Tornado Climatology of Poland

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(Manuscript received 9 June 2014, in final form 1 December 2014)

ABSTRACT

Very few studies on the occurrence of tornadoes in Poland have been performed and, therefore, their temporal and spatial variability have not been well understood. This article describes an updated climatology of tornadoes in Poland and the major problems related to the database. In this study, the results of an investigation of tornado occurrence in a 100-yr historical record (1899–1998) and a more recent 15-yr observational dataset (1999–2013) are presented. A total of 269 tornado cases derived from the European Severe Weather Database are used in the analysis. The cases are divided according to their strength on the F scale with weak tornadoes (unrated/F0/F1; 169 cases), significant tornadoes (F2/F3/F4; 66 cases), and waterspouts (34 cases). The tornado season extends from May to September (84% of all cases) with the seasonal peak for tornadoes occurring over land in July (23% of all land cases) and waterspouts in August (50% of all waterspouts). On average 8–14 tornadoes (including 2–3 waterspouts) with 2 strong tornadoes occur each year and 1 violent one occurs every 12–19 years. The maximum daily probability for weak and significant tornadoes occurs between 1500 and 1800 UTC while it occurs between 0900 and 1200 UTC for waterspouts. Tornadoes over land are most likely to occur in the south-central part of the country known as the “Polish Tornado Alley.” Cases of strong, and even violent, tornadoes that caused deaths indicate that the possibility of a large-fatality tornado in Poland cannot be ignored.

1. Introduction

Severe weather phenomena (e.g., large hail, tornadoes) associated with deep, moist convection create a threat to life and property. Tornado forecasting and risk estimation face many difficulties because of the lack of observational data and the incomplete understanding of physical processes leading to tornadogenesis. In Europe, tornadoes are not as frequent as in the United States (Groenemeijer and Kühne 2014), and because of temporal and spatial inhomogeneities it is a significant challenge to create tornado climatologies for different European countries. Because of problems related to collecting data on their occurrence, it has to be accepted that climatological results will always be uncertain. Nevertheless, knowing the primary modes of spatial and temporal variability can help various groups such as weather forecasters, emergency managers, insurance companies, and the public to be better prepared (Brooks et al. 2003a).

In the twentieth century, tornadoes in Europe were often regarded as strange and rare phenomena (Dotzek 2001) and after the work of Wegener (1917), only a few studies (e.g., Fujita 1973; Meaden 1976; Peterson 1982; Meaden and Elsom 1985; Dessens and Snow 1989) were devoted to the European tornadoes in that period. Probably because of the infrequent occurrence of high-impact tornadoes in most of the European countries and as well in Poland, tornado reports have not been officially collected as they are, for example, in the United States. A significant growth in severe weather awareness of the public in the last decade has meant that more attention has been devoted to data collection, and the analysis of these phenomena. Reporting of tornadoes in the last 10 years has become much better than it was earlier when mostly strong tornadoes were identified on the basis of
their damage. Cameras in mobile phones have also given us the opportunity to document weak, short-lived tornadoes. The access to the Internet and mass media has allowed information to be shared quickly and extensively.

An increasing number of tornado reports in the media and more systematic efforts to collect reports allowed for the development of the European Severe Weather Database (ESWD; Groenemeijer et al. 2004; Dotzek et al. 2009), hosted by the European Severe Storms Laboratory (ESSL). ESWD stores information about the location, time, intensity, and a description of the phenomenon, allowing researchers to collect reports and develop severe weather climatologies for Europe. ESSL has conducted extensive research on archival European media sources to extend ESWD tornado database to long historical timeframes.

In Poland, the foundation of the Polish Stormchasing Society [Skywarn Poland (Polscy Łowcy Burz)] in 2008 significantly contributed to the promotion of severe weather awareness of the public and an increase in the quality of tornado reporting. The network of storm observers and regional damage survey experts led to a better estimation of F-scale (Fujita 1971) ratings and to the inclusion of historical records in the ESWD. Prior to this, tornadoes in Poland were considered to be very rare events, mainly in comparison to Tornado Alley in the United States.

Since the early 2000s, interest in tornado research has increased. This is partially due to the series of European Conferences on Severe Storms that have promoted research on severe weather phenomena in Europe. Recently, tornado climatologies have been published for many of the European countries: Romania (Antonescu and Bell 2015), Turkey (Kahraman and Markowski 2014), Finland (Rauhala et al. 2012), Greece (Sioutas et al. 2011), Spain (Gayá 2011), Italy (Giaiotti et al. 2007), and Hungary (Szilard 2007). Other climatological researches that were held before the foundation of ESWD included Portugal (Leitao 2003), the Balearic Islands (Gayá et al. 2001), Germany (Dotzek 2001), Austria (Holzer 2001), Lithuania (Marcinioniene 2003), the United Kingdom (Holden and Wright 2004), France (Paul 2001), the Czech Republic (Setvák et al. 2003), and Ireland (Tyrrell 2003).

Tornado occurrence in Europe as a whole has been studied by Wegener (1917), Reynolds (1999), Dotzek et al. (2003), and Groenemeijer and Kühne (2014).

