REVIEW

Tornadoes in Europe: Synthesis of the Observational Datasets

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ABSTRACT

A synthesis of tornado observations across Europe between 1800 and 2014 is used to produce a pan-European climatology. Based on regional tornado-occurrence datasets and articles published in peer-reviewed journals, the evolution and the major contributions to tornado databases for 30 European countries were analyzed. Between 1800 and 2014, 9563 tornadoes were reported in Europe with an increase from 8 tornadoes per year between 1800 and 1850 to 242 tornadoes per year between 2000 and 2014. The majority of the reports came from northern, western, and southern Europe, and to a lesser extent from eastern Europe where tornado databases were developed after the 1990s. Tornadoes occur throughout the year with a maximum in June–August for most of Europe and in August–November for southern Europe. Tornadoes occur more frequently between 1300 and 1500 UTC over most of Europe and between 0900 and 1100 UTC over southern Europe. Where intensity was known, 74.7% of tornadoes were classified as F0 and F1, 24.5% as F2 and F3, and 0.8% as F4 and F5. Comparing this intensity distribution over Europe with the intensity distribution for tornadoes in the United States shows that tornadoes over western and eastern Europe are more likely to be supercellular tornadoes and those over northern and southern Europe are likely to also include nonsupercellular tornadoes.

1. Introduction

Our current knowledge of the climatology of tornadoes in Europe has been built from historical collections of tornado reports (e.g., Peltier 1840; Wegener 1917), case studies (e.g., Hepites 1887; Lemon et al. 2003), and local climatologies (e.g., Snitkovskii 1987; Dessens and Snow 1989). Unfortunately, these datasets were limited by inconsistencies in observational networks and reporting practices across Europe and have only allowed a simplified and inaccurate understanding of the pan-European tornado climatology. Recently, this situation began to change with more tornadoes reported in the last decade compared to previous decades and with reports now coming from the majority of European countries. This recent increase in the number of reports can be attributed to increased public awareness (e.g., Rauhala et al. 2012; Antonescu and Bell 2015), to the development of databases maintained by national meteorological services (e.g., Renko et al. 2013), and to efforts at collecting reports on a European level (e.g., Dotzek et al. 2009). Thus, we are now able to build more accurate and complete climatologies of European tornadoes.

There are three reasons why a review is needed at this point. First, there is not a widespread recognition of the threat of tornadoes to Europe and, as a result, many European meteorological services do not forecast tornadoes. Rauhala and Schultz (2009) showed, based on a

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questionnaire sent to 39 European meteorological services, that tornado warnings have been issued for only 8 of the 33 countries that responded. Specifically, the first tornado warning in Europe was issued in the Netherlands in 1967 and the second in Cyprus in 1977. Between 2003 and 2006, tornado warnings were issued for Spain, Germany, Romania, Malta, Turkey, and Estonia (Rauhala and Schultz 2009). Groenemeijer and Kühne (2014) speculated that tornadoes failed to become "a well-established subject of research in European academia" and are not a high priority for European meteorological services because tornadoes occur less frequently in Europe compared with the United States. Ex-socialist bloc countries (e.g., Romania, Czech Republic) did not even acknowledge that tornadoes could occur in their country until recently. This lack of recognition led to an underestimate of tornadoes in Europe.

Second, a review would contribute to a better understanding of the climatology of tornadoes in Europe by showing the evolution of tornado databases for different European countries and by identifying the major influences on the development of these databases (e.g., the First and Second World War, the socialist regimes in eastern Europe). As we will show, prior to World War II, more tornado research occurred in Europe compared with the United States.

Third, understanding how severe convective storms and their associated phenomena (e.g., tornadoes) would change in a future climate remains a great challenge (e.g., Brooks 2013; Tippett et al. 2015). When considering the possible influence of climate change on severe convective storms, the first step is to consider the observational data. Without knowing what is occurring now, analyses of the influence of climate change on tornadoes are premature. Unlike the temperature records for which instrumental observations started in the 1850s (e.g., Jones 1994) or even in the 1660s for central England (e.g., Manley 1974), organized and centralized tornado records started relatively recently [e.g., the U.S. tornado database goes back to the 1950s; Verbout et al. (2006)]. The lack of longer tornado records is mainly because tornadoes are "targets of opportunity" (Brooks 2013). Thus, they require the presence of an observer and a system for collecting the observations. Although collecting tornado reports started in the nineteenth century in Europe (e.g., Peltier 1840), no system was in place until very recently to collect reports on a European scale (i.e., the European Severe Weather Database began in 2006). Also, many of these efforts for collecting tornado reports in Europe occurred outside of the national meteorological services, resulting in less certainty for the long-term continuity of the databases.

For these reasons, this review seeks to summarize what is currently known about the climatology of tornadoes in Europe. This review builds upon the efforts of researchers, professional meteorologists, and amateurs who have collected and analyzed tornado reports in their home countries. Other authors have provided reviews of the European tornado climatology (e.g., Peterson 1982), collections of references on tornadoes in Europe (e.g., Peterson 1981), or have developed pan-European climatologies (e.g., Groenemeijer and Kühne 2014, based on the data from the European Severe Weather Database), but to our knowledge this is the first exhaustive study of the literature on tornadoes in Europe in nearly a century (i.e., Wegener 1917).

This paper is organized as follows. The definition of a tornado and the methods used to collect tornado reports are discussed in section 2. A historical overview of the studies on tornadoes in Europe is given in section 3. The evolution of tornado databases for European countries is presented in section 4 and detailed in appendixes A and B. The spatial distribution of tornadoes in Europe based on the literature review is described in section 5, and the monthly and hourly distributions are discussed in sections 6 and 7, respectively. Section 8 describes the intensity distribution of tornadoes in Europe. Section 9 summarizes this review.

2. Data

Section 2a begins with the definition of a tornado used in this article and continues with a discussion of how waterspouts are handled within this definition. Section 2b describes the different methods employed to identify and develop tornado climatologies for different European countries.

a. *Tornado definition*

The *Glossary of Meteorology* defines a tornado 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 2015a). The *Glossary of Meteorology* defines a waterspout as "any tornado over a body of water" (American Meteorological Society 2015b). The National Weather Service classifies tornadoes separate from waterspouts. Yet, as Rauhala et al. (2012) have argued, a strict separation between tornadoes and waterspouts would be restrictive for some European countries. Several countries have a large part of their landscape covered by lakes (e.g., 187 000); others countries contain peninsulas (e.g., southern Italy). Other countries consist entirely of a single island (e.g., Malta in the Mediterranean Sea) or comprise archipelagos (e.g., Greece has more than a thousand islands). To accommodate these countries, in this article, the following tornado definition adapted from Rauhala et al. (2012) is used: *a tornado is a vortex between a cloud and the land or water surface, in which the*

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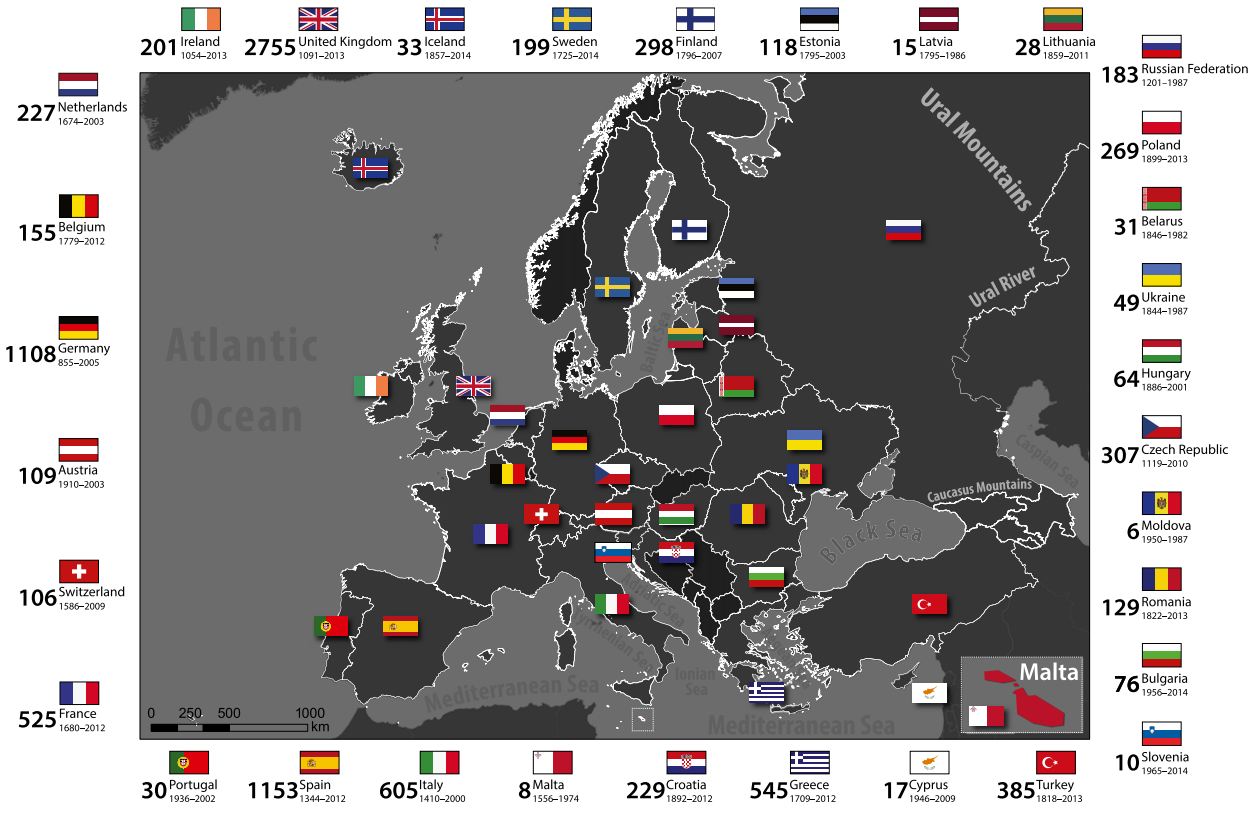

FIG. 1. Map showing the European countries (indicated by their flags) for which tornado databases have been developed. The number of tornado reports and the period covered by each database is indicated around the edges of the map (see appendix A). Countries without tornado databases are represented in dark gray. For Iceland and Slovenia, reports were available mainly from personal communication (see appendix B).

connection between the cloud and surface is often visible. According to this definition, all waterspouts would be included as tornadoes, which is consistent with the *Glossary* definitions. However, the inclusion of the waterspouts inflates the inventory of tornadoes in Europe.

This inflation is due to two reasons. First, there are two types of waterspouts: (i) tornadic waterspouts associated with supercells or quasi-linear convective systems [i.e., type I and type II in the taxonomy proposed by Agee (2014)] and (ii) fair-weather waterspouts associated with localized convective and shear vortices [i.e., type III in the taxonomy proposed by Agee (2014)]. In most tornado climatologies, the fair-weather waterspouts are not generally included because they are considered to have a lower impact compared with the tornadic waterspouts. In this article, the fair-weather waterspouts are considered tornadoes because (i) they can move inland and produce substantial damage and (ii) for some waterspouts reports, in particular for historical reports, it is not possible to differentiate between tornadic and fair-weather waterspouts. Second, waterspouts tend to occur in groups (e.g., Rauhala and Schultz 2009). If these are reported as separate events, the inventory would be biased toward waterspouts. In this article, all waterspouts that have been reported as a part of a group are considered a single event.

Thus, due to the ambiguity of what constitutes a tornado or waterspout in the datasets of some countries, we have included the waterspout reports in the inventory for this article. This inflates the inventory, but ensures that all tornado reports were included. Wherever it was possible, we have analyzed the waterspout reports, for which the vortex began and stayed over water during its entire lifetime, separately to show their contribution to the climatology. In particular, this separation was necessary for the analysis of the monthly and hourly distributions.

b. *Collecting tornado reports*

The most common definition of Europe is used in this article: Europe is bordered by the Arctic Ocean to the north, the Atlantic Ocean to the west, the Mediterranean Sea to the south, and the Ural Mountains, Caucasus Mountains, Ural River, and Caspian Sea to the east (Fig. 1). Based on this definition, there are 50 internationally recognized sovereign European states, of which 44 have their capital city within Europe; 6 (Armenia, Azerbaijan, Georgia, Kazakhstan, Russia, and Turkey) have their territory both in Europe and Asia.

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TABLE 1. Tornado climatologies for European countries.

Country	Study	Years	No. of reports
Austria	Holzer (2001) Svabik and Holzer (2005)	1910–2003	109
Belarus	Snitkovskii (1987)	1846–1982	31
Belgium	Frique (2012)	1779–2012	155
Bulgaria	Simeonov et al. (2013) Bocheva and Simeonov (2015)	1956–2014	76
Croatia	Mohorovičić (1892) Poje (1957) Pokorny (1962) Čapka (1978) Ivančan-Picek et al. (1995) Stiperski (2005) Simon and Kovačić (2006) Renko et al. (2013) Irha (2014)	1892–2012	229
Cyprus	Hardy (1971) Hyde (1971) Jones and Williams (1977) Sioutas et al. (2006)	1946–2004	17
Czech Republic	Brázdil et al. (2012)	1119–2010	307
Estonia	Tárand (1995) Tooming and Merilain (2004)	1795–2003	118
Finland	Rauhala et al. (2012)	1796–2007	298
France	Dessens and Snow (1989) Paul (2001) Dessens and Paul (2013)	1680–2012	525
Germany	Dotzek (2001) Bissolli et al. (2007) TorDACH v1.6.00	855–2005	1108
Greece	Matsangouras et al. (2014)	1709–2012	545
Hungary	Rethly (1925) Kecskŕs (1988) Szilárd (2007) János (2010)	1886–2001	64
Ireland	Rowe (1989) Tyrrell (2001, 2003, 2004, 2005, 2006) Tyrrell (2007, 2008, 2010, 2012, 2014)	1054–2013	201
Italy	Crestani (1924, 1926, 1927, 1928, 1936) Baldacci (1958, 1966) Palmieri and Pulcini (1979) Peterson (1988, 2000a) Gianfreda et al. (2005) Giaiotti et al. (2007)	1410–2000	605
Latvia	Snitkovskii (1987) Tárand (1995)	1795–1986	15
Lithuania	Snitkovskii (1987) Marcinoniene (2003) Stankūnaitė (2006)	1859–2011	28
Malta	Peterson (1986)	1556–1974	8
Moldova	Lyakhov (1987) Snitkovskii (1987)	1950–87	6
Netherlands	van Everdingen (1925) Peterson (1981) Groenemeijer (2004)	1674–2003	227
Poland	Taszarek and Brooks (2015)	1899–2013	269
Portugal	Leitão (2003)	1936–2002	30
Romania	Antonescu and Bell (2015)	1822–2013	129
Russian Federation	Lyakhov (1987) Snitkovskii (1987)	1201–1987	183

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TABLE 1. (*Continued*)

Country	Study	Years	No. of reports
Spain	Gayà (2015)	1344–2012	1153
Sweden	Peterson (2000b)	1725–2014	199
	SMHI database		
Switzerland	Jeanneret (2010)	1586–2009	106
Turkey	Kahraman and Markowski (2014)	1818–2013	385
Ukraine	Lyakhov (1987)	1844–1987	49
	Snitkovskii (1987)		
United Kingdom	Lacy (1968)	1091–2013	2755
	Rowe (1999)		
	Meaden (1985a)		
	Brown et al. (2012,2013a,b,c,d)		
	Brown and Meaden (2014)		
	Mulder and Schultz (2015)		

The tornado climatologies for European countries were mainly obtained from articles published in peer-reviewed meteorological journals. Online archives available for the 77 journals listed in 2014 by the Institute of Scientific Information (ISI) Web of Knowledge (www.isiwebofknowledge.com, accessed 1 March 2015) under the subject category "Meteorology and Atmospheric Science" were examined using keyword searches (e.g., tornado, waterspout). An additional 12 atmospheric journals for which only parts of their archives were available online or were not ranked by ISI were consulted at the University of Manchester Library, either from their archives or from intralibrary loans. This search resulted in 50 articles on tornado climatologies for 23 European countries (Table 1 and appendix A).

Climatologies for eight countries in which tornado climatologies had not yet been developed or published (i.e., Belgium, Croatia, Cyprus, Iceland, Malta, the Netherlands, Sweden, and Switzerland) were constructed using the following sources:

1) case studies and annual reports on tornadoes identified through a literature search using the same methodology as above;
2) historical scientific papers accessed via fully searchable online archives (i.e., *Philosophical Transactions of the Royal Society of London; Journal des Sçavans; Annalen der Physik; Journal de Physique, de Chimie, d'Histoire Naturelle et des Arts*) or historical climatologies (Peltier 1840; Wegener 1917);
3) conference talks and posters presented at European (e.g., European Geoscience Union, European Conference on Severe Storms) and other international conferences (e.g., American Meteorological Society Severe Local Storm Conference) identified through online archives or published in proceedings;
4) tornado databases developed and maintained by national meteorological services (i.e., Sweden) or by amateur meteorological organizations (i.e., Belgium) accessed online; and
5) theses (e.g., on tornadoes in Switzerland), dissertations (e.g., on tornadoes in Hungary), and reports (e.g., on tornadoes in Belgium) identified through web searches.

