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A Climatology of Tornadoes in Europe: Results from the European Severe Weather Database

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ABSTRACT

A climatology of tornadoes (over land and water) is presented, based on the European Severe Weather Database (ESWD), which contains reports of 9529 tornadoes. With the exception of a few small countries, tornadoes have been reported from all regions of Europe. The highest density of tornado reports is in western and central Europe. ESWD tornado reports increased strongly from 1995 to 2006 as a result of increased data collection efforts, followed by a decrease that likely has a meteorological nature. There is strong underreporting in the Mediterranean region and eastern Europe. The daily cycle of tornadoes over land (sea) peaks between 1500 and 1600 (0900 and 1000) local time. The Mediterranean annual maximum is in autumn and winter, while regions farther north have a maximum in summer. In total, 822 tornado fatalities have been recorded in the ESWD, which include 10 tornadoes with more than 20 fatalities. The average annual number of tornado fatalities in Europe is estimated to be between 10 and 15. The F2 and F3 tornadoes are responsible for the majority of the fatalities.

1. Introduction

Although many tornadoes take place in Europe every year, few scholars have studied them on a European level since the work *Wind- und Wasserhosen in Europa* (*Wind- and Waterspouts in Europe*; Wegener 1917) by well-known geophysicist, polar researcher, and meteorologist Alfred Wegener. He estimated the annual number of tornadoes in Europe to be "at least 100." We will show that this estimate was correct.

Peterson (1992) notes that during the early twentieth century there was actually more interest in tornado research in Europe than in the United States, but in the 1950s and 1960s tornadoes in Europe were often regarded as strange and rare phenomena according to Dotzek (2001). The infrequent occurrence of high-impact tornadoes has probably prevented tornadoes from becoming a well-established subject of research in European academia, or a high priority for weather services, as discussed by Rauhala and Schultz (2009).

This does not mean that tornadoes have received no attention at all, because several researchers and amateur meteorologists throughout Europe have put considerable time and effort in collecting tornado data in recent decades. These individuals have documented tornadoes occurring in their respective home countries. Many of these studies were first presented to an international audience at the European Conference on Tornadoes and Severe Storms (ETSS), held in Toulouse, France, in February 2000 (Snow and Dessens 2001, www.eurotornado.ou.edu), and at subsequent European conferences on severe storms. At these conferences, it became clear that a European effort was needed to establish a climatology across borders. Such an effort was made by the European Severe Storms Laboratory (ESSL) and has resulted in the European Severe Weather Database (ESWD; Dotzek et al. 2009). In this study, we present a climatology of tornadoes from a European perspective using the ESWD.

In contrast to the U.S. tornado database *Storm Data* (Schaefer and Edwards 1999; McCarthy 2003), which is co-maintained by the National Climatic Data Center (NCDC; http://www.ncdc.noaa.gov) and the Storm Prediction Center (SPC; http://www.spc.noaa.gov), the ESWD is not (co-)hosted by an authority engaged in forecasting tornadoes or even weather forecasting in general. Nevertheless, the ESWD is used for forecast verification by several weather services (Dotzek et al. 2009) and in the European Storm Forecast Experiment (Brooks et al.

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2011). It is also used to evaluate new automated forecast tools (e.g., Dotzek and Forster 2011) and remote sensing–based severe weather proxies (Bedka 2011).

Another important application of databases such as the ESWD is the study of meteorological conditions associated with the occurrence of severe weather events. Both *Storm Data* (e.g., Rasmussen and Blanchard 1998; Thompson et al. 2003; Craven and Brooks 2004), and the ESWD (Kaltenböck et al. 2009; Brooks 2009, 2013) have been used in such studies, combining storm reports with radiosonde measurements or data from numerical atmospheric models. Such studies provide insight into the prerequisites of tornado formation that cannot be obtained from individual case studies. For instance, the association of strong wind shear in the lowest 1–2 km above ground level with significant tornadoes was first documented in peer-reviewed literature (Thompson et al. 2003; Rasmussen 2003; Craven and Brooks 2004) using *Storm Data*, after being hypothesized almost 80 years earlier by Van Everdingen (1925) when studying a violent tornado case in the Netherlands.

Statistical methods can be developed to model the probability of severe weather occurrence from numerical atmospheric models that are too coarse to explicitly simulate tornadoes or even their parent storms. In regions of very inhomogeneous reporting rates such methods can be used to infer tornado occurrence with more accuracy than would be possible from observations. Moreover, changes in severe weather frequency as a result of climate change can thus be studied by applying these methods to climate model data (e.g., Brooks 2013; Diffenbaugh et al. 2013) or reanalysis data (e.g., Sander et al. 2013).

Databases of severe weather observations almost always suffer from a temporally and spatially inhomogeneous reporting rate (i.e., the fraction of occurred events that is reported varies with time and from region to region). For example, Verbout et al. (2006) discuss causes for the increased number of tornadoes in *Storm Data*, from 600 in the 1950s to about 1200 in the 2000s. They argue that report discrepancies, public awareness, Doppler radar, National Weather Service vigilance, and an increased emphasis on enhanced forecast verification efforts have jointly contributed to this upward trend. Such nonmeteorological artifacts are even more pronounced in the ESWD, as will be discussed in section 3.

We will describe the main characteristics of the ESWD dataset in section 2. In section 3, we will present and discuss the spatial distribution of ESWD tornado reports, their temporal distribution, annual and daily cycles, their intensity distribution, tornado-related fatalities, and tornado path width and length. In section 4, we will summarize the results and draw a number of conclusions.

2. Data and methods

a. The database

Version 3 of the ESWD has been described by Dotzek et al. (2009). The database was initially developed as an implementation of a standardized, flexible data format for severe weather reports to create a dataset to verify forecasts of the European Storm Forecast Experiment developed by Groenemeijer et al. (2004). Upon the founding of ESSL, ESWD development and management became a statutory purpose of ESSL (Dotzek et al. 2009). Here, we give an updated summary of the functionality of the current ESWD version 4.2.2.

The database is designed to facilitate the collection of information on local intense severe weather phenomena. The phenomena large hail, tornadoes (including waterspouts), heavy rain, and severe wind gusts are covered best. In addition, funnel clouds, gustnadoes, dust, sand- or steam devils, heavy snowfalls–snowstorms, ice accumulations, avalanches, and damaging lightning strikes are stored in the database.

The ESWD covers the World Meteorological Organization's region VI, which includes Europe and adjacent regions in the Middle East, as well as a few countries that are not part of region VI (almost) bordering the Mediterranean Sea. There is no fixed beginning time of the ESWD dataset, although its current implementation only accepts dates after the year 0 A.D.

b. Data collection and quality control

ESWD data are entered into the database by a member of any of these four categories: ESSL, Voluntary Observer Networks (VON) of storm spotters, weather services, or individuals. The reports are submitted through its web interface (http://www.eswd.eu), or through alternative interfaces that ESSL makes available to its partners.

VONs are associations of storm spotters: individuals who have organized to report severe weather to public authorities, media, and ESSL. Often, but not always, these networks collaborate with the weather service in their respective country and relay their data to them. Sometimes the ESWD is used for this data flow, sometimes other direct channels have been arranged. Presently, we are aware of such collaborations between spotters and weather services in Austria (Krennert et al. 2013), Germany, the Czech Republic, Finland (Tuovinen et al. 2009), and Spain.

All data entered into the ESWD by the general public are reviewed by ESSL within a few days of submission. Reports that are obviously not correct are deleted and other reports receive the appropriate quality level (see below). Additionally, an annual review at the beginning of each year ensures that no ''delayed'' reports have bypassed the initial, near-real-time check. However, even after this annual review, the data of the respective year may still be expanded, updated, or corrected at any time if new information warrants this.

