ADAM MICKIEWICZ UNIVERSITY IN POZNAŃ

CLIMATOLOGY OF THUNDERSTORMS AND TORNADOES IN POLAND

(Charakterystyka występowania burz oraz trąb powietrznych na obszarze Polski)

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Tornado on 9 May 2016 photographed by the author near Connorville (Oklahoma, United States)

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List of publications

1. **Taszarek M.**, 2013. Możliwości prognozowania trąb powietrznych w Polsce. *Przegląd Geograficzny*, **85**, 323–340. DOI: 10.7163/PrzG.2013.3.2.

2. **Taszarek M.**, Kolendowicz L., 2013. Sounding-derived parameters associated with tornado occurrence in Poland and Universal Tornadic Index. *Atmospheric Research*, **134**, 186–197. DOI: 10.1016/j.atmosres.2013.07.016.
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3. **Taszarek M.**, Brooks H.E., 2015. Tornado climatology of Poland. *Monthly Weather Review*, **143**, 702–717. DOI: 10.1175/MWR-D-14-00185.1.
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4. **Taszarek M.**, Czernecki B., Kozioł A., 2015. A cloud-to-ground lightning climatology for Poland. *Monthly Weather Review*, **143**, 4285–4304. DOI: 10.1175/MWR-D-15-0206.1.
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5. **Taszarek M.**, Czernecki B., Walczakiewicz S., Kolendowicz L., Mazur A., 2016. An isolated tornadic supercell of 14 July 2012 in Poland - a prediction technique within the use of coarse-grid WRF simulation. *Atmospheric Research*, **178**, 367–379. DOI: 10.1016/j.atmosres.2016.04.009.
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6. **Taszarek M.**, Gromadzki K., 2016, Deadly tornadoes in Poland from 1820 to 2015. *Monthly Weather Review*, in press. DOI: 10.1175/MWR-D-16-0146.1.
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Table of Contents

Abstract

Introduction

Severe weather phenomena associated with deep moist convection create a significant threat to human lives and property. In Poland, an average of 10 people are killed each year due to severe thunderstorms including tornadoes up to F4 in Fujita scale, large hail up to 10 cm in diameter and convective wind gusts up to 40 m s^{-1}. Despite such an impact, not many studies on severe thunderstorm risk were made for Poland. Except studies that analyzed basic distributions of thunderstorm days based on human observations, no climatological analyzes involving lightning data were performed. A similar situation arose with tornadoes. Although some of the tornado reports from 21st century have been collected and analyzed, no comprehensive study on tornado occurrence existed for Poland. However, the development of such studies has now become possible thanks to changes that took place in Poland in the last 15 years. These included the development of POLRAD and PERUN networks, the increase in the exchange of weather information, the increase in severe weather monitoring, and more systematic efforts to collect severe weather reports (the foundation of the European Severe Weather Database and the Polish Stormchasing Society). In order to rectify the absence of severe thunderstorm studies for Poland and take advantage of the changes that has taken place in recent years, the main goal of this research was to investigate the occurrence of thunderstorms and tornadoes in Poland.

Objectives

a. To determine the climatology of a cloud-to-ground lightning.
b. To determine the climatology of tornadoes.
c. To investigate historical sources in the search of yet undocumented tornado events.
d. To estimate the return period of rare events such as violent and killer tornadoes.
e. To investigate atmospheric conditions conducive to the tornado formation and assess their forecasting possibilities.

Datasets

a. European Severe Weather Database – tornado reports from the territory of Poland for the years 1820–2015.
b. PERUN lightning detection network – a cloud-to-ground lightning data for the years 2002–2013.
c. NOAA National Climatic Data Center – daily summaries regarding thunderstorm occurrence over 44 meteorological stations in the years 2002–2013.
d. University of Wyoming sounding database – radiosonde observations from 10 sounding stations in and around Poland for the years 1977–2012.
e. Digital libraries – 12 Polish digital libraries containing original scans of various archival newspapers with a local and national coverage.
f. Other sources – web searches (media reports, social media, forum of the Polish Stormchasing Society), damage surveys, in-situ observations, lightning data, satellite data, radar data, aerial and global forest change project data. The boundary and initial conditions derived from the Global Forecast System (for the purposes of Weather Research and Forecasting Model simulations).