For Iceland and Slovenia, tornado reports were also available, but the sources of these reports were mainly personal communications. Thus, we have not included reports for Iceland and Slovenia in the subsequent analyses, but we have described the reports for these countries in appendix B. For each European country, the tornado reports with dates before the adoption of the Gregorian calendar were converted to their equivalent in the Gregorian calendar.

There are limitations to this approach to identify climatologies, case studies, and databases of tornadoes in Europe. First, only the international or national scientific journals with a high circulation were surveyed. Potentially, studies of European tornadoes were also published in low-circulation journals (e.g., those published by amateur meteorologists, local meteorological societies, meteorological services). Second, given the large number of European languages in which articles, conference presentations, posters, or dissertations on tornadoes have been potentially published, not all the contributions have been included in this review. The likelihood of missing relevant contributions to the European tornado climatology arising from these two situations was possible, but likely small.

3. Historical overview of the observational and climatological studies of tornadoes in Europe

This section describes the evolution of tornado studies in Europe from ancient Greece to the contemporary period and presents the prominent figures in the field of tornado research.

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a. The historical period (330 BC–1799)

To our best knowledge, the ancient Greeks were the first to make regular meteorological observations and also the first to propose theories about weather phenomena (Hellmann 1908; Shaw 1926; Taub 2003). For example, tornadoes and waterspouts were topics for speculation by the natural philosophers—*natural philosophy* being the term used for the study of the physical universe before the nineteenth century when the term *science* developed its modern meaning (e.g., French 1994). Theories on the formation of tornadoes and waterspouts were proposed by Greek natural philosophers such as Aristotle (384–322 BC) in *Meteorologica* [dated between 356 and 330 BC; Wilson (2013)] and Theophrastus of Ereus (ca. 372–ca. 287 BC) in *Meteorology* (Daiber 1992), and Roman natural philosophers such as Seneca (ca. 4 BC–AD 65) in *Naturales Quaestiones* [dated approximately AD 65; Williams (2012)] and Titus Lucretius Carus (ca. 90–ca. 50 BC) in *De Rerum Natura* [dated first-century BC; Greenblatt (2012)]. These theories, in which the tornado occurred as the result of the deflection of the wind within the surrounding cloud, were generally repeated by authors during the Early Middle Ages [e.g., Isidore of Seville (ca. 560–636) in *Etymologiae* (ca. 600–25)] and High Middle Ages [e.g., Vincentius Bellovacensis (ca. 1190–ca. 1264) in *Speculum Naturale* (ca. 1260)].

The systematic study of tornadoes in Europe began in the seventeenth century (Peterson 1982) during the transition period from the Renaissance to the Early Modern period. In France, the theologian Francois Lamy (1636–1711) described two tornadoes that occurred at Sillery (Marne, northeastern France) on 10 August 1680 and Bannost-Villegagnon (Seine-et-Marne, northern France) on 15 August 1687 (Lamy 1689). In Italy, the astronomer and mathematician Geminiano Montanari (1633–87) studied a tornado that occurred in the Veneto region (northeastern Italy) on 29 July 1686. Published posthumously in 1694, Montanari's study is one of the earliest detailed accounts of a tornado in Europe. One of the most influential studies on tornadoes in Europe published before the nineteenth century was written by Boscovich (1749) (Peterson 1982). Roger Joseph Boscovich (1711–87), a Jesuit polymath who was a precursor of atomic theory and made contributions to astronomy and geodesy, investigated a tornado that occurred on the night of 11–12 June 1749. The tornado started as a waterspout over the Tyrrhenian Sea (Fig. 1) and then moved inland, parallel with the river Tiber from Ostia to Rome (Peterson 1992a). At the request of Cardinal Silvio Valenti Gonzaga (1690–1756), Boscovich conducted a three-week study of the damage caused by the tornado in Rome, and the results were published in a book in 1749. The book, which also contains information on other tornadoes that occurred in Italy and discussions on tornado formation, had a great influence on Benjamin Franklin's theories on the formation of waterspouts, which he described in a February 1753 letter to Massachusetts physician John Perkins (1698–1781) (http://franklinpapers.org/franklin//framedNames.jsp, accessed on 11 December 2015).

TABLE 2. The number of tornadoes and waterspout reports based on data collected by Peltier (1840) between 1456 and 1939 and Wegener (1917) between 1456 and 1913. One tornado in the Wegener dataset has no exact location.

Country	Peltier (1840)	Wegener (1917)
Austria	—	16
Belgium	—	1
Croatia	—	1
Germany	3	79
France	37	57
Finland	1	2
Ireland	1	—
Italy	12	16
Malta	1	—
Netherlands	3	1
Poland	1	—
Romania	—	1
Russia	—	9
Spain	1	—
Sweden	1	8
Switzerland	6	24
United Kingdom	18	27
Mediterranean Sea	6	15
Total	91	257

b. The modern period (1800–1999)

The number of descriptions and accounts of tornadoes and waterspouts in Europe published in scientific journals increased toward the end of the eighteenth century and the beginning of the nineteenth century (e.g., Swinton 1761; Demarquoy 1823). Jean Charles Athanase Peltier (1785–1845), a French physicist mainly known for the discovery of the thermoelectric effect, analyzed tornado and waterspout reports and the theories on their causes and formation (e.g., Tilloch 1817; Inglis 1818) in a study published in 1840. Peltier (1840) contains probably the first climatology of European tornadoes, based on 91 tornado reports collected mainly from the scientific literature between 1456 and 1839, mostly for tornadoes that occurred over western Europe (Fig. 2a and Table 2). No other efforts were made to collect and analyze tornado reports in Europe until the early twentieth century.

In 1917, Alfred Wegener (1880–1930), a German meteorologist, geophysicist, and pioneer polar researcher, published *Wind- und Wasserhosen in Europa* (*Tornadoes and Waterspouts in Europe*) a classic study on the climatology

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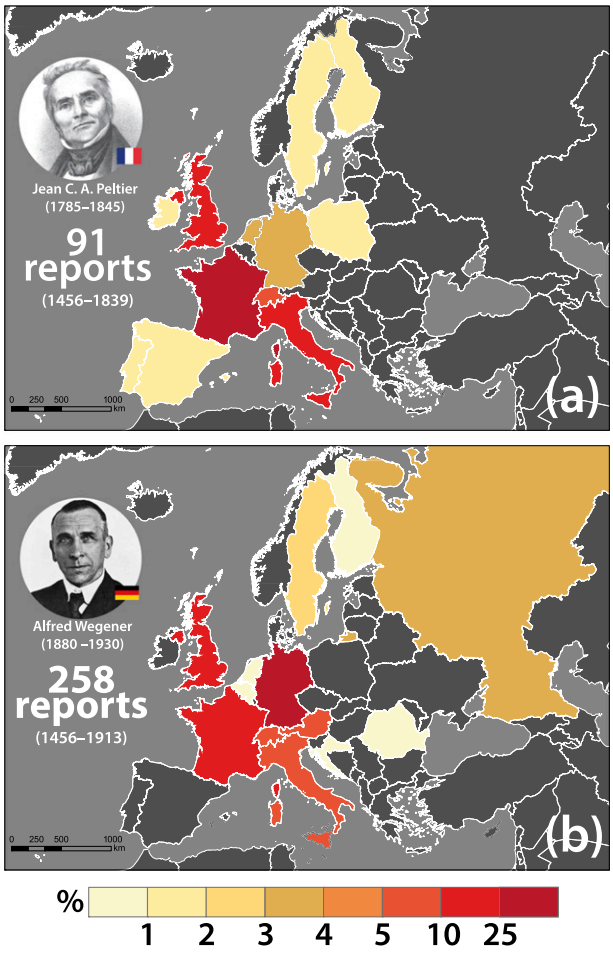

FIG. 2. The spatial distribution of tornado reports in Europe based on the data collected by (a) Peltier (1840) between 1456 and 1839 and (b) Wegener (1917) between 1456 and 1913. The percentage for each country of the total number of reports collected in each study is shaded according to the scale. [The photos of Peltier (source http://www.thermoelectrics.caltech.edu/thermoelectrics/history.html) and Wegener (source Bildarchiv Foto Marburg Aufnahme-Nr. 426.294) are from the public domain.]

and formation of tornadoes.[1] His study was based on tornado reports collected from previous studies (e.g., Peltier 1840), from a wide range of scientific literature (e.g., *Philosophical Transactions of the Royal Society*; *Meteorologische Zeitschrift*; *Journal de Physique, de Chimie, d'Histoire Naturelle et des Arts*), and personal observations.

According to Wegener (1917), tornadoes that occurred in Europe were less intense, less frequent, and were associated with less damage compared with those that occurred in the United States. Wegener used the U.S. tornado climatology developed by John Park Finley (1854–1943), an American meteorologist and Army Signal Service officer (Galway 1985) who was the first to study U.S. tornadoes intensively (Finley 1887). Wegener (1917) showed that 777 tornadoes were reported in the United States between 1883 and 1886, whereas 35 tornadoes were reported in Europe between 1884 and 1887. Wegener's view that the tornado threat was lower in Europe compared with the United States was shared by other meteorologists at that time. For example, in the section on tornadoes and waterspouts from *Lehrbuch der Meteorologie* (*Textbook on Meteorology*), Julius von Hann, an Austrian meteorologist considered one of the founders of modern meteorology, described these phenomena using mainly examples of tornadoes that occurred in the United States (von Hann 1915).

The dataset developed by Wegener (1917) contained 258 tornadoes (Table 2), of which 120 (46% of all reports) were reported between 1880 and 1913. The spatial distribution of all reports shows that they were mainly collected from western European countries (205 reports, 80% of all reports) (Fig. 2b). Wegener (1917), as Peltier (1840) before him, was not only interested in the climatology of tornadoes and waterspouts, but also in explaining their formation. In his view, what became known as the "mechanical theory" was the only one capable of explaining the formation of these phenomena: "the temperature conditions are not considered the primary cause and the rotation the effect, but the rotation, whether produced mechanically or hydrodynamically, is believed to be the cause of the thermodynamic effects, the latter manifesting themselves in the condensation of the funnel cloud" Wegener (1917).

Given his meteorological expertise (e.g., Wegener 1911), Wegener worked in the German military weather service during the First World War, seeing duty in France, Bulgaria, and finally at Dorpat (today Tartu) in Estonia in 1918 (Greene 2015). In Dorpat, he met Johannes Letzmann (1885–1971), an Estonian meteorologist, and stimulated Letzmann's interest in tornadoes and, in particular, on the low-level wind fields associated with tornadoes (Peterson 1992a). From 1918 to the 1950s, Letzmann studied European tornadoes by gathering case studies, conducting detailed damage surveys and collecting sketches and photographs of tornadoes in the Baltic region (i.e., Estonia, Latvia, Lithuania) (Letzmann 1920). In the mid-1930s, Letzmann announced an initiative at

[1] Because of the outbreak of the First World War in July 1914, Wegener, who was a reserve officer, was called to join his regiment in the German army. Being injured twice while fighting on the Western Front, he was declared unfit for active service and assigned to the army weather service. By January 1916, Wegener was the commanding officer of the Field Weather Station 12 in Mülhausen (France). He devoted most of his free hours during the first seven months of 1916 to writing the book on tornadoes and waterspouts in Europe. As the preface shows, the book was finished "In the field, in August 1916" (Greene 2015).

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the University of Dorpat for collecting tornado reports across Europe. Unfortunately, it is not known if a database was assembled (Peterson 1982, p. 63). Being recognized as one of the leading experts on tornadoes, Letzmann was asked in 1937 by the International Meteorological Commission to collaborate with the German meteorologist Harald Koschmieder (1897–1966) on a guideline for investigations of tornadic phenomena published by the World Meteorological Organization in 1937 (Letzmann and Koschmieder 1937; Peterson 1992b).

Before 1950, European universities and meteorological services were at the forefront of tornado research, led by the work of Wegener and Letzmann. Their work ranged from climatologies and damages surveys to laboratory simulations (Letzmann 1931). In contrast, ''American meteorologists were less interested [in tornadoes] than were many Europeans'' (Peterson 1992a, p. 166). These roles reversed after 1950, perhaps driven by the forecasting advances of Miller and Fawbush (e.g., Grice et al. 1999) and the resulting systematic collection of tornado data in the United States. As American interest in tornadoes and forecasting grew from 1950 to 2000, in Europe, however, few efforts were made to develop climatologies of tornadoes from a pan-European perspective (e.g., Peterson 1982; Meaden and Elsom 1985; Reynolds 1999).

c. *Contemporary period (2000–15)*

A special issue of *Atmospheric Research* (2001, Vol. 56, Nos. 1–4) is devoted to the first European Conference on Tornadoes and Severe Storms, which was held in Toulouse, France, in 2000. At the follow-up conference, the European Conference on Severe Storms that took place in 2002 in Prague (Czech Republic), Nikolai Dotzek (1966–2010) one of the leading experts on convective storms and extreme weather events in Europe (Feuerstein and Groenemeijer 2011), distributed a survey among the participants from 28 European countries with the aim of estimating the number of tornadoes and waterspouts per year in Europe. Previously, Wegener (1917) estimated that at least 100 tornadoes occur each year in Europe. Based on the results from the survey, Dotzek (2003) estimated that a total of 329 ± 12 tornadoes and waterspouts occur every year in Europe.

Recently, a new pan-European database has become available that allows a step-change in our ability to understand the spatial and temporal distribution of tornadoes on a European scale. This European Severe Weather Database (ESWD; Dotzek et al. 2009) has been developed by the European Severe Storm Laboratory (ESSL). 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., reports on tornadoes, severe wind, large hail, heavy rain, heavy snowfall, ice accumulation, avalanche, damaging lightning) is assessed and flagged (http://www.eswd.eu/, accessed on 11 December 2015). Groenemeijer and Kühne (2014) provided a description of the ESWD and also discussed the issues and caveats of the tornado data for Europe. Using the tornado reports from ESWD, Groenemeijer and Kühne (2014) developed a climatology of tornadoes in Europe based on 9529 tornado reports between AD 0 and 2013 and showed that 483 tornadoes were reported on average each year in Europe during 2006–13. This result shows that more tornadoes are now being reported annually than the participants from the 2002 European Conference on Severe Storms were aware of (Dotzek 2003).

4. European tornado databases

The evolution of the tornado databases for each of the 30 European countries included in this article is described in appendix A. For each country, the major data sources for local climatologies are presented and summarized (Table 1). For countries with published tornado climatologies, information on the original source of the reports and on their credibility was not available for all the events included in the synthesis of those databases (e.g., United Kingdom, Spain). For countries without published tornado climatologies, the tornado reports included in the databases were those that were classified as (i) confirmed, where the report contained a direct observation of the tornado, a photograph or a video of the tornado, or a damage survey indicating tornado damage; and (ii) probable, where the report was based on credible eyewitness observation of the tornado or tornado damage. This classification is consistent with the approach used by Brázdil et al. (2012) for the Czech Republic, Rauhala et al. (2012) for Finland, Kahraman and Markowski (2014) for Turkey, and Antonescu and Bell (2015) for Romania.

Groenemeijer and Kühne (2014) and the present study have used similar pan-European tornado databases to analyze aspects of the tornado climatology (i.e., annual and spatial variations, monthly and hourly cycles, intensity distribution). This poses the question of how the dataset synthesized for this study, consisting of 9930 tornado reports for 30 countries, compares with the ESWD, consisting of 9344 reports for the same countries. Before the 1900s, 1673 tornado reports have been included in the synthesis and 967 reports in the ESWD. The difference in the two datasets is mainly due to the large number of reports for tornadoes that occurred in

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the United Kingdom, Spain, and the Netherlands (988 reports) compared with the number of reports in the ESWD (17 reports) for the same countries. Also, more reports for Germany, Poland, and France have been included in the ESWD (710 reports) than in the current synthesis (349 reports). Between 1900 and 1999, 4633 reports are present in our synthesis and 2921 reports are present in the ESWD. The difference is mainly due to the databases for the United Kingdom, Spain, and Italy (2395 reports in the synthesis and 457 in the ESWD). Also, during this period, more reports for tornadoes that occurred in Germany, Cyprus, Russia, and France (1490 reports) were included in the ESWD than in the synthesis (993 reports). For the recent period (2000–14), the number of reports in the synthesis decreased to 3621 and the number of reports in the ESWD increased to 5456. More tornadoes that occurred in Russia, Italy, Germany, France, and Ukraine were included in the ESWD (2751 reports) than in the synthesis (471 reports). In the synthesis, a larger number of reports were from Spain, Greece, and the United Kingdom (1625 reports) compared with the reports in ESWD (695 reports). Thus, the comparison between the current synthesis and the ESWD shows that, in general, more tornadoes were included in the synthesis for the historical and modern period than in the ESWD (with the exception of the tornado dataset for Germany). This difference can be attributed, as previously indicated by Groenemeijer and Kühne (2014), to some national tornado datasets that have not yet been integrated into the ESWD [e.g., Brown et al. (2012, 2013a,b,c,d), Mulder and Schultz (2015), and Kirk et al. (2015) for the United Kingdom; Gayà (2015) for Spain]. The comparison for the contemporary period shows that a larger number of reports have been included in the ESWD than in the synthesis due to the efforts of the ESWD of collecting and verifying reports at a pan-European level. As a result of a collaboration between the University of Manchester and the ESSL, efforts have also been made recently to integrate the synthesis of tornado datasets developed in this article into the ESWD (where appropriate and where permission to do so has been given).