Upon being entered, all data receive a quality control level, which may be upgraded at a later stage. The four levels are, in order of increasing quality:

- QC0: as received.
- QC0+: plausibility checked.
- QC1: confirmed by reliable source.
- QC2: verified through detailed analysis.

Reports with quality level QC0 have been entered through the public web interface and have not undergone any review by ESSL or its partners. QC0+ reports have undergone minimal quality control, in which a superficial validation with meteorological data such as radar or satellite imagery has been made. QC1 reports have undergone a more detailed quality control by ESSL or its partners. To be given QC1, conclusive photo or video material must be available, or an accredited storm spotter must deliver an eyewitness report. Finally, QC2 is the highest level of verification, meaning that the event has been the subject of a detailed case study by an expert. Users of ESWD data can select the quality level required for their respective purpose upon extracting the data. For the analyses in this study, all data up to 31 December 2013 having at least QC0+ status have been used.

Several national datasets have been merged into the ESWD since its official start in 2006. These are datasets on tornadoes from Germany (Dotzek 2001), Austria (Holzer 2001), the Czech Republic (Brázdil et al. 2004), Estonia (Tooming, 2001), Finland (Rauhala et al. 2012), France (Dessens and Snow 1989; Paul 2001), and Russia (Snitkovsky 1987). Additional data are being added continuously by a dedicated team at ESSL and through collaborations with networks of storm spotters, researchers, amateur meteorologists, and weather services. The ESWD team hopes that more national datasets will be provided so that they can be integrated. The database will, however, never be complete, as historical events may be uncovered and added at any time, and recent events are entered continuously. As a consequence, this study should be regarded as a snapshot of the database at a somewhat arbitrary moment.

c. *Tornadoes, waterspouts, and their intensities*

The ESWD definition of a tornado is the following:

> "A tornado or waterspout is a vortex extending between a convective cloud and the earth's surface, in which the wind is strong enough to cause damage to objects. It may be visible by condensation of water (a funnel cloud) and/or by material (e.g. water, in case of a waterspout) that is lifted off the earth's surface."

The ESWD does not have separate categories for tornadoes over land and tornadoes over water (i.e., waterspouts). Instead, they are both stored as "tornadoes," along with the type of surface over which the phenomenon was first observed and the types of surface that were crossed during its lifetime. Any end users requiring a distinction can do so by applying a filter using this metadata. They can thus choose whether tornadoes moving on- or offshore, or staying over water, are included in their dataset or not. In this study, the word tornado refers to either a tornado over land or over water, except where a distinction is explicitly made. Each database entry normally refers to an individual tornado. Occasionally, however, several tornado (or waterspout) occurrences may be summarized within one entry. This is the case whenever the individual coordinates of the tornado locations cannot be distinguished, for example when several waterspouts occur in close vicinity.

A total of 3818 ESWD tornado reports have received an intensity rating, which was done either by ESSL or by the original source of the tornado report, in which case it was checked by ESSL. The tornadoes were rated using the Fujita scale (Fujita 1971, 1981), and sometimes also on the twice as fine T- or TORRO-scale (Meaden 1976). Feuerstein et al. (2011) describe the de facto procedure that was followed (i.e., a comparison was made between damage to structures and vegetation to the description of each level on the scale). The structural integrity of damaged objects was taken into account in a similar way to that proposed by Fujita (1992). Since many more events (3181) have been assigned a Fujita-scale rating than a T-scale rating (1667), we only discuss Fujita-scale ratings this study. Tornadoes that lack sufficient information to assign a rating with a reasonable level of confidence have not been rated at all. This contrasts with the practice of *Storm Data*, where every tornado is rated, a practice that has been criticized by Doswell et al. (2009). In the ESWD, tornadoes that occurred exclusively over bodies of water are never rated on an intensity scale, except in the rare cases where they caused damage to ships or offshore platforms.

In 2007, the enhanced Fujita scale (EF scale; McDonald and Mehta 2006) was introduced in the United States and has since been adopted in Canada (Environment Canada 2013). The EF scale has the advantage that it introduces multiple damage indicators and the concept of "degrees of damage," which lends the tornado rating procedure more objectivity. However, the EF scale has not yet been adopted by ESSL for a number of reasons. First, the present EF scale uses damage indicators and degrees of damage to estimate wind speeds that are for a large

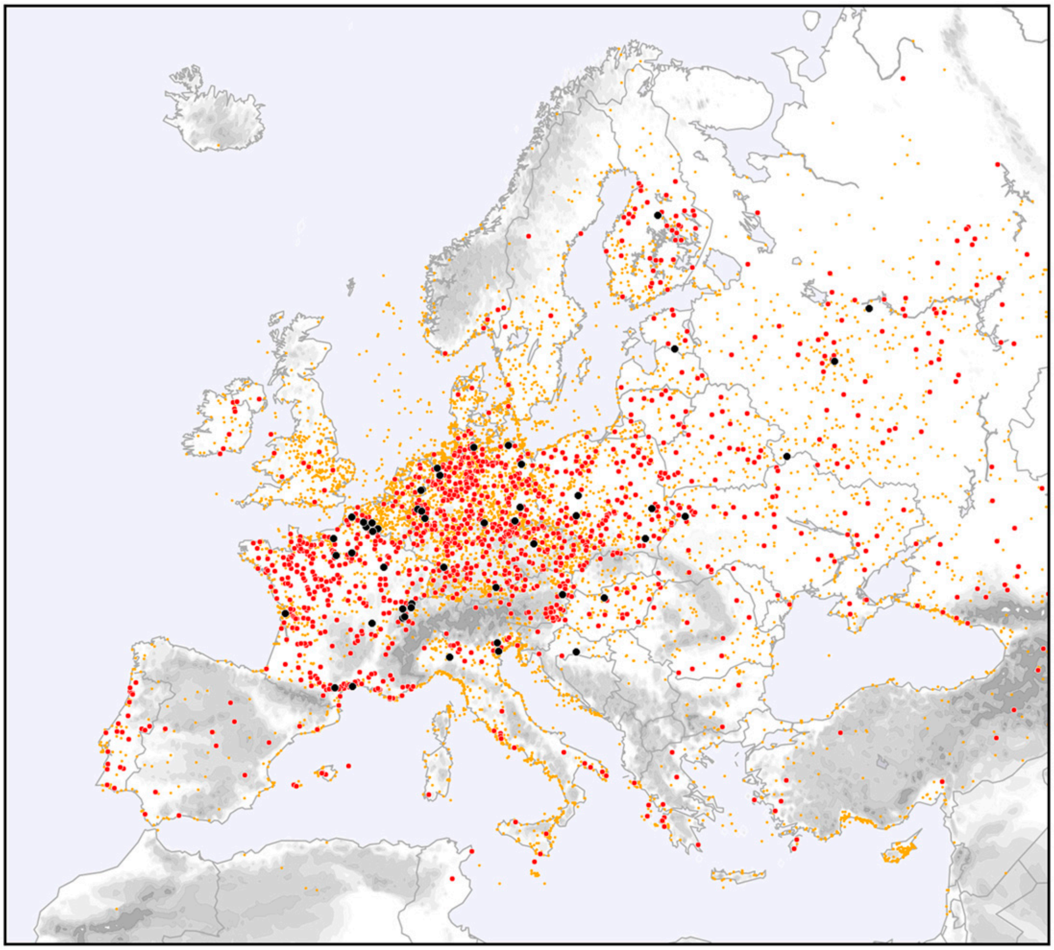

FIG. 1. Locations of all tornado reports contained in the European Severe Weather Database. Orange points are weak (F0, F1) and unrated tornadoes; red points are strong (F2, F3) tornadoes; and black points violent (F4, F5) tornadoes.

part based on U.S.-specific construction codes and practices (Doswell et al. 2009). Since these differ from European codes and practices, the scale needs substantial adaptation to be applicable in Europe. This is an effort that has yet to be undertaken. Second, ESSL is not aware of an objective motivation for the downward adjustment of wind speeds (cf. the F scale) at the upper end of the scale. Last, the wind speeds currently assigned to the EF scale cannot be easily translated to the original F scale, which would create a discontinuity in the ESWD.