Methodology

a. Statistics of annual, monthly and hourly variation of cloud-to-ground lightning flashes in years 2002–2013 are computed. Data is presented in the form of charts, tables and maps. Temporal and spatial variability of polarity, peak current and percentage of nighttime cloud-to-ground lightning flashes is involved as well.
b. All available tornado reports in years 1899–2014 are collected. Cases are divided on waterspouts, weak tornadoes, and strong tornadoes. Statistics involving monthly, diurnal and spatial variability are computed. A comparison of Polish tornado records with records from United States and Europe are presented as well.
c. All available deadly tornado reports in years 1820–2015 are collected. An investigation into historical records from 19th and 20th centuries is performed. Cases are analyzed in terms of their intensity and temporal variability in decades, months and time of the day. The most important factual information on each case is provided as well.
d. Atmospheric conditions conducive to the tornado occurrence in Poland are defined by combining tornado reports with radiosonde measurements. Proximity sounding are considered if tornado event took place up to 3 hours prior to 6 hours after the sounding time, and no farther than 200 km away from the sounding site. Cases are divided

according to their intensity and surface temperature. Results are presented in the form of scatter-plots and box-and-whisker charts.

e. Possibilities to forecast tornadoes are evaluated by: reviewing scientific literature, analyzing available forecasting techniques, local climate characteristics and the prevalence of the tornadoes in Poland.
f. A tornado event of 14 July 2012 is studied by analyzing: the course of the event, synoptic and mesoscale meteorological conditions, and by assessing the possibilities of its short-term prediction within the use of Weather Research and Forecasting Model simulation.

Results

a. The annual average of around 360 000 cloud-to-ground lightning flashes occur each year in Poland. This results in an average of 150 days with thunderstorms appearing anywhere in Poland. The average annual number of days with a thunderstorm within a particular location increases from the coast of the Baltic Sea in the northwest (15−20 days), to the Carpathian Mountains in the southeast (30−35 days).
b. The spatial distribution of the mean annual cloud-to-ground lightning flash density varies from 0.2 to 3.1 flashes km^{-2} yr^{-1} reaching the lowest values along the coast of Baltic Sea and the highest in the southwest-northeast belt from the Kraków-Częstochowa Upland to the Masurian Lake District.
c. The vast majority of cloud-to-ground lightning flashes are detected during the daytime with the peak activity at 1400 UTC and the minimum at 0700 UTC. While the activity of less severe thunderstorms drops after 1700 UTC, intense thunderstorms remain active until the late evening hours.
d. The days with the most intense thunderstorms occur from May to August and peak in July (an average of 4 days with at least 10 000 cloud-to-ground lightning flashes).
e. On average 8–14 tornadoes occur each year in Poland, of which 5–7 are weak tornadoes and 1–3 are significant ones. A mean of 2–3 waterspouts are reported annually. Violent tornadoes occur once every one or two decades.
f. An average of 1–2 killer tornadoes with 5 fatalities may be depicted for each decade. It is estimated that around 5–10% of significant tornadoes cause fatalities.
g. Tornadoes in Poland occur most likely from May to September with July as the peak month for tornadoes forming over land, and August for waterspouts.
h. Tornadoes forming over land take place mostly between 1500 and 1800 UTC, whereas waterspouts peaks between 0900 and 1200 UTC.

i. In years 1899-2013 significant tornadoes were the most frequent in the southwest-northeast belt from the Kraków-Częstochowa Upland up to the Masovian Lowland.
j. Warm airmass tornadoes feature with high atmospheric instability and moderate wind shear while cold airmass tornadoes are characterized by dynamic wind field (high wind shear) and marginal instability.
k. Significant tornadoes are characterized by higher than in weak cases: convective available potential energy, deep layer wind shear, low-level wind shear, storm relative helicity, boundary layer's moisture, and the presence of low-level jet stream. Their occurrence is related to supercell thunderstorms that are possible to predict within the use of the numerical weather prediction models.
l. Weak tornadoes are characterized by increased convective available potential energy released below 3 km above ground level, low lifted condensation level and weak vertical wind shear. They are related to wind-shift boundaries with preexisting vertical vorticity and developing convection. Tornadoes forming this way are difficult to predict.
m. The use of Weather and Research Forecasting Model simulations may be supportive of predicting atmospheric conditions conducive to severe convective weather, including tornadic supercells.

