TORNADOES IN EUROPE

An Underestimated Threat

Bogdan Antonescu, David M. Schultz, Alois Holzer, and Pieter Groenemeijer

The threat of tornadoes in Europe is not widely recognized, despite causing injuries, fatalities, and damages.

There was a time when tornado research in Europe was more active than in the United States. Before the beginning of the Second World War, European scientists and meteorologists were actively researching tornadoes (e.g., Peltier 1840; Reye 1872; Weyher 1889; Wegener 1917; Letzmann 1931), while the word "tornado" was banned by the United States Weather Bureau (Galway 1992). This situation changed after 1950, driven by the tornado forecasting advances of Miller and Fawbush (e.g., Grice et al. 1999). The interest in European tornadoes declined after 1950, with the majority of the efforts of collecting tornado reports occurring outside the national meteorological services (Antonescu et al. 2016). The lack of national databases resulted in an underestimate of the tornado threat to Europe, a situation that persists today despite the interest in recent years on tornadoes in Europe (e.g., Dotzek 2003; Groenemeijer and Kühne 2014). Thus, it is often assumed by the general public, and even by meteorologists and researchers, that tornadoes do not occur in Europe or, if they do occur, they are less frequent and less intense than those in the United States. For example, in 2015, 206 tornadoes were reported in Europe versus 1,177 tornadoes in the United States. The lower number of tornadoes in Europe is likely the reason why tornadoes are not a well-established subject of research in Europe and are not a priority for European meteorological services (Rauhala and Schultz 2009; Groenemeijer and Kühne 2014), despite the fact that they are associated with damages, injuries, and even fatalities.

Although the tornado threat seems to be less in Europe compared with the United States, the true magnitude is unknown because of the lack of data resulting from a long-lived, uniform pan-European effort to monitor tornado occurrence. Antonescu et al. (2016) showed that tornado datasets have been developed and maintained for a few countries in Europe (e.g., France, Germany, United Kingdom). Furthermore, few European countries have issued or are currently issuing tornado warnings. Based on the responses to a questionnaire on severe thunderstorm warnings sent to European meteorological services, Rauhala and Schultz (2009) showed that tornado warnings had been issued only for eight out of 32 responding countries (i.e., the Netherlands, Cyprus, Spain, Germany, Romania, Malta, Turkey,

AFFILIATIONS: Antonescu and Schultz—Centre for Atmospheric Science, School of Earth and Environmental Sciences, University of Manchester, Manchester, United Kingdom; Holzer and Groenemeijer—European Severe Storms Laboratory, Wessling, Germany
CORRESPONDING AUTHOR E-MAIL: Bogdan Antonescu, bogdan.antonescu@manchester.ac.uk

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-16-0171.1

In final form 16 November 2016

and Estonia) between 1967 and 2006. More recently, Holzer et al. (2015) showed that, as of 2015, only one meteorological service (i.e., Royal Netherlands Meteorological Institute) issues tornado warnings. Thus, without systems to document past events (i.e., frequency, spatial distribution, intensity, societal and economic impact, and meteorological conditions), without research programs to support the forecasting and nowcasting of tornadoes, and without measures to reduce tornado vulnerability, European tornadoes will always be perceived as a curiosity and their threat will be underestimated (Doswell 2003, 2015).

Recently, a pan-European tornado dataset [i.e., the European Severe Weather Database (ESWD); see sidebar] has become available that will allow a step change in our understanding of European tornadoes and their associated threat. Tornado reports from ESWD are used here to analyze the annual frequency of tornadoes, their spatial distribution and their societal and economic impact in Europe between 1950 and 2015. The purpose of this paper is to further increase public and institutional awareness of the threat of tornadoes in Europe.

TORNADOES IN EUROPE. Between 1950 and 2015, 5,478 tornadoes have been reported in 42 European countries. Approximately 33% of all reports are for tornadoes that have occurred over central and western Europe (i.e., the United Kingdom, Belgium, the Netherlands, Germany, Denmark, and the Czech Republic; Fig. 1). Over continental Europe, the highest density of tornado reports is over Belgium, Germany, and the Netherlands (Table 1). This high density of reports is likely due to the high population density over western and central Europe compared with other regions of Europe in combination with favorable environments for deep, moist convection. Over southern Europe, there is an elevated number of tornado reports along the coastlines (e.g., western Italy and eastern Spain; Fig. 1). This elevated number of reports is likely due to a higher population density along the coasts, but also due to the waterspouts that develop over the Mediterranean Sea and move inland, where they are reported as tornadoes (Sioutas et al. 2013, 2014). The highest tornado density over southern Europe is over Malta and Cyprus, two island countries in the Mediterranean Sea, and also over Mallorca, the largest island in the Balearic Islands archipelago, which is a part of Spain (Fig. 1, Table 1).

The low population density in northern and eastern Europe compared with western Europe can explain the low tornado density in these regions (Fig. 1). Also, some of the meteorological services in eastern Europe, in particular those from former Eastern Bloc countries (e.g., Romania and the Czech Republic), only recently recognized that tornadoes can occur over their territory (Setvák et al. 2003; Antonescu and Bell 2015; Antonescu et al. 2016). Relatively few tornadoes were reported in eastern Europe between the end of the Second World War and the fall of the Iron Curtain in

THE EUROPEAN SEVERE WEATHER DATABASE

Tornado reports for Europe covering the period 1950–2015 were obtained from the ESWD developed and maintained by the European Severe Storms Laboratory (Groenemeijer and Kühne 2014). Europe is defined in this article as the region between the Arctic Ocean to the north; the Atlantic Ocean to the west; the Mediterranean Sea to the south; and the Ural Mountains, Ural River, and Caspian Sea to the east (Fig. 1). According to this definition, there are 49 internationally recognized sovereign European states (Table 1), of which 44 have their capital city within Europe; five (Armenia, Azerbaijan, Georgia, Russia, and Turkey) have their territory both in Europe and Asia.

The ESWD collects information on convective storms over Europe using a web-based, multilingual user interface where collaborating national weather services, volunteer severe weather spotter networks, and the public can contribute and retrieve observations. The quality of the collected data (i.e., tornadoes, severe wind, large hail, heavy rain, heavy snowfall, damaging lightning) is assessed and flagged. For the analyses presented in this article, only tornado reports that have undergone a validation with meteorological data (i.e., radar and/or satellite imagery) have been used (i.e., quality control level 0 + reports). In the ESWD, tornadoes and waterspouts are both being recorded as tornadoes along with the surface type (e.g., land, forest, sea, lake) over which were initially observed and the surface types that were crossed during their lifetime. In this article, we have considered only tornadoes over land, which the *Glossary of Meteorology* defines as "a rotating column of air, in contact with the surface, pendant from a cumuliform cloud, and often visible as a funnel cloud and/or circulating debris/dust at the ground" (American Meteorological Society 2016). This definition also includes waterspouts that moved inland and were reported as tornadoes. The intensity of tornadoes was assessed, either by the ESWD or by the original source of the report and verified by ESWD, based on the Fujita scale (Fujita 1981). Tornadoes were not rated on the F scale if the details of the damage description were not sufficient to rate them unambiguously. In addition, tornado reports for Spain were obtained from Gayà (2015) and for Poland from Taszarek and Gromadzki (2017) and incorporated into the ESWD.

1989. During this period, any observations of tornadoes were considered erroneous observations or they were described as high-wind events, which resulted in an underestimate of the tornado threat.

The mean annual number of tornado reports in Europe between 1950 and 2015 was 83 tornadoes per year, approximately 11 times lower than the annual mean for the United States during the same period. Before 1950, tornadoes were reported infrequently in Europe, with an annual mean of 7 tornadoes per year between 1800 and 1899 and 18 tornadoes per year between 1900 and 1949. During 1950–95, the annual number of tornadoes was relatively constant with 32 tornadoes per year (Fig. 2a). The local maximum in the number of tornadoes in 1981 corresponds to a large tornado outbreak (i.e., 90 plausible reports) associated with a cold front that swept from the west to the east coast of the United Kingdom on 23 November (Rowe and Meaden 1985; Apsley et al. 2016). After the mid-1990s, the increase in the number of tornado reports can be attributed to increased public awareness after high-impact events (e.g., Lemon et al. 2003); increased use of communication technology (e.g., increase in the number cellular phone subscriptions and in the percentage of individuals using the Internet); efforts to develop regional tornado databases (Antonescu et al. 2016); and the "*Twister* effect" (Rauhala et al. 2012), consisting of an increased public awareness associated mainly with the movie *Twister* (released in 1996) and also with television reality series on tornadoes (e.g., *Storm Chasers*, which premiered in 2007 and was available to the European audience). The peak in the number of tornado reports in 2006 marks the start of European Severe Weather Database activities at the European Severe Storms Laboratory (Groenemeijer and Kühne 2014). The period 2006–10 represents a relatively stable period with an average of 250 tornadoes per year, with a standard deviation of 79.4 (Fig. 2a). Given this increase in the number of tornado reports in Europe since 1950 and especially