5. Annual distribution

During the first half of the nineteenth century, 403 tornadoes (8 tornadoes per year) were reported in 16 European countries (Fig. 3a). The majority of tornadoes during this period (78% of all reports) were reported in the United Kingdom, France, and Germany. During the second half of the nineteenth century, the number of tornado reports increased to 900 (18 tornadoes per year), with reports coming from 21 European countries (Fig. 3b). Similar to 1800–49, the majority of reports between 1850 and 1899 (75% of all reports) were for tornadoes that occurred in the United Kingdom, Germany, France, and Spain. Factors that influenced the spatial distribution and temporal evolution of the European tornado databases (Fig. 4) during the nineteenth century were the following:

1) contemporary efforts of collecting tornado reports at a European scale, in particular (Peltier 1840) (Fig. 2a);
2) the emergence of organized meteorological observations. For example, the Societas Meteorologica Palatina [Meteorological Society of Mannhein] founded in 1780 by the Elector Palatine Karl Theodor of Bavaria (1724–99) was the first society devoted solely to meteorology with the aim of collecting international weather observations (Cassidy 1985). The society collapsed in 1795 due to the political turmoil in Europe during the Napoleonic Wars (1795–1815), but served as a model for later national and international meteorological organizations (Walker 2011). Specifically, three national meteorological services were founded during 1800–49 and 13 during 1850–99 (Fig. 4);
3) the development of scientific journals in which articles describing and analyzing tornado reports were published (e.g., *Philosophical Transactions of the Royal Society* in the United Kingdom and *Annales de Chimie et de Physique* in France were established in 1665 and 1789, respectively). The first scientific journals devoted to meteorology appeared during the second half of the nineteenth century (e.g., *Meteorologische Zeitschrift* in Austria in 1866, *Quarterly Journal of the Royal Meteorological Society* in the United Kingdom in 1873);
4) increased public awareness due to the occurrence of high-impact events [e.g., the tornado that occurred in Madrid, Spain, on 12 May 1886 and produced 47 fatalities; Gayà (2007)] and the development of national and regional newspaper-type publications in which descriptions of high-impact weather events were published (e.g., *The Times* in the United Kingdom in 1785, *Le Figaro* in France in 1828, *Faro de Vigo* in Spain in 1853) (Fig. 4); and
5) the social and political context, especially during wars (e.g., Napoleonic Wars) and periods of political instability (e.g., the revolutions of 1848), which resulted in a declining interest in atmospheric phenomena, as well as difficulties in reporting and recording such events.

From the second half of the nineteenth century through the beginning of the twentieth century, there was an increased interest among European researchers

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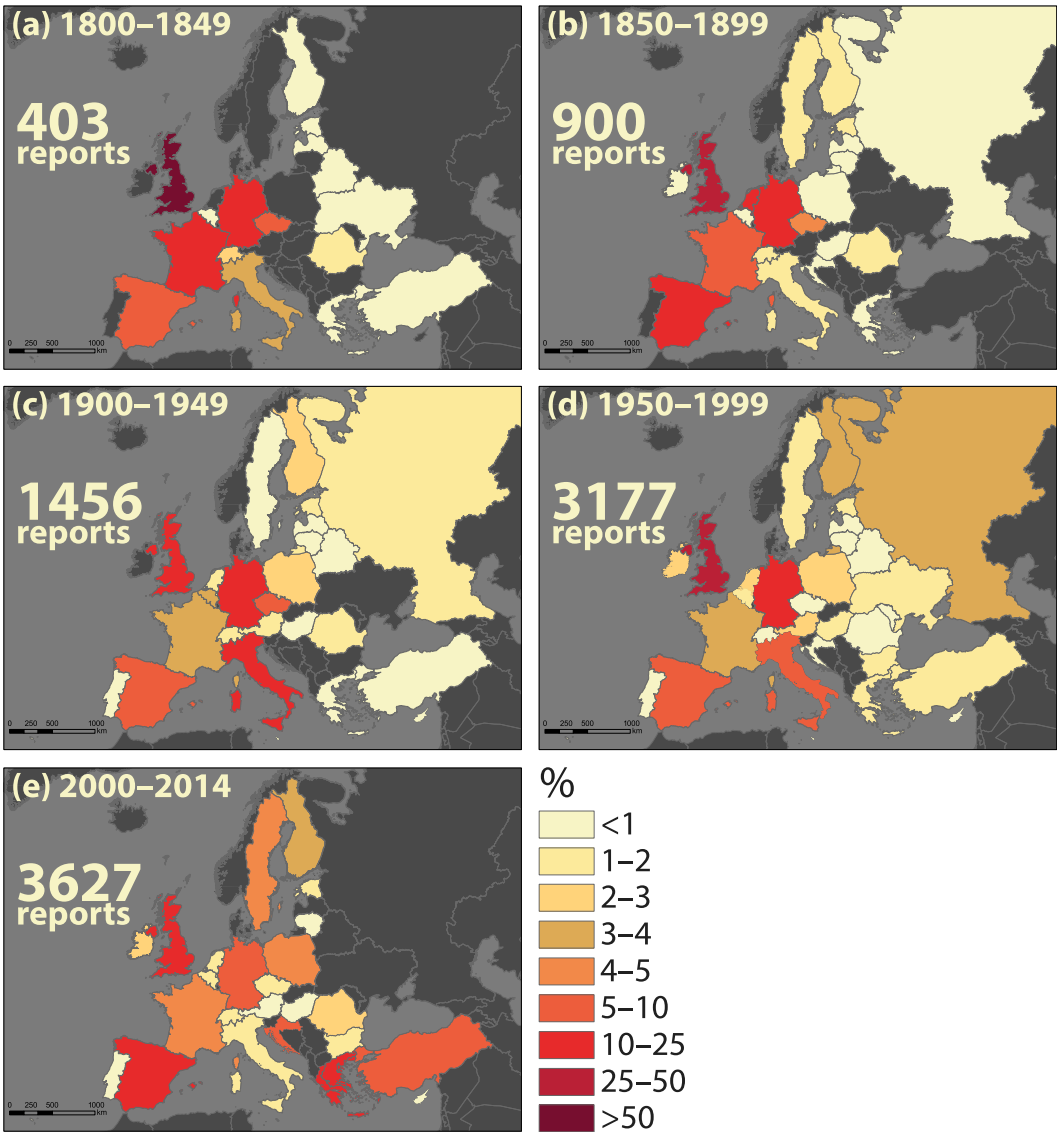

FIG. 3. The spatial distribution of tornadoes in Europe during (a) 1800–49, (b) 1850–99, (c) 1900–49, (d) 1950–99, and (e) 2000–14. Each panel shows the percentage from the total number of reports for each country during each of the five periods (shaded according to the scale). The interval covered by the tornado databases for each country is shown in Table 1 and Fig. 4.

and meteorologists to understand the formation and occurrence of tornadoes. Thus, postdisaster investigations (e.g., Hepites 1887), theoretical studies (e.g., Reye 1872), climatologies (e.g., Wegener 1917), and laboratory experiments (e.g., Mascart 1889; Letzmann 1927) were pursued at European universities and national weather services. Between 1900 and 1949, the number of tornado reports increased to 1456 (29 tornadoes per year) from 25 countries. In total, 50% of these reports came from the United Kingdom, Germany, and Spain. The influence of the First World War (1914–18) and the Second World War (1939–45) during this period is clearly shown in the evolution of some of the tornado databases, with no reports or fewer reports compared with the previous periods (e.g., United Kingdom, Belgium, Romania; Fig. 4).

After the Second World War, between 1950 and 1999, the number of tornado reports increased to 3177 reports (63 tornadoes per year) from 30 countries. In total, 56% of these tornadoes were reported in the United Kingdom, Germany, and Italy. These countries are part of the so-called "Blue Banana"—the discontinuous corridor of urbanization in western Europe where the Industrial Revolution spread over Europe after 1800—stretching from Manchester in northwestern England to Milan in

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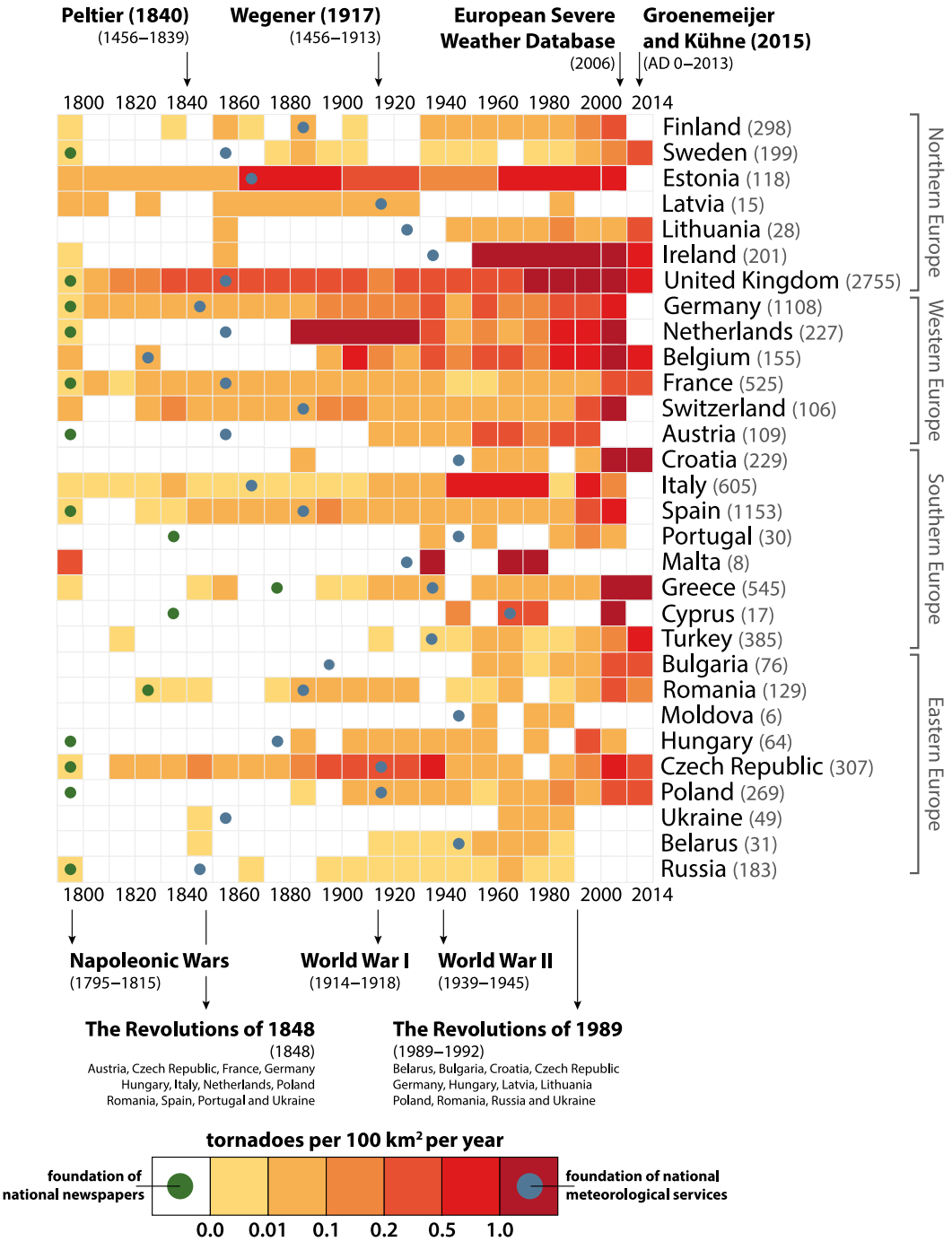

FIG. 4. Heat map showing the evolution of tornado databases in Europe. Each cell represents the number of tornado reports every 10 years normalized by the area of country (shaded according to the scale). For each country, the first column contains all the tornado reports for 1799 and before and the last column contains the reports between 2010 and 2014. Tornado reports for which the exact date could not be retrieved are grouped together as one box. The European regions are based on the definition from the United Nations Statistics Division (available online at http://unstats.un.org/unsd/methods/m49/m49regin.htm, accessed 11 Dec 2015). The interval covered by each database is indicated in Table 1. The green dot represents the decade when national newspapers were founded; all the newspapers founded before 1799 were represented in the first column. The blue dot represents the decade when national meteorological services were founded based on Table 1 from Kutzbach (1979, 12–13) and Table 2.1 from Anderson (2005, 44–45).

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northern Italy (Brunet 1989). The area is densely populated and comprises many large or medium-sized cities (e.g., London, Amsterdam, Brussels, Frankfurt), in which it was estimated that 40% of the population of the European Union lived in 1996 (Hospers 2003).

During the second half of the twentieth century, a particular situation occurred in some of the eastern European countries during their socialist period (1948–89) that resulted in a low number of tornado reports (Fig. 4). For example, in Romania and the Czech Republic during the 1970s and 1980s, the existence of tornadoes was not officially recognized and the word *tornado* was forbidden in both official meteorological reports and mass-media reports. Thus, "a *tornado* was something that was related to the U.S. Great Plains" [Setvák et al. (2003), for the Czech Republic], or "the Coriolis effect will not allow the formation of tornadoes" for countries situated too far north (approximately 45°N) [Lemon et al. (2003), for Romania]. The tornadoes that occurred during this period were reported as high-wind events and thus not recognized as tornadoes (Antonescu and Bell 2015). Doswell (2003) described this situation as a self-fulfilling prophecy, in which denying the existence of tornadoes resulted in no record-keeping for such events, and, when a tornado occurred, it was not reported or was considered an erroneous observation. The situation began to change after the revolutions in eastern Europe between 1989 and 1992 (Fig. 4).

The number of tornadoes after 2000 abruptly changed. Specifically, 3627 tornadoes were reported during 2000–14 (242 tornadoes per year). This increase is likely due to the following:

1) the efforts of collecting tornado reports for Europe by the ESWD after 2006;
2) increased public awareness after high-impact events [e.g., the number of tornado reports increased in Romania after 2002 when an F3+ tornado killed three people in southeastern Romania; Antonescu and Bell (2015)];
3) increased use of communication technology (e.g., cellular telephone subscriptions per 100 inhabitants increased in Europe from 40 in 2000 to 124 in 2013, the percentage of individuals using the Internet increased from 19% in 2000 to 70% in 2013 (ITU 2013);
4) the development of volunteer severe-weather spotter networks (e.g., Skywarn Austria was founded in 2002);
5) the *Twister effect* hypothesized by Rauhala et al. (2012) in which the movie *Twister* (released in 1996) resulted in an increased awareness among the public about tornadoes.

The increase in the number of tornado reports between 1800 and 2014 suggests that many events were not reported, although this underreporting seems to be less of a problem since 2000 across a limited part of central Europe (Groenemeijer and Kühne 2014).

6. Monthly distribution

The monthly distribution of tornado reports for most of Europe is maximum in June–August with a minimum in November–March (Fig. 5). Compared with the monthly distribution of tornado reports, the distribution of waterspouts that occurred entirely over water throughout their entire life span is delayed, showing a maximum in July–November (Fig. 6). Groenemeijer and Kühne (2014) speculated that this delay is due to the water surface temperature for large water bodies lagging behind the atmospheric boundary layer temperature and thus the average magnitude of instability over water lags behind that over land. The monthly distribution of tornadoes in Fig. 5 is consistent with the distribution based on the ESWD dataset (Groenemeijer and Kühne 2014, their Fig. 6). They showed that the peak of the tornado season is in late spring over eastern Europe; midsummer over western, central, and northern Europe; autumn over southern Europe; and winter over the eastern Mediterranean. We next consider each region in Europe in more detail.

Over eastern Europe, the peak of the tornado season is from late spring to late summer (Fig. 5). For example, the majority of tornadoes in Romania and Hungary occur during May–July (78% of all reports in Romania and 81% in Hungary) with a peak in May (29% of all reports in Romania and 32% in Hungary reports) (Szilárd 2007; Antonescu and Bell 2015). For other eastern European countries, the peak of the tornado season occurs in June (e.g., Bulgaria) and July (e.g., Russia, Poland, Czech Republic).