3. Results

a. Spatial distribution

The ESWD contains 8741 reports of 9529 tornadoes. Their distribution across Europe (Figs. 1 and 2a) shows a very high density of reports across Germany, the Netherlands, Belgium, France, Austria, the Czech Republic, and Poland. Smaller clusters of reports can be found along many coastlines, such as the coasts of the Mediterranean Sea, the Black Sea, the North Sea, and the Baltic Sea. Few reports have come from (i) areas with low population density (e.g., northern Scandinavia, North Africa, the Alps), (ii) areas in which nationally collected datasets have not yet been integrated into the ESWD [e.g., Spain (Gayà 2011), Greece (Matsangouras et al. 2014; Sioutas 2011), or Turkey (Kahraman and Markowski 2014)], and (iii) from regions where few, if any, contacts with local tornado researchers have been made (some of the Balkan countries, North Africa, and the Middle East).

Tornadoes have been reported in all countries of Europe except in the former Yugoslav republics of Macedonia, Montenegro, and a number of microstates. The distribution appears to be strongly affected by varying reporting rates from one country to another.

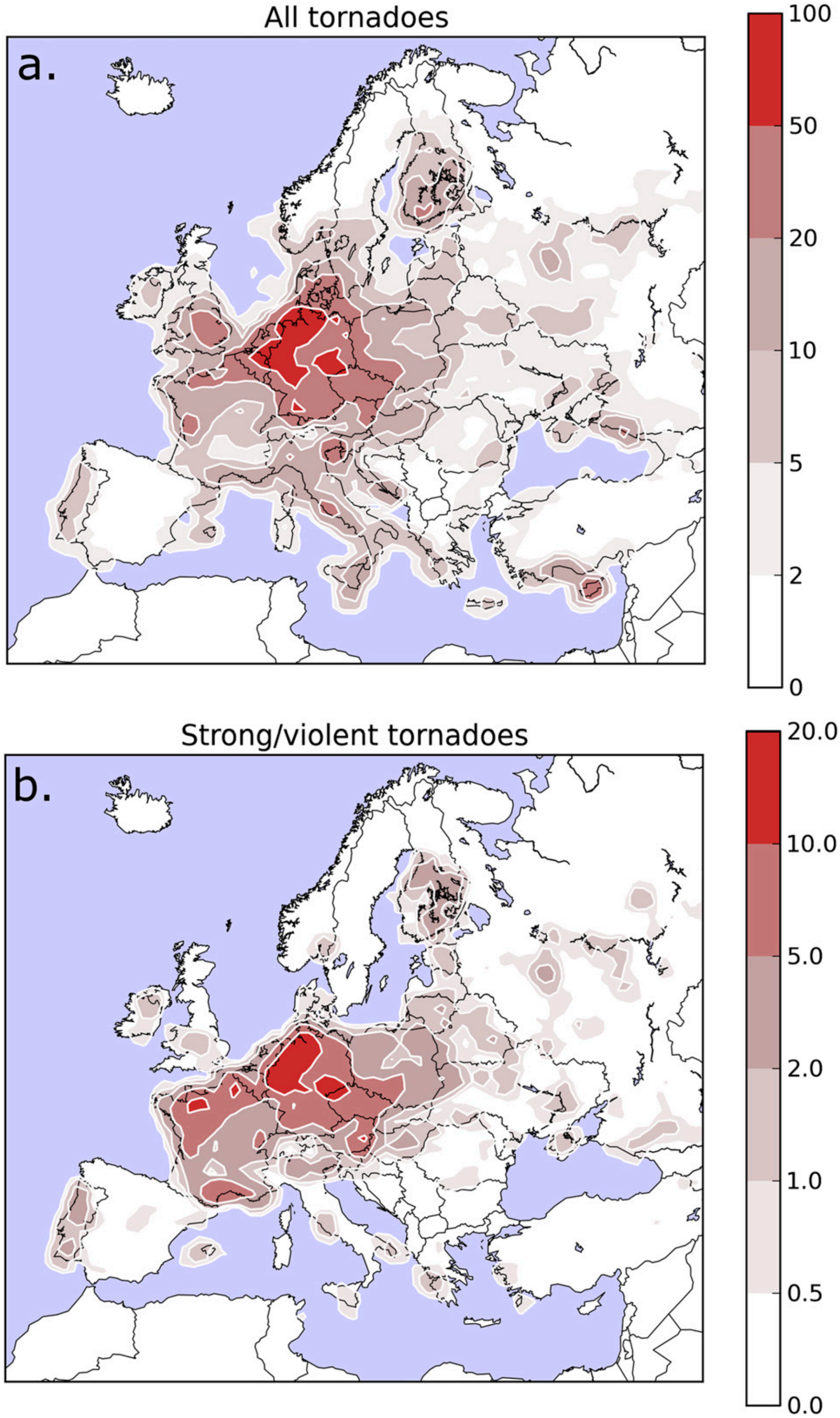

FIG. 2. (a) Number of tornado events and (b) strong–violent (F2 and stronger) tornado events per 10 000 km^2. The density was computed by dividing the number of events within (a) 100 and (b) 200 km of a point by the surface area of a circle with the respective radius. Please note the different scales in (a) and (b).