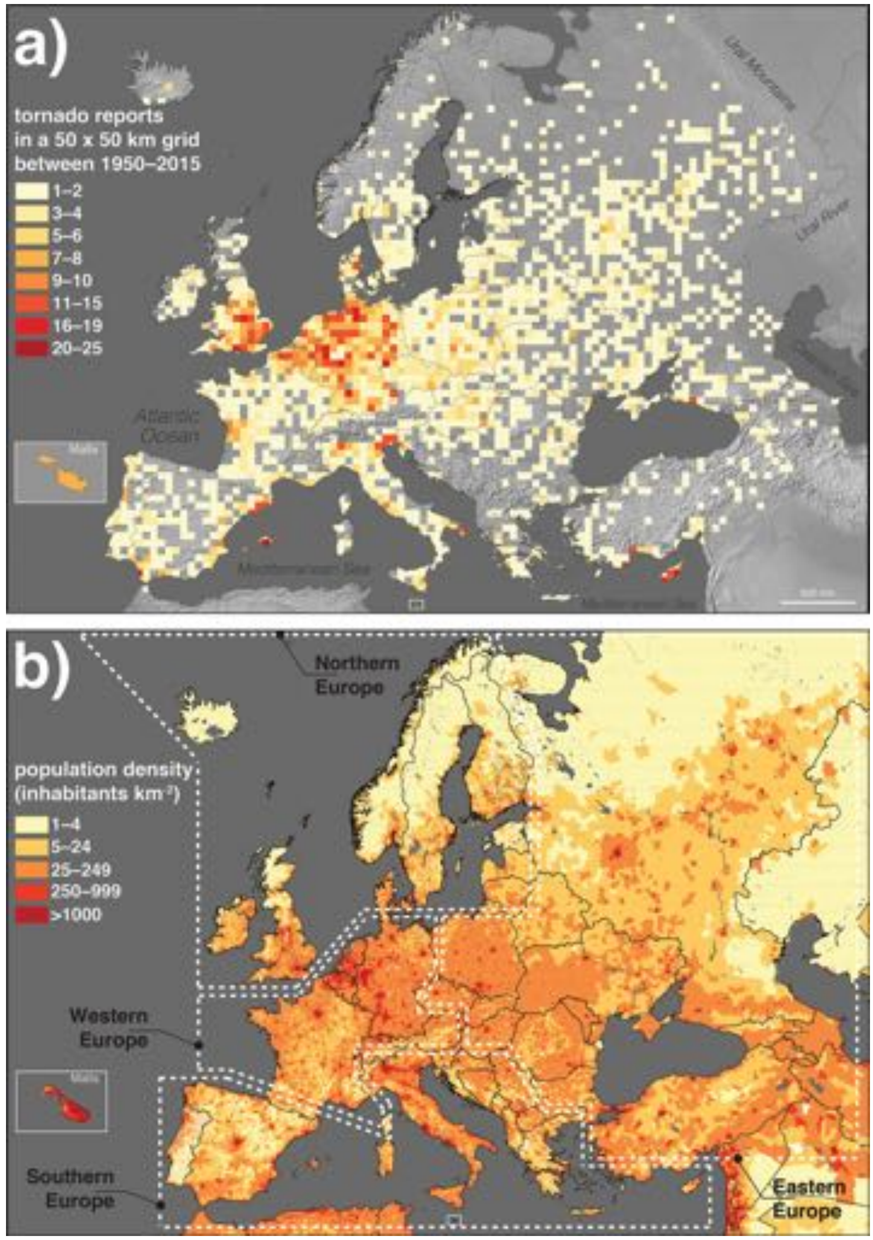

Fig. 1. (a) The spatial distribution of tornado reports (tornadoes per 10,000 km²) in Europe in between 1950 and 2015 on a 50 km × 50 km grid, shaded according to the scale. (b) The population density (inhabitants per km²) estimated for 2015, shaded according to the scale. The population density was obtained from SEDAC (2015). The four main regions of Europe are also indicated (dashed lines).

Table 1. Tornado reports, normalized tornado reports, injuries, normalized injuries, fatalities, normalized fatalities, and normalized damages for each European country between 1950 and 2015. The top five values for each category are indicated in bold, and the rank is indicated in parentheses.

Country	Tornadoes	Normalized tornadoes (tornadoes per km^2 × 1000)	Injuries	Normalized injuries (injuries per km^2 × 1000)	Fatalities	Normalized fatalities (fatalities per km^2 × 1000)	Damages (million euro)
Albania	—	—	—	—	—	—	—
Andorra	—	—	—	—	—	—	—
Armenia	3	0.1	—	—	—	—	0.004
Austria	30	0.4	1	0.01	—	—	0.7
Azerbaijan	6	0.1	—	—	—	—	0.1
Belarus	99	0.5	20	0.1	—	—	**218.0 (2)**
Belgium	107	**3.5 (3)**	13	0.4	—	—	2.3
Bosnia and Herzegovina	2	0.04	—	—	—	—	0.1
Bulgaria	24	0.2	4	0.04	—	—	12.0
Croatia	27	0.5	13	0.2	—	—	0.05
Cyprus	76	**8.2 (2)**	22	**2.4 (5)**	6	**0.6 (2)**	1.5
Czech Republic	96	1.2	6	0.1	1	0.01	5.0
Denmark	77	1.8	1	0.02	—	—	0.1
Estonia	25	0.6	—	—	1	0.02	0.3
Finland	29	0.1	5	0.01	4	0.01	—
France	**396 (5)**	0.6	**331 (5)**	0.5	19	0.03	9.4
Georgia	20	0.3	12	0.2	3	0.04	0.005
Germany	**1027 (1)**	**2.9 (4)**	**669 (3)**	1.9	**28 (5)**	**0.1 (4)**	39.6
Greece	87	0.7	19	0.1	3	0.02	2.1
Hungary	90	1.0	2	0.02	—	—	1.2
Iceland	8	0.1	—	—	—	—	—
Ireland	33	0.5	—	—	—	—	2.7
Italy	348	1.2	**753 (2)**	**2.5 (4)**	**69 (2)**	**0.2 (3)**	**318.3 (1)**
Latvia	34	0.5	—	—	—	—	0.08
Lichtenstein	—	—	—	—	—	—	—
Lithuania	33	0.5	3	0.05	—	—	0.1
Luxembourg	5	1.9	1	0.4	—	—	0.01
Macedonia	1	0.04	—	—	—	—	—

Malta	7	**22.2 (1)**	2	**6.3 (1)**	—	—	0.02
Moldova	10	0.3	—	—	—	—	20.0
Monaco	—	—	—	—	—	—	—
Montenegro	—	—	—	—	—	—	—
Netherlands	95	**2.3 (5)**	193	**4.6 (2)**	**30 (3)**	**0.7 (1)**	0.8
Norway	60	0.2	3	0.01	—	—	0.8
Poland	299	1.0	128	0.4	6	0.02	25.3
Portugal	59	0.6	282	**3.0 (3)**	5	**0.05 (5)**	0.2
Romania	93	0.4	14	0.1	3	0.01	9.6
Russia	**685 (2)**	0.2	**1239 (1)**	0.3	**89 (1)**	0.02	**132.7 (3)**
San Marino	—	—	—	—	—	—	—
Serbia	16	0.2	—	—	1	0.01	5.4
Slovakia	19	0.4	—	—	—	—	0.04
Slovenia	8	0.4	—	—	—	—	0.008
Spain	**426 (4)**	0.8	**521 (4)**	1.0	8	0.02	**103.0 (4)**
Sweden	128	0.3	2	0.004	—	—	0.1
Switzerland	17	0.4	1	0.02	—	—	—
Turkey	181	0.2	96	0.1	**29 (4)**	0.04	**69.6 (5)**
Ukraine	255	0.4	28	0.05	11	0.02	17.8
United Kingdom	**437 (3)**	1.8	78	0.3	—	—	3.5
Vatican City	—	—	—	—	—	—	—

after the 1990s, tornadoes were and still are likely underreported in Europe.

The tornado season for Europe is mostly from May to August, when 66.4% of the 5,460 tornado reports that included information on the occurrence month were reported, with a peak in July (Fig. 2b). But the tornado season varies across Europe, with tornadoes more frequently reported over eastern Europe during the spring and early summer, over western Europe during the summer, and over northern Europe from mid to late summer (Groenemeijer and Kühne 2014; Antonescu et al. 2016). Tornadoes occur more frequently during autumn and early winter over southern Europe, which reflects the occurrence of waterspouts in the Mediterranean Sea (unlike the United States, waterspouts are classified as tornadoes herein).

Weak tornadoes (F0 and F1; Hales 1988) represent 74% of all 3,023 tornado reports for which information on their damage magnitude was available (Fig. 2c). By comparison, in the United States, weak tornadoes account for 80.1% of all tornadoes during the same period (60,114 reports). For tornadoes reported in Europe, there is a bias toward F1 tornadoes, with F0 tornadoes representing 23% of all reports and F1 tornadoes representing 51%. This bias is because F0 tornadoes have low societal and economic impact and thus are reported less frequently than other F-scale tornadoes. Significant tornadoes (F2 and greater) have been reported every year since 1950, with an annual mean of 12 significant tornadoes (Fig. 2c). There are only 13 reports for violent (F4 and F5) tornadoes, with the most recent being the F4 Mira, Italy, tornado that occurred on 8 July 2015.