As previously shown by Wegener (1917, his Fig. 15), the monthly distribution of tornadoes over western Europe has peaks in July (e.g., Germany, Switzerland, Austria) and August (e.g., Netherlands, Belgium, France), which reflects the seasonal maximum of continental instability (Siedlecki 2009; Tilev-Tanriover and Antonescu 2015) and thunderstorms (e.g., Anderson and Klugmann 2014; Wapler and James 2015) (Fig. 5). Tornadoes have also been reported during winter (e.g., Netherlands, Belgium, France, Germany), mainly associated with the passage of cold fronts as speculated by Dotzek (2001) for winter tornadoes reported over northern Germany and by Mulder and Schultz (2015) for tornadoes reported over the British Isles. The waterspouts over western Europe tend to occur mainly in

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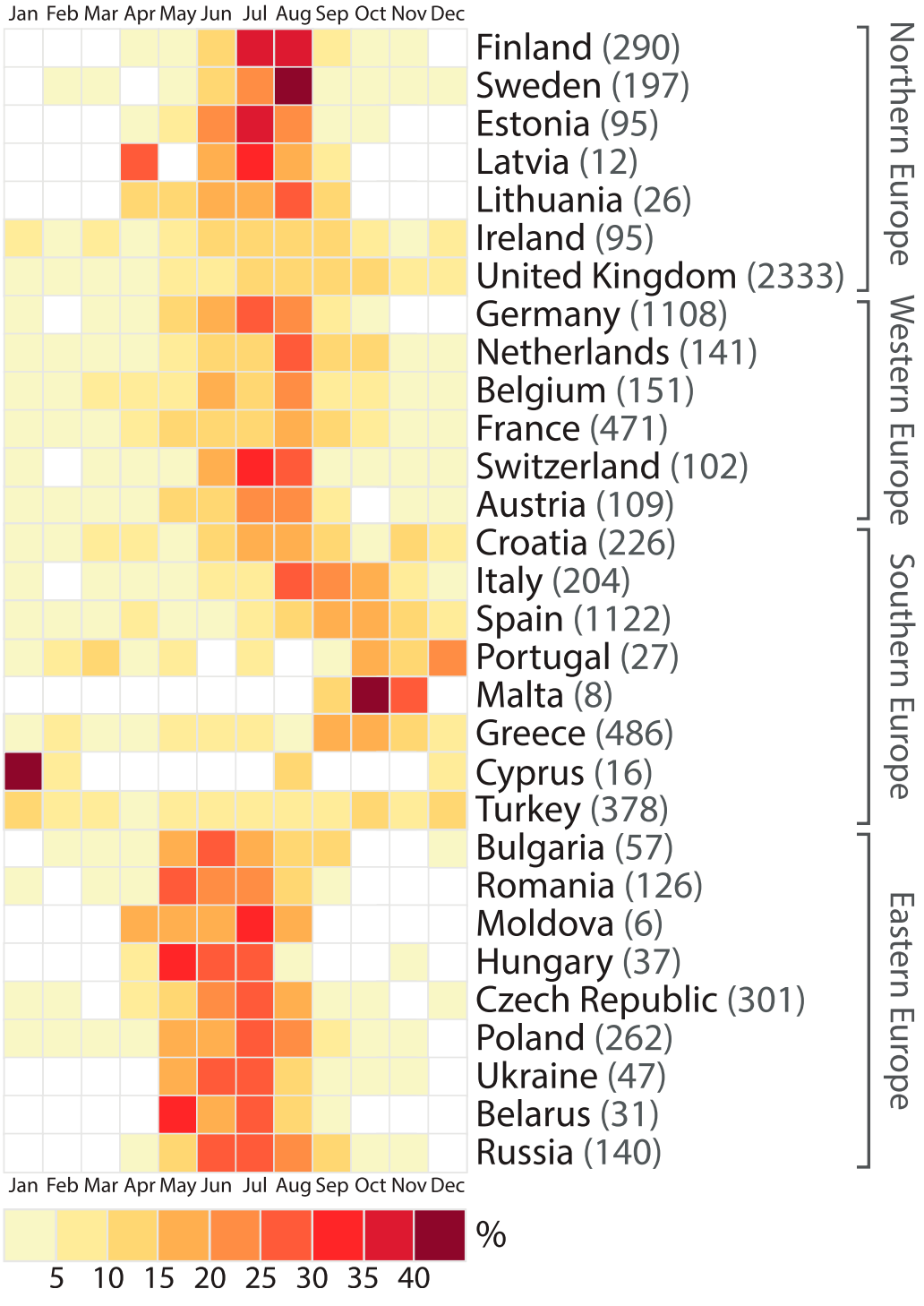

FIG. 5. Heat map showing the monthly occurrence of tornado reports in Europe. Each cell represents the monthly percentage of the total number of tornadoes reported in each country (indicated in parentheses) containing information on the occurrence month (shaded according to the scale).

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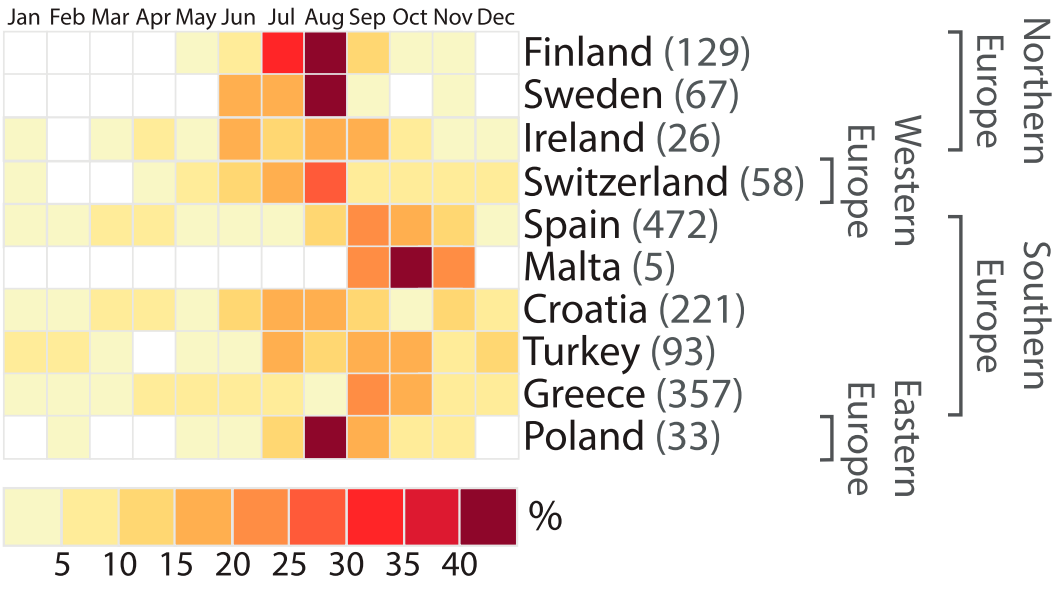

FIG. 6. As in Fig. 5, but for waterspout reports.

late summer (Fig. 6). For example, 48% of all waterspouts reported in Switzerland occurred in July–August (Jeanneret 2010) when the water surface temperature is maximum and rapid cumulus congestus development can lead to the initiation of waterspouts (Dotzek 2001).

Over northern Europe, tornadoes are observed from mid- to late summer (Fig. 5). For example, Rauhala et al. (2012) showed that 74% of all tornadoes reported in Finland occurred in July and August with a peak in July (38% of all reports). Similar distributions occur in Estonia with a peak in July and in Sweden with a peak in August. Tornadoes occur year-round in the United Kingdom and Ireland, with a peak from May through October (e.g., Mulder and Schultz 2015).

For southern Europe, a large number of tornadoes are observed later in the year (August–November) compared with the other regions of Europe (Fig. 5). In Italy, the majority of tornadoes have been observed during August–November (66% of all reports), with the peak in August (26%). During spring and early summer, the majority of reports were for tornadoes that occurred over the Po Valley and the Friulian Plain (Giaiotti et al. 2007). Giaiotti et al. (2007) speculated that these tornadoes are associated with the interaction between cold fronts and orography (e.g., Morgan 1973). As cold fronts approach the Alps, low-level shear for the onset of mesocyclones is produced leeward of the ridge. Giaiotti et al. (2007) also showed that during late summer and autumn, troughs interacting with the Alps are the origin of cutoff lows over the Mediterranean Sea. These low pressure centers advect warm and moist air from over the Tyrrhenian and Ionian Sea (Fig. 1) to the Alps, resulting in conditions favorable for deep, moist convection. Similar distributions, with the tendency of the monthly distribution toward autumn, were also reported for Portugal, Spain, and Turkey. For Spain, Gayà (2011) showed that 58% of tornadoes are reported in August–November.

The monthly distribution of tornadoes in Croatia (Fig. 5) shows that the majority of the tornado reports are for waterspouts (Fig. 6). Waterspouts can develop in all seasons in the Adriatic Sea, with a maximum in summer (July–August) due to the high sea surface temperature. A secondary maximum occurs in late autumn (November) when the sea surface temperature is still high, especially over the southern Adriatic (Renko et al. 2013). For Turkey, the monthly distribution peaks during October–January (39% of all tornado reports), which in part reflects the occurrence of waterspouts on the Mediterranean, Aegean, and Black Seas between July and December (Fig. 6). Kahraman and Markowski (2014) showed that tornadoes in Turkey between May and June are mainly mesocyclonic tornadoes. They speculated that less favorable conditions for tornadogenesis occurs in July–August likely because southern Europe is under the influence of the subsidence associated with the Azores anticyclone. Similarly, Matsangouras et al. (2014) showed that tornadoes in Greece tend to occur more frequently in June–July (Fig. 5), especially in northern Greece, and waterspouts tend to occur in September–October (Fig. 6). Monthly distributions with a peak during autumn have also been observed for Spain (Gayà 2015)

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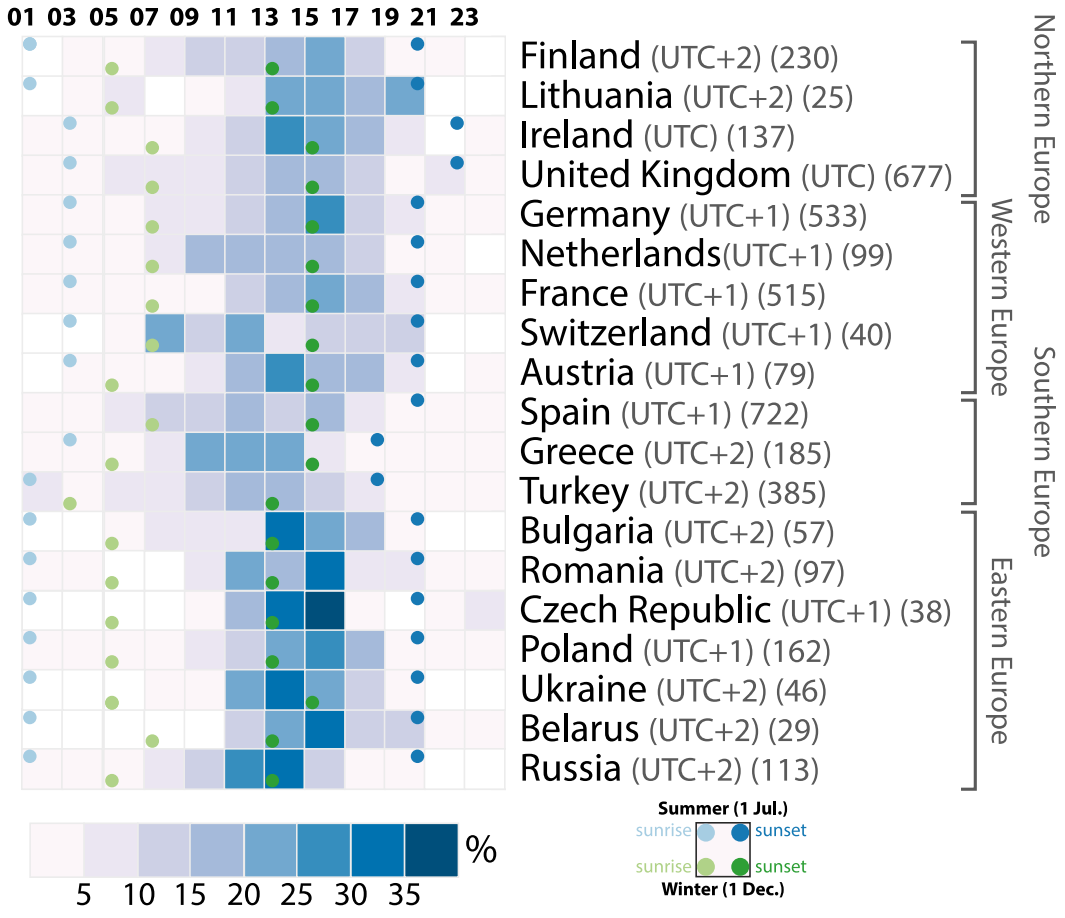

FIG. 7. Heat map showing the diurnal occurrence of tornadoes in Europe using 2-h UTC bins (i.e., 0500–0659, 0700–0859 UTC). Local solar time for each country is indicated in the first set of parentheses. The total number of reports containing information on the occurrence time are indicated in the second set of parentheses. Each cell represents the percentage of the total number of tornadoes reported in each country containing information on the occurrence time (shaded according to the scale). The dots represent the sunrise and sunset times during summer (blue) and winter (green).

and Malta (Figs. 5 and 6). Similar to the monthly distribution of tornadoes, waterspouts that had their life cycle entirely over water were reported more frequently in June–September over northern, western, and eastern Europe (cf. Figs. 5 and 6).

7. Diurnal distribution

The diurnal distribution of tornado reports for which information on the occurrence time was available is shown in Fig. 7 using 2-h UTC bins (i.e., 0500–0659, 0700–0859 UTC). The number of tornado reports increases during the morning and afternoon, with a peak between 1100 and 1700 UTC over western and, to some extent, southern Europe and between 1300 and 1500 UTC over eastern and northern Europe (Fig. 7). Based on the ESWD dataset, Groenemeijer and Kühne (2014) showed that tornadoes over Europe occur most frequently during the late afternoon and early evening. There is a minimum in the diurnal distribution between 2100 and 0700 UTC, possibly because of the difficulties of observing tornadoes during the night, because tornadoes occur when there are fewer outdoor activities, or because the public tends to be asleep (e.g., Simmons and Sutter 2005; Ashley et al. 2008).

For western Europe, Dessens and Snow (1989) showed that significant tornadoes [F2 and greater on the Fujita scale, Fujita (1981); Hales 1988] in France were more likely to occur between 1600 and 1700 UTC. They showed that there was a close association between the occurrence of significant tornadoes and solar heating [Fig. 7 in Dessens and Snow (1989)], with tornadoes being reported mainly around noon during November–March and between mid and late afternoon

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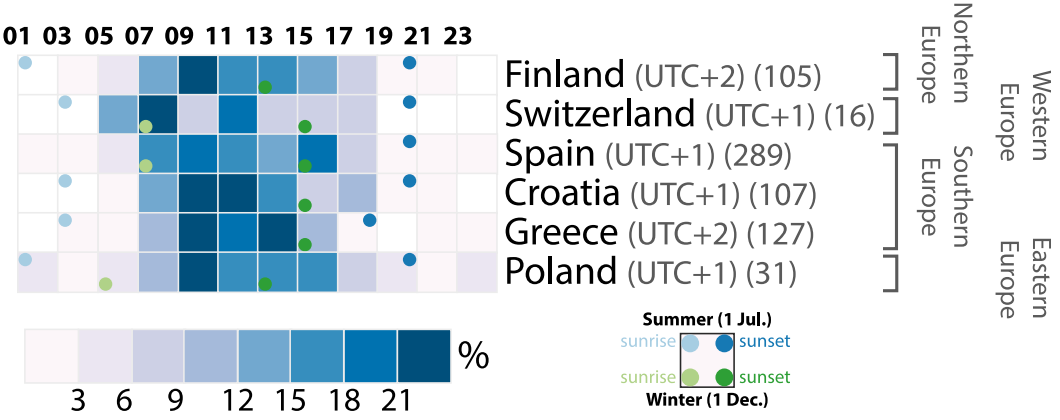

FIG. 8. As in Fig. 7, but for waterspout reports.

during April–October. The tornado database developed by Dessens and Snow (1989) contained 20 significant nighttime tornadoes, which shows that the solar forcing was not directly associated with some of the French tornadoes. The nighttime tornadoes in France may be associated with thunderstorms initiated by strong synoptic-scale forcing or fronts.