In Poland, tornado reports during 1979–88 and 1998–2010 have been collected by Lorenc (1996, 2012). There have also been case studies (e.g., Gumiński 1936; Rafalowski 1958; Parczewski and Kluzniak 1959; Kolendowicz 2002; Niedźwiedź et al. 2003; Parfiniewicz 2009; Chmielewski et al. 2013), annual summaries (Kolendowicz 2009, 2010, 2011; Kolendowicz and Taszarek 2014), and some analysis of environmental conditions related to tornado occurrence (Walczakiewicz et al. 2011; Lorenc 2012; Taszarek 2013; Taszarek and Kolendowicz 2013), but no comprehensive climatology of tornadoes exists for Poland. Dramatic cases in recent years, when strong and violent tornadoes have caused deaths and significant damage to property (15 August 2008, Chmielewski et al. 2013; 14 July 2012, Kolendowicz and Taszarek 2014), make it worthwhile to carry such a study.

Since an understanding of the local climatology is essential to help forecasters predict severe weather phenomena, the main aim of this work is to create a tornado climatology for Poland. The authors aim to estimate where and when tornadoes are most likely to occur and to determine the return period of violent tornadoes. The study summarizes general features of the tornado and waterspout statistics, including the annual, monthly, diurnal, and geographical variability. It is a first attempt to consider Polish tornadoes with a database of over 100 years.

The paper is organized as follows. Section 2 gives an overview of the definition of a tornado and describes the main characteristics of the tornado database with the methods used in the study. It also compares the F-scale distribution with the U.S. and European tornado records. Sections 3, 4, and 5 contain analyses of annual, monthly and diurnal, and spatial distributions of tornadoes in Poland, respectively. The occurrence of significant tornadoes is presented in section 6. The last section summarizes the results and provides a number of conclusions.

2. Data and methodology

a. Tornado definition

The development of a tornado climatology requires us to evaluate all available tornado reports from Poland and determine a definition of a tornado and a “tornado case” that will ensure the highest possible quality of the analysis. The AMS 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” (Glickman 2000, term updated 8 October 2013). Typically, damage is used after the fact to indicate tornado occurrence and a tornado should be strong enough to cause at least F0 damage (Forbes and Wakimoto 1983). The dependence on damage to verify tornadoes can create difficulties with reports, because some of the tornadoes pass through areas where they do not have the possibility to cause any damage or they occur over water (waterspouts). In Poland, numerous waterspouts and weak tornadoes have been documented recently and
reported as tornadoes in spite of the absence of damage. However, this was often caused by the lack of information about what happened, rather than by the lack of damage. Therefore, to overcome this challenge in the climatology, we follow the definition of a tornado used by Rauhala et al. (2012) for Finland: “A tornado is a vortex between a cloud and the land or water surface, in which the connection between the cloud and surface is visible, or the vortex is strong enough to cause at least F0 damage.” In our study, tornadoes that occurred over water and have been not assigned to any F scale are called waterspouts.

b. Tornado reporting

The quality of the available tornado reports in Poland varies in time and space. We have divided the entire period for analysis (115 years) into two periods. The first period is for historical tornado reports (1899–1998) with decreased credibility (low detailed descriptions of damage, in many cases a lack of photographs or eyewitnesses, and reports based mostly on the archival newspaper information), and, second, recent observations (1999–2013) with higher credibility (mostly documented with photographs, eyewitnesses, damage survey experts, radar data) that allows us to make better estimates of actual occurrence.

Although the recent observational dataset potentially allows for probabilistic analyses, historical tornado reports cannot be used for high-fidelity estimates of truth for two reasons. First, they are undoubtedly incomplete, particularly for weak tornado cases. The tornado database is likely to be more consistent over time for more intense tornadoes that have caused significant damage to property and, therefore, have been identified in the media reports (Brooks and Doswell 2001; Verbout et al. 2006; Rauhala et al. 2012). Second, the World Wars, changes in the Polish borders, and the heavy political influence of the Soviet Union up to 1989 (the political system affected the flow of information related to catastrophic events) affected the quantity and quality of tornado reports. Similar political influence on tornado reporting up to 1989 has been also observed in Romania (Antonescu and Bell 2015).

Considerable inhomogeneity in tornado reporting can be seen during the first half of the twentieth century when the western parts of Poland belonged to Germany (more historical tornado reports in this region). Most of the ESWD tornadoes reported in that time have been derived from Wegener’s German records. Tornado reports before the 1980s were retrieved from local newspapers archives by Polish Stormchasing Society and ESSL. Most of these tornadoes caused damage in urban areas, but, in many cases, photographs and the description were too limited to assign any F-scale ratings. Investigation of tornado occurrence from media reports in the 1979–88 timeframe was covered by Lorenc (1996).

After Poland gained sovereignty in 1989 (transformation of political system), a small increase in tornado reporting was observed. Nevertheless, the remaining lack of severe weather awareness, lack of access to the Internet, and lack of tornado databases and storm observers limited the increase in tornado reporting. People generally assumed that tornadoes did not occur in Poland and their occurrence was mainly limited to the Great Plains in United States. However, beginning with the “Polish Millennium” flooding in 1997, severe weather phenomena received more media attention. Awareness of the severe weather risks has led to the development of a Doppler radar network (POLRAD; Jurczyk et al. 2008), lightning detection network (PERUN; Loboda et al. 2009), and a general increase in severe weather monitoring. Thus, beginning in the late 1990s, an increase in tornado reporting for both weak and strong events is seen.