Conclusions and discussion

It has to be accepted that due to only 12 years of lightning detection measurements and limitations regarding tornado reporting, obtained climatological results will always be uncertain and remain only an approximation of the real distributions. Nevertheless, knowing at least the primary modes of spatial and temporal variability of thunderstorms and tornadoes, can help various groups such as weather forecasters, emergency managers, insurance companies, and the public to be better prepared. For this reason, it is believed that obtained results carry a practical value and may be used alike in operational forecasting, as well as in other studies on severe thunderstorm occurrence in Poland.

Perhaps one of the most important finding concerns the discovery of historical tornado cases that took place over the last 200 years, and proved that Poland is threatened to the occurrence of even F4 tornadoes. This finding stays in the opposition to the popular statement that "*tornadoes in Poland are a new thing and become more frequent due to changing climate*". Obtained results indicate that this phenomenon is not new for Poland and that numerous significant and killer tornadoes occurred in the past. High-quality European tornado observations that began only in the late 2000s also do not allow to determine any reliable climate trends regarding tornado occurrence.

The second important finding concerns study on a cloud-to-ground lightning climatology that is the first of this type ever performed for Poland. Although the occurrence of thunderstorms based on human observations has been previously studied, this research introduced numerous new findings regarding temporal and spatial variability of lightning. One of the most important ones indicates that severe thunderstorms are most likely to appear in the southwest-northeast belt from the Kraków-Częstochowa Upland up to the Masovian Lowland. Almost the same conclusion is to be found in the study regarding spatial distribution of significant tornadoes over the course of the last 100 years.

The analysis regarding possibilities of tornado forecasting in Poland indicate that thanks to numerical weather prediction models and POLRAD radar network, it is possible to issue tornado forecasts and real-time warnings for Poland. However, due to rather low frequency of tornadoes in Poland, still low severe weather awareness of the Polish society, and lack of systems that would allow to share such an information quickly and efficiently to the public, one may question the need for such procedures. Perhaps unjustly. Based on the records from the entire period of study, it is estimated that an average of 20 significant and 1–2 deadly tornadoes occur each decade in Poland. Each year Poland experiences 150 days with the thunderstorm including 10 with at least 10 000 CG lightning flashes. Approximately 10 people die due to severe thunderstorms each year. For these reasons, the author believe that the consideration of a real-time severe thunderstorm and tornado warning procedures in Poland (similar to those performed by the National Weather Service in the United States) should be taken into account. This way people would have a possibility to receive a highly credible information about a possible danger in their surroundings, and shortly before the incident, take action to protect their lives. We can neither prevent nor control the occurrence of severe thunderstorms, but because human safety is the most important issue, we should be able to do everything in order to inform people, about upcoming danger. Numerous high-impact killer tornadoes that occurred over the last 200 years, indicate that similar events are highly likely to appear in the future. The question is whether we will be able to protect people when the next such an event is going to happen.

Streszczenie (in Polish)