For eastern Europe, an afternoon peak in the diurnal distribution of tornadoes occurs around 1500 UTC, as shown by Brázdil et al. (2012) for the Czech Republic, Taszarek and Brooks (2015) for Poland, and Antonescu and Bell (2015) for Romania. Similarly, for northern Europe, Rauhala et al. (2012) showed that the afternoon maximum (1500–1659 UTC) in the occurrence of tornadoes in Finland is consistent with the diurnal distribution of thunderstorms. Rauhala et al. (2012) also noted that the cloud-to-ground lightning rate peaks around 1300–1459 UTC (Tuomi and Mäkelä 2008). They speculated that stronger storms, which ultimately produced tornadoes, were initiated later in the day (compared to the weaker and more typical thunderstorms). Mulder and Schultz (2015) showed that an afternoon peak in the tornado reports for the British Isles occurred from spring to autumn (March–November). During the winter (December–January), tornado occurrence was similar during the day and night (with a dip between 0000 and 0100 UTC) [Fig. 13 in Mulder and Schultz (2015)]. This diurnal distribution during the winter was associated with the reduced number of daylight hours (i.e., less than 8 h) and a reduction in solar heating during winter over the British Isles.

Figure 8 shows the diurnal distribution of waterspouts that occurred entirely over water during their lifetime. The waterspout reports containing information on the occurrence time were available for six countries over northern Europe (Finland), southern Europe (Spain, Croatia, Greece), western Europe (Switzerland), and eastern Europe (Poland). Compared with the distribution of all reports, the diurnal distribution of waterspouts is shifted toward the early hours (0700–1500 UTC) with a maximum between 0900 and 1300 UTC. Based on data from the ESWD, Groenemeijer and Kühne (2014) showed that the occurrence of waterspouts in Europe is constant during the day in winter compared with summer. A possible explanation of this winter distribution is that the warm water surface compared to the air temperature can be associated with the development of convection at any time during the day (Rauhala et al. 2012).

Over Spain and Greece, the majority of the waterspouts were reported during the morning (0700–1059 UTC), with a secondary peak during the afternoon (1300–1659 UTC). Dotzek (2001) argued that the morning maximum in the diurnal distribution of waterspouts could be associated with the temperature difference (especially over large lakes) between the water surface and the atmospheric boundary layer, which is maximum around sunrise (light green dots in Fig. 8). This temperature difference would result in a moist unstable boundary layer that will be "highly susceptible to any convective forcing," thus, enhancing the likelihood of nonsupercell tornadoes (Dotzek 2001, p. 239). For Greece, the diurnal distribution of waterspouts peaks around 1000 UTC and around 1400 UTC. Similar distributions have been observed by Golden (1973) for waterspouts in the Lower Florida Keys, United States; Peterson (1978) for Nassau, Bahamas; and Gayà et al. (2011) for Catalonia, Spain. Matsangouras et al. (2014) speculated that the two peaks in the diurnal distribution of waterspouts are in agreement with the timing of the land–sea-breeze circulation, which, in conjunction with low-level instability and low-level shear, provides the conditions favorable for waterspout development (e.g., Simpson et al. 1986).

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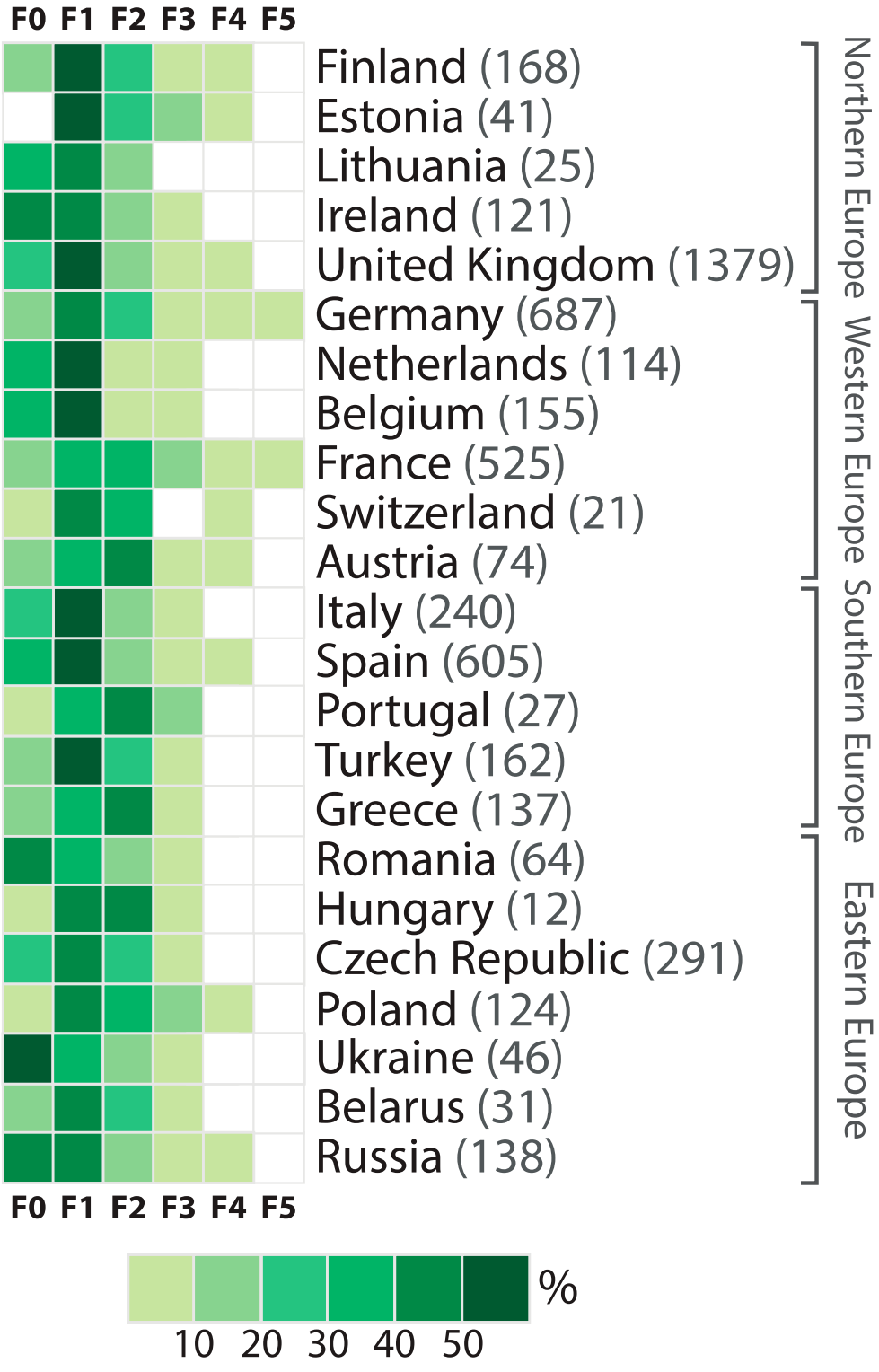

FIG. 9. Heat map showing the intensity distribution of tornadoes in Europe. Each cell represents the percentage for each F scale of the total number of tornadoes reported in each country (shown within parentheses) and for which an estimate of the F scale was possible (shaded according to the scale).

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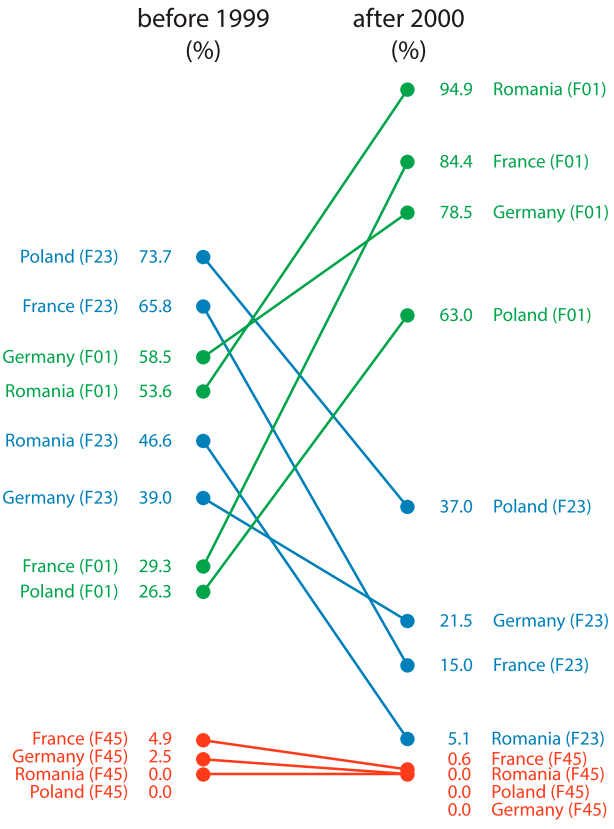

FIG. 10. A slopegraph (Tufte 1983, p. 158) showing the changes in time for the intensity distribution of tornadoes reported in France, Germany, Poland, and Romania, before 1999 and after 2000. Three categories were considered: (i) weak tornadoes (F0 and F1) (F01, green lines), (ii) significant tornadoes (F2 and F3) (F23, blue lines), and (iii) violent tornadoes (F4 and F5) (F45, red lines). For each period, the number represents the percentage of each category from the total number of tornadoes reported in each country.

8. Intensity distribution

Estimates of tornado intensity were available for 23 European tornado databases. The intensity of tornadoes in the majority (79%) of European tornado databases was assessed based on the Fujita scale [e.g., Rauhala et al. (2012) for Finland, Dessens and Snow (1989) for France, Antonescu and Bell (2015) for Romania, Gayà (2015) for Spain]. Other European countries (21%) used the tornado intensity scale [T scale, Elsom et al. (2001); Kirk (2014)] developed by the Tornado and Storm Research Organization (TORRO), a U.K.-based, volunteer organization (Meaden 2015). The T scale has twice as many classifications as the F scale and was developed based on the assumption that tornadoes in Europe tend to be less intense compared with U.S. tornadoes (Meaden 1985b). Brooks and Doswell (2001) converted the T scale to F scale using: $F \approx 0.5T$, and rounding down to the nearest integer. In this article, the F scale was chosen because of its more widespread use (Brooks and Doswell 2001). Thus, all the estimates expressed on the T scale have been converted to the F scale following Brooks and Doswell (2001).

The intensity distribution for the 5187 tornado reports for which an estimate of the F scale was possible is shown in Fig. 9. The majority of tornado reports, 74.7% of all tornado reports, were for weak tornadoes [F0 or F1; Hales (1988)], 24.5% for strong tornadoes (F2 or F3), and 0.8% for violent tornadoes (F4 and F5). A similar intensity distribution was obtained by Groenemeijer and Kühne (2014) based on 3818 reports from the ESWD dataset, with weak tornadoes representing 65% of all reports and strong and violent tornadoes representing 33.7% and 1.3%, respectively. With few exceptions (i.e., Romania, Russia, Ukraine), there is a clear bias of the intensity distributions toward F1 tornadoes. Because F0 tornadoes have shorter lifetimes and pathlengths compared with more intense tornadoes, they are less likely to be reported (Brooks and Doswell 2001), resulting in an underestimate of the number of F0 tornadoes. Other sources of errors that can influence the distributions shown in Fig. 9 are as follows:

1) Underestimation of the number of tornado reports. Figure 4 shows that there are periods during which there were no reports or very few reports (e.g., France between the 1940s and 1960s, Romania between the 1970s and 1980s), and this would result in an underestimate.
2) The underestimate of tornadoes that occur in rural or sparsely populated areas because the estimates of tornado intensity on the F scale are based on the maximum damage associated with tornadoes (Doswell and Burgess 1988). The assignment of an F scale is particularly challenging for historical events given the lack of documentation (e.g., photos, damage surveys) and the different construction standards across Europe (e.g., Feuerstein et al. 2011).
3) The differences in the intensity distribution between the historical and modern period (before 1999) and recent reports (after 2000). Figure 10 shows these changes in the intensity distributions for France and Germany (western Europe) and Poland and Romania (eastern Europe). These countries have been selected because they are representative of the well-established datasets (e.g., France, Germany) or relatively recent developed datasets (e.g., Poland, Romania) and also because they are likely to contain more supercellular tornadoes. For these four countries, there is an increase in the percentage, of the total number of reports for each country and for each period, of weak tornadoes (e.g., from 53.6% before

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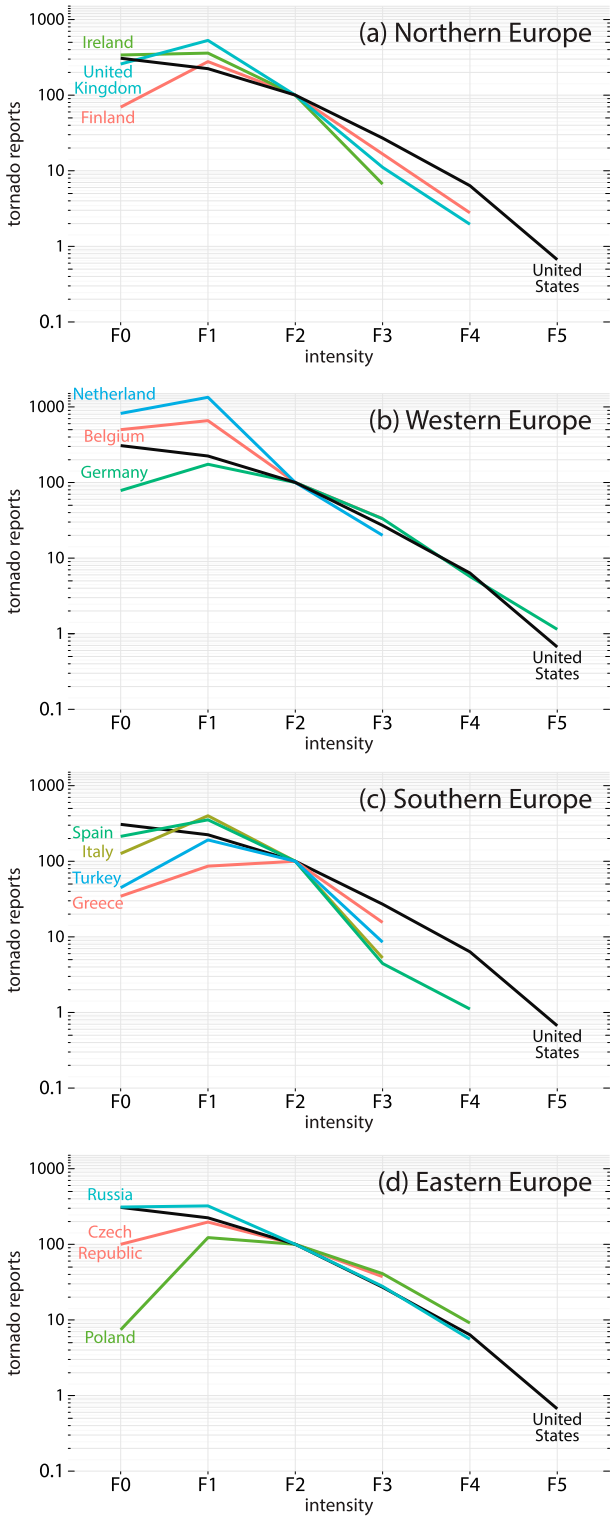

FIG. 11. Tornado reports by F scale for (a) northern, (b) western, (c) southern, and (d) eastern Europe. The period of record for each country is indicated in Table 1. The period of record for the U.S. reports is 1950–2014. To compare the slopes, all distributions have been normalized to 100 F2 tornadoes, as in Brooks and Doswell (2001).

1999 to 94.9% after 2000 for Romania) and a decrease of strong (e.g., from 73.7% to 37.0% for Poland) and violent tornadoes (e.g., from 2.5% to no reports for Germany). The increase in the percentage of weak tornadoes can be attributed to the recent efforts of collecting and verifying tornado reports either at a country level (e.g., databases developed by European meteorological services, storm-spotter networks) or increased public awareness. The large percentage of significant tornadoes during the historical and modern period compared with the recent distribution is because strong and violent tornadoes are more likely to be reported than weak tornadoes (Brooks and Doswell 2001; Verbout et al. 2006).

4) The errors in the assignment of F scale (Brooks and Doswell 2001). For example, Grünwald and Brooks (2011) showed that European tornadoes without an estimate of the F scale (i.e., unrated) are likely to consist of mostly F0 tornadoes. They have considered all the unrated tornadoes as weak tornadoes. Here, all the unrated tornadoes were not considered in our analyses of intensity.