INJURIES AND FATALITIES. The first known European tornado associated with fatalities occurred on 23 October 1019 in London, United Kingdom (Rowe 1999; Kirk et al.

2015). Before 1950, tornado fatalities were reported infrequently in Europe, with 119 tornadoes associated with fatalities reported between AD 0 and 1949 compared with 103 tornadoes associated with fatalities between 1950 and 2015 (Fig. 3). Between 1950 and 2015, 103 tornadoes were associated with 316 fatalities and 276 tornadoes with 4,462 injuries (Figs. 4a,b). The changes in the number of tornado reports (Fig. 2a) are reflected in the changes in the annual number of tornadoes associated with fatalities and injuries (Fig. 4a).

Prior to 1990, the annual number of tornadoes associated with injuries and fatalities was relatively constant (Fig. 4a). There is a prominent minimum in both the number of tornadoes with injuries and fatalities at the beginning of the 1990s, but the reasons for this minimum are not known. This minimum was followed by a rapid increase in the number of reports, which resulted in about 4 times more tornadoes with injuries per year and 2 times more tornadoes with fatalities per year between 2006 and 2015 compared with 1950–89 (Fig. 4a).

Also, there is an increase in the annual average number of tornado injuries and a decrease in the annual average number of tornado fatalities per 5 million inhabitants between 2006 and 2015 compared with 1950–89 (Fig. 5, lower thick blue line). With one exception, over western Europe, there is an increase in tornado injuries in Europe (Fig. 5a). In contrast, the number of fatalities has decreased over Europe since the 1950s, except eastern Europe, where fatalities have increased (Fig. 5b).

For comparison, both the number of injuries and fatalities per 5 million inhabitants have decreased in the United States and in the central United States (i.e., Kansas, Nebraska, Oklahoma, and Texas) since the 1950s (although this decrease has leveled off in the recent years; e.g., Ashley 2007; Ashley and Strader 2016). This decrease can be attributed to development of the tornado forecasting process, improved communication, development of severe storm spotter networks, changes in construction practices (Doswell et al. 1999; Brooks and Doswell 2002), development of

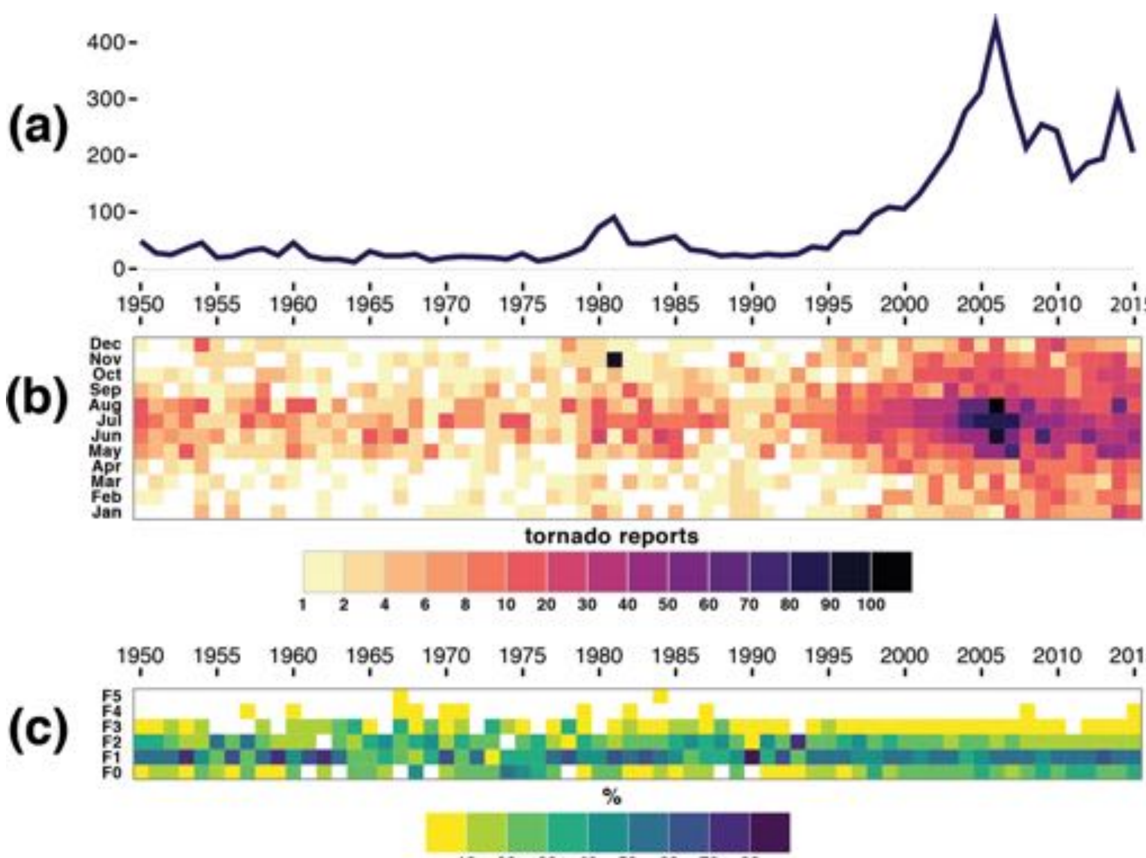

Fig. 2. (a) The annual number of tornado reports in Europe between 1950 and 2015. (b) A heat map showing in each cell the number of tornado reports for each month and for each year, shaded according to the scale. (c) A heat map showing in each cell the percentage from the total number of reports, for which information on their damage magnitude was available, for each F scale and for each year, shaded according to the scale.

the radar networks, and the watch–warning process (Simmons and Sutter 2005). Furthermore, Brooks and Doswell (2002) have shown that the decrease in the number of tornado fatalities between 1925 and 2000 has resulted primarily from a decrease in the number of deadly tornadoes and a decrease in the number of fatalities in the most deadly tornadoes. Similarly, tornado fatalities per 5 million inhabitants in Europe decreased (Fig. 5b) as a result of a decrease in the number of deadly tornadoes (Fig. 4b) and also because of a decrease in the number of fatalities per tornado from 4.5 between 1950 and 1989 to 1.5 between 2006 and 2015. A similar decrease is observed in the number of injures per tornado, from 28 between 1950 and 1989 to 12 between 2006 and 2015. This decrease in the number of injuries and fatalities per tornado does not mean that tornadoes have become less dangerous, but only that more weak tornadoes, associated in general with few injuries and fatalities, have been reported in the recent period.

Tornadoes associated with injuries and fatalities can occur throughout the year in Europe, but they are more frequently reported during the tornado season between June and August. The peak in the number of tornadoes associated with injuries is in July and in June and July for tornadoes associated with fatalities (Figs. 6a,c). Tornado injuries and fatalities are more frequent in May–November (92% of all injuries and 89% of all fatalities), with a peak in June (27% of all injuries and 38% of all fatalities) toward the beginning of the tornado season (Figs. 6b,d). This peak in June is due to a small number of tornadoes that produced a large number of injuries and fatalities, in particular the 9 June 1984 tornado outbreak in Russia that resulted in 804 injuries and 69 fatalities (Finch and Bikos 2012).

Tornadoes have a relatively high societal impact over eastern and southern Europe and a relatively low impact over western and northern Europe. Thus, the number of injuries is 2 times higher and the number of fatalities 3 times higher over eastern and southern Europe than over western and northern Europe (Figs. 6b,d). Despite the low population density over eastern Europe (51.7 inhabitants per km^2) compared with western Europe (158.9 inhabitants per km^2),