Wstęp

Niebezpieczne zjawiska atmosferyczne związane z głęboką konwekcją, stwarzają duże zagrożenie dla życia i mienia ludzkiego. Każdego roku w Polsce z powodu silnych burz, statystycznie ginie około dziesięciu osób. Polska narażona jest na występowanie trąb powietrznych o sile dochodzącej do F4 w skali Fujity, opadów gradu o średnicy do 10 cm oraz konwekcyjnych porywów wiatru osiągających do 40 m s^{-1}. Pomimo zagrożenia jakie te zjawiska generują, niewiele prac naukowych zostało poświęconych tematyce występowania silnych burz w Polsce. Dotychczas podstawowe charakterystyki zjawisk burzowych bazowały na tradycyjnych obserwacjach wykonywanych przez człowieka. Brak jednak było kompleksowego opracowania klimatologicznego wykorzystującego dane (z niezależnych od czynnika ludzkiego) systemów detekcji wyładowań atmosferycznych. Podobna sytuacja dotyczyła także trąb powietrznych. Pomimo, że część raportów z XXI wieku poddano analizie w pojedynczych artykułach naukowych, to w dalszym ciągu brak było kompleksowego opracowania dotyczącego klimatologicznych aspektów występowania trąb powietrznych w Polsce. Opracowanie takich badań stało się jednak możliwe dzięki rozwojowi meteorologicznej infrastruktury pomiarowej, która uległa znacznym zmianom na przestrzeni ostatnich 15 lat. Zmiany te dotyczyły m. in. rozwoju sieci pomiarów teledetekcyjnych POLRAD oraz PERUN, wzrostu wymiany informacji pogodowej, poprawy jakości monitoringu zjawisk niebezpiecznych oraz bardziej efektywnego zbierania raportów o niebezpiecznych zjawiskach atmosferycznych (założenie bazy danych European Severe Weather Database oraz stowarzyszenia Polskich Łowców Burz). Z tych względów, celem tej pracy było wykorzystanie ww. zmian oraz uzupełnienie międzynarodowej literatury naukowej o charakterystyki występowania burz oraz trąb powietrznych na obszarze Polski.

Cele

a. Określenie przestrzennej oraz czasowej charakterystyki występowania doziemnych wyładowań atmosferycznych.

b. Określenie przestrzennej oraz czasowej charakterystyki występowania trąb powietrznych.
c. Analiza źródeł historycznych celem znalezienia opisów trąb powietrznych nieznanych dotąd literaturze naukowej.
d. Oszacowanie częstości występowania trąb powietrznych powodujących duże straty materialne oraz ofiary śmiertelne.
e. Analiza warunków atmosferycznych sprzyjających powstawaniu trąb powietrznych oraz oszacowanie możliwości ich prognozowania na obszarze Polski.

Dane

a. European Severe Weather Database – raporty trąb powietrznych z obszaru Polski dla okresu 1899–2013.
b. Sieć detekcji wyładowań atmosferycznych PERUN – około 5 milionów doziemnych wyładowań atmosferycznych z obszaru Polski dla okresu 2002–2013.
c. NOAA National Climatic Data Center – dobowe podsumowania dotyczące raportowania zjawiska burzy z 44 stacji meteorologicznych z obszaru Polski dla okresu 2002–2013.
d. Baza danych radiosondażowych Uniwersytetu Wyoming – pomiary radiosondażowe z 10-ciu stacji aerologicznych z obszaru Polski oraz krajów sąsiedzkich dla okresu 1977–2012.
e. Biblioteki cyfrowe – 12 polskich bibliotek cyfrowych zawierających oryginalne skany historycznych dzienników informacyjnych o zasięgu lokalnym oraz krajowym z XIX i XX wieku.
f. Inne źródła – doniesienia prasowe, informacje pochodzące z mediów społecznościowych, forum internetowego Polskich Łowców Burz, produkty obrazowań satelitarnych oraz zdjęcia lotnicze, dane radarowe, analizy zniszczeń, dane z detektorów wyładowań doziemnych, naziemne pomiary meteorologiczne, projekt Global Forest Change oraz warunki brzegowe modelu Global Forecast System (na potrzeby *downscalingu* przy użyciu modelu Weather and Research Forecasting Model).

Metody

a. Opracowanie czasowych (lata, miesiące, pory dnia) oraz przestrzennych statystyk występowania doziemnych wyładowań atmosferycznych dla okresu 2002–2013. Dane zaprezentowano w formie tabel, wykresów oraz map. W pracy przedstawiono również przestrzenne oraz czasowe zróżnicowanie polarności, prądu szczytowego oraz odsetka doziemnych wyładowań atmosferycznych występujących w nocy.