In recent observations, tornado reports in the ESWD are derived from media reports and photographs and descriptions from the public. After the foundation of the Polish Stormchasing Society in 2008, most cases had credible documentation often accompanied by damage survey experts, witnesses, and, in some cases, by radar data. Networks of storm observers and regional damage survey experts increased the quality of tornado reports. An increase in tornado reports can be also seen with waterspouts, which began to be recorded in 2002. Much of this is undoubtedly related to more widespread access to digital cameras.

c. Data and quality control assumptions

Reporting of phenomena such as tornadoes shares a number of problems associated with the lack of witnesses, evidence of the phenomenon (photography, video), a system to archive the event, and, finally, the accuracy of the report [e.g., some events are described as tornadoes rather than wind gusts because of a desire to experience a tornado; Groenemeijer and van Delden (2007)].

As a starting point, a total of 429 tornado reports from the area of Poland (312 679 km²) were derived from the ESWD for the years 1899–2013. These required extensive quality control in order to minimize errors that could potentially influence the results of any analyses.

Tornadoes may occur in groups within the same storm or be associated with the same boundary (especially nonmesocyclonic waterspouts) or in connection with separate supercells (mesocyclonic tornadoes), sometimes
as a long-track single tornadoes or a series of shorter-track tornadoes (Carbone 1982; Bluestein 1985; Wakimoto and Wilson 1989; Davies-Jones et al. 2001; Markowski and Richardson 2009). Such a large diversity creates many difficulties in defining the climatology (especially when estimating probability). ESWD sometimes contain numerous reports related presumably to one tornado and, in many cases, there is uncertainty whether they correspond to one long-track tornado or a series of tornadoes that occurred in the same area. If, for example, one tornado with a long track was included in the database several times (reports from different locations) while in the other cases a single short-track tornado was reported as an individual event, it could affect the results and interpretation of the climatology. The same problem also occurs with groups of waterspouts that often occur along the same wind shift boundaries and may be reported in the database as separate tornadoes.

To obtain consistent results, a concept of a tornado case has been adopted. One tornado case may include the occurrence of a single tornado or a group of tornadoes related to the same supercell or boundary. To minimize the impact of errors in reporting, we define tornado reports that occur in a time interval of less than 1 h and at a distance closer than 50 km. In this category, additional quality control incorporating satellite imagery and radar data were provided.

Table 1. Credibility categories of historical and recent tornado reports included in the analysis.

<table>
<thead>
<tr>
<th>Category</th>
<th>Criteria</th>
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<tbody>
<tr>
<td>Historical reports (1899–1998)</td>
<td>QC0+, QC1, QC2 ESWD reports, excluding cases that were reported in the same day, simultaneously for the time interval of less than 1 h and at a distance closer than 50 km</td>
</tr>
<tr>
<td>Recent observations (1999–2013)</td>
<td>QC1, QC2 ESWD reports including QC0+ with a credible eyewitness observation of a tornado and excluding cases that were reported in the same day, simultaneously for the time interval of less than 1 h and at a distance closer than 50 km. In this category, additional quality control incorporating satellite imagery and radar data were provided.</td>
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After quality control, a total of 269 tornado cases (108 from historical reports and 161 from recent observations) were selected to be included in the climatology. All cases that caused damage have been assessed according to their strength on the F scale (Table 2). Cases over land that did not have information on damage were unrated and cases occurring over water (on the Baltic Sea coast) were assigned to the waterspout category.

Tornado intensity assessment was based on the F scale from damage surveys. In the vast majority of cases, the assessment was conducted by Artur Surowiecki (Skywarn Poland) for recent observations and Thilo Kühne (ESSL) for historical events. Since more than one person took part in the rating process, inhomogeneities in the database are possible (Doswell and Burgess 1988). Damage caused by the tornado is not equivalent to intensity, because it strongly depends on the trajectory of the tornado and the presence of things that can be damaged. Some of the strong tornadoes might have been underestimated because of a lack of objects to damage. Thus, rural areas may be prone to more problems with underestimating tornado intensity than urban areas.

Tornadoes that have not been assigned damage ratings in ESWD are likely to be weak (Grünwald and Brooks 2011; Taszarek and Kolendowicz 2013).
Unrated tornadoes are typically short lived and as a result they are less likely to cause enough damage to be rated. Therefore, unrated cases have been assigned to the weak tornado category along with F0 and F1 cases (169 cases, 63% of all cases). A second category includes F2, F3, and F4 tornadoes (significant tornadoes—66 cases, 24% of all cases), while the waterspout category consists of 34 cases (13% of all cases) (Table 2, Fig. 1).

We are aware that damage ratings may have been assigned incorrectly, especially if we take into account that the original F scale was designed for buildings in the United States that may differ from those in Poland (Feuerstein et al. 2011). Additional reporting problems might have also been caused by the uneven distribution of population in Poland (highest density in the south-central part of the country).

Differences in the historical reports and recent observations can be found in the intensity distributions. In the historical dataset, unrated tornadoes were 65% of all cases, while in recent observations it was 19%. This can be explained by less evidence for damage in the historical dataset and, hence, a lack of sufficient information that would enable damage estimation. The percentage of significant tornadoes in the historical dataset was a little higher (28%) than in the recent observations (22%). Similar findings have been presented by Brooks and Doswell (2001), Verbout et al. (2006), and Rauhala et al. (2012), and could be explained by the more efficient collection of reports of weak tornadoes in the recent observations. Strong tornadoes that last longer, influence larger areas, and cause intense damage usually have a larger impact on society and thus are better documented in the media reports.

e. F-scale log-linear distribution

Brooks and Doswell (2001) presented a long-term relatively high-quality tornado dataset from the United States that was used to develop distributions that indicate that the number of tornadoes decreases approximately log-linearly with increasing F scale. They compared the U.S. tornado distribution with distributions from other countries and found similar behavior in many locations. Assuming that the distribution is at least similar in other regions, it is possible to provide background expectations for reports of tornadoes from other parts of the world. To do this, we can compare the distributions in proportion to the reports at a reference F-scale value (Fig. 2a) or analyze the percentage of particular F-scale ratings (Fig. 2b).