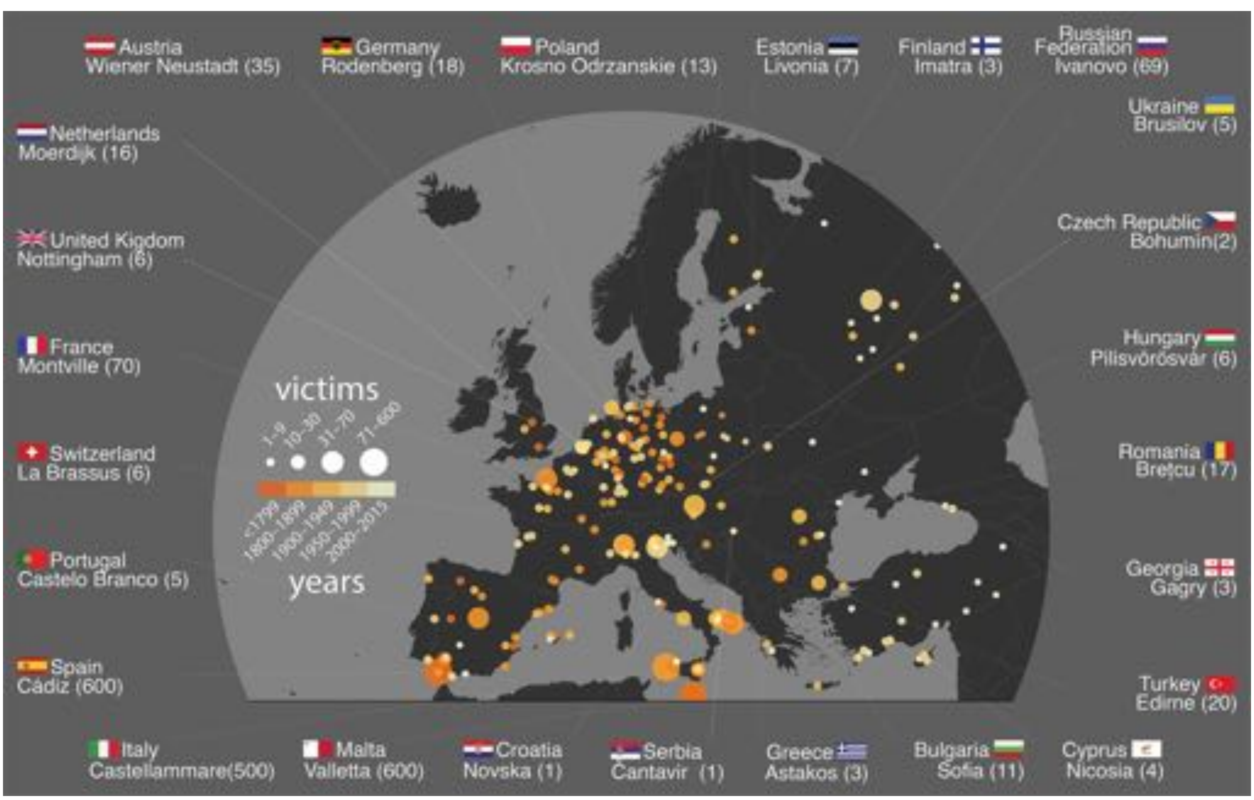

Fig. 3. Deadly European tornadoes between 1091 and 2015. The number of fatalities is represented by varying the size of the circle (according to the scale) and the period when the tornado occurred by changing the fill color (shaded according to the scale). For each country, the deadliest tornado is indicated on the sides by showing the tornado location and the number of fatalities in parentheses. The high-impact tornadoes over Malta (1556; de Boisgelin de Kerdu 1804), Spain (1671; Gayà 2015), and Italy (1851; *Illustrated London News* 1851) were documented from secondary sources that can result in over- or underestimation of the number of fatalities.

fatalities and injury rates are the highest in this region of Europe. The high fatality and injury rates in eastern Europe are dominated by injuries and fatalities associated with the 9 June 1984 tornado outbreak in Russia. The population density is comparable in western and southern Europe (121.3 inhabitants per km^2), but there are more injuries between September and November and fatalities in September over southern Europe compared with western Europe (Figs. 6b,d).

DAMAGES. No study has systematically analyzed the damages associated with tornadoes in Europe. The task of analyzing the magnitude of tornado damages is a difficult one given, for example, the lack of damage descriptions, especially for historical events; different methods for assessing tornado damages for different European countries; and different construction practices across Europe. To better understand the trend and the magnitude of tornado damages, all the damages were normalized using the House Price Index (Knoll et al. 2014). Considering only the tornado reports with damage descriptions (1,152 reports) between 1950 and 2015, tornadoes resulted in €1 billion in damages. For comparison, between 2005 and 2014, tornadoes in the United States resulted in losses estimated at approximately €20 billion (NWS 2016).

The mean annual damages (estimated based on tornado reports from ESWD and using a methodology described in the appendix) increased more than a factor of 3 from €7 million per year between 1950 and 1989 to €25 million between 2006 and 2015 (Fig. 7). In comparison to the United States, Brooks and Doswell (2001) have analyzed the damages from major tornadoes in the United States between 1890 and 1999 and shown that damages from individual tornadoes have not increased in time, except only as result of the increasing cost of goods and accumulation of wealth. Thus, this increase in tornado damage in the recent period in Europe is likely not associated with changes in the frequency or characteristics of the environments leading to tornadogenesis, but likely due to the increase in the number of reports. However, even without significant changes in the annual number of tornado reports, the annual

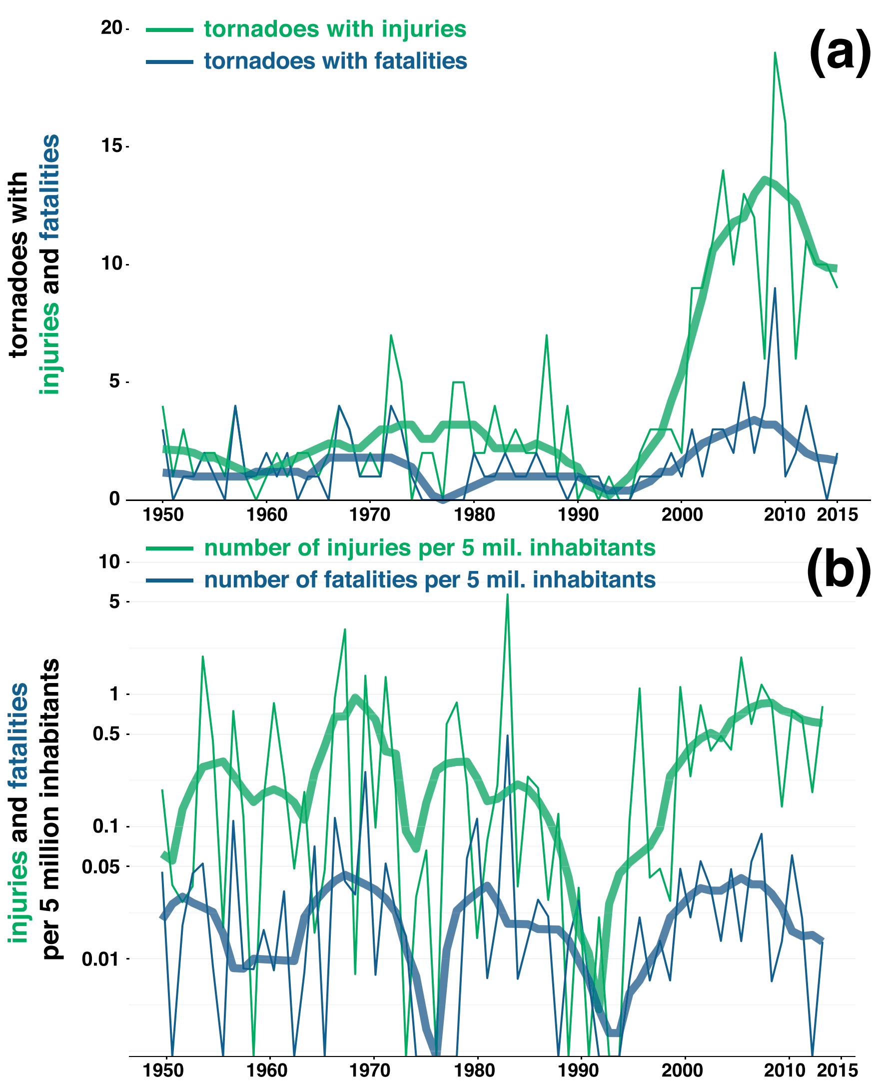

Fig. 4. Tornadoes associated with injuries and fatalities in Europe between 1950 and 2015. (a) The number of tornadoes associated with injuries (thin green line) and fatalities (thin blue line). The smoothed values (thick line) were obtained by using the median values for three consecutive values and then by applying a running mean over five consecutive medians (Brooks and Doswell 2002). (b) As in (a), but for the number of tornado victims per 5 million inhabitants and using a vertical axis on a logarithmic scale. For each year, the number of victims is normalized by the total population of Europe.