b. Skatalogowanie wszystkich dostępnych raportów trąb powietrznych dla okresu 1899–2014. Przypadki podzielono na trąby wodne, trąby powietrzne słabe oraz trąby powietrzne silne. Statystyki ich występowania opracowano w ujęciu lat, miesięcy, pory dnia oraz w aspekcie zróżnicowania przestrzennego. Dane zaprezentowano w formie tabel, wykresów oraz map. W pracy porównano występowanie trąb powietrznych w Polsce z ich występowaniem na obszarze Stanów Zjednoczonych oraz w Europie.
c. Ryzyko występowania trąb powietrznych powodujących ofiary śmiertelne oszacowano na podstawie analizy wszystkich dostępnych raportów z okresu 1820–2015. W tym celu przeszukano 12 bibliotek cyfrowych, posiadających źródła historyczne z XIX oraz XX wieku. Zebrane przypadki poddano analizie pod kątem intensywności zjawiska, zmienności przestrzennej oraz występowania w ujęciu dekadowym, miesięcznym oraz w porach dnia. W pracy przedstawiono również najważniejsze informacje faktograficzne dotyczące każdego przypadku.
d. Warunki atmosferyczne w jakich powstają trąby powietrzne w Polsce zostały ustalane poprzez porównanie ich występowania z pomiarami radiosondażowymi ze stacji oddalonych nie dalej niż 200 km od miejsca raportowania zdarzenia. Sondowania, które uwzględniono w analizie zostały wykonane na 6 godzin przed lub do 3 godzin po wystąpieniu trąby powietrznej. Przypadki podzielono ze względu na ich intensywność oraz temperaturę masy powietrza. Wyniki zaprezentowano w formie wykresów pudełkowych oraz punktowych.
e. Możliwości prognozowania trąb powietrznych w Polsce oceniono poprzez analizę dostępnej infrastruktury radarowej, dostępnych metod prognozowania, uwarunkowań klimatycznych Polski oraz poprzez przegląd literatury naukowej opisującej mechanizmy powstawania trąby powietrznej.
f. Przypadek trąby powietrznej z dnia 14 lipca 2012 r. przeanalizowano pod kątem ustalenia przebiegu wydarzeń, warunków meteorologicznych w skali synoptycznej i mezoskalowej oraz oceny możliwości prognozowania tego zdarzenia przy pomocy symulacji modelowej Weather and Research Forecasting Model.

Rezultaty

a. Każdego roku w Polsce występuje średnio 360 000 doziemnych wyładowań atmosferycznych oraz około 150 dni burzowych. Średnia roczna liczba dni z burzami dla określonej lokalizacji wzrasta od 15–20 dni w Polsce północno-zachodniej, aż do 30–35 w Polsce południowo-wschodniej.

b. Przestrzenne zróżnicowanie średniej rocznej gęstości doziemnych wyładowań atmosferycznych waha się od 0,2 do 3,1 wyładowania km^{-2} rok^{-1}. Najniższe wartości występują wzdłuż wybrzeża Morza Bałtyckiego natomiast najwyższe w pasie rozciągającym się od Wyżyny Krakowsko-Częstochowskiej aż do Pojezierza Mazurskiego.
c. Zdecydowana większość doziemnych wyładowań atmosferycznych została zarejestrowana w ciągu dnia, osiągając szczyt aktywności o godzinie 1400 UTC przy minimum o godzinie 0700 UTC. Podczas gdy aktywność burz spada po godzinie 1700 UTC, silne burze potrafią pozostać aktywne do późnych godzin wieczornych.
d. Burze o wysokiej aktywności elektrycznej występują w Polsce od maja do sierpnia ze szczytem swojej aktywności przypadającej na lipiec.
e. Każdego roku w Polsce występuje średnio 8–14 trąb powietrznych, spośród których 5–7 to słabe przypadki, 1–3 to silne, a 2–3 to trąby wodne. Trąby powietrzne o bardzo dużej intensywności występują średnio raz na jedną lub dwie dekady.
f. Statystycznie w każdej dekadzie występują średnio 1–2 trąby powietrzne, które powodują 5 ofiar śmiertelnych. Szacuje się, że około 5–10% silnych trąb powietrznych występujących w Polsce powoduje ofiary śmiertelne.
g. Okres zwiększonego występowania trąb powietrznych trwa od maja do sierpnia, z lipcem jako miesiącem o szczytowej aktywności dla trąb powietrznych formujących się nad lądem oraz sierpniem dla trąb wodnych.
h. Trąby powietrzne występują najczęściej w godzinach od 1500 do 1800 UTC, podczas gdy szczyt aktywności występowania trąb wodnych przypada pomiędzy godziną 0900 a 1200 UTC.
i. W latach 1899-2013 silne trąby powietrzne występowały najczęściej w pasie rozciągającym się od Wyżyny Krakowsko-Częstochowskiej aż do Niziny Mazowieckiej.
j. Trąby powietrzne w ciepłych masach powietrza charakteryzują się wysoką niestabilnością termodynamiczną oraz umiarkowanymi pionowymi uskokami wiatru. W chłodnych masach powietrza występują przy jednoczesnym wystąpieniu wysokiej dynamiki pola wiatru (silne pionowe uskoki wiatru) oraz marginalnej niestabilności termodynamicznej.
k. Silne trąby powietrzne charakteryzują się wyższymi niż w przypadku słabych trąb powietrznych wartościami parametrów: deep layer shear, low-level shear, storm relative helicity, niestabilności termodynamicznej, zawartości wilgoci w warstwie granicznej oraz obecności niskotroposferycznego prądu strumieniowego. Ich występowanie związane jest