In this study we used the relatively high-quality U.S. tornado dataset [over 10000 reports derived from Brooks and Doswell (2001)] to compare with Polish tornado records from historical and recent observations, and also with European reports from ESWD [derived from Groenemeijer and Kühne (2014)]. Since almost all tornadoes in the United States are rated, unrated cases from Polish and European databases were placed in a separate category (waterspouts were omitted).

Assuming that the U.S. pattern reflects a physically based distribution that the Polish dataset might have, a large underreporting of F0 tornado cases is observed. This distribution points to considerable problems with the data, especially in the historical dataset. The same underreporting issues are seen in other European records that probably share similar problems with the database and reports quality. The distribution of Polish tornadoes in the more reliable recent observational dataset seems to be a little more similar to the U.S. distribution, thus presumably providing more realistic
estimates of truth (especially if unrated cases in the recent years in ESWD are considered to be F0; Grünwald and Brooks 2011; Taszarek and Kolendowicz 2013; Groenemeijer and Kühne 2014).

Analyzing the percentage of tornado reports in a particular F scale (Fig. 2b) we find the same problems related to underreporting of weak tornado cases in Polish and European datasets. The percentage of strong and violent tornadoes in Poland seems to be higher than in the United States. An especially high percentage of F2 tornadoes in more reliable recent observational datasets is seen. This may result from an overestimation of the F scale in these cases or the relatively low number of weak and unrated tornado cases in the database. In spite of the quality control measures in the ESWD, it is possible that some F2 tornado reports in database might have been less intense in reality (F1) or misidentified severe convective wind gusts. The higher percentage of strong tornadoes, compared to the United States, is also observed in other European records.

3. Annual frequency

A reason for dividing the dataset into the historical and recent periods (section 2b) can be seen when reports are examined by decade (Fig. 3). There is a significant difference in the annual average number of the tornado reports between these two periods. In the historical dataset
there is an average of 0.5–1 tornado cases per year. The exception is the decade of the 1980s, which was studied by Lorenc (1996) with an average of 3.6 cases per year.

In the more recent dataset (Fig. 4), the mean number of tornado cases rises to 10–12 per year with a peak of 18 tornado cases in 2007 and 16 in 2008. Significant tornadoes occur on average from 0 to 5 times per year (annual average: 2.4), while weak tornado cases appear from 2 up to 10 per year (annual average: 6.1). The beginning of waterspout reporting was in 2002 and 2.8 cases per year have been reported on average (ranging from 1 to 5).

It is also worth mentioning that after the Polish Stormchasing Society was organized in 2008, the annual average number of tornado reports (especially significant) has decreased. Apart from the interannual variability of the weather, this could be explained by an improvement in the quality of tornado identification and damage surveying, and increasing societal interest in the topic of severe weather. However, given the short period record, the extent of real interannual variability is unknown with the small sample size. As the mean number of significant and weak tornado cases per year drops since 2007, the annual mean number of waterspouts remains at the same level.

4. Monthly and diurnal distribution

The tornado threat in Poland occurs almost year-round except December when no tornadoes have been reported in the last 115 years (Fig. 5). The majority of the tornadoes (84%) have been reported during the warm months from May to September, and this period could be considered to be the Polish tornado season. Studies that identify the environmental conditions favorable for tornadoes (Rasmussen and Blanchard 1998; Thompson et al. 2003; Brooks et al. 2003b; Craven and Brooks 2004; Groenemeijer and van Delden 2007; Grünwald and Brooks 2011; Taszarek and Kolendowicz 2013) find that moderate and high convective available potential energy (CAPE; Miller 1967) environments together with moderate to high deep layer shear, low-level shear, storm relative helicity (SRH; Hart and Korotky 1991), and high boundary layer moisture content are conducive for tornadogenesis. In Poland, the highest average monthly values of CAPE are observed from June to August (Riemann-Campe et al. 2009), while the highest SRH and wind shear are related to wintertime (Romero et al. 2007). The study of Taszarek and Kolendowicz (2013) has shown that in Poland in the days when high instability overlaps with moderate wind shear, or marginal instability overlaps with significant wind shear, tornadoes occur. According to studies of Bielec-Bąkowska (2003), Kolendowicz (2006, 2012), Walczakiewicz et al. (2011), and Lorenc (2012) thunderstorms and severe convective weather phenomena occur in Poland most often in the late spring and whole summer. Similar findings about the tornado season have
been also found in climatologies of Romania (Antonescu and Bell 2015), Finland (Rauhala et al. 2012), the United States (Verbout et al. 2006), and most central European countries: Austria (Holzer 2001), Hungary (Szilárd 2007), the Czech Republic (Setvák et al. 2003), and Germany (Dotzek 2001). In southern Europe, the tornado season shifts more toward the autumn (Kahraman and Markowski 2014; Sioutas 2011; Gayá 2011; Giaiotti et al. 2007).