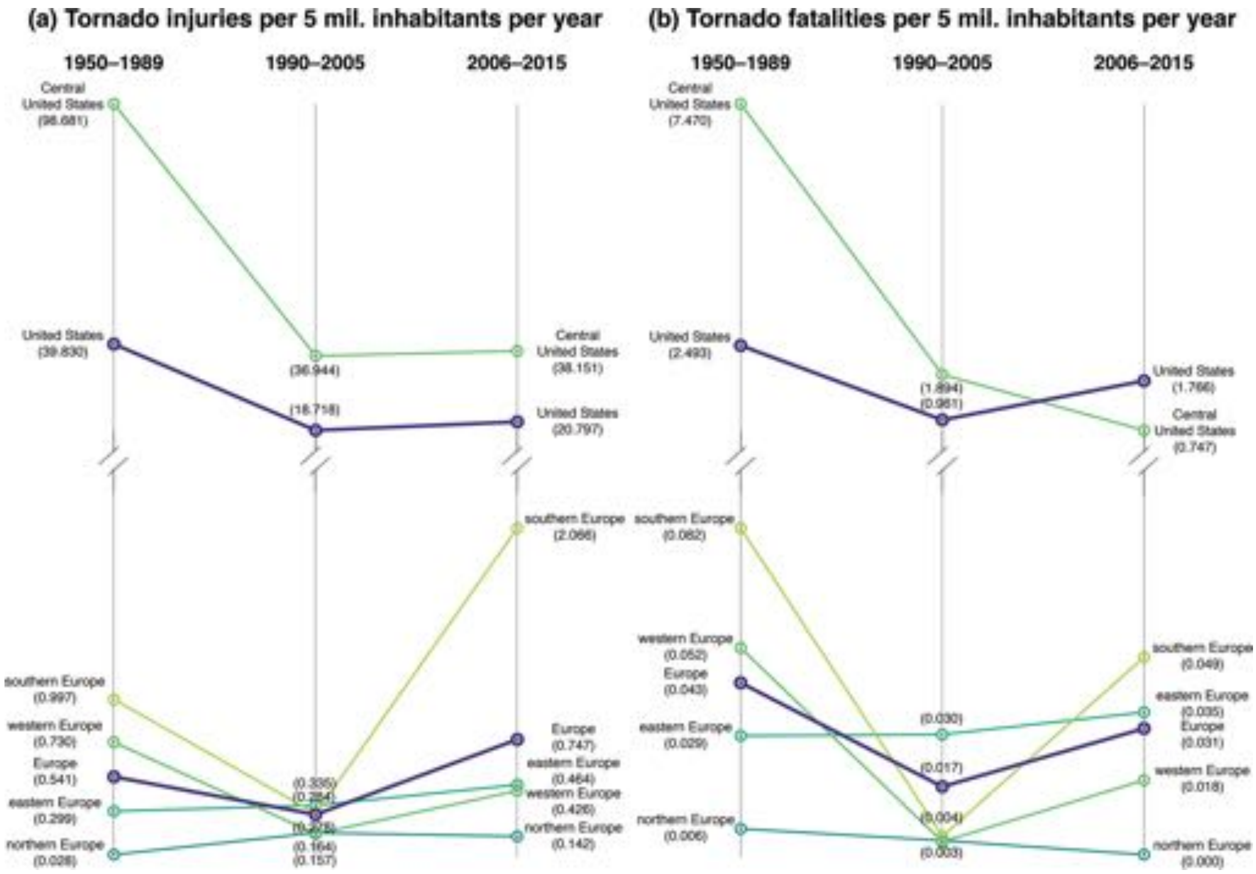

Fig. 5. A slope graph (Tufte 1983) showing the changes for three periods (i.e., 1950–89, 1990–2005, 2006–15) in (a) the number of tornadoes injuries per 5 million inhabitants per year and (b) the number of tornado fatalities per 5 million inhabitants per year (indicated in parentheses). The bottom of the slope graphs shows the changes for Europe (thick blue line) and for different regions of Europe (thin green lines). The top of the slope graphs shows the changes for the United States (thick blue line) and central United States (i.e., Kansas, Nebraska, Oklahoma, Texas; thin green line).

damages will increase as societal changes will lead to increases in wealth and property exposure to tornadoes (Simmons et al. 2013; Ashley and Strader 2016).

CONCLUSIONS. Despite their considerable societal and economic impact, tornadoes in Europe generally receive very little attention from the public, meteorologists, researchers, and emergency managers. Between 2000 and 2015, 33 case studies of tornadoes in Europe have been published in peer-reviewed meteorological journals, based on keyword searches (e.g., tornado, Europe) on the Thomson Reuters Web of Science (accessed on 24 May 2016). Unfortunately, these studies had a limited impact on the development of national programs for the detection and forecasting of tornadoes in Europe and the mitigation of their effects. For example, a study of an F3 tornado that occurred in southeastern Romania on 12 August 2002 (Lemon et al. 2003) resulted in increased awareness of tornadoes in Romania, especially among meteorologists. This culminated with the issue of the first (and so far the only) tornado warning for Romania in 2005 (Rauhala and Schultz 2009). After 2005, the Romanian National Meteorological Service started a systematic documentation of tornado reports that resulted in the development of a tornado database for Romania (Antonescu and Bell 2015). As shown by Holzer et al. (2015), other European meteorological services indicated that tornado warnings are foreseen, although clear warning strategies and warning concepts for tornadoes seem to be absent. Unfortunately, in tornado-prone and vulnerable regions of Europe (such as northern Italy, where there are many campsites and outdoor mass events), specific tornado warnings are currently not foreseen by the national and regional weather services, neither for critical infrastructure managers nor for the general public. However, developing national tornado warning programs is not necessarily an easy task. As pointed out by Rauhala and Schultz

(2009), there are a series of challenges in issuing tornado warnings in Europe associated with the lack of 1) adequate nowcasting tools (e.g., radar networks), 2) local research and knowledge for nowcasting (e.g., understanding of the local severe storm environments and interpretation of radar data), and 3) forecasters' experience given that tornadoes have a relatively low frequency of occurrence.

Given their relatively low frequency of occurrence, one could argue that there is no real need to study and forecast tornadoes in Europe. However, we believe that this argument is flawed for three main reasons:

1) Tornadoes are underreported in Europe. The underreporting is associated with the lack of systems to collect and verify the tornado reports. Many meteorological services do not maintain, or have only recently started to develop, tornado databases, a situation similar to that in the United States before the 1950s (Galway 1989; Doswell 2001). The lack of tornado records results in an underestimate of the tornado threat in those countries.
2) Tornadoes do pose a threat to Europe. Tornadoes reported in Europe between 1950 and 2015 were associated with 4,462 injuries and 316 fatalities and resulted in damages estimated at €1 billion. Some European countries have a low number of injuries and fatalities and little damage reported from tornadoes (Table 1), but this does not mean that tornadoes do not pose a threat in those countries. More likely, this is an artifact of the database (i.e., a 66-year period was not long enough to observe tornadoes associated with high societal and economic impact in those countries).
3) There is an increase of exposure of property and human life. Even if we assume that tornadoes

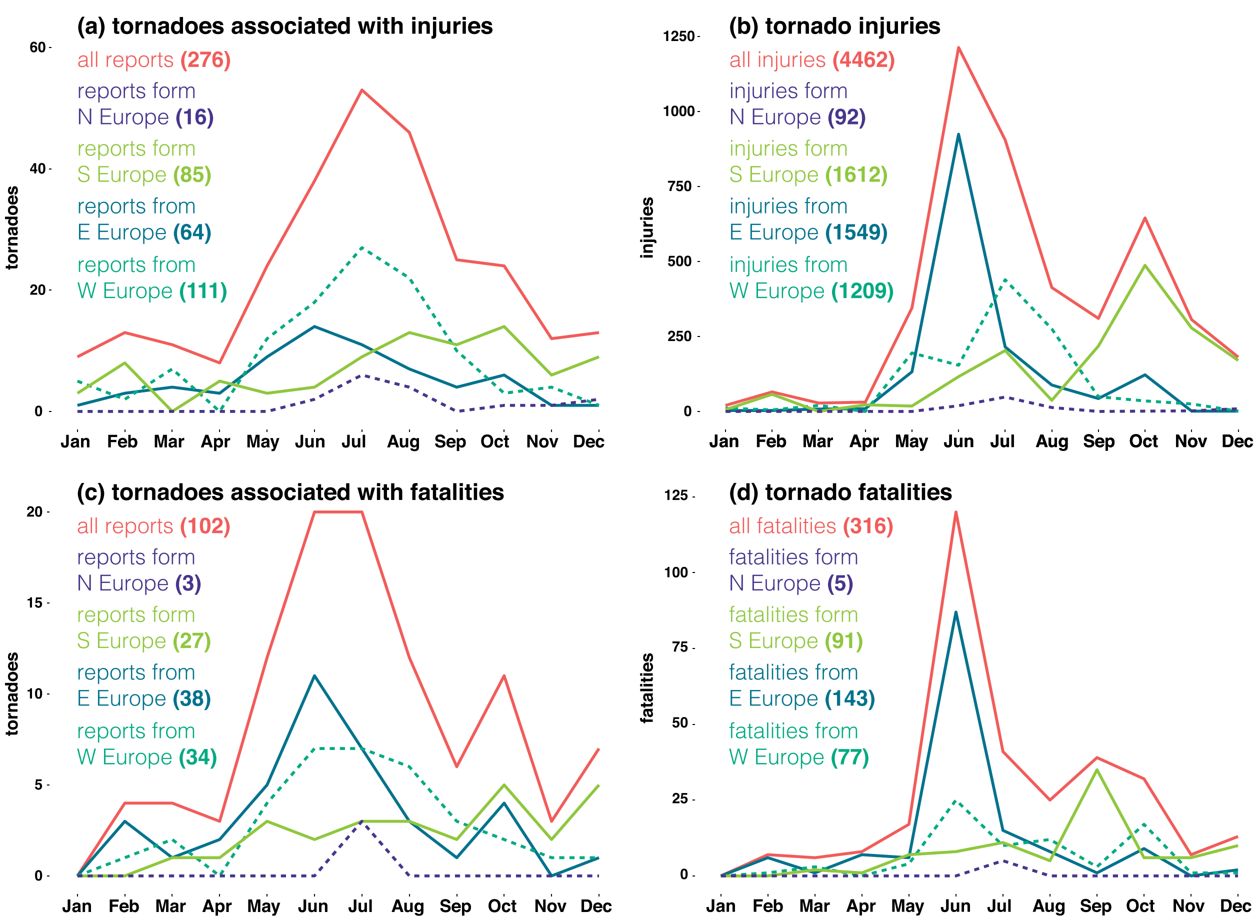

Fig. 6. Monthly distribution of the number of (a) tornado associated with injuries, (b) tornado injuries, (c) tornadoes associated with fatalities, and (d) tornado fatalities reported in Europe between 1950 and 2015. The monthly distributions are shown for the total number of reports (red line) and for northern (N, blue dashed lines), southern (S, light green lines), eastern (E, light blue lines), and western (W, green dashed lines) Europe. For each region of Europe, the total number of tornadoes, injuries, and fatalities is indicated in parentheses.

are not underreported in Europe and the current damages associated with them are minimal, tornado damages tend to increase with time. The societal and economic impact of significant tornadoes will be greater today than in the previous periods. Factors contributing to this increase include increases in population and inflation (except for economic recessions or depressions) and the tendency of both individuals and institutions to acquire more wealth in time (Brooks and Doswell 2001; Ashley 2007; Simmons et al. 2013; Ashley and Strader 2016).