Previous studies have established that the distribution of tornadoes by F scale approximates a log–linear distribution (e.g., Brooks and Doswell 2001). Other distributions of tornado intensities have been proposed, for example, by Dotzek et al. (2003) who showed that tornado intensities can be better described by a Weibull distribution. Brooks and Doswell (2001) speculated that the difference in the slopes of log–linear intensity plots for different regions of the United States or for different countries are the result of different physical processes leading to tornadogenesis or underreporting. For the United States, Smith et al. (2012) showed, using radar-based convective modes assigned to tornadoes reported during 2003–11 (10 724 reports), that right-moving and left-moving supercells were associated with approximately 72% of all reports (7704 reports). As discussed by Brooks and Doswell (2001), steep slopes in the intensity distribution are associated with regions dominated by nonsupercellular tornadoes [e.g., Florida in Fig. 3 from Brooks and Doswell (2001)] and less steep slopes are associated with regions dominated by supercellular tornadoes [e.g., the central United States in Fig. 3 from Brooks and Doswell (2001)].

Here, we have extended the speculation from Brooks and Doswell (2001) by comparing the intensity distribution of tornadoes from the U.S. database (1950–2014) (available from Storm Prediction Center at http://www.spc.noaa.gov/gis/svrgis/zipped/tornado.zip, accessed 11 December 2015) and the intensity distributions for 14 European countries that have more than 100 tornadoes with an

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estimated F scale [excluding France because Dessens and Snow (1989) did not include reports from F0 and F1 tornadoes in their inventory]. To compare the different intensity distributions, each distribution was normalized to 100 F2 tornadoes. For western and eastern European countries with a more continental climate (Figs. 11b,d), the intensity distribution is similar to the U.S. distribution for F3 and higher intensities (e.g., Germany, Russia). Even the relative number of F1 reports is close to the U.S. distribution (e.g., Germany, Czech Republic), suggesting that the tornadoes reported over western and eastern Europe are dominated by supercellular tornadoes.

On the other hand, countries with a more maritime climate tend to have more nonsupercellular tornadoes. Over northern and southern Europe, the slopes of the intensity distributions for F3 and higher intensities are steeper compared with the U.S. distribution, suggesting that the databases for northern and southern Europe also include nonsupercellular tornadoes (Figs. 11a,d). For the Netherlands, the dataset may also include nonsupercellular tornadoes, as shown by the decrease by approximately two orders of magnitude from F1 to F3. By comparison, the decrease in the U.S. distribution is of approximately one order of magnitude. A normalization to F2 tornadoes results in a distribution of F3 tornadoes in the Netherlands more similar to the United States. A normalization to F1 tornadoes shows that the distribution for the Netherlands is consistent with the nonsupercellular regions in the United States (Brooks and Doswell 2001). For Italy, Brooks and Doswell (2001) speculated that some of the tornadoes included were waterspouts that have moved onshore. For Finland, Rauhala et al. (2012) have included in the database all the waterspouts that moved inland as tornadoes. Mulder and Schultz (2015) showed that tornadoes over the British Isles are most commonly associated with linear storms, which tend to be weaker compared with the tornadoes associated with isolated cells such as supercells (Trapp et al. 2005). Thus, different distributions across Europe may indicate different ratios of supercell to nonsupercell tornadoes (Fig. 11), with the latter more common in more coastal areas (e.g., Tyrrell 2003).

9. Summary

With the recent efforts of collecting tornado reports at the pan-European level (e.g., ESWD) and with the recent developments of tornado databases maintained by national meteorological services (e.g., Finland, Romania), we are at a point in the history of tornado observations at which more accurate climatology of tornadoes in Europe begins to emerge. The efforts of understanding tornadoes in Europe resulted in a large body of knowledge (i.e., historical collections of tornado reports, case studies, local and pan-European climatologies) that this review summarizes.

There is a long history of tornado observations in Europe. The Greek and Roman natural philosophers (e.g., Aristotle, Seneca) were the first to speculate about the causes of tornado and waterspout formation. Their theories were then repeated by the authors during the Middle Ages (e.g., Isidore of Seville, Vincentius Bellovacensis). During the seventeenth century, the early modern period of Europe witnessed an increase in the number of studies devoted to tornadoes, through the works of, among others, Francois Lamy in France and Geminiano Montanari in Italy. With the emergence of national newspapers and scientific journals toward the end of the eighteenth century, the number of accounts of tornadoes and waterspouts increased, culminating with the influential study by Roger Joseph Boscovich on a tornado that occurred at Rome in June 1749. One of the earliest climatologies of tornadoes in Europe, based on tornado reports between 1456 and 1839, was published by Jean Charles Athanase Peltier in 1840. At the beginning of the twentieth century, Alfred Wegener further developed the study of tornadoes in Europe in his classic 1917 study *Wind- und Wasserhosen in Europa*. The beginning of the twentieth century also saw the first attempts to develop local tornado climatologies (e.g., Italy, the Netherlands). For nearly the next hundred years, few efforts were made to develop pan-European tornado climatologies, with most of the research being focused on local country-specific climatologies. Using the tornado reports from the European Severe Weather Database between AD 0 and 2013, Groenemeijer and Kühne (2014) published the first contemporary pan-European climatology and estimated that 483 tornadoes and waterspouts are reported on average each year in Europe.

The main conclusions of this review, based on data collected mainly from articles published in peer-reviewed journals, are as follows:

1) The number of tornado reports in Europe increased from 8 tornadoes per year during the first half of the nineteenth century to 18 tornadoes per year during the second half. This increase was associated with the efforts of collecting tornado reports and with the emergence of organized meteorological observations and scientific journals. From the 1850s to the 1920s, there is an increase in the number of studies on tornadoes published in Europe, either postdisaster investigations, theoretical studies, climatologies, or laboratory experiments. Between the 1900s and 1950s, the number of tornado reports increased again

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to 29 tornadoes per year, despite the influence of the two World Wars. The majority of tornado reports before the 1950s came from northern and western Europe, in particular from the United Kingdom, Germany, and Spain. These countries are part of an area that is densely populated and comprises many urban areas. Another increase in the number of tornado reports occurred between the 1950s and 1990s (63 tornadoes per year), followed by an abrupt change after 2000 (242 tornadoes per year). The recent increase in the number of tornado reports can be attributed to the efforts of collecting tornado reports at a European scale, greater prevalence of communication technologies, and the development of severe-weather spotter networks. These changes in the number of tornado reports suggest that tornadoes were underreported before the 2000s, but this is less of a problem more recently over parts of central Europe (Groenemeijer and Kühne 2014).

2) The tornado season is in spring and early summer over eastern Europe, during the summer over western Europe, and from mid- to late summer over northern Europe. The monthly distribution of tornadoes reflects the seasonal maximum of thunderstorm frequency over Europe. The monthly distribution over southern Europe, with a maximum during autumn or early winter, reflects the occurrence of waterspouts in the Mediterranean Sea.
3) Tornadoes are more frequently reported during the morning and afternoon over western Europe and around noon over eastern and northern Europe. Over southern Europe where a large number of waterspouts are reported, the diurnal distribution occurs earlier compared with the distribution of all reports. A minimum in the diurnal distribution occurs between 2100 and 0700 UTC, maybe because of the difficulties of observing and reporting tornadoes during the night.
4) The distribution of tornado intensity reports shows that the majority of reports are for weak tornadoes (F0 or F1), with a clear bias toward F1 tornadoes or greater. This bias can be explained by the fact that F0 tornadoes have a lower impact on society and thus are reported less frequently than other F-scale tornadoes. The distribution of tornado intensities on a log–linear plot shows that different slopes of these curves may indicate different ratios of supercell to nonsupercell tornadoes over different parts of Europe. Regions favorable for supercells tend to be more continental (e.g., Germany, Russia, Czech Republic) compared to regions apparently more favorable for nonsupercell tornadoes such as Italy, the Netherlands, Finland, and the United Kingdom.

We hope that this review of the current knowledge on tornadoes in Europe will encourage further discussions and stimulate the interest of the scientific community, national meteorological services, and the public on European tornadoes. We hope that this review will result in increased awareness, the identification of new data sources (e.g., historical archives, climatologies, case studies), and the initiation of new databases that would allow an extension of the current European tornado database both in time and in space.

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APPENDIX A

European Tornado Climatologies

This appendix contains a description of the evolution of the tornado databases and of the main contributions toward local tornado climatologies for 30 European countries.

1. *Austria*

Wegener (1917) reported several tornadoes in Austria and its former crown land and, more recently, Pühringer (1973) developed a database containing reliable tornado reports (e.g., weather service reports) available between 1946 and 1971. Since 1998, efforts have been made to obtain information on tornadoes in Austria within TorDACH, a network of scientists and amateur meteorologists with the aim of collecting information on tornadoes in Germany (D), Austria (A), and Switzerland (CH) (Dotzek 2001).

Based on data from the TorDACH database, Holzer (2001) developed a tornado climatology for Austria and showed that 10 tornadoes (9.2% of all reports) were reported between 1910 and 1946. One of the tornadoes reported during this period was an F4 tornado that occurred on 10 July 1916 and caused 32 fatalities and 328 injuries in Wiener Neustadt, Austria, on 10 July 1916 (Dörr 1917). Svabik and Holzer (2005) updated the tornado climatology for Austria and showed that the majority of reports (52 reports, 47.7% of all reports) included in the Austrian tornado database were from 1946 to 1971. The increase in the number of reports during this period can be attributed to efforts of collecting tornado reports for Austria by Pühringer (1973). The number of tornado reports decreased between 1972 and 1999, with 33 tornadoes reported (30.3% of all reports). This decrease can be attributed to reduced public awareness: some Austrians ''do not exactly know what a tornado looks like'' and many reports ''mention a column of smoke as description of the phenomenon (i.e., tornado)'' (Holzer 2001, p. 209). This situation resulted in some events not being recognized as tornadoes by the eyewitnesses and thus not being reported to the Central Institution for Meteorology and Geodynamics (CIMG) or to the mass media. This situation changed after the 2000s as shown by the larger number of tornadoes per year between 2000 and 2003 (12 tornadoes, 12.8% all reports) compared with the previous periods. Thus, 109 tornadoes were reported in Austria between 1910 and 2003.

2. *Belarus*

A tornado climatology has not yet been developed for Belarus. Data on tornado occurrence in Belarus, 31 reports between 1846 and 1982, were retrieved from Snitkovskii (1987).

3. *Belgium*

Baes and Joukoff (1949) developed the first tornado climatology for Belgium based on 51 tornadoes reported between 1880 and 1940. Between 1940 and 1982, only a few case studies on tornadoes and waterspouts in Belgium were published, without a systematic collection of reports (e.g., Poncelet 1961; Lambert 1980). Since 1982, the Royal Meteorological Institute of Belgium (RMIB) maintains a tornado database. Between 1982 and 2011, 103 tornado reports were included in the RMIB tornado database (http://www.meteo.be/meteo/view/fr/69130-Archives.html?view=127496, accessed 11 December 2015). Another database of tornadoes in Belgium was developed and maintained by Belgorage (http://www.belgorage.com/, accessed 11 December 2015), an amateur network with the aim of collecting and studying severe weather phenomena in Belgium. The tornado reports included in the Belgorage database were collected from mass-media reports, the RMIB tornado database, and newspaper archives. The reports were classified as verified (strong evidence exists to support a tornado report), probable (some evidence exists to support a tornado reports), and possible (little information is available to support a tornado report). Based on verified and probable tornado reports from the Belgorage database, Frique (2012) showed that 155 tornadoes were reported in Belgium between 1779 and 2012. Thus, 155 tornadoes were reported in Belgium between 1779 and 2012.

4. *Bulgaria*

The first tornado climatology for Bulgaria was developed by Simeonov et al. (2013) based on published case studies in scientific and popular literature (e.g., Simeonov and Georgiev 2001, 2003), mass-media stories, and eyewitnesses reports. Between 1956 and 2010, 57 tornadoes were reported in Bulgaria. Only 11 reports (19% of all reports) were collected before 1989 because ''most people in Bulgaria thought that tornadoes were exotic and not typical events for our country'' during this period (Simeonov et al. 2013, p. 62). Between 1990 and 2010, the number of tornado reports increased (46 reports, 81% of all reports), which was attributed to the development of communications and the Internet making available the tornado reports collected by amateurs. An update to the Bulgarian tornado dataset by Bocheva and Simeonov (2015) added 19 tornadoes between 2011 and 2014. Thus, the Bulgarian tornado database contains 76 reports between 1956 and 2014.

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5. Croatia

One of the earliest descriptions of a tornado in Croatia was given by Mohorovičić (1892) for a tornado that occurred on 31 May 1892 at Novska, southwestern Croatia. Before 1970, only one tornado that occurred on 26 September 1962 was reported in Croatia (Pokorny 1962). Čapka (1978) using observations and Jurčec(1978) using numerical simulations analyzed a tornado that occurred on 22 July 1973 in Zagreb, northwest Croatia. More recently, Stiperski (2005) documented a tornadic supercell that occurred on 30 August 2002 in northwestern Croatia, and Simon and Kovačić (2006) analyzed two tornadoes that occurred at Novigrad, western Croatia, on 14 August 2006.

Because Croatia is bordered to the west by the Adriatic, a semienclosed sea in which waterspouts occur frequently (e.g., Sioutas and Keul 2007; Renko et al. 2013), waterspout climatologies have previously been developed for Croatia. Poje (2004) and Ivančan-Picek and Jurčec (2005) showed that between 2000 and 2003 an average of four days per year have waterspouts in the coastal regions of Croatia. Renko et al. (2013) analyzed the spatial and temporal distribution of waterspouts on the Adriatic coast. Data were obtained from meteorological stations, newspapers, reports on the damage caused by waterspouts that moved inland, and from a public survey (''You saw a waterspout/tornado? Report to us!'') launched in the spring of 2011 and available on the website of the Meteorological and Hydrological Service of Croatia (http://meteo.hr, accessed 11 December 2015). These efforts resulted in a database of 220 waterspout reports between 2001 and 2011. Additional cases of waterspouts in Croatia were obtained from Poje (1957) for a waterspout at Rovinj on 19 February 1955, Ivančan-Picek et al. (1995) for a waterspout that occurred on 14 August 1994 in the vicinity of Zadar, and Irha (2014) for a waterspout that occurred on 5 January 2012 at Dubrovnik. Thus, 229 tornadoes and waterspouts were reported in Croatia between 1892 and 2012.

6. Cyprus

Tornadoes, and in particular waterspouts, occur in the southern populated regions of Cyprus, an island country in the eastern Mediterranean Sea. A tornado climatology has not been yet developed for Cyprus, but Dotzek (2003) estimated that two tornadoes and three waterspouts occur each year in Cyprus. Case studies of tornadoes in Cyprus have been published by Jones and Williams (1977) for a tornado that occurred at Nicosia, Cyprus, on 3 August 1966, Hardy (1971) for a tornado that occurred on 22 December 1969, and Hyde (1971) for a waterspout reported on 14 January 1970. Two additional reports for tornadoes that occurred in 1946 and 20 February 1970 were obtained from Ormerod (1971).

Recently, Sioutas et al. (2006) described a tornado that occurred in August 2001 and presented an overview of the meteorological conditions associated with two tornado outbreaks on 27 January 2003 and 22 January 2004. The tornado outbreak from January 2003 was also analyzed by Doe (2003) who described four tornadoes (three of which were waterspouts that moved inland) that affected the Limassol area of southern Cyprus. Seven tornadoes were reported during the outbreak from 22 January 2004 that affected the area between Paphos and Larnaca, southern Cyprus (Sioutas et al. 2006). Thus, 17 tornadoes were reported in Cyprus between 1946 and 2004.

7. Czech Republic

Brázdil et al. (2012) developed a tornado climatology for the Czech Republic based on documentary evidence for 307 tornadoes that occurred between 1119 and 2010. The earliest known tornado recorded in the Czech Republic was described by the Cosmae Pragensis (1045–1125) in his *Chronica Boemorul* (*Chronicle of Bohemians*) written between 1119 and 1125 (Bretholz 1923). The tornado occurred on 30 July 1119 at Vyšehrad (the royal seat in Prague) and according to the damage descriptions, it appears to have been one of the strongest tornadoes (probably F4) ever recorded in Bohemia in the western Czech Republic (Setvák et al. 2003). Only three other tornadoes were reported before AD 1500. A few tornadoes (42 reports, 14% of all reports) were also reported between the sixteenth and eighteenth centuries. The low number of tornado reports during this period was attributed by Setvák et al. (2003) to limited access to chronicles and historical documents in order to collect historical reports, to the sociological and historical context (i.e., less attention was devoted in the chronicles to natural phenomena during the times of political instability and war), and to the normal interannual variability and climate (e.g., the Little Ice Age from central Europe during the seventeenth century and the first half of the eighteenth century).