Outside of the main Polish tornado season, some tornadoes (16% of all data) are also reported. The reasons for their occurrence during winter months can be found in Taszarek and Kolendowicz (2013) who have analyzed cold tornado cases in Poland. Cold-season tornado environments are characterized by marginal instability and strong airflow with significant wind shear and SRH, and the presence of upper and lower jet streams. On the synoptic scale, these conditions occur most often in cases of deep surface lows (winter cyclones) passing through central and northern Europe [example of cases with tornadoes: 19 February 2002, 18 January 2007, 23 February 2008; Walczakiewicz et al. (2011)].

Tornadoes forming over land occur most often in July while waterspouts peak in August. (50% of all waterspouts in the database were reported in this month). This can be explained by the warm waters of the Baltic Sea in the late summer, which during cold air advection episodes cools down slower than the land surface, and thus creates more favorable conditions for convection.

The diurnal distribution of tornadoes has been analyzed in 3-h time intervals (UTC) taking into account only cases with sufficient information on the time of their occurrence (166 cases, 62% of all data). In Poland, the strongest solar heating takes place between 1000 and 1300 UTC while the highest soil and, thus, boundary layer temperature is usually between 1300 and 1600 UTC when convection is the most likely. Tornadoes occur most frequently (37%) in the late afternoon hours between 1500 and 1800 UTC (1700–2000 LT during summer), reaching the highest activity for both weak and significant tornado cases (Fig. 6). The second most frequent time of their occurrence falls between 1200 and 1500 UTC (28%), while lower activity takes place in the late morning (0900–1200 UTC, 14%) and in the evening (1800–2100 UTC, 10%). These results are consistent with previous work on tornado occurrence in Poland (Walczakiewicz et al. 2011; Lorenc 2012).

In contrast to tornadoes occurring over land, waterspouts on the Baltic Sea coast appear to be most frequent in the late morning and culminate around noon. Similar findings in waterspout distribution have been also found for the north German coast (Dotzek et al. 2010), Finland (Rauhala et al. 2012), and Greece (Sioutas 2011). An explanation for this can be related to a smaller-amplitude diurnal cycle for convection over water resulting from the smaller diurnal cycle in surface temperature over water. Conversely, convection over land peaks in the afternoon as the surface temperature responds quickly to radiation providing the largest CAPE values that may favor severe weather outbreaks, especially in the presence of strong wind shear and a weak capping inversion (Johns and Doswell 1992). This helps to explain why most of the Polish significant tornadoes occur between 1700 and 2000 LT.

During the night (2100–0600 UTC), tornado activity is uncommon (8%). Since solar radiation at night is zero, the potential for convection is considerably smaller, and thunderstorms form only under special conditions (e.g., strong large-scale forcing, atmospheric front, elevated convection). The low number of tornado reports between 2100 and 0600 UTC may be also explained by the darkness and the smaller number of people outdoors (Rauhala et al. 2012).

Although the small sample size requires caution in interpretation (Doswell 2007), the recent observation dataset (1999–2013) allow us to make some preliminary probabilistic estimates related to monthly and diurnal occurrence (Brooks et al. 2003a). The probability of tornado occurrence per day in any particular month

![Fig. 6. Diurnal distribution of all tornado cases (green), significant tornadoes (orange), and waterspouts (blue) in Poland in 1899–2013 (time in UTC).](image-url)
anywhere in Poland during the tornado season (May–September) ranges from 3% in September to almost 10% in August (Fig. 7a). Daily probability for tornado over land is roughly 6% for May–August, while waterspouts peak at 4% in August. If we take into account only days with at least one tornado reported during the tornado season (May–September), it can be estimated that if a tornado is going to form it will most likely occur between 1500 and 1800 UTC with 40% of all tornadoes occurring during that time (Fig. 7b).

5. Spatial distribution

The spatial distribution of tornado cases is obviously of great importance in understanding tornado occurrence (Fig. 8). Because of historical and political issues (section 2b), the historical dataset was more prone to favor tornado reporting (especially unrated tornadoes) in western parts of the country, and thus the spatial difference in the number of weak tornado reports between west and east is observable. On the other hand, significant tornadoes, which are less sensitive to changing reporting practices, show better agreement between the historical and recent data periods.

In general, it can be seen that weak tornadoes occur over almost all the country, while significant cases occur most frequently in the north-central (South Pomeranian Lake District), northeastern (Masurian Lake District), southeastern regions (Lubelska Upland), and in a southwest–northeast belt extending from south-central to central Poland—the so-called Polish Tornado Alley (from Kraków-Częstochowa Upland to central Mazovian Lowland; Kondracki 2002; Lorenc 2012; Figs. 8a,b,c,e and 9a). Some of the significant tornadoes in the historical dataset were also reported in the southwestern upland part of the country, but that has not been seen in the recent observations.

Since recent observations are likely of better quality and more uniform in tornado reporting, a quantitative analysis for this period can be performed. We have performed kriging on a 50 × 50 km² grid to estimate the average number of tornado cases per year (Fig. 8c). This shows that the largest tornado density is on the coastal areas that are mostly hit by nonmesocyclonic tornadoes that form over the Baltic Sea (waterspouts) and are predominantly weak. The peak area of their occurrence is the west side of the Słowińskie Coast with the annual average exceeding 0.4 tornado cases per year. In the inland areas, tornadoes are most likely to occur in the previously mentioned Polish Tornado Alley with an annual mean ranging from 0.3 to 0.4. Although this area has the highest population density in Poland (374 inhabitants per square kilometer in the Silesian province, Fig. 9b) which may influence reporting, it experienced one of the most devastating tornadoes in Polish history, an F4 tornado that occurred near Strzelce Opolskie on 15 August 2008, as well as numerous F3 and F2 cases.