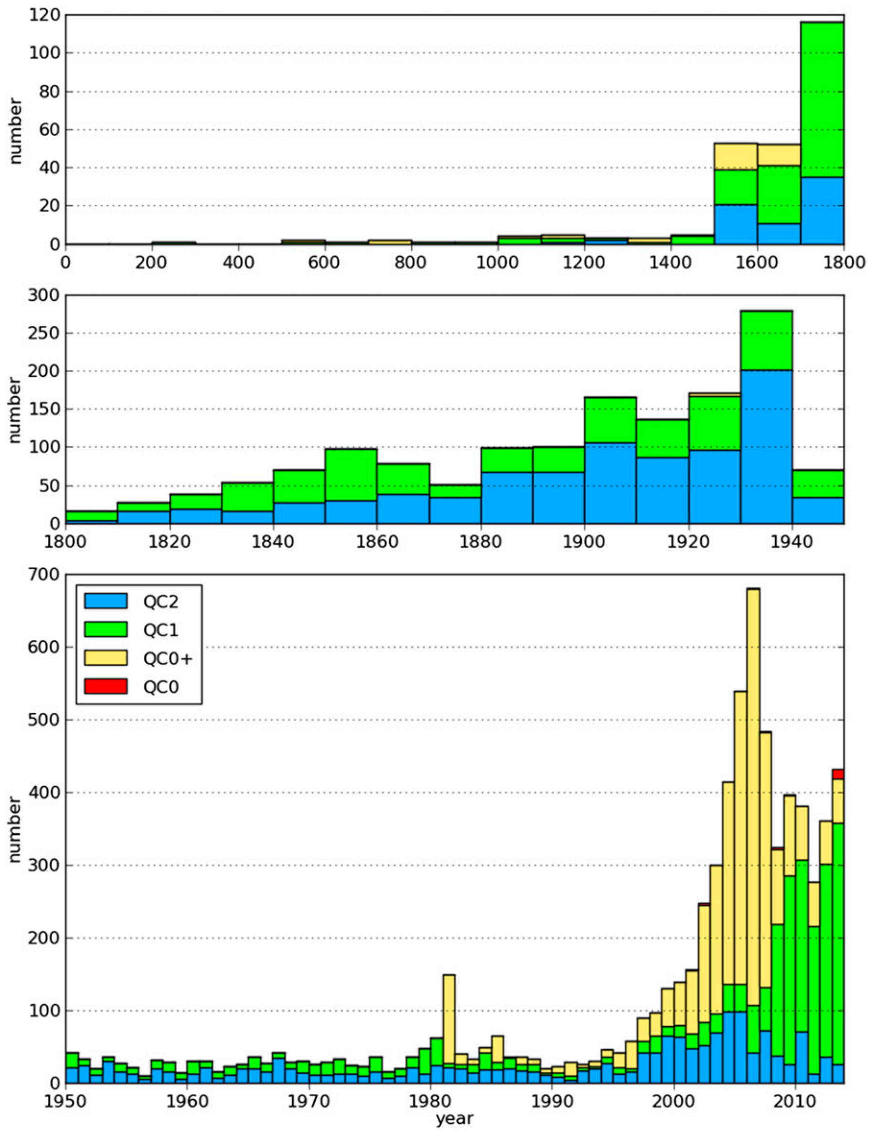

FIG. 3. Temporal distribution of tornado reports and their respective quality control levels: (top) 0000–1700, (middle) 1800–1940, and (bottom) 1950–2013.

There are, however, gradients within countries that cannot be easily explained by varying reporting rates. For instance, there is a decrease of tornado frequency from the northwest to the southeast in both France and Germany, and an increase from northeast to southwest Poland.

The distribution of strong tornadoes (F2 and higher) differs from that of all tornadoes in that there are only a few reports of strong tornadoes from southern Europe (Fig. 2). The majority of strong tornado reports stems from research of historical events, whereas weaker tornadoes are more likely to be recent events that have occurred after the establishment of the ESWD. This is illustrated by the fact that the average year of occurrence of weak (F0 and F1) tornado events in the database is 1985 and that of strong tornado events is 1949. Since no comprehensive studies from Spain, Italy, Greece, or Turkey have yet been integrated into the ESWD, this effect can to a large extent explain the scarcity of reported strong tornadoes from southern Europe.

b. Temporal distribution

The temporal distribution of tornado reports shows a gradual increase of reports over the centuries and in recent years (Fig. 3). A break is found during the 1940s during World War II and the first postwar years. After 1950, a relatively constant average number of reports is maintained up to 1995, only interrupted by a peak in

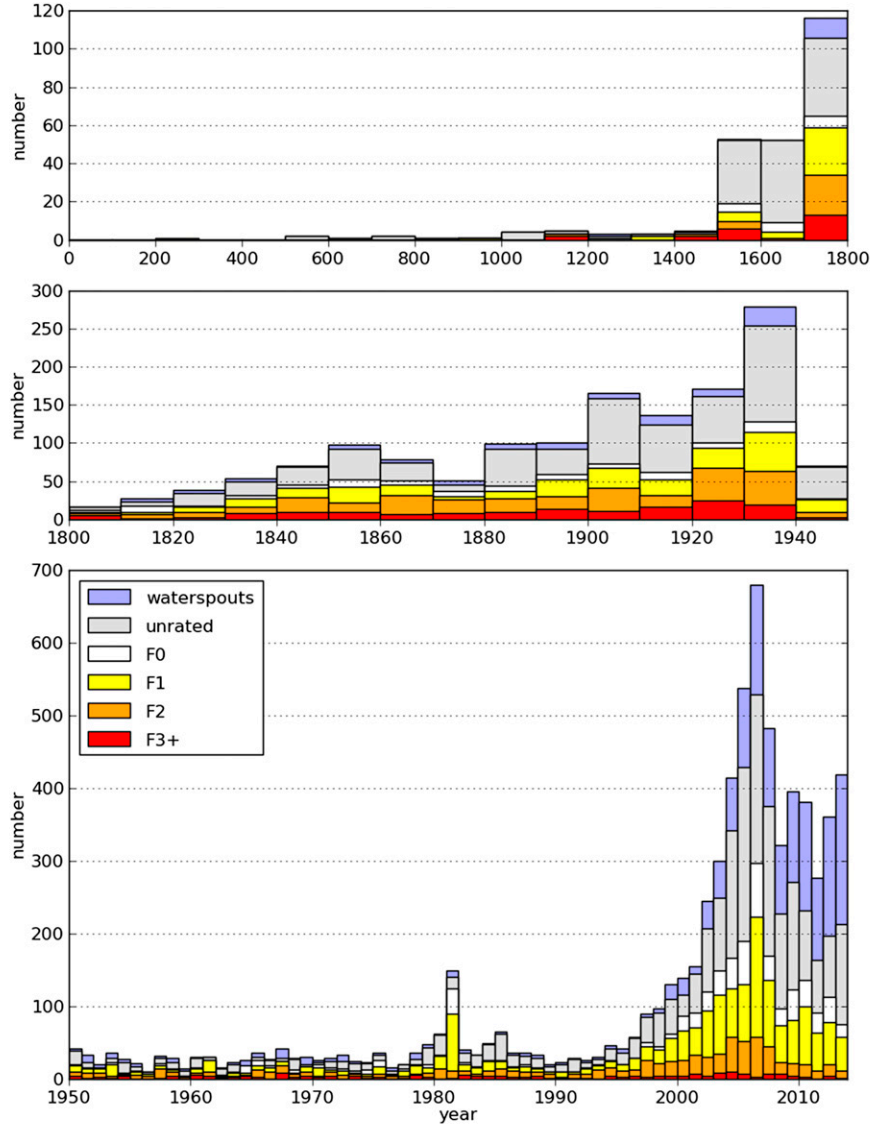

FIG. 4. The number of tornado reports within a given year and with a given rating in the European Severe Weather Database: (top) 0000–1700, (middle) 1800–1940, and (bottom) 1950–2013.

1981 attributable to an unusually large outbreak of F0 and F1 tornadoes in the United Kingdom, documented by Rowe and Meaden (1985).

After the mid-1990s, the number of tornado reports increases strongly, reaching a peak of 680 tornado reports in 2006. This increase is largely due to a revived interest in tornadoes after the European Conference on Tornadoes and Severe Storms (ETSS) in Toulouse, France, in February 2000 (Snow and Dessens 2001). The peak of tornado reports in 2006 also coincides with the start of ESWD operations at ESSL.

In 2006, the ESWD quality control levels were introduced and in the following years, gradually more resources could be devoted to data quality control. For many reports collected earlier on, it was not possible to obtain the *confirmation from a reliable source* required for the QC1 level, so that these have, therefore, mostly undergone only a superficial check resulting in a QC0+ quality level.