For all these reasons, the tornado threat to Europe is not one that can be ignored. Floods, hail, and damaging winds pose a bigger threat for Europe than tornadoes (e.g., Swiss Re 2015, 2016), but here we argue that high-impact tornadoes are more common in Europe than most of the general public (and many meteorologists) realize (Doswell 2003, 2015).

We have not included in this discussion the possible influence of climate change on tornadoes or high-impact weather events, in general. Indeed, recent climate model studies of the atmospheric environments associated with severe convective storms (i.e., tornadoes, hail, and damaging wind) indicate an increased frequency of these environments over the United States, Europe, and Australia (e.g., Tippett et al. 2015). For example, Marsh et al. (2009) indicated a small increase in environments favorable for severe weather (i.e., a high convective available potential energy and high 0–6-km layer shear) over Europe, more pronounced near the Mediterranean Sea, but an increased frequency of favorable environments does not necessarily lead to an increased frequency of tornadoes resulting from those environments. Thus, before discussing the possible influence of climate change on tornadoes, we first need to understand their climatology in the current climate in Europe. Given these potential small increases in the frequency of severe weather, the question is, what can be done about it? Schultz and Janković (2014) argue that weather events will happen whether or not climate change is occurring, and reducing carbon dioxide emissions will not eliminate the damage from tornadoes. Thus, reducing societal vulnerability to severe weather is as important, if not more so, than reducing the effects of anthropogenic climate change.

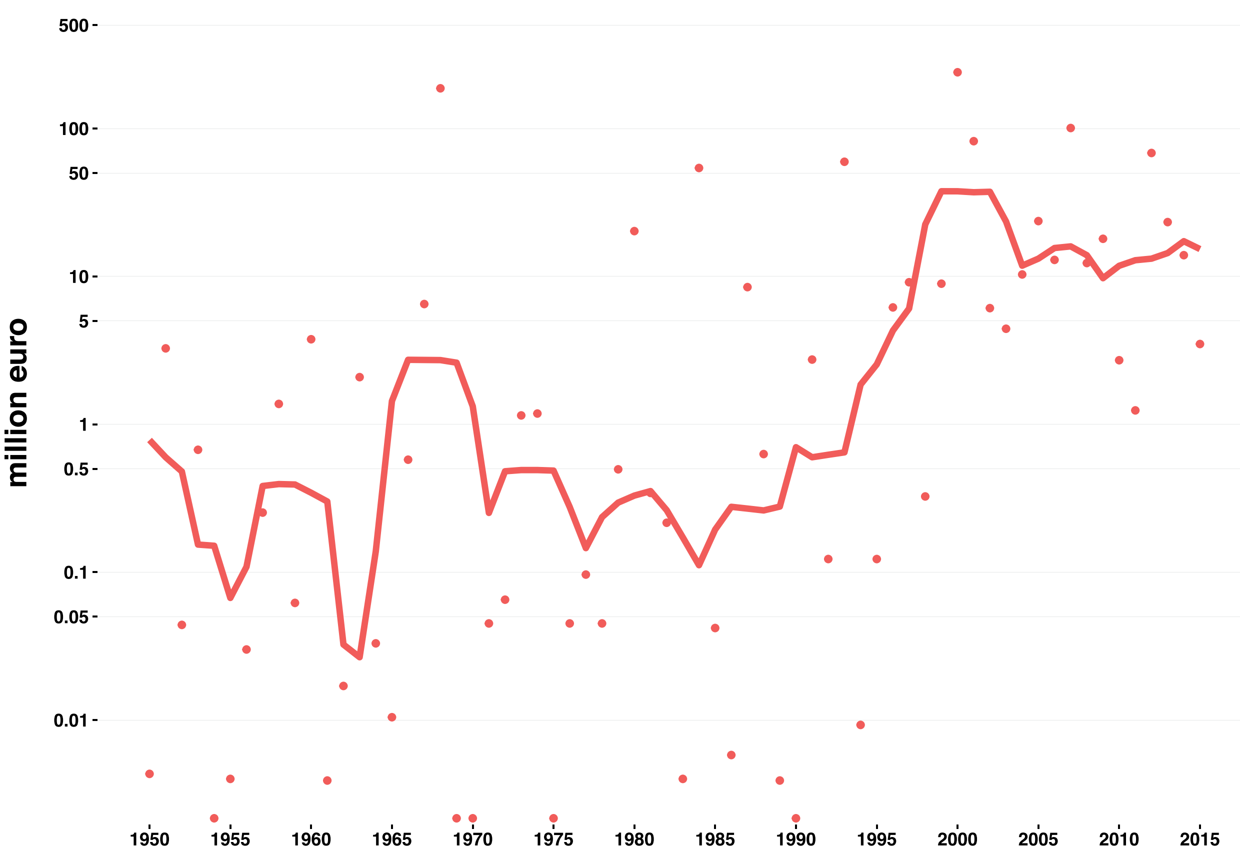

Fig. 7. Annual estimate of damages associated with European tornadoes between 1950 and 2015 (red dots). The red line represents the smoothed values as in Fig. 4.

To better understand the climatology of European tornadoes and to reduce the current threat of tornadoes to Europe, we end our discussion with a call to action for the general public, meteorological and scientific communities, policy-makers, and emergency managers.

1) A better understanding of the current spatial and temporal distribution of tornadoes in Europe is necessary, not only for the meteorological services to develop and maintain individual tornado databases, but also for the public to contribute to these databases. Citizen science projects (e.g., Muller et al. 2015), such as the ESWD, are an effective way to develop pan-European tornado databases. The tornado threat to Europe can only be understood from a pan-European perspective. As argued by Doswell (2003), the individual European countries have relatively small areas and the impact of tornadoes is going to be perceived as low for any single nation, especially compared with the impact of tornadoes in the United States. This low impact will not justify the development of tornado databases for individual countries. Thus, there is a need for European meteorological services to collaborate toward a pan-European tornado database and, in general, toward a severe-weather database.
2) To reduce the current threat of tornadoes to Europe, national meteorological services will need to develop new and enhance existing forecasting and warning systems. This is a difficult task, one that requires specialized knowledge (e.g., ingredients-based methodology for convective storms producing tornadoes and local severe storms environments) and tools (e.g., weather radars; Doswell 2003; Rauhala and Schultz 2009). Few efforts have been made to identify, based on high-resolution numerical simulations, the local-scale mechanisms associated with supercellular convection [e.g., Homar et al. (2003) for Spain and Miglietta et al. (2016) for Italy]. Again, closer collaborations between the scientific and operational communities and between different national meteorological services are necessary. Recent efforts have been made in this direction, for example, the European Operational Program for Exchange of Weather Radar Information (OPERA; Huuskonen et al. 2014), which covers more than 30 countries and contains more than 200 weather radars, and the European Storm Forecast Experiment (ESTOFEX; Brooks et al. 2011), which provides pan-European convective outlooks similar to those provided by the Storm Prediction Center for the United States. However, ESTOFEX is based on the voluntary engagement of individual persons rather than institutional support, which means that the daily availability of the outlook bulletins is not guaranteed. The focus of each weather service on its respective national territory has probably prevented the development of a collaborative and sustainable pan-European effort to forecast tornadoes and other convective hazards.
3) Although tornadoes cannot be prevented, the number of injuries and fatalities can potentially be reduced. Thus, decision-makers and emergency managers have to include tornadoes in their policies and strategies. In developing these policies and strategies, six of the seven global targets from the Sendai Framework for Disaster Risk Reduction (2015–30; Aitsi-Selmi et al. 2015) are relevant: 1) substantial reduction of global disaster mortality by 2030, 2) substantial reduction of the number of affected people by 2030, 3) reduction of direct disaster economic losses by 2030, 4) substantial reduction of disaster damages to critical infrastructure and of basic services by 2030, 5) substantial increase of the number of countries with national and local disaster risk reduction strategies by 2020, and 6) access to multihazard early warnings (UNISDR 2016). Currently, as far as the authors are aware, there are no tornado preparedness and response programs for Europe.