głównie z burzami superkomórkowymi, które są możliwe w prognozowaniu przy użyciu numerycznych modeli pogody.

l. Słabe trąby powietrzne charakteryzują się podwyższoną niestabilnością termodynamiczną do wysokości 3 km nad poziomem gruntu, niskim poziomem kondensacji oraz słabym pionowym uskokiem wiatru. Tworzą się zazwyczaj wzdłuż stref konwergencji wiatru z wbudowanymi strefami pionowej wirowości powietrza oraz rozwijającą się konwekcją. Trąby powietrzne rozwijające się w ten sposób są trudne w prognozowaniu.

m. Użycie modelu mezoskalowego Weather and Research Forecasting Model może być pomocne w prognozowaniu warunków atmosferycznych sprzyjających powstawaniu niebezpiecznych zjawisk konwekcyjnych, w tym superkomórek tornadowych.

Wnioski oraz dyskusja

Należy zauważyć, że prezentowane wyniki pozostają tylko przybliżeniem stanu rzeczywistego. Uzyskane charakterystyki klimatologiczne są niepewne, ze względu na ograniczenia związane z raportowaniem trąb powietrznych oraz relatywnie krótki ciąg pomiarowy systemu detekcji wyładowań atmosferycznych. Niemniej jednak, wiedza dotycząca zmienności czasowej oraz przestrzennej występowania silnych burz może pomóc synoptykom, centrom zarządzania kryzysowego, firmom ubezpieczeniowym oraz społeczeństwu w lepszym przygotowaniu na ewentualne zagrożenia związane z występowaniem tych zjawisk. Z tego powodu, uzyskane rezultaty posiadają wartość praktyczną i mogą być zastosowane zarówno w meteorologii operacyjnej, jak i w przyszłych badaniach dotyczących niebezpiecznych zjawisk burzowych w Polsce.

Jednym z najważniejszych wniosków wynikających z przeprowadzonych badań jest odkrycie wielu historycznych przypadków trąb powietrznych, które miały miejsce w ciągu ostatnich 200 lat. Przypadki te udowodniły, że Polska jest zagrożona zjawiskami o sile dochodzącej nawet do F4 w skali Fujity. Wyniki pracy znajdują się w opozycji do popularnego stwierdzenia, że *„trąby powietrzne w Polsce są czymś nowym i pojawiają się coraz częściej poprzez postępujące zmiany klimatyczne”*. Uzyskane rezultaty wskazują, że trąby powietrzne powodujące duże straty materialne oraz ofiary śmiertelne występowały w przeszłości regularnie i zjawisko to nie jest niczym nowym dla obszaru Polski. Ponadto, systematyczne obserwacje trąb powietrznych, które rozpoczęły się dopiero na początku XXI wieku, nie pozwalają na wiarygodne określenie trendów klimatycznych dotyczących występowania tych zjawisk.