After 2006, a modest decline in report numbers occurs, which is followed by a stabilization near an annual number of 300 to 400 tornado reports. One might suppose that the better quality control was a key factor in this decline. However, there are a number of reasons why this is unlikely. First, it is untypical for a QC0+ report to be deleted upon closer review. Second, the

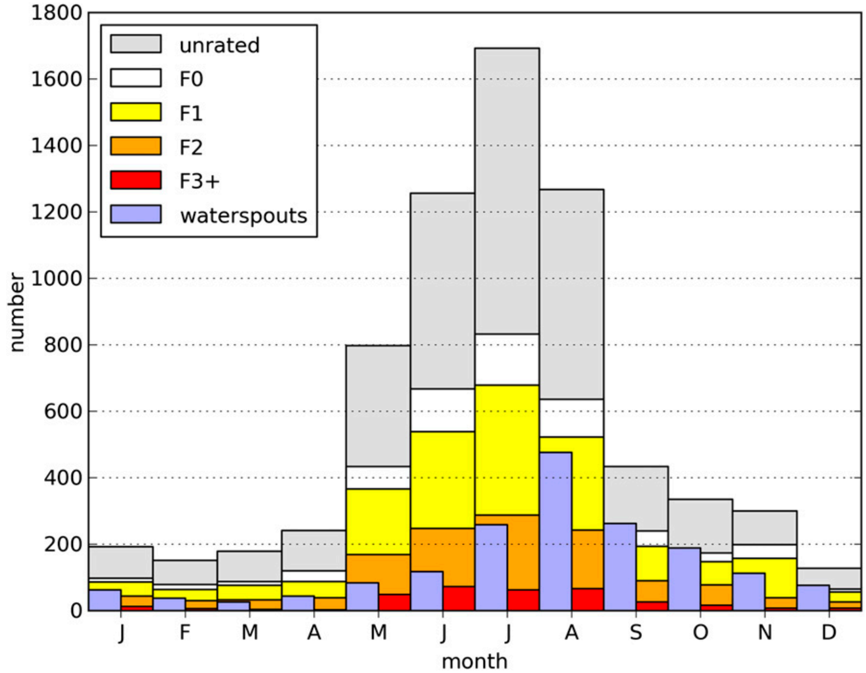

FIG. 5. The number of tornadoes reported in each month of the year. Tornadoes of which the date was not certain have not been included.

ESSL network has expanded rather than become smaller during this period. This is illustrated by a very strong increase of ESWD hail reports, from 911 ± 465 (2004–08) to 1735 ± 397 (2009–13). Last, from a deteriorating network, it would be expected that the number of weak tornadoes would decline more over time than stronger tornadoes, since stronger tornadoes tend to be reported more consistently over time (Brooks and Doswell 2001). Instead the decline occurs for tornadoes of all intensities (Fig. 4), while the number of waterspouts even shows an increasing trend. Therefore, we think that this decline is a true meteorological signal.

c. Annual cycle

The European tornado season has a clear summer maximum in July and a minimum in December (Fig. 5). Strong tornadoes and weak tornadoes over land have a similar annual cycle. The cycle of waterspout events is slightly delayed relative to that of tornadoes over land as it exhibits a maximum in August and a minimum in March. This is probably so because the temperature of water bodies lags behind the air temperature, so that the average magnitude of instability over water correspondingly lags behind that over land.

The annual cycle of tornado days differs across Europe. Figure 6 shows the annual peak month of tornado activity for each region. The peak month was determined from a gridded monthly number of tornadoes computed on a $0.5° \times 0.5°$ grid, where the monthly number of tornadoes is the number of days on which a tornado occurred within the grid box. This field, available for each month, was subsequently smoothed with a 200-km radius Gaussian kernel and then divided by the annual number of tornadoes, yielding the fraction of tornadoes occurring within the specific month. The fractions were then smoothed temporally by a three-point filter giving the monthly fraction n_i according to $n_i = 0.25n_{i-1} + 0.5n_i + 0.25n_{i+1}$. Finally, for each point, the month with the highest number of tornado days was plotted for all areas, masking out areas where data coverage was low and judged to be noisy (<2.5 events per 10 000 kilometers squared).

The result shows that the peak of the tornado season in western, central and northern Europe is in midsummer. The eastern Balkans have a maximum in late spring, and much of the Mediterranean region in autumn. The eastern Mediterranean, however, has its maximum in winter.

d. Daily cycle

An analysis of the hourly occurrence of tornadoes uses local mean time, a form of solar time that corrects the variations of local apparent time and is computed from longitude (Fig. 7). The frequency of tornadoes over land increases during the morning and early afternoon, reaching a peak between 1500 and 1600 LT, and then decreases during the evening, reaching a minimum between 2300 and 0700. The diurnal cycle of waterspouts is

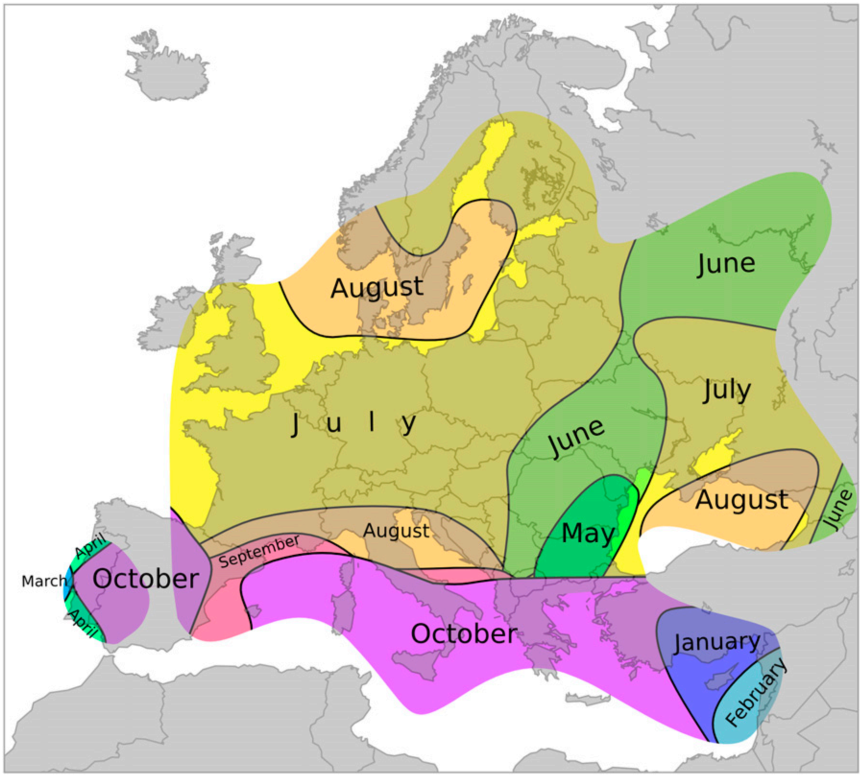

FIG. 6. Month of maximum number of tornado days.

shifted to earlier times, exhibiting a maximum between 0900 and 1000. Little spatial variation of the diurnal cycle was noted when selecting particular regions of Europe (not shown). Compared to the annual average diurnal cycle, the wintertime cycle has waterspouts occurring more equally across the day than the summer events (Fig. 8), and the peak of maximum activity of tornadoes over land is somewhat earlier in winter (1500–1600) than in summer (1600–1700 with a slow decrease afterward).

e. Tornado intensity

In total, 3818 of the 8749 tornado events were rated on the Fujita scale, leaving 4931 reports unrated. The distribution (Fig. 9) shows that the number of tornadoes decreases strongly for ratings F1 and higher. A comparison with the fractional distribution of tornadoes in *Storm Data* (1950–2013) shows that the tornado frequency in the ESWD decreases somewhat faster with increasing intensity than the American tornadoes (Fig. 10). In addition, the fraction of F0 tornadoes is lower for the European tornadoes than for American tornadoes. This is probably because many of the unrated tornadoes would be assigned to the F0 class if they could have been rated. This is in line with the conclusions of Grünwald and Brooks (2011), who, in a study on sounding parameters in tornado environments, concluded that the unrated tornadoes are likely to consist of mostly F0 tornadoes.