We hope this article will 1) increase awareness of the threat of tornadoes to Europe; 2) encourage further discussion within and between different European countries to improve monitoring and recording of tornado occurrence, better understand the local environments associated with tornadoes, and eventually lead to the development of forecasting and warning systems; 3) stimulate the interest of the scientific community; and 4) influence decision-makers to develop tornado preparedness and response programs.

ACKNOWLEDGMENTS. Funding for Antonescu and Schultz was provided by the Risk Prediction Initiative of the Bermuda Institute of Ocean Sciences through Grant RPI2.0-2016-SCHULTZ. Partial funding for Antonescu was provided by the AXA Research Fund to the University of Manchester for Assessing the Threat of Severe Convective Storms across Europe project. Partial funding for Schultz was provided by the Natural Environment

Research Council to the University of Manchester through Grants NE/H008225/1, NE/I005234/1, and NE/N003918/1. We thank Mateusz Taszarek (Adam Mickiewicz University, Poland) for providing data on deadly tornadoes in Poland.

APPENDIX: INJURIES, FATALITIES, AND DAMAGES DATA. In the ESWD, tornado reports include the number of injuries and fatalities and the associated damages. In this study, only the injuries and fatalities directly associated with tornadoes were considered. Damages are defined as direct economic losses caused by tornado winds as determined in the postevent analysis. The ESWD does not use a consistent approach to damage data collection because the damages have been collected by multiple agencies and users. In general, the tornado reports from ESWD contain damage estimates obtained from official sources that were available from mass media, publications, and damage surveys. Despite these limitations, the ESWD is the best source of information currently available for Europe for the damages associated with tornadoes.

In the ESWD, the damages are estimated for property damage, crop and forest damage, and total damage (property, crop, forest, and other types of damages). The damages estimated or described in these three categories have been used to estimate the annual damages associated with tornadoes in Europe between 1950 and 2015:

1) All the damages for which estimates were included in ESWD have been converted to euros using two online resources (i.e., Historical Exchange Rates 2016; Historical Currency Converter 2016).
2) For the tornado reports for which only a description of the damages was available, the average price of a house in Europe in 2015, estimated at €150,000, was used as a reference. The house price was used as a reference because the house represents "typically the largest component of the household wealth" (Knoll et al. 2014). The average house price before 2015 was estimated by adjusting with the House Price Index (HPI; Knoll et al. 2014). Knoll et al. (2014) developed, based on extensive historical research, a novel dataset that covers residential house price indices for 14 advanced economies since 1870. Their results indicated that the house prices increased since 1950 mainly because of an increase in land prices and not construction costs. For countries for which the historical evolution of HPI was not available, the European mean HPI was used (i.e., based on the HPI for Belgium, Denmark, Finland, France, Germany, Norway, Sweden, Switzerland, and the United Kingdom). The HPI values between 2013 and 2015 were obtained assuming a linear relationship of the HPI values between 2008 and 2012.
3) Once the average price of the house was estimated, different types of damage descriptions were quantified as a percentage from the average house price as house destroyed (100%), house damaged (25%), roof damaged (2%), greenhouse damaged (3%), and any other damage (5%). A conservative view was adopted for estimating damages when vague values were provided. For example, a report reading "millions of euro" was considered in this analysis as €2 million, and "many houses were destroyed" was considered to be two houses destroyed.

Although we acknowledge the potential problems associated with our approach (e.g., underestimation of real damages, HPI estimations), we are confident that they do not affect the trends discussed in this article.

Injuries, fatalities, and damages were analyzed for individual European countries (Table 1) and for different European regions (Figs. 5, 6). European countries were divided into four regions based on the definition from the United Nations Statistics Division (2016): 1) northern Europe (Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, United Kingdom), 2) eastern Europe (Belarus, Bulgaria, Czech Republic, Hungary, Poland, Moldova, Romania, Russia, Slovakia, Ukraine), 3) southern Europe (Albania, Andorra, Bosnia and Herzegovina, Croatia, Greece, Holy See, Italy, Malta, Montenegro, Portugal, San Marino, Serbia, Slovenia, Spain, Macedonia), and 4) western Europe (Austria, Belgium, France, Germany, Liechtenstein, Luxembourg, Monaco, Netherlands, Switzerland). Four countries that are classified by that United Nations Statistical Division as part of western Asia were considered here as part of eastern Europe (Armenia, Azerbaijan, Georgia, Turkey) and southern Europe (Cyprus; Fig. 1).

REFERENCES

Aitsi-Selmi, A., S. Egawa, H. Sasaki, C. Wannous, and V. Murray, 2015: The Sendai Framework for Disaster Risk Reduction: Renewing the global commitment to people's resilience, health, and well-being. *Int. J. Disaster Risk Sci.*, **6**, 164–176, doi:10.1007/s13753-015-0050-9.

American Meteorological Society, 2016: Tornado. Glossary of Meteorology. [Available online at http://glossary.ametsoc.org/wiki/tornado.]

Antonescu, B., and A. Bell, 2015: Tornadoes in Romania. *Mon. Wea. Rev.*, **143**, 689–701, doi:10.1175/MWR-D-14-00181.1.

——, D. M. Schultz, F. Lomas, and T. Kühne, 2016: Tornadoes in Europe: A synthesis of the observational datasets. *Mon. Wea. Rev.*, **144**, 2445–2480, doi:10.1175/MWR-D-15-0298.1.

Apsley, M. L., K. J. Mulder, and D. M. Schultz, 2016: Reexamining the United Kingdom's greatest tornado outbreak: Forecasting the limited extent of tornadoes along a cold front. *Wea. Forecasting*, **31**, 853–875, doi:10.1175/WAF-D-15-0131.1.

Ashley, W. S., 2007: Spatial and temporal analysis of tornado fatalities in the United States: 1880–2005. *Wea. Forecasting*, **22**, 1214–1228, doi:10.1175/2007WAF2007004.1.

——, and S. M. Strader, 2016: Recipe for disaster: How the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bull. Amer. Meteor. Soc.*, **97**, 767–786, doi:10.1175/BAMS-D-15-00150.1.

Brooks, H. E., and C. A. Doswell, 2001: Normalized damage from major tornadoes in the United States: 1890–1999. *Wea. Forecasting*, **16**, 168–176, doi:10.1175/1520-0434(2001)016<0168:NDFMTI>2.0.CO;2.

——, and ——, 2002: Deaths in the 3 May 1999 Oklahoma City tornado from a historical perspective. *Wea. Forecasting*, **17**, 354–361, doi:10.1175/1520-0434(2002)017<0354:DITMOC>2.0.CO;2.

——, and Coauthors, 2011: Evaluation of European Storm Forecast Experiment (ESTOFEX) forecasts. *Atmos. Res.*, **100**, 538–546, doi:10.1016/j.atmosres.2010.09.004.

de Boisgelin de Kerdu, P. M. L., 1804: *Ancient and modern Malta, containing a description of the ports and cities of the Islands of Malta and Goza, as also the history of the Knights of St. John of Jerusalem*. Vol. II, G. & J. Robinson, Paternoster-Row, 258 pp.

Doswell, C. A., 2001: Severe convective storms—An overview. *Severe Convective Storms, Meteor. Monogr.*, Vol. 50, Amer. Meteor. Soc., 1–26.

——, 2003: Societal impacts of severe thunderstorms and tornadoes: Lessons learned and implications for Europe. *Atmos. Res.*, **67–68**, 135–152, doi:10.1016/S0169-8095(03)00048-6.

——, 2015: Severe convective storms in the European societal context. *Atmos. Res.*, **158–159**, 210–215, doi:10.1016/j.atmosres.2014.08.007.

——, A. R. Moller, and H. E. Brooks, 1999: Storm spotting and public awareness since the first tornado forecasts of 1948. *Wea. Forecasting*, **14**, 544–557, doi:10.1175/1520-0434(1999)014<0544:SSAPAS>2.0.CO;2.

Dotzek, N., 2003: An updated estimate of tornado occurrence in Europe. *Atmos. Res.*, **67–68**, 153–161, doi:10.1016/S0169-8095(03)00049-8.

Finch, J. D., and D. Bikos, 2012: Russian tornado outbreak of 9 June 1984. *Electron. J. Severe Storms Meteor.*, **7** (4), 1–28. [Available online at www.ejssm.org/ojs/index.php/ejssm/article/viewArticle/98.]

Fujita, T. T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.*, **38**, 1511–1534, doi:10.1175/1520-0469(1981)038<1511:TADITC>2.0.CO;2.

Galway, J. G., 1989: The evolution of severe thunderstorm criteria within the weather service. *Wea. Forecasting*, **4**, 585–592, doi:10.1175/1520-0434(1989)004<0585:TEOSTC>2.0.CO;2.

——, 1992: Early severe thunderstorm forecasting and research by the United States Weather Bureau. *Wea. Forecasting*, **7**, 564–587, doi:10.1175/1520-0434(1992)007<0564:ESTFAR>2.0.CO;2.