The uniqueness of this area can be related to the orography (Fig. 8c) that may provide various effects on thunderstorm activity. Increased probability of storm initiation and moisture channeling might increase the chances for storms, and from that, increase the occurrence of tornadoes. We speculate that environmental conditions favorable for tornadic storms may be associated with the airmass advection relative to the gradients in elevation. Similar orographic influences can also be observed in other parts of Poland where increased annual probability is observed over uplands (Figs. 8c,e). The impact of the orography on tornado occurrence was also noticed in Greece (Sioutas 2011).

Annual tornado probability normalized to an area of 10000 km² has also been estimated for provinces (Fig. 8d). The highest threat is in the West Pomeranian (0.8) and Pomeranian (0.6) provinces. If we exclude
FIG. 8. Geographical distribution of tornado cases in Poland plotted by the F scale as in the legend (a) from 1899–1998 historical reports, and (b) 1999–2013 recent observations. (c) Average annual number for tornadoes (weak, significant, waterspout) in 50 × 50 km² area estimated using kriging, and (d) in provinces with values normalized to 10 000 km² (based on the 1999–2013 tornado reports). (e) Hypsometric map of Poland based on SRTM3 data (Farr et al. 2007), and (f) 1951–2013 annual average number of days with thunderstorms based on SYNOP reports (49 stations). Main rivers (blue lines).
waterspouts, these values would be reduced to 0.1 and 0.3 putting those regions at the bottom of occurrence (Table 3). Excluding waterspouts, the most vulnerable region to tornado occurrence are the Lesser Poland, Łódź, and Opole provinces (the area of the Polish Tornado Alley) with annual averages exceeding 0.4. On a national basis including all cases from recent observations, a yearly average of 0.3 tornado cases per 10,000 km² is seen in Poland, which is lower than the 1.1 yr⁻¹ estimated for Greece (Sioutas 2011) and similar to southeastern Romania (0.4; Antonescu and Bell 2015).

Despite the fact that tornado occurrence is directly associated with the presence of convective storms, we do not observe similarities in tornado occurrence with the geographical distribution of the 1951–2013 annual mean thunderstorm days (based on the SYNOP reports; Fig. 8f). Areas with the highest tornado report density (Fig. 8c) do not coincide with a highest annual average number of days with thunderstorms (except Lubelska Upland). This is due to the fact that specific types of thunderstorm, rather than ordinary convective storms are needed to produce a tornado (Markowski and Richardson 2009). Therefore, instead of comparing tornado occurrence with the mean number of thunderstorm days, it would be more valuable to consider thunderstorm type rather than frequency of thunderstorms over an area. Brooks et al. (2003b) carried out an analysis of favorable conditions for severe thunderstorms from

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**Table 3.** Number of tornadoes from the recent observations (1999–2013) according to provinces.

<table>
<thead>
<tr>
<th>Province</th>
<th>Area (km²)</th>
<th>No. of tornadoes (1999–2013)</th>
<th>Annual avg No. of tornadoes</th>
<th>Avg annual No. of tornadoes normalized to 10,000 km² area</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Pomeranian</td>
<td>22,896</td>
<td>28 (4)*</td>
<td>1.87 (0.26)*</td>
<td>0.82 (0.12)*</td>
</tr>
<tr>
<td>Pomeranian</td>
<td>18,293</td>
<td>17 (8)*</td>
<td>1.13 (0.53)*</td>
<td>0.62 (0.29)*</td>
</tr>
<tr>
<td>Lesser Poland</td>
<td>15,108</td>
<td>10</td>
<td>0.67</td>
<td>0.44</td>
</tr>
<tr>
<td>Łódź</td>
<td>18,219</td>
<td>12</td>
<td>0.80</td>
<td>0.44</td>
</tr>
<tr>
<td>Opole</td>
<td>9,412</td>
<td>6</td>
<td>0.40</td>
<td>0.42</td>
</tr>
<tr>
<td>Lubusz</td>
<td>13,984</td>
<td>8</td>
<td>0.53</td>
<td>0.38</td>
</tr>
<tr>
<td>Silesian</td>
<td>12,294</td>
<td>7</td>
<td>0.47</td>
<td>0.38</td>
</tr>
<tr>
<td>Warmian-Masurian</td>
<td>24,191</td>
<td>13</td>
<td>0.87</td>
<td>0.36</td>
</tr>
<tr>
<td>Świętokrzyskie</td>
<td>11,627</td>
<td>6</td>
<td>0.40</td>
<td>0.34</td>
</tr>
<tr>
<td>Kuyavian-Pomeranian</td>
<td>17,969</td>
<td>9</td>
<td>0.60</td>
<td>0.33</td>
</tr>
<tr>
<td>Podlaskie</td>
<td>20,180</td>
<td>9</td>
<td>0.60</td>
<td>0.30</td>
</tr>
<tr>
<td>Subcarpathian</td>
<td>17,844</td>
<td>6</td>
<td>0.40</td>
<td>0.22</td>
</tr>
<tr>
<td>Lublin</td>
<td>25,155</td>
<td>8</td>
<td>0.53</td>
<td>0.21</td>
</tr>
<tr>
<td>Mazovian</td>
<td>35,579</td>
<td>10</td>
<td>0.67</td>
<td>0.19</td>
</tr>
<tr>
<td>Greater Poland</td>
<td>29,826</td>
<td>8</td>
<td>0.53</td>
<td>0.18</td>
</tr>
<tr>
<td>Lower Silesian</td>
<td>19,948</td>
<td>4</td>
<td>0.27</td>
<td>0.13</td>
</tr>
</tbody>
</table>