f. Tornado fatalities

Several individual tornadoes with several dozens of fatalities are recorded in the ESWD since 1800. Table 1 lists the 10 deadliest tornadoes contained in the ESWD. The numbers of deadly victims are very uncertain in some cases. The tornado in Ivanovo, Russia, is reported to have caused anywhere between 69 and 400 casualties. The number of 400, recently reported by Finch and Bikos (2012) is of questionable quality, as they discuss themselves. No original sources except a newspaper citing diplomats and a study by Peterson (2000), which states this number as a fact without specifying sources, were available to them. We think the number of 400 was indeed merely a first rough estimate by diplomats relating to the entire severe storm outbreak that consisted of several tornadic storms, and which may also include victims from other hazards such as flash floods. The number 69 in the ESWD stems from the newspaper *Pravda* (2011) citing official sources, even though Pravda mentions that this number stems from ‘‘Soviet statistics’’ that ‘‘should not be trusted,’’ since the USSR ‘‘did not want to talk about such

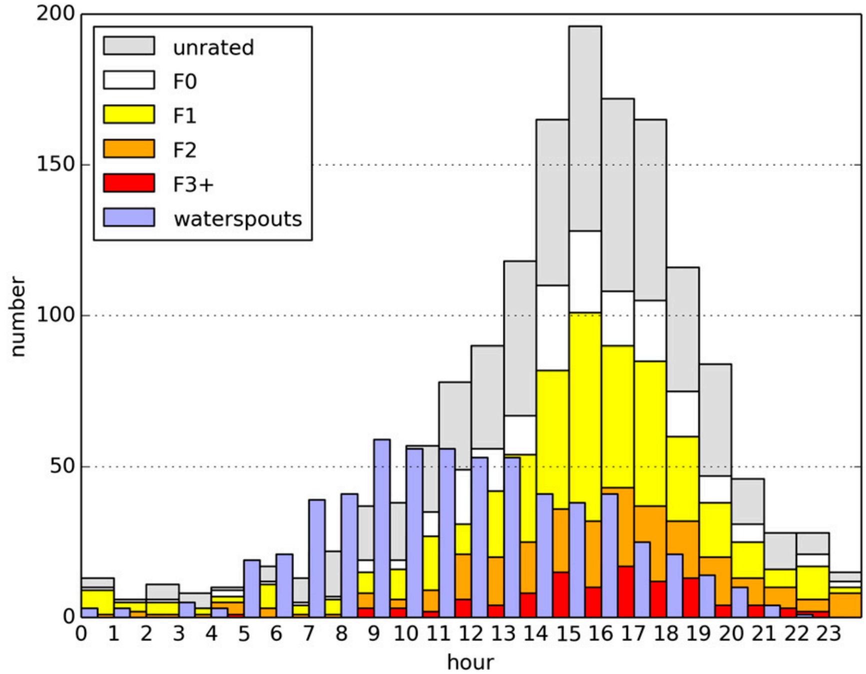

FIG. 7. The number of tornadoes reported for each hour of the day in local time. Only tornado reports with a temporal accuracy < 1 h were used.

things.'' Fatality numbers from some of the other tornadoes probably suffer from uncertainties as well.

Of the 10 high-fatality events listed in Table 1, 5 have occurred in Italy and 7 in Mediterranean countries, despite the fact that relatively few significant tornadoes in these areas are contained in the ESWD (Fig. 2b). In addition to this list, the authors are aware of several claims on web sites of tornadoes that have allegedly caused hundreds of fatalities, but have not yet been able to find any first-hand or otherwise reliable sources documenting them. Therefore, these events have not been entered into the ESWD.

Tornado-related fatalities before the year 2000 were dominated by a handful of individual tornadoes causing several dozens of fatalities, which were typically spaced several years or decades apart (Fig. 11). If they could be rated, such events were usually F3, F4, or F5. Many years have no recorded fatalities at all. In contrast, since 2001, no single year has passed without recorded tornado fatalities, but these were typically associated with F1, F2, or unrated events. We conclude that many similar events with low numbers of fatalities occurring before 2000 have likely not reached the ESWD. This needs to be taken into account when attempting to estimate an average annual tornado fatality rate, in order to compare it with other (natural) hazards.

In total, 822 tornado fatalities are recorded in the ESWD in the period 1800–2013, 519 in the period 1900–2013, 294 in the period 1950–2013, and 82 in the period 2000–13. This corresponds to 3.8, 4.6, 4.6, and 5.8 fatalities per year, respectively. The highest number of 5.8 was computed over a period that had no F3, F4, or F5-rated tornadoes with more than 5 fatalities, suggesting that the true average annual fatality rate is probably higher.

A better estimate of the fatality rate can be made by multiplying the occurrence frequency with the average number of tornado fatalities per tornado per F-scale class (Table 2). We take the occurrence frequency of violent tornadoes (F4, F5) over the period 1900–2013. For weak (F0, F1) and strong tornadoes (F2, F3), a strong increase in their occurrence frequency is seen so that we argue the value over the recent period 2000–13 is a better estimate. Multiplying this with the average reported number of fatalities over these same periods, an annual fatality rate is computed per F class. The F2 tornadoes are responsible for most tornado fatalities. The sum over all F classes is 5.6. Taking into account that an additional 35% of tornadoes were associated with unrated tornadoes, we arrive at a rate of 7.6 fatalities per year.

Since there are several historical events in the ESWD describing widespread destruction of residences without a number of fatalities indicated, so that 0 fatalities were implicitly assumed, and the fact that Fig. 1 hints at strong underreporting in some regions, we believe the true