Drugi istotny wniosek dotyczy opracowania charakterystyki występowania doziemnych wyładowań atmosferycznych, które jest pierwszym tego typu opracowaniem stworzonym dla Polski. Pomimo, że charakterystyki występowania burz w oparciu o tradycyjne obserwacje wykonywane przez człowieka były już dobrze udokumentowane w polskiej literaturze klimatologicznej, to dzięki zastosowaniu danych teledetekcyjnych mogły być one uzupełnione o szereg nowych ustaleń dotyczących m.in. czasowej i przestrzennej zmienności wyładowań doziemnych. Jedno z najważniejszych ustaleń wskazuje, że silne burze występują najczęściej w pasie rozciągającym się od Wyżyny Krakowsko-Częstochowskiej aż do Niziny Mazowieckiej. Podobne rezultaty uzyskane zostały również na podstawie analizy występowania silnych trąb powietrznych na przestrzeni ostatnich 100 lat.

Przeprowadzone badania dotyczące możliwości prognozowania trąb powietrznych w Polsce wskazują, że dzięki numerycznym modelom pogody i sieci radarowej POLRAD, możliwe jest wydawanie prognoz oraz ostrzeżeń w czasie rzeczywistym. Jednakże ze względu na niską częstość występowania trąb powietrznych w Polsce, wciąż małą świadomość społeczeństwa o występowaniu zjawisk burzowych, a także brak ogólnodostępnych systemów przekazu takich informacji w sposób szybki i efektywny - procedury takie nie istnieją. Wymienione powyżej czynniki sprawiają, że potrzeba ich utworzenia jest często kwestionowana. Być może jest to działanie niesłuszne. Na podstawie danych z całego analizowanego okresu (1820–2015) szacuje się, że każdej dekady występuje w Polsce około 20 silnych i 1–2 trąb powietrznych powodujących ofiary śmiertelne. Każdego roku w Polsce występuje 150 dni burzowych, a statystycznie około 10 osób ginie z powodu silnych burz. Mając na uwadze powyższe przesłanki, zdaniem autora wprowadzenie w Polsce ostrzeżeń meteorologicznych (przed trąbami powietrznymi oraz silnymi burzami) wydawanych w czasie rzeczywistym, kiedy zjawisko już powstało (podobnych do tych, jakie wydawane są przez National Weather Service w Stanach Zjednoczonych) powinno zostać rozważone. W ten sposób ludzie mogliby otrzymać wysoce wiarygodną informację o nadchodzącym zagrożeniu oraz uzyskać czas na podjęcie działań mających na celu ochronę ich życia. Nie możemy zapobiegać występowaniu silnych burz ani ich kontrolować, ale ponieważ życie ludzkie jest najważniejsze, powinniśmy zrobić wszystko, aby informować społeczeństwo o możliwym zagrożeniu. Liczne trąby powietrzne o dużej sile, które miały miejsce na przestrzeni ostatnich 200 lat, świadczą o tym, że wystąpienie kolejnych takich zjawisk w przyszłości nie może zostać wykluczone. Pozostaje tylko pytanie, czy będziemy wtedy przygotowani, aby ostrzec ludzi przed niebezpieczeństwem.

Chapter 1

Introduction

Severe weather phenomena associated with the deep moist convection create a significant threat to human lives and property. One of such examples may be tornadic thunderstorms that in a short period of time may cause great damage. In spite of the common opinion, Poland is threatened to the occurrence of such a strong phenomena as tornadoes up to F4 in Fujita scale (Fujita 1971), large hail up to 10 cm in diameter and convective wind gusts up to 40 m s^{-1} (European Severe Weather Database, ESWD; Groenemeijer et al. 2004, Dotzek et al. 2009). On average 10 people are killed in Poland each year by severe thunderstorms, as shown by the data from the Polish National Institute of Statistics and ESWD. Cases in recent years when Poland experienced violent storms with severe wind and tornadoes that have caused the death of people (e.g.: 21.08.2007, 15.08.2008, 14.07.2012) make it worth performing studies that aim to improve the predictability and understanding of such events. However, severe convective events are very rare and site specific, often difficult in reporting. It therefore becomes a significant challenge to create accurate climatological maps of their occurrence.