* Excluding waterspouts.
reanalysis data, calculating the average annual number of days with favorable mesocyclonic tornado parameters. Those values do not correspond to the spatial distribution of annual mean number of thunderstorm days very well, and their frequency (≈1–3 yr⁻¹) is much lower than average annual number of tornado reports derived from recent observational dataset (1999–2013). That may indicate that many of the reported tornadoes are not classic supercellular tornadoes but rather nonmesocyclonic or quasi-linear convective system (QLCS) tornadoes. Unfortunately the low resolution of that analysis (200 km) does not allow us to draw further conclusions related to spatial differentiation and compare it with tornado distribution in Poland.

6. Estimating significant tornado risk

Recent cases of strong and even violent tornadoes that caused fatalities indicate that the possibility of a large-fatality tornado in Poland cannot be ignored. On the basis of the tornado frequency in the recent observational dataset, it can be estimated that on average there are 8–14 tornadoes per year in Poland including 2–3 waterspouts, 2–3 F0s, 3–4 F1s, and 1–3 F2s (Table 4). In addition, F3 tornadoes occur on average every other year while one F4 happened during the 15-yr record. Issues related to the quality of tornado reports, the short timeframe, and the small sample size of tornado cases (161 in 15 years) mean that these results have great uncertainty for quantitative estimates.

Spatially, the highest number of significant tornadoes (taking into account 1899–2013 timeframe) has been reported in the South Pomeranian Lake District and the belt from Kraków-Częstochowa Upland to Masurian Lake District (Fig. 9a). Strong to violent tornadoes have also been reported in the Silesia Lowland, Lubelska Upland, and foothills of the Carpathian Mountains. These results partially coincide with the highest population density in south-central Poland (Fig. 9b), and it is plausible that the high population density could influence tornado reporting. Tornadoes that do more damage have a higher impact on society, and thus are better documented in the media reports. If a tornado occurred in a region of high population density, more things could be damaged and there would be a possibility to estimate the F scale more accurately. Also, a higher number of people outdoors would increase the probability of someone witnessing the tornado.

In Poland, no F5 tornado has been reported in the period of record. However the existence of a reasonably reliable log-linear distribution of tornadoes with increasing F scale provides the opportunity to make estimates of the return period of extremely rare events such as F4 and F5 tornadoes (Brooks and Doswell 2001). Given that the percentage of the violent tornadoes (F4+) for the entire United States in the 1990s was between 0.5% and 1%, an average of 8–9 tornadoes in Poland per year (excluding waterspouts) would lead to a F4 tornado every 12–17 years. Following this method, we can estimate that an F5 tornado (percentage ≈0.1%) would occur in Poland on average every 100–120 years.

In the entire period of record (115 years), Poland experienced seven tornadoes that caused fatalities and/or are suspected for having a violent intensity (Table 5). Since there are considerable problems with the lack of the detailed information related to damage in the historical reports, it is very difficult to state clearly how many violent tornadoes have occurred. Taking into consideration that there are probably six cases when F4

### Table 4. Recent observations (1999–2013) and estimated periodicity statistics for the tornado occurrence in Poland depending on the F-scale categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Tornado recent observations in Poland (1999–2013)</th>
<th>Periodicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterspout</td>
<td>33</td>
<td>2–3 yr⁻¹</td>
</tr>
<tr>
<td>F0/UR</td>
<td>35</td>
<td>2–3 yr⁻¹</td>
</tr>
<tr>
<td>F1</td>
<td>57</td>
<td>3–4 yr⁻¹</td>
</tr>
<tr>
<td>F2</td>
<td>28</td>
<td>1–2 yr⁻¹</td>
</tr>
<tr>
<td>F3</td>
<td>7</td>
<td>1 for 2 yr</td>
</tr>
<tr>
<td>F4</td>
<td>1</td>
<td>1 for 15 yr</td>
</tr>
<tr>
<td>F5</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>All</td>
<td>161</td>
<td>8–14 yr⁻¹</td>
</tr>
</tbody>
</table>

### Table 5. The most destructive tornado cases in the 1899–2013 Polish tornado climatology. The asterisk indicates that the current state of the knowledge about this event does not allow us to specify with high accuracy the exact intensity and damage path.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
<th>Location</th>
<th>Total damage path (km)</th>
<th>Fatalities</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Jul 1931</td>
<td>Daytime</td>
<td>Lublin</td>
<td>20*</td>
<td>6</td>
<td>F4–F5*</td>
</tr>
<tr>
<td>20 May 1960</td>
<td>1400 (± 3 h)</td>
<td>Rzeszów</td>
<td>19*</td>
<td>3</td>
<td>F4*</td>
</tr>
<tr>
<td>15 Aug 2008</td>
<td>1500</td>
<td>Częstochowa</td>
<td>52</td>
<td>2</td>
<td>F3–F4</td>
</tr>
<tr>
<td>15 May 1958</td>
<td>Daytime</td>
<td>Rawa Mazowiecka</td>
<td>27*</td>
<td>2</td>
<td>F3–F4*</td>
</tr>
<tr>
<td>14 Jul 2012</td>
<td>1500</td>
<td>Bory Tucholskie</td>
<td>42</td>
<td>1</td>
<td>F3</td>
</tr>
<tr>
<td>20 Aug 1946</td>
<td>Daytime</td>
<td>Kłodzko</td>
<td>10*</td>
<td>0</td>
<td>F4*</td>
</tr>
<tr>
<td>25 Jul 1977</td>
<td>Daytime</td>
<td>Strzałkowo</td>
<td>*</td>
<td>0</td>
<td>F3–F4*</td>
</tr>
</tbody>
</table>
damage was possible (Fig. 10), that gives an estimate of F4 case every 19 years, reasonably close to the value derived from assuming a log-linear distribution.