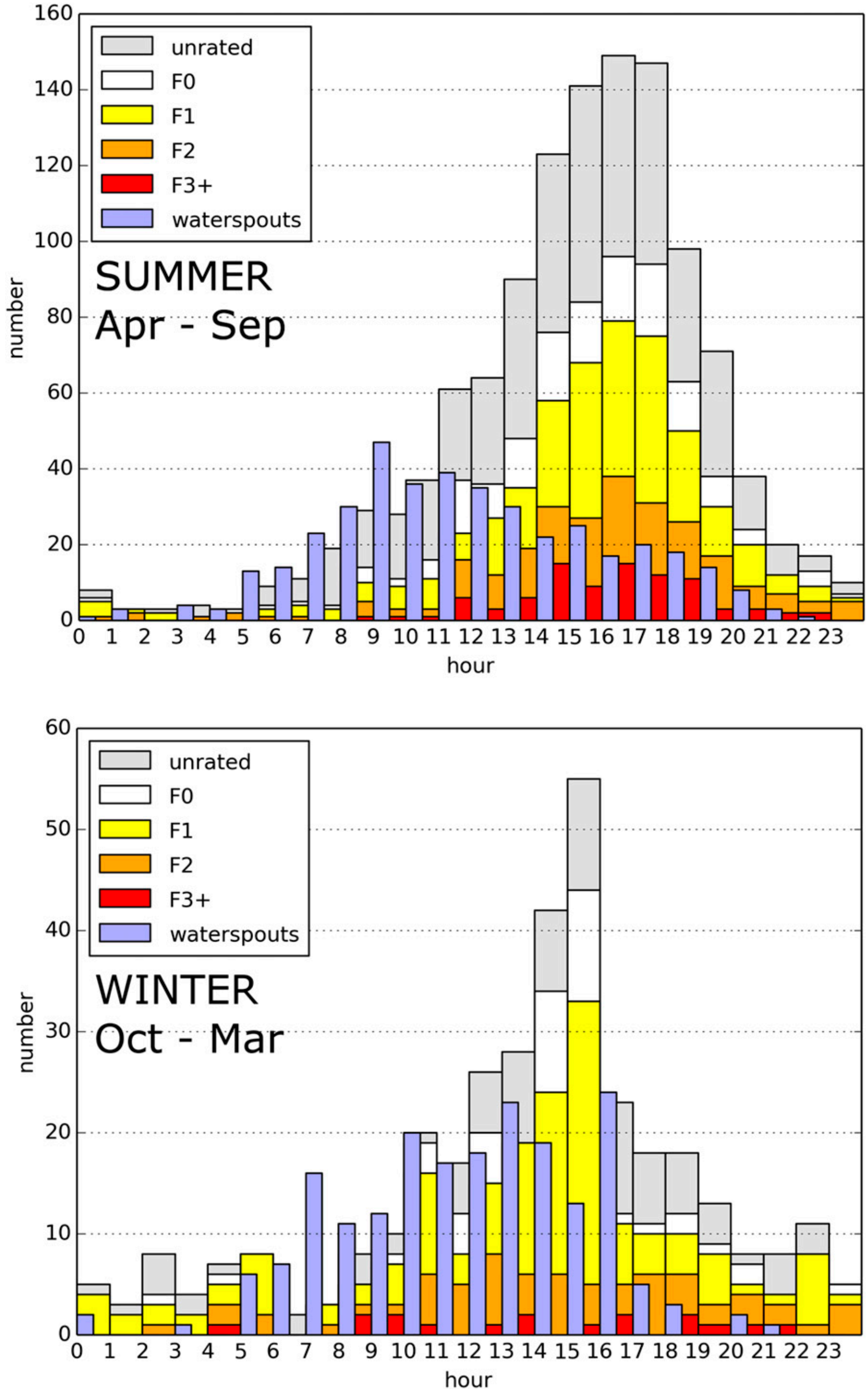

FIG. 8. The number of tornadoes reported for each hour of the day in local time in (top) summer and (bottom) winter.

annual number of (both recorded and unrecorded) fatalities is likely substantially higher, and estimate it to be between 10 and 15. As a comparison, the annual tornado fatality count in the United States in the period 1975–2012 was 69 (Brooks 2014).

g. Pathlength and width

Table 3 lists the average lengths and average mean path widths of tornadoes for each F-scale class in Europe. Within brackets, the corresponding values from *Storm*

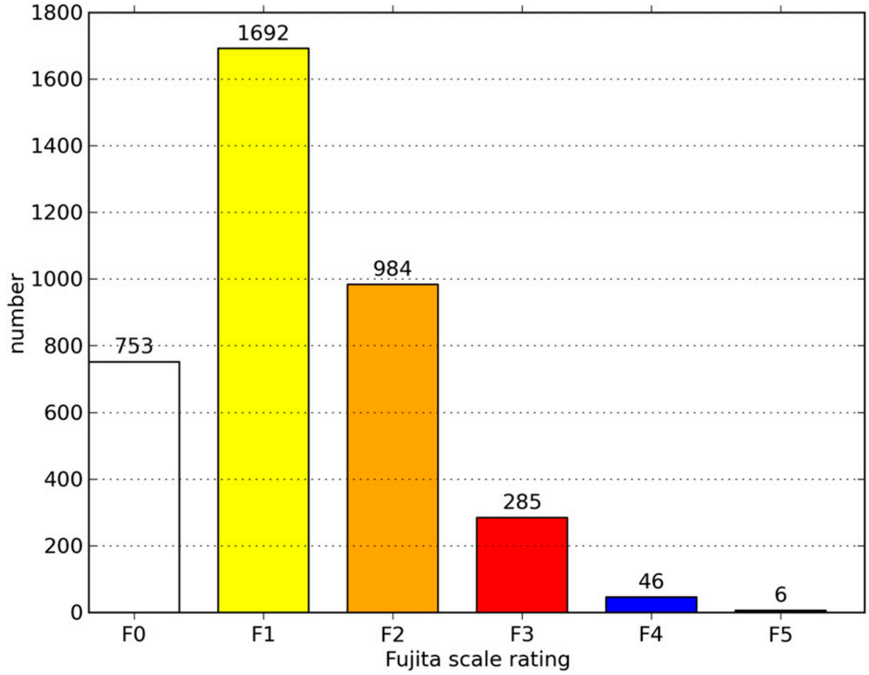

FIG. 9. Distribution of the 3818 tornadoes that received an intensity rating, rated on the Fujita scale.

Data (Schaefer and Edwards 1999; McCarthy 2003) have been added for comparison. For pathlength, *Storm Data* from the entire period 1950–2013 were used; for maximum path width, data after 1995 were used; and for mean path width, the data before 1995 were used (McCarthy 2003). American tornadoes rated according to the enhanced Fujita scale were treated as if they had been rated on the Fujita scale.

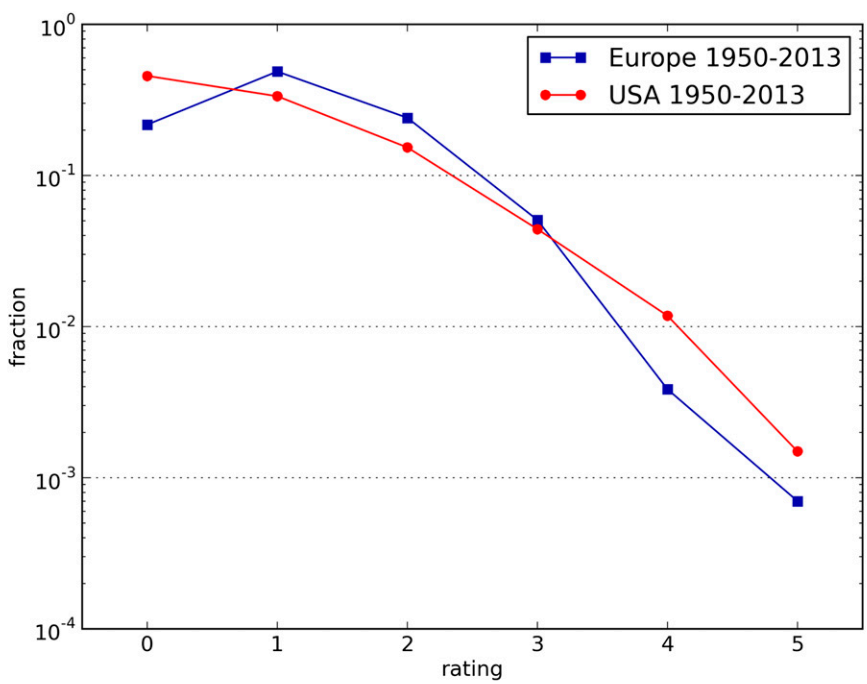

FIG. 10. Tornado rating distributions in Europe (ESWD) and in the United States (*Storm Data*) for 1950–2013.

TABLE 1. The 10 ESWD tornadoes with the highest fatality counts.

Date	Place	Country	Rating	No. killed	Selected sources
19 Aug 1845	Montville	France	F5	70	Dessens and Snow 1989; Paul (2001)
9 Jun 1984	Ivanovo	Russia	F5	69 (see text)	Snitkovsky (1987); Peterson 2000; *Pravda* (2011); Finch and Bikos (2012)
12 May 1886	Madrid	Spain	F3	47	Gayà (2007)
21 Sep 1897	Oria, Sava	Italy	Unrated	40	*La Stampa* (1897);
23 Jul 1910	Saronno	Italy	Unrated	36	*La Stampa* (1910)
10 Jul 1916	Wiener Neustadt	Austria	F4	35	Dörr (1917); Holzer et al. (2013)
11 Sep 1970	Teolo, Fusina, Venice	Italy	F4	34	*Stampa Sera* (1970)
7 Oct 1884	Catania	Italy	Unrated	30	*Tilburgsche Courant* (1884)
24 Jul 1930	Volpago del Montello	Italy	F5	23	*La Stampa* (1930)
28 Jul 1930	Edirne	Turkey	Unrated	20	*De Telegraaf* 1930

The average pathlengths for each F scale in Europe and the United States are quite similar, although for stronger tornados (F3, F4) they are a bit smaller in Europe and for weak tornadoes (F0, F1) a bit longer. The latter may result from an overestimation arising because path widths and lengths are often not reported for weak tornadoes, because these were unspectacular or hard to determine given a lack of significant damage. As a consequence, the average lengths and widths are calculated from the remaining weak tornadoes, which are more likely to be those cases that, despite their weak intensity, had large pathlengths or widths.

