frequency and intensity as a result of global climate change cannot be addressed without reasonable estimates of the "true" baseline climatology. A reasonably long, stable record of reports is an important aspect of this effort. It may be possible to use climatologies of environmental observations from upper-air soundings (e.g., Rasmussen and Blanchard, 1998), coupled with high-quality reports, to develop covariates relating the well-observed environmental variables and the poorly observed severe weather occurrences (Brown and Murphy, 1996). If that can be done, then changes in the environmental variables can be tested. The disadvantage to this is the need to develop a strong relationship between the environment and severe weather, which may be problematic.

Severe thunderstorms are, by their very nature, rare at any particular location. As a result, awareness by weather forecasters, emergency managers, and the general public may not be very good. In the absence of good estimates of the climatology, based fundamentally on a high-quality database of reports, if is unlikely that awareness can be developed in any of those groups. Without that awareness and the concomitant preparedness, the likelihood of major disasters occurring somewhere is high. The historical record in Europe (e.g., Boscovich, 1749; Wegener, 1917) demonstrates that significant tornadoes have occurred in the past in the vicinity of metropolitan areas. With population increases and growth of urban areas since many of those events, the possibility of a large-fatality tornado cannot be ignored.

Acknowledgements

We thank all of the individuals and groups that provided us with data (see Appendix A) In addition, Willi Schmid (Switzerland) Alois Holzer (Austria), Heino Tooming (Estonia), David Dehenauw (Belgium), and Dag Kristoffersen (Norway) provided data from their countries, but the sample sizes of rated tornadoes were too small to analyze.

Appendix A. Data sources (N is number of tornadoes in record)

Argentina (1930–1979), Altinger de Schwarzkopf and Rosso (1982) ($N = 368$)
Australia (variable), courtesy Phil Alford, Australian Bureau of Meteorology ($N = 239$)
Canada (1950–1998), courtesy David Etkin, Environment Canada ($N = 625$)
France (1680–1998), courtesy Francois Paul (1999) ($N = 294$)
Germany (1594–1999), courtesy Nikolai Dotzek (2001) ($N = 136$)
Italy (1991–1999), courtesy Mauro Giovannoni ($N = 158$)
South Africa (1905–1996, 1998–199), Goliger et al. (1997) and Estelle de Coning, South Africa Weather Bureau ($N = 195$)
UK (1950–1997), courtesy David Reynolds, Tornado and Storm Research Organization ($N = 942$)
US (1920–1998), courtesy United States National Weather Service ($N = 44417$)

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