Gayà, M., 2015: *Els Fiblons a Espanys: Climatologia i catàled de tornados i trombes (Whirlwinds in Spain: Climatology and catalog of tornadoes and waterspouts).* Universitat de les Illes Balears, 441 pp.

Grice, G. K., and Coauthors, 1999: The golden anniversary celebration of the first tornado forecast. *Bull. Amer. Meteor. Soc.*, **80**, 1341–1348, doi:10.1175/1520-0477(1999)080<1341:TGACOT>2.0.CO;2.

Groenemeijer, P., and T. Kühne, 2014: A climatology of tornadoes in Europe: Results from the European Severe Weather Database. *Mon. Wea. Rev.*, **142**, 4775–4790, doi:10.1175/MWR-D-14-00107.1.

Hales, J. E., Jr., 1988: Improving the watch/warning program through use of signicant event data. *Preprints, 15th Conf. on Severe Local Storms*, Baltimore, MD, Amer. Meteor. Soc, 165–168.

Historical Currency Converter, 2016: Currency converter. Accessed on 15 July 2016. [Available online at www.historicalstatistics.org/Currencyconverter.html.]

Historical Exchange Rates, 2016: Exchange rates. Accessed 15 July 2016 [Available online at http://fxtop.com/en/historical-exchange-rates.php.]

Holzer, A. M., and Coauthors, 2015: Present state of risk monitoring and warning systems in Europe: RAIN project report. Tech. rep., 132 pp. [Available online at http://rain-project.eu/wp-content/uploads/2015/11/D2.3-Warning-Systems.pdf.]

Homar, V., M. Gayá, R. Romero, C. Ramis, and S. Alonso, 2003: Tornadoes over complex terrain: An analysis of the 28th August 1999 tornadic event in eastern Spain. *Atmos. Res.*, **67–68**, 301–317, doi:10.1016/S0169-8095(03)00064-4.

Huuskonen, A., E. Saltikoff, and I. Holleman, 2014: The operational weather radar network in Europe. *Bull. Amer. Meteor. Soc.*, **95**, 897–907, doi:10.1175/BAMS-D-12-00216.1.

Illustrated London News, 1851: Five hundred persons destroyed by a waterspout. *Illustrated London News*, 20 December, 731.

Kirk, P., T. Prosser, and D. Smart, 2015: Tornadoes in the United Kingdom and Ireland: Frequency and spatial distribution. *Extreme Weather: Forty Years of the Tornado and Storm Research Organisation (TORRO)*, R. K. Doe, Ed., Wiley-Blackwell, 61–76.

Knoll, K., M. Schularick, and T. M. Steger, 2014: No price like home: Global house prices, 1870–2012. Discussion Paper DP10166, Centre for Economic Policy Research, 158 pp.

Lemon, L. R., A. Stan-Sion, C. Soci, and E. Cordoneanu, 2003: A strong, long-track, Romanian tornado. *Atmos. Res.*, **67–68**, 391–416, doi:10.1016/S0169-8095(03)00063-2.

Letzmann, J., 1931: Experimentelle Untersuchungen an Luftwirbeln (Experimental investigations on air vortices). *Gerlands Beitr. Geophys.*, **33**, 130–172.

Marsh, P. T., H. E. Brooks, and D. J. Karoly, 2009: Preliminary investigation into the severe thunderstorm environment of Europe simulated by the Community Climate System Model 3. *Atmos. Res.*, **93**, 607–618, doi:10.1016/j.atmosres.2008.09.014.

Miglietta, M. M., A. Manzato, and R. Rotunno, 2016: Characteristics and predictability of a supercell during HyMex SOP1. *Quart. J. Roy. Meteor. Soc.*, 142, 2839–2853, doi:10.1002/qj.2872.

Muller, C. L., L. Chapman, S. Johnston, C. Kidd, S. Illingworth, G. Foody, A. Overeem, and R. R. Leigh, 2015: Crowdsourcing for climate and atmospheric sciences: Current status and future potential. *Int. J. Climatol.*, **35**, 3185–3203, doi:10.1002/joc.4210.

NWS, 2016: Summary of U.S. natural hazard statistics 2006–2015. Accessed 18 July 2016 [Available online at www.nws.noaa.gov/om/hazstats.shtml.]

Peltier, J. C. A., 1840: *Météorologie: Observations et recherches expérimentales sur les causes qui concourent à la formation des trombes (Meteorology: Observations and experimental research on the causes that contribute to the formation of tornadoes).* H. Cousin, Librare-Editeur, Paris, 444 pp.

Rauhala, J., and D. M. Schultz, 2009: Severe thunderstorm and tornado warnings in Europe. *Atmos. Res.*, **93**, 369–380, doi:10.1016/j.atmosres.2008.09.026.

——, H. E. Brooks, and D. M. Schultz, 2012: Tornado climatology of Finland. *Mon. Wea. Rev.*, **140**, 1446–1456, doi:10.1175/MWR-D-11-00196.1.

Reye, T., 1872: *Die Wirbelstürme, Tornados und Wettersäulen in der Erdatmosphäre mit Berücksichtigung der Stürme in der Sonnen-Atmosphäre (Hurricanes, tornadoes and "weather columns" in the Earth's atmosphere with respect to storms in the Sun's atmosphere).* Carl Rümpler, 250 pp.

Rowe, M. W., 1999: "Work of the devil": Tornadoes in the British Isles to 1660. *J. Meteor.*, **24**, 326–338.

——, and G. T. Meaden, 1985: Britain's greatest tornado outbreak. *Weather*, **40**, 230–235, doi:10.1002/j.1477-8696.1985.tb06883.x.

Schultz, D. M., and V. Janković, 2014: Climate change and resilience to weather events. *Wea. Climate Soc.*, **6**, 157–159, doi:10.1175/WCAS-D-14-00005.1.

SEDAC, 2015: Population count grid. Gridded Population of the World, version 4, d accessed 16 November 2016, doi:10.7927/H4VH5KS4.

Setvák, M., M. Salek, and J. Munzar, 2003: Tornadoes within the Czech Republic: From early medieval chronicles to the "internet society." *Atmos. Res.*, **67–68**, 589–605, doi:10.1016/S0169-8095(03)00075-9.

Simmons, K. M., and D. Sutter, 2005: WSR-88D radar, tornado warnings, and tornado casualties. *Wea. Forecasting*, **20**, 301–310, doi:10.1175/WAF857.1.

——, ——, and R. Pielke Jr., 2013: Normalized tornado damages in the United States: 1950–2011. *Environ. Hazards*, **12**, 132–147, doi:10.1080/17477891.2012.738642.

Sioutas, M., W. Szilagyi, and A. Keul, 2013: Severe convective storms in the European societal context. *Atmos. Res.*, **123**, 167–179, doi:10.1016/j.atmosres.2012.09.013.

——, T. Renko, W. Szilagyi, and A. Keul, 2014: Waterspout climatology over the central-eastern Mediterranean. *Proc. 12th Int. Conf. on Meteorology, Climatology and Atmospheric Physics*, Vol. 3, Heraklion, Greece, University of Crete, 154–158. [Available online at http://comecap2014.chemistry.uoc.gr/en10_conferenceProc.html.]

Swiss Re, 2015: Natural catastrophes and man-made disasters in 2014: Convective and winter storms generate most disasters. Sigma 2/2015, Swiss Re, 52 pp. [Available online at http://media.swissre.com/documents/sigma2_2015_en_final.pdf.]

——, 2016: Natural catastrophes and man-made disasters in 2015: Asia suffers substantial losses. Sigma 1/2016, Swiss Re, 52 pp. [Available online at www.swissre.com/sigma/.]

Taszarek, M. and J. Gromadzki, 2017: Deadly tornadoes in Poland from 1820 to 2015. *Mon. Wea. Rev.*, doi:10.1175/MWR-D-16-0146.1, in press.

Tippett, M. K., J. T. Allen, V. A. Gensini, and H. E. Brooks, 2015: Climate and hazardous convective weather. *Curr.*

Climate Change Rep., **1**, 60–73, doi:10.1007/s40641-015-0006-6.

Tufte, E., 1983: *The Visual Display of Quantitative Information.* Graphic Press, 199 pp.

UNISDR, 2016: Sendai framework for disaster risk reduction 2015–2030. United Nations International Strategy for Disaster Reduction, 37 pp. [Available online at www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf.]

United Nations Statistics Division, 2016: Composition of macro geographical (continental) regions, geographical sub-regions, and selected economic and other groupings. Accessed 4 August 2016. [Available online at http://unstats.un.org/unsd/methods/m49/m49regin.htm.]

Wegener, A., 1917: *Wind- und Wasserhosen in Europa (Tornadoes and Waterspouts in Europe).* Vieweg, 301 pp.

Weyher, C. L., 1889: *Sur les tourbillons, trombes, tempêtes et sphères tournantes: Etude et expériences (On whirlwinds, tornadoes, thunderstorms and rotating spheres: Study and experiments).* Gauthier-Villars, 152 pp.