The number of tornado reports increased during the nineteenth century (65 reports, 21% of all reports). One of the tornadoes that occurred during this period, the Brno tornado from 13 October 1870, was described and analyzed by the father of genetics Gregor Mendel (1822–84) (Mendel 1871). Mendel's work is considered to be the first contribution of the modern era of tornado research in the Czech Republic (Setvák et al. 2003). During the first half of the twentieth century, the number of tornado reports increased to 109 reports (36% of

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all reports) and then, for the second half of the twentieth century decreased to 31 reports (10% of all reports). This decrease in the number of reports was mainly because, during the socialist period (1948–89), tornadoes were virtually ignored in the Czech Republic and the damage produced by tornadoes were attributed to damaging winds. The term *tornado* was forbidden in both official and mass-media reports because ''a *tornado* was something that was related to the U.S. Great Plains, but had no *official* presence in Central Europe'' (Setvák et al. 2003, p. 599). After the fall of the Iron Curtain in 1990, the situation changed and efforts were made to summarize past events (e.g., Munzar 1993) and also analyze recent events (e.g., Šálek 1994; Setvák et al. 1996; Setvák 1999). Other factors that contributed to the increased tornado awareness in the Czech Republic were close contacts between the Czech Hydrometeorological Institute and the National Severe Storms Laboratory (Norman, Oklahoma) and the development of a Czech website containing information about tornadoes in general and details about individual cases (http://www.chmi.cz, accessed 11 December 2015). This resulted in an increase in the number of tornado reports between 2001 and 2010 to 56 tornadoes (18% of all reports). Thus, 307 tornadoes were reported in the Czech Republic between 1119 and 2010.

8. Estonia

The earliest tornado documented in Estonia occurred on 22 June 1795 in Livonia, a historic region along the eastern shores of the Baltic Sea today divided between Latvia and Estonia. The event was documented by Johann Christoph Brotze (1742–1823) a German pedagogue, artist, and ethnographer in his 10-volume work titled *Sammlung verschiedner Liefländischer Monumente, Prospekte, Münzen und dergleichen* (*A Collection of Various Livonian Monuments, Catalogs, Coins and the Like*). The description appears in volume 10, 151–152 (Leighly 1974). Only three other tornadoes were reported in Estonia before 1859, as shown in the climatology developed by Tárand (1995). Between 1859 and 1897, 27 tornadoes have been documented in local and national newspapers (in Estonia and Germany) and in the historical climate database maintained by the Tallinn Botanical Garden (Tárand 1995). The 12 tornado reports during 1898–1928 came entirely from the archive maintained by Johannes Letzmann (Tárand 1995).

Between 1929 and 1959, only five cases were reported: three of them in newspapers and two described by eyewitnesses directly to the author Andres Tárand. According to Tárand (1995), the low number of tornadoes reported in periodicals can be attributed to the outbreak of the Second World War and to the fact that during ''the Stalin-era [i.e., 1927–1953] descriptions of catastrophic events in nature were not favored'' in the national newspapers (Tárand 1995, p. 135). Thus, high impact events (e.g., tornadoes) during this period are questionable since the weather became a propaganda issue, with events being promoted when warnings were issued or the authorities were able to deal with the situation, or with events being hidden from the public when the event was not forecast or the authorities were overwhelmed by the disaster. The number of reports increased after 1960, with 37 tornadoes reported between 1960 and 1992 and after 1990, with 34 tornadoes reported between 1993 and 2003 (Tooming and Merilain 2004). The tornado reports between 1960 and 1992 were published mainly in the journal of *Eesti Loodus* and all the recent reports between 1993 and 2003 were retrieved from mass-media reports. Thus, the Estonian tornado database contains 118 reports between 1795 and 2003.

9. Finland

Rauhala et al. (2012) constructed the first tornado climatology for Finland based on 298 tornado reports between 1796 and 2007. Given the changes over time in the methods of collection, evaluation, and classification, the tornado climatology for Finland was divided into two periods. The first period, the historical period (1796–1996), contains 129 tornadoes (43% of all reports) of which (i) 98 reports were collected from historical newspaper archives and from Finnish Meteorological Institute (FMI) archive, (ii) 17 reports (mainly from the 1970s and 1980s) were obtained from the general public and collected by FMI, (iii) 12 reports (mainly from the 1930s) came from published meteorological descriptions, and (iv) two reports were from Wegener (1917).

The second period, the recent period (1997–2007), contains 169 tornado reports (57% of all reports) that were obtained mainly from the general public through a tornado observation report form placed on the FMI website (http://www.fmi.fi, accessed 11 December 2015) and from mass media. Before the 1930s, only a few tornadoes were reported in Finland (16 reports, 5% of all reports). In the 1930s, 30 tornadoes (10 of which were for F2 or greater tornadoes) were reported in Finland, which raised the interests of meteorologists during that period. After the Second World War, that interest declined and 74 tornadoes (25% of all reports) were reported between 1940 and 1990. As late as the mid-1990s, ''Finnish meteorologists generally assumed that severe convective storms or tornadoes do not occur in Finland and, if they occurred, they were rare'' (Rauhala et al. 2012, p. 1446). The increased number of tornadoes starting in the late 1990s was attributed by Rauhala et al. (2012) to an increased awareness due the movie *Twister*

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and television documentaries on tornadoes. Between 2000 and 2007, 131 tornadoes (44% of all reports) were reported in Finland.

10. France

Dessens and Snow (1989) developed a climatology of tornadoes for France based on 107 reports for significant tornadoes (F2–F5) that occurred between 1680 and 1988. The French tornado climatology was divided into two periods: (i) the historical period comprising 49 tornadoes reported between 1680 and 1959, and (ii) the modern period comprising 58 tornadoes reported between 1960 and 1988. One example of a deadly tornado is the Montville, France, tornado of 19 August 1845, which killed at least 70 people and injured another 136. Tornadoes such as these attracted the interest of French physicists like Jean Charles Athanase Peltier (1785–1845) and astronomers like Camille Flammarion (1842–1925) who published studies on tornadoes (e.g., Peltier 1840; Flammarion 1888). Data on tornadoes before 1960 were obtained by Dessens and Snow (1989) from the scientific literature, mainly from *Comptes Rendus à l'Academie des Sciences, Annuaire de la Société de France,* and *La Météorologie*. For the modern period, reports were obtained from mass media and supplemented with written and oral statements of eyewitnesses, detailed reports from town administrations, and damage surveys.

Paul (2001) further developed the French tornado database, which since 1993 has been maintained by *Climate–Energy–Environment* (http://climat-energie-environnement.info/, accessed 11 December 2015) by adding 199 reports (including reports for F0 and F1 tornadoes) from 1989 to 1999. More recently, Dessens and Paul (2013) presented an updated climatology of tornadoes in France, using 525 tornado reports from *Climate–Energy–Environment* and Keraunos (Observatoire Français des Tornades et des Orages Violents; French Observatory of Tornadoes and Severe Storms, http://www.keraunos.org/, accessed 11 December 2015) between 1680 and 2012. Thus, the French tornado database contains 525 reports between 1680 and 2012.

11. Germany

Dotzek (2001) developed a climatology of tornadoes based on the TorDACH database, and 517 tornadoes were reported in Germany between 1587 and 1999. Only 11 tornadoes were reported before 1799. The interest of scientists (e.g., Martins 1850; Reye 1872) and the public on tornadoes increased in the mid-nineteenth century, which resulted in 95 tornadoes reported between 1800 and 1899. In 1886, the Deutsche Meteorologische Gesellschaft (German Meteorological Society) started the publication of *Meteorlogische Zeitschrift*, in which articles on tornadoes in Germany, Austria, Switzerland, as well as other central European areas, were published. After the First World War, tornado research in Germany was continued by Letzmann (1927) and Wegener (1928). Between 1900 and 1939, the number of reports increased to 92, followed by a decrease to 8 reports during the 1940s mainly due to the outbreak of the Second World War.

In the 1950s and 1960s, tornadoes were "often referred to as strange and rare phenomena" (Dotzek 2001) despite the large number of tornado reports in the 1950s (83 reports). This increase in the number of tornado reports was associated with a peculiarity of the political situation after the Second World War in Germany [i.e., "the presence of many meteorologists in the U.S. armed forces who were familiar with tornadic storms" (Dotzek 2001, p. 237)]. The interests of meteorologists from the German weather service Deutscher Wetterdienst increased again because of strong tornadoes that occurred in the late 1960s and early 1970s. As a result, climatological data on tornadoes in Germany were published by Jurksch and Cappel (1976) on the risk of tornadoes to nuclear power plants, Fuchs (1981) on the risk of tornadoes to aviation, and Christoffer and Ulbricht-Eissing (1989) on the characteristics of the low-level wind field in Germany.

Bissolli et al. (2007) used the TorDACH database to develop a climatology of tornadoes in Germany and showed that 468 tornadoes were reported between 1950 and 2003, of which 113 were reported between 1980 and 1997 and 155 between 1998 and 2003. The increase in the number of reports in the recent period can be attributed to the efforts of collecting tornado reports in Germany and also to increased public awareness. The last version of the TorDACH database (TorDACH v1.6.00, accessed 11 December 2015) contained 1108 tornadoes and waterspouts reported in Germany between 855 and 2005.

Besides TorDACH, other groups and organizations have collected data on tornadoes in Germany. In 1999, the meteorologist Thomas Sävert founded *Tornadoliste Deutschland*, a web page (http://www.tornadoliste.de/, accessed 11 December 2015) listing probable and confirmed tornado reports in Germany. This list became well known during the following years, which was also a result of a fast-growing storm-chasing community in Germany and the foundation of the Skywarn Deutschland (http://www.skywarn.de/, accessed 11 December 2015) volunteer observing network in 2003. In 2007, a group of meteorologists, experts in the field of building standards and forestry, as well as storm chasers, started a

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Skywarn Deutschland-based working group [Tornado-Arbeitsgruppe Deutschland, Kollmohr et al. (2015)] dealing with mapping tornado paths and analyzing damage factors. Consequently, the working group became an organization in the spring of 2016. Thus, the German tornado database contains 1108 reports between 855 and 2005.

12. Greece

A systematic collection and analysis of tornadoes and waterspouts in Greece was first initiated in 2000 by the Hellenic National Agricultural Insurance Organization (Sioutas 2002, 2006). Tornado reports were also collected after 2007 by the Laboratory of Climatology and Atmospheric Environment (LACAE; http://lacae.geol.uoa.gr, accessed 11 December 2015) at the University of Athens. Matsangouras et al. (2014) used the LACAE database to develop a climatology of tornado and waterspout for Greece between 1709 and 2012. The climatology was divided into two periods: a historical period (1708–1999) containing 55 reports (10% of all reports), and a recent period (2000–12) containing 490 reports (90% of all reports) uniformly distributed over all the years. The historical dataset is based on the newspaper archives from the nineteenth and twentieth centuries available from the National Library of Greece. Also, historical data were retrieved from the scientific literature and from the records maintained by the Hellenic National Meteorological Service. The recent dataset represents the period during which systematic efforts have been made to collect tornado reports, especially by LACAE. Thus, 545 reports (171 for tornadoes and 374 for waterspouts) were reported in Greece between 1709 and 2012.

13. Hungary

The first tornado documented in Hungary occurred at Gadány, a village in Somogy county, southwestern Hungary, in June 1886 (Rethly 1925). Kecskés (1988) developed the first tornado climatology for Hungary based on 17 tornadoes reported between 1889 and 1972 in the scientific literature. Tornado reports were collected after 1993 by amateur meteorologists, which resulted in 34 reports between 1995 and 1998 (János 2010). Szilárd (2007) developed a synoptic climatology based on 19 damaging tornadoes reported between 1996 and 2001 and collected by the Hungarian National Disaster Management. Thus, 64 tornadoes were reported in Hungary between 1886 and 2001.

14. Ireland

The earliest documented tornado in Ireland, and one of the earliest documented in Europe, occurred on April 1054 at Rosdalla, County Westmeath (northwestern Ireland) (Rowe 1989). Before 1950, only three other tornadoes were reported in Ireland (Tyrrell 2001). The low number of tornadoes before 1950 was attributed to the turmoils in the nineteenth and twentieth centuries in Europe and to a public perception that tornadoes were ''tropical storms'' and could not occur in Ireland. Thus, tornadoes were not a relevant subject, and their scientific study was not justified (Tyrrell 2001).

Tyrrell (2003) presented the results of detailed records and site investigations of tornadoes reported in Ireland between 1999 and 2001. The analysis of Irish tornadoes also included fragmented records starting from 1950. Between 1950 and 2011, 113 tornadoes and waterspouts were reported over Ireland, of which 31 (27%) were reported during a period of intense investigations (1999–2001). Tyrrell (2003) speculated, based on a sounding climatology, that the environments in Ireland are not conducive to supercellular convection and thus concluded that the majority of the Irish tornadoes are nonsupercellular. Between 2002 and 2013, based on annual summaries, 84 tornadoes were reported in Ireland (Tyrrell 2003, 2004, 2005, 2006, 2007, 2008, 2010, 2012, 2014). These increases in the number of reports after 1999 are a reflection of the research activities on tornadoes and increased public awareness. Thus, 201 tornadoes were reported in Ireland between 1054 and 2013.

15. Italy

The earliest Italian tornado for which a detailed account exists occurred on 24 August 1456 and was described by Niccolo Machiavelli (1469–1527) in his history of Florence published in 1532. Pioneering works on tornadoes in Italy include a detailed account by Montanari (1694) of a tornado that occurred in Venice on 29 July 1686 and the analysis by Boscovich (1749) of a tornado that occurred on 11 June 1749 and produced great damage in Rome. An observation by de Monconys (1665) of a waterspout that occurred on 31 December 1648 near Sardinia (the second largest island in the Mediterranean Sea after Sicily), contains what seems to be the first published drawing of a waterspout. Peterson (1988) and Gianfreda et al. (2005) described 24 other tornadoes that occurred between 1410 and 1796. Between 1800 and 1899, only 23 tornadoes were described in the scientific literature (Peltier 1840; Reye 1872; Hellmann 1917; Wegener 1917; Desio 1925; Gianfreda et al. 2005).

During the first half of the twentieth century, tornadoes in Italy were studied, among others, by Crestani (1926, 1927, 1928) and Baldacci (1958, 1966), which resulted in 33 reports between 1900 and 1939. Tornadoes

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that occurred after the Second World War were analyzed by Palmieri and Pulcini (1979), mainly based on newspaper reports. Thus, 280 tornadoes occurred between 1946 and 1973. According to Palmieri and Pulcini (1979), only 38 reports (13% of all reports) analyzed were verified. Four other tornadoes that occurred during the 1970s were collected from Peterson (1988) and Gianfreda et al. (2005).

More recently, tornadoes that occurred in southern Apulia, southeastern Italy, have been collected and analyzed by Gianfreda et al. (2005). Based on historical chronicles and newspaper archives, 30 tornadoes (26 of which occurred in the last two centuries) were identified between 1546 and 2000. Giaiotti et al. (2007) developed a climatology based on mass-media reports and reports from amateur meteorologists between 1991 and 1999. Also, starting from the late 1990s, some of the regional meteorological services in Italy (e.g., Friuli Venezia Giulia, Eimilia-Romagna) have collected tornado reports. The dataset developed by Giaiotti et al. (2007) contained 241 tornadoes reported in Italy between 1991 and 2000. There is an increase in the number of reports from 1991, which was associated with the growing public attention and interest on these phenomena. Thus, 605 tornadoes were reported in Italy between 1410 and 2000.

16. Latvia

Tornado climatologies have not yet been developed for Latvia. Data on tornado occurrence in Latvia were retrieved from Tárand (1995), 11 reports between 1795 and 1928 and from Snitkovskii (1987), four reports between 1980 and 1986. Thus, 15 tornadoes were reported from 1795 to 1986.

17. Lithuania

The first tornado climatology for Lithuania was developed by Marcinoniene (2003). Between 1950 and 2001, 23 tornadoes were reported in Lithuania. The reports were collected by the Lithuanian Hydrometeorological Service with detailed observations being carried out after 1967. Additional tornado reports were collected from Snitkovskii (1987) who described two tornadoes that occurred on 25 April 1859 and 6 July 1945 at Vilnius, Lithuania, and Stankūnaitė (2006) who described three tornadoes that occurred in 2011. In summary, 28 tornadoes were reported in Lithuania between 1859 and 2011.

18. Malta

Tornado climatologies for Malta have not yet been developed despite the strong tornadoes and waterspouts that have been recorded as early as 1556 on this archipelago situated in the central Mediterranean Sea between Sicily and the North African coast. One of the most deadly waterspouts in history occurred in Malta's Grand Harbour on 23 September 1556. The event was described by de Boisgelin de Kerdu (1804, p. 59) as a ''dreadful storm [. . .] as the kind to which seamen gave the name of waterspout, which the modern Greeks call *syphen*.'' de Boisgelin de Kerdu (1804, p. 60) also mentions that ''more than six hundred persons, consisting of knights, officers, soldiers, slaves, and galley-slaves, were either drowned or crushed to death by the overturning of the galleys.'' Peterson (1986) described another seven tornadoes reported between 1757 and 1974, including one of the most devastating tornadoes in the modern history of Malta that occurred on 14 October 1960 at Qormi in central Malta, analyzed by Kirk and Dean (1963). Thus, eight tornadoes and waterspouts were reported in Malta between 1556 and 1974.