The maximum path widths for the American tornadoes are higher for all categories excluding F0. A possible explanation is that most European cases are older and have not been surveyed as carefully as U.S. cases since 1995. The maximum width, which per definition is the largest width along the track, may therefore have been underestimated more easily in Europe. In contrast, the average mean path widths in *Storm Data* before 1995

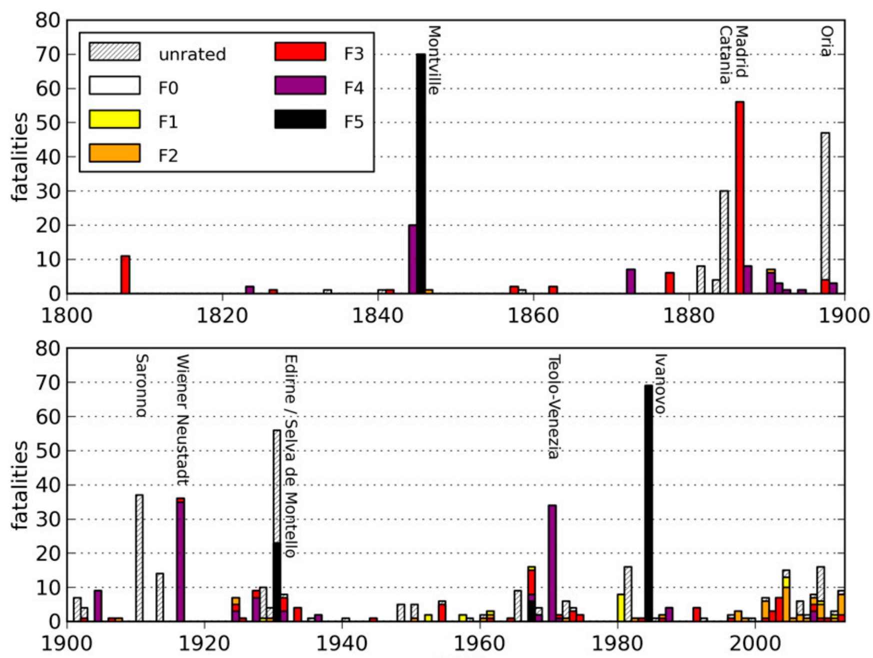

FIG. 11. Annual number of fatalities from tornadoes with their respective F-scale ratings color coded.

TABLE 2. Average number of injuries and fatalities per tornado event. Tornadoes without reported fatalities or injuries were not included. Boldface numbers are the estimate of the annual fatality rate.

Rating	Annual frequency 1900–2013	Annual frequency 1950–2013	Annual frequency 2000–13	No. of fatalities per tornado assuming no fatalities where no data are available	Annual fatality rate per F class
F5	**0.026**	0.031	0.000	32.7 (1900–2013)	0.9
F4	**0.211**	0.172	0.071	4.5 (1900–2013)	0.9
F3	1.89	2.44	**4.21**	0.28 (2000–13)	1.2
F2	7.46	11.1	**27.1**	0.059 (2000–13)	2.3
F1	13.8	22.4	**69.4**	0.013 (2000–13)	0.4
F0	5.94	10.0	**35.1**	0.000 (2000–13)	0.0

are very similar to the corresponding values in the ESWD.

4. Summary and conclusions

Using the European Severe Weather Database, we performed a climatological analysis of tornado occurrence in Europe. Although the data show that reporting rates vary from country to country, and they cannot be used to determine past trends in tornado occurrence, several important conclusions can be drawn.

First, the ESWD shows that no regions in Europe are void of tornadoes, and that strong tornadoes occur throughout Europe. No fewer than 278 tornadoes over land and an additional 139 waterspout events (comprising 205 waterspouts, i.e., 483 in total), have been reported across Europe on average each year (2006–13). This proves that Alfred Wegener's estimate (Wegener 1917), that at least 100 tornadoes occur in Europe every year, was correct. In 2002, Dotzek (2003) carried out interviews with participants to the European Conference on Severe Storms in Prague in 2002. These participants originated from many different European countries and were asked for the annual number of reported tornadoes in their home country, as well as an estimate of tornado occurrence taking underreporting into account. It was then estimated that 329 ± 12 tornadoes are reported and 697 ± 36 occur in reality across Europe on average each year. The ESWD number of 483 indicates that more events are now being reported annually than the participants were aware of in 2002.

Second, weak (F0–F1) tornadoes are much more frequent than strong (F2–F3) ones, which in turn are more frequent than violent ones (F4–F5). Although violent tornadoes are the most deadly per tornado, strong tornadoes are responsible for most tornado-related fatalities in Europe because of their much higher frequency of occurrence.

Third, the main tornado season is in summer in central and northern Europe, in autumn in the western and central Mediterranean region, and in winter in the eastern Mediterranean. Tornadoes over land occur most frequently during the late afternoon and early evening. Waterspouts typically occur earlier in the day, with a maximum at midmorning.

Fourth, there is an important lack of data from Mediterranean countries in the ESWD, which is illustrated by the fact that 7 of the 10 most deadly tornadoes in the database occurred there (Table 1), whereas the report density is much lower than in central Europe (Fig. 2). A low coverage over eastern Europe is also evident. Future data collection work must therefore focus on these regions.

Last, considering that the estimated annual number of people killed in tornadoes (10–15) in Europe is estimated to be 15%–22% of the number in the United States (i.e., 69), the threat posed by them is clearly much smaller. The threat is, however, not negligible in

TABLE 3. Average and maximum pathlengths, and mean path widths for tornadoes in a particular damage rating. Data from the United States have been added in italic font within parentheses for pathlengths and maximum path width. The N numbers refer to the number of cases averaged.

Rating	Avg pathlength (km)	$N_{pathlength}$	Avg max path width (m)	N_{max_width}	Avg mean path width (m)	N_{mean_width}
F5	53.4 (*57.2*)	6 (*88*)	440 (*1425*)	5 (*17*)	450 (*514*)	2 (*71*)
F4	23.1 (*42.5*)	29 (*696*)	600 (*837*)	21 (*151*)	383 (*431*)	7 (*545*)
F3	17.5 (*24.2*)	142 (*2604*)	394 (*581*)	103 (*628*)	343 (*254*)	39 (*1976*)
F2	10.2 (*11.4*)	371 (*9036*)	182 (*289*)	239 (*2029*)	124 (*121*)	123 (*7007*)
F1	6.9 (*5.1*)	418 (*19 730*)	111 (*131*)	253 (*6608*)	82 (*61*)	185 (*13 122*)
F0	2.6 (*1.6*)	122 (*26 825*)	48 (*45*)	77 (*14 889*)	35 (*27*)	59 (*11 936*)

comparison either. From this point of view, the fact that only 7 out of 39 European weather services have a procedure to warn for tornadoes (Rauhala and Schultz 2009) does not seem adequate.

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