The deadliest reported tornado in the twentieth century in Poland was on 20 July 1931 in Lublin city, which was estimated to be F4. It passed through urban areas and killed six people, causing significant damage—including the overturning of railway wagons (Fig. 11). Some sources (Gumiński 1936) estimated a wind speed that could be associated with F5 intensity; however, the information available on this event is insufficient and, in its current state, does not allow confirmation of this assessment.

### 7. Conclusions and discussion

We have used the available information on tornadoes in Poland to make estimates of their spatial and temporal distributions. Knowing the basic distribution can help various groups, such as emergency managers, insurance companies, and the public to be better prepared. Using 108 cases from historical reports (1899–1998) and 161 cases from more recent observations (1999–2013), we performed a climatological analysis of tornado occurrence in Poland. Recent observations have allowed us to perform quantitative analysis, while in the historical dataset this was not possible because of problems with reporting. The data are not homogeneous in time and space, and thus we cannot determine past trends in tornado occurrence, but several conclusions can be drawn.

By comparing Polish database with U.S. records, we can estimate that there is a large underreporting of weak tornadoes and the percentage of significant tornadoes is higher than in American and other European databases. It is clear in our analysis that after the foundation of the Polish Stormchasing Society (Skywarn Poland) in 2008, the quality of the tornado reports has improved. The Society contributed to the promotion of severe weather awareness of the public and developed a network of storm observers with regional damage survey experts.

On average 8–14 tornadoes occur each year in Poland, of which 5–7 are weak tornadoes and 1–3 are significant tornadoes. A mean of 2–3 waterspouts are reported annually. We estimate violent tornadoes occur once every one or two decades.

Looking at the annual cycle, the tornado season lasts from May to September with July as the peak month for tornadoes forming over land, and August for waterspouts. The highest probability for tornado occurrence during the day is between 1500 and 1800 UTC, whereas waterspouts tend to a weaker diurnal cycle with a peak at noon. The diurnal and monthly estimates are consistent with results previously obtained for Poland (Lorenc 2012) and with those observed in other European countries (Dotzek 2001; Holzer 2001; Setváková et al. 2003; Szilárd 2007; Sioutes 2011; Rauhala et al. 2012, Groenemeijer and Kühne 2014; Antonescu and Bell 2015).

Excluding waterspouts, which are most likely on the Słowiński coast, the region of Poland with the highest annual tornado probability lies in the south-central part of the country (Kraków-Częstochowa Upland). This

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**Fig. 10.** F4 damage in Rusinowice village associated with tornado from 15 Aug 2008 that occurred in south-central Poland. (Photography: Tomasz Gajda, shared on the basis of CCBY-SA 3.0 license.)

**Fig. 11.** Overturned railway wagons associated with tornado that passed through Lublin on 20 Jul 1931 [Source: Światowid newspaper, No. 31 (364)-01.08.1931].
region experienced the highest number of significant tornadoes in the 115-yr record. Taking into account tornado occurrence in other parts of the country, an apparent correlation between tornado frequency and orography can be seen.

Finally, the awareness of the significant tornado threat has increased in the last 5 years, and currently more attention is devoted to severe thunderstorm forecasting. The Polish National Institute of Meteorology and Water Management issues official warnings for severe thunderstorms and severe thunderstorms with hail. Because of the lack of specific tornado forecasting system and procedures, tornado warnings are not issued. In comparison with the United States, which has a well-organized tornado forecasting and warning system to deal with the 1200 tornadoes that occur per year, some may call into question the need for such a procedure in Poland where a mean of two significant tornadoes is reported each year. In Europe only 7 out of 39 weather services have a procedure to warn for tornadoes (Rauhala and Schultz 2009). Although the tornado threat in Europe is lower than in the United States (Groenemeijer and Kühne 2014), recent cases of strong and violent tornadoes that caused deaths in Poland indicate that consideration of a tornado warning procedures may be justified. Climatological results obtained in this paper indicate that the possibility of a large-fatality tornado in Poland cannot be ignored.

Acknowledgments. The authors thank the Polish Stormchasing Society and all volunteer observers for their contribution in tornado reporting and improvements in the quality of severe weather reports. Many thanks go to Thilo Kühne for his significant effort in investigating Polish historical tornado reports and to Artur Czernecki for assigning the F scale to the majority of tornado reports in our database. Special thanks also go to Thomas Schreiner for providing ESWD tornado data and Leszek Kolendowicz for sharing thunderstorm data. We also thank Pieter Groenemeijer, Thilo Kühne, Bartosz Czernecki, Alois M. Holzer, and the anonymous reviewers for interesting discussions that helped to improve the study. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce.

REFERENCES