19. Moldova

Tornado climatologies have not yet been developed for Moldova. Data on tornado occurrence in Moldova were retrieved form Snitkovskii (1987) and Lyakhov (1987). Thus, only six tornadoes were reported in Moldova between 1950 and 1987.

20. The Netherlands

Tornado climatologies have not yet been developed for the Netherlands. The earliest tornado reported in the Netherlands occurred on 1 August 1674 at Utrecht, the Netherlands (Hauer and Pfeifer 2011). Based on data from the Royal Netherlands Meteorological Institute, 82 tornadoes were reported in the Netherlands between 1882 and 1925 (van Everdingen 1925). In total, 32 tornado reports between 1926 and 1978 were obtained from Peterson (1981) who collected reports mainly from *Hemel en Dampkring*, a journal published by the Dutch Society for Meteorology and Astronomy. Data on tornado occurrence were also retrieved from Groenemeijer (2004) who studied the sounding-derived parameters associated with severe convective storms in the Netherlands. Groenemeijer (2004) analyzed 114 reports of tornadoes and waterspouts that occurred between 1979 and 2003. The majority (110 reports, 96% of all reports) were obtained from the monthly magazine *Weerspiegel* of the amateur weather organization Vereniging voor Weerkunde en Klimatologie (Association of Meteorology and Climatology; http://www.vwkweb.nl/, accessed 11 December 2015). Thus, 227 tornadoes were reported in the Netherlands between 1674 and 2003.

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21. Poland

In Poland, tornado reports have been collected based on mass-media reports by Lorenc (1996) for tornadoes that occurred between 1979 and 1988 and by Lorenc (2012) for tornadoes that occurred between 1998 and 2010. Except for case studies (e.g., Chmielewski et al. 2013), annual summaries (e.g., Kolendowicz and Taszarek 2014), and analysis of environmental conditions related to tornado occurrence (e.g., Taszarek and Kolendowicz 2013), no comprehensive climatology of tornadoes existed for Poland before 2013. Taszarek and Brooks (2015) presented a climatology of tornadoes in Poland based on the data from the ESWD. The 269 tornadoes reported between 1899 and 2013 were divided into a historical dataset (1899–1998) containing 108 reports and a recent dataset (1999–2013) with 161 reports.

The majority of the tornado reports from the historical dataset before 1980 were retrieved by the Polish Stormchasing Society, ESWD, and from mass-media sources. The quality and quantity of the reports in the historical dataset were affected by the two World Wars, the changes in the Polish border, and the influence of the Soviet Union up to 1989. Only a small increase in the number of tornado reports was observed after Poland gained sovereignty in 1989 because the public generally ''assumed that tornadoes did not occur in Poland and their occurrence was mainly limited to the Great Plains in United States'' (Taszarek and Brooks 2015, p. 704). Public awareness of the impact of severe convective weather increased after the ''Polish Millennium'' flood in 1997. Beginning from the late 1990s, the number of tornado reports increased, with 175 reports (65% of all reports) between 1990 and 2013. Thus, the number of tornadoes reported in Poland from 1899 to 2013 is 269.

22. Portugal

Leitão (2003) developed a climatology of tornadoes in Portugal based on tornado reports between 1936 and 2002. For a long time, it was believed that tornadoes do not occur or are very rare in Portugal. Thus, a tornado database for Portugal was not officially maintained. The first tornado officially reported by the Portugal Meteorological Institute occurred on 21 April 1999 at Vila do Conde, northwestern Portugal. After this event, it was accepted that tornadoes can occur in Portugal. While working on analysis of the Vila do Conde tornado, Coelho and Leitao (2000) became aware that other tornadoes had occurred in Portugal. They begin collecting tornado reports to develop a tornado database for Portugal based on photographs, severe-wind reports, private meteorological records, local newspapers archives, and reports from local authorities and the public. Thus, 30 tornadoes were reported in Portugal between 1936 and 2002.[A1]

23. Romania

The first tornado climatology for Romania was developed by Antonescu and Bell (2015) based on a dataset obtained from three periods between 1822 and 2013. The historical period (1822–1944) contains 33 reports (25% of all reports) collected from the historical archives of local and national newspapers and publications of the Romanian Meteorological Institute. Tornadoes were observed in Romania before 1822 as shown by the Romanian folk mythology in which tornadoes are represented as ''dragons'' (*balauri* in Romanian). The socialist period (1945–89) contains only seven reports (5% of all reports). During the 1970s and 1980s, the word *tornado* was not allowed in either the official meteorological reports or in the mass-media reports. The recent period (1990–2013) contains 89 reports (70% of all reports) that came from mass-media sources and eyewitness reports. The recent increase in the number of tornado reports in Romania was attributed by Antonescu and Bell (2015) mainly to increased public awareness. Thus, 129 tornadoes were reported in Romania between 1822 and 2013.

24. Russian Federation

Descriptions of tornadoes are found in the majority of Russian chronicles. For example, in 1406 at Nizhniy Novgorod, ''a mighty storm and whirlwind ravage[d] the village'' (Anonymous 1851). However, climatologies of tornadoes in Russia were completely lacking before the 1980s, resulting in conflicting opinions about the occurrence of tornadoes in Russia. For example, Khromov (1983) considered that several tornadoes were observed in the European part of the Soviet Union (modern-day Belarus, Estonia, Latvia, Lithuania, Moldova, Russia, and Ukraine) each summer at different locations, whereas Kolobkov (1951) stated that tornadoes are rare within the Soviet territory compared with the United States and that ''at any given point they can occur 1–2 times per century.''

Lyakhov (1987) analyzed the tornadoes that occurred in the ''midland belt'' of Russia (a region that comprises the Central Federal District, Nizhny Novgorod and Kirov oblasts, and the Volga–Vyatka region) and showed that approximately 43 tornadoes were mentioned in the Russian chronicles between the thirteenth

[A1] Between 2001 and 2010, 64 tornadoes occurred in Portugal (P. Leitão, personal communication).

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and eighteenth centuries. Snitkovskii (1987) developed a climatology of tornadoes for the Soviet Union based on 248 tornadoes reported between 1844 and 1986. Three other tornadoes that occurred in 1987 were mentioned by the editor of Lyakhov's article. From the 251 reports between 1844 and 1987, 141 reports were for tornadoes that occurred in the European part of modern-day Russia. In summary, 183 tornadoes were reported between 1201 and 1987 in the Russian Federation.

25. Spain

The earliest tornado in Spain [classified as possible by Gayà (2015)] was described in the second volume of *Historiae de rebus Hispaniae* (*General History of Spain*) written in Latin by Juan de Mariana (1536–1624) and published in 1601. Describing one of the battles that took place during the Second Punic War (218–201 BC) close to the River Ebro (ca. 205 BC), Mariana mentions the presence of a snake that ''demolished everything in its path with a swirling mass of water that kept on coming.''

The Spanish tornado database, containing verified and possible reports, has been described by Gayà (2015). Gayà (2015) divided the Spanish tornado database containing verified reports into four periods. The first period covers classical antiquity up to 1799. The 31 tornadoes (2.7% of all reports) reported during this period were collected from chronicles and archives. For example, a high-impact tornado occurred on March 1671 at Cádiz in southwestern Spain and was responsible, according to contemporary estimates, for 600 fatalities (Gayà 2011). The second period (1800–99) corresponded to an increasing diversity of information. The 163 tornadoes (14.1% of all reports) reported during this period were collected from historical newspaper archives and from the archives of the Spanish meteorological service (after 1860). The increase in the number of tornado reports during this period can be associated with increased public awareness especially after the Madrid tornado of 12 May 1886, which was widely reported in the newspapers (Gayà 2007). The 204 tornadoes (17.7% of all reports) reported during the third period (1900–79) were mainly collected from newspaper archives. There is a decrease in the number of reports after 1901 probably due to the Spanish Civil War (1936–39) and the Second World War and also due to ''journalist's progressive loss of interest in this subject'' (Gayà 2011, p. 337) followed by an increase after 1980. The fourth period (1980–2012) contains 755 tornadoes (65.5% of all reports) collected from mass-media reports, the Internet, and damage surveys conducted by expert meteorologists. In summary, 1153 tornadoes were reported in Spain between about 1344 and 2012.

26. Sweden

Sweden has a relatively long history of tornado observations. One of the earliest tornadoes reported in Sweden occurred at Möklinta, southeastern Sweden, on 27 September 1725 (Kalsenius 1725). Although Sweden is situated at high latitudes, which would seem to inhibit the conditions for tornadoes, the long summer days can contribute to the heating (Peterson 2000b), as well as making reporting more likely. Only eight tornadoes were reported between 1730 and 1910, the majority being collected from the scientific literature (e.g., Hildebrandsson 1876; Wegener 1917). In one of the most detailed studies on tornadoes in Sweden, Båth (1945) analyzed four tornadoes that occurred in 1939 (one report) and 1942 (three reports). According to Peterson (2000b) who developed a climatology of tornadoes in Sweden, after the 1950s, tornadoes have not received much scientific attention in Sweden with most tornadoes being reported by the mass media. Before 1990, the Swedish tornado database contained 21 tornadoes, most of which developed near cold fronts (Peterson 2000b). Since the 1990s, a tornado database was maintained by the Swedish Meteorological and Hydrological Institute (SMHI; http://www.smhi.se/kunskapsbanken/meteorologi/tromber-1.3875, accessed 11 December 2015), which contains 178 tornadoes reported between 1990 and 2014. Thus, the Swedish tornado database contains 199 reports between 1725 and 2014.

27. Switzerland

Tornadoes in Switzerland have been studied by Jeanneret (2010) in a comparative analysis of the main causes leading to different occurrence frequencies of tornadoes in Switzerland, France, and Germany. Jeanneret (2010), building off previous efforts on collecting tornado reports [i.e., TorDACH, ESWD, Swiss Severe Weather Database (http://www.sturmarchiv.ch/, accessed on 11 December 2015)] showed that 106 tornadoes were reported in Switzerland between 1586 and 2009. The majority of tornadoes were reported after 2000 (49 reports, 46% of all reports). The recent increase in the number of reports was associated with increased public awareness. We use these 106 tornadoes for this study.

28. Turkey

Kahraman and Markowski (2014) developed a tornado climatology for Turkey. Previously, the Turkish State Meteorological Service maintained a database that consisted of 31 tornadoes reported between 1940 and 2010. The lack of official documentation of Turkish

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tornadoes is in part because tornadoes were regarded as extremely rare and exceptional weather events. To develop the tornado climatology for Turkey, Kahraman and Markowski (2014) collected data from (i) the Turkish State Meteorological archives from 1939 to 2012 (59 reports), (ii) the European Severe Weather Database (118 reports), (iii) newspapers archives from 1950 to 2004 (92 reports), (iv) search engines (i.e., Google and Yahoo!) (149 reports), and (v) scientific literature and the Ottoman archive (3 reports). The resulting 421 reports were classified depending on the credibility of the report and the weight of the evidence as verified (77 reports, 18% of all reports), very likely (308 reports, 73% of all reports), and possible (36 reports, 9% of all reports). More than half of these reports (225 reports, 58% of all reports) were reported between 2009 and 2013. This increase in the number of reports compared with the previous periods was attributed by Kahraman and Markowski (2014) to advancements in technology (e.g., Internet and mobile phones) and also to the efforts of documenting tornadoes in Turkey. Thus, the climatology of Turkish tornadoes used in the present study consists of 385 tornadoes (those classified as verified and very likely) reported between 1818 and 2013.

29. Ukraine

Tornado climatologies have not yet been developed for Ukraine. Data on tornado occurrence in Ukraine were retrieved from Lyakhov (1987) and Snitkovskii (1987). Thus, 49 tornadoes were reported in Ukraine between 1844 and 1987.

30. United Kingdom

The British Isles are defined here as the territory of the United Kingdom of Great Britain and Northern Ireland (which includes England, Scotland, Wales, and Northern Ireland), as well as the Channel Islands and the Isle of Man. The earliest tornado in the British Isles occurred in London on 23 October 1091 and appears to be the ''most violet tornado on record in the British Isles'' (Rowe 1999). Rowe (1999) described 32 other British tornadoes up to 1660 based on the data collected by Britton (1937) from medieval chronicles between 1091 and 1450 and after 1450 from early printed chronicles and pamphlets (e.g., Holinshed 1807; Stow and Howes 1631). After the foundation of the Royal Society in 1660, tornado reports appeared in the *Philosophical Transactions*, the Royal Society journal published since 1665 [e.g., the Hatfield tornado from 15 August 1687 described by de la Pryme (1702)]. Between 1661 and 1799, 110 tornadoes and waterspouts were observed in the British Isles, the majority of them being reported after 1760 (71 reports) (Brown et al. 2012). The number of tornado reports increased during the nineteenth century, with 560 tornadoes in the British Isles retrieved from historical newspapers archives (Brown et al. 2013a,b,c).

Lamb (1957), in his detailed account of the tornadoes that produced significant damage over southeastern England on 21 May 1950, also included a list with 54 ''destructive'' tornadoes that occurred between 1868 and 1950 (19 reports between 1900 and 1949) in the British Isles. The list was based on publications of the Royal Meteorological Society (i.e., *Weather*, *Quarterly Journal of Royal Meteorological Society*) and the *Meteorological Magazine*. Brown et al. (2013d,e) provided descriptions for 295 other tornadoes reported between 1900 and 1949. Tornadoes that occurred between 1950 and 1979 in the British Isles were analyzed by Brown et al. (2013d) (1950–60, 136 reports), Lacy (1968) (1963–66, 78 reports), and Meaden (1985a) (1970–79, 302 reports).

In 1974, the Tornado and Storm Research Organization (TORRO; http://www.torro.org.uk, accessed 11 December 2015) was founded with the aim collecting severe-weather reports from mass-media sources and from a network of observers in the British Isles (Meaden 1985b; Elsom et al. 2001). Mulder and Schultz (2015) used the TORRO database to develop a tornado climatology for the British Isles based on 1241 reports for 1980–2012. An unusually large tornado outbreak occurred during this period on 23 November 1981 when 104 tornadoes were reported across the British Isles. This large number of reported tornadoes may be a result of an appeal made by TORRO and mass-media for further reports (Rowe 1985). Thus, some of these reports may not be valid or may refer to the same tornado. Based on a recent analysis of the reports from the November 1981 outbreak, we have included in the database only 58 reports that were classified as verified (Apsley et al. 2016). An additional 27 tornado reports for 2013 were obtained from Brown and Meaden (2014). In summary, 2755 tornadoes were reported in the British Isles between 1091 and 2013.

APPENDIX B

Tornadoes in Other European Countries

This appendix contains a description of tornado reports for countries for which tornado climatologies have not been developed and for which the data were retrieved mainly based on personal communications. These

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countries have not been included in the climatology of tornadoes in Europe developed in sections 4–8.

1. Iceland

Tornado climatologies have not yet been developed for Iceland. Data on tornado occurrence in Iceland were retrieved from Hlynur Sigtryggsson (1921–2005) who was the manager of the Icelandic Weather Service (Veðourstófa Íslands) in Reykjavík from 1963 to 1989. Sigtryggsson (1958, 1959) described three tornadoes that occurred between 1857 and 1958, one of which occurred at Kollsvík in the Western Fjords region on 3 December 1857 and was associated with two fatalities. Additional reports for 11 tornadoes that occurred between 1934 and 2010 were collected by one the authors (i.e., Thilo Kühne) for the ESWD, based on historical newspapers archives and mass-media reports. Most of these events occurred in the Reykjavík metropolitan area and the Reykjanesskagi Peninsula region, southwest of the Icelandic capital. Reports from other regions are rare, possibly due to very low population density. Notwithstanding, an intense tornado hit the city of Akureyri in northern Iceland on 29 September 1964. Furthermore, a high number of observed landspout-type tornadoes developing from pyrocumulus clouds is known from the eruption of Surtsey in November 1963 (1 report) and from the recent Bàrðoarbunga eruption in the Holuhraun Desert in the central highlands (1–13 September 2014, 21 reports). Thus, 33 tornadoes and waterspouts were reported in Iceland between 1857 and 2014.

2. Slovenia

Tornado climatologies have not yet been developed for Slovenia. Data on tornado occurrence in Slovenia were retrieved from Trontelj and Zupančič (1987) for a tornado that occurred on 23 August 1986 in Hotedršcica, southwestern Slovenia, and Korošec and Cedilnik (2009) for a tornado that occurred on 13 July 2008 near Gozd, northwestern Slovenia. Additional reports for four tornadoes that occurred between 1965 and 1982 were retrieved from Trontelj and Zupančič (1987), and four reports were provided by Mateja Iršič Žibert from the Slovenian Environment Agency (2015, personal communication). Thus, 10 tornadoes were reported in Slovenia between 1965 and 2014.

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