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). Another problem arises when trying to determine the long-term climatology across multiple regions. A lack of uniformity in standards for data collection, high degree of underreporting during socialistic period and changes through time in the way data is collected makes comparisons across space and time very problematic (Antonescu et al. 2016). For a long time, tornadoes in Poland were regarded by society as strange and rare phenomena reserved mainly for the territory of the United States (Dotzek 2001). Doswell (2003) described this situation as a self-fulfilling prophecy, in which denying the existence of tornadoes resulted in no record keeping of such events. Due to such problems, it has to be accepted that climatological results will always be uncertain and remain only an approximation of the real distribution. Nevertheless, knowing at least 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 contrast to the United States and Western Europe, not many studies on severe thunderstorms were made for Poland. Before 2013, except some studies that analyzed basic distributions of thunderstorm days based on human observations (e.g. Bielec-Bąkowska 2003, Bielec-Bąkowska and Łupikasza 2009, Kolendowicz 2006, 2012), no climatological studies were performed within the use of lightning data. Although human observations of thunderstorms allow one to analyze long-term changes in the number of thunderstorm days, they cannot estimate intensity of such a phenomena (Rakov and Uman 2003). For this reason, a new study (within the use of a lightning data) with more detailed information related to thunderstorm occurrence and its intensity was necessary for Poland. A similar situation arose with tornadoes. Although tornado reports from 1979–1988 and 1998–2010 have been collected by Lorenc (1996, 2012), and there have been some case studies (e.g. Gumiński 1936, Rafałowski 1958, Parczewski et al. 1959, Kolendowicz 2002, Niedźwiedź et al. 2003, Parfiniewicz 2009, Chmielewski et al. 2013) no comprehensive study on environmental conditions and climatology of tornadoes existed for Poland. Such a study was needed e.g. to estimate the future threat of rare events (violent and deadly tornadoes) that have the potential to create a major disasters (Doswell 2003).

In contrast to previous decades, the development of such analyzes has now become possible. Beginning with the “Polish Millennium” flooding in 1997 (Kundzewicz et al. 1999), severe weather phenomena received more media attention. The 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; Łoboda et al. 2009), and a general increase in severe weather monitoring. Reporting of severe weather phenomena in the last 10 years has also become much better thanks to mobile phones equipped with camers and the development of social media. Easier access to the Internet and mass media have allowed information to be shared quickly and extensively. An increasing number of severe thunderstorm reports in the media and more systematic efforts to collect reports allowed for the development of ESWD, hosted by the European Severe Storms Laboratory (ESSL). The foundation of the Polish Stormchasing Society (Skywarn Poland – Polscy Łowcy Burz) in 2008 also significantly contributed to the promotion of severe weather awareness and an increase in the quality of severe weather reporting in Poland.

In order to rectify the absence of severe thunderstorm studies for Poland and take advantage of the changes that took place in recent years, the main goal of this research was to estimate spatial and temporal variability of thunderstorms and tornadoes, and study their prediction possibilities. This has resulted in a a series of 6 publications released between 2013 and 2016. One regarding a lightning climatology of Poland, three related to tornado occurrence in Poland and two focusing on tornado prediction.

Chapter 2

Objectives

The main objective of the research was to estimate spatial and temporal variability of thunderstorms and tornadoes in Poland. In accordance with the general objective, the specific objectives are:

a. To determine the climatology of a cloud-to-ground (CG) lightning. To estimate in which months, time of the day and in which area, Poland is threatened to the occurrence of severe thunderstorms. To assess how often thunderstorms with a particular intensity occur.

b. To determine the climatology of tornadoes. To estimate in which months, time of the day and in which area, Poland is threatened to the occurrence of tornadoes. To assess how often tornadoes with a particular intensity occur.

c. To perform a research on historical sources (newspaper reports) from the 19th and 20th century in the search of tornado descriptions which are undocumented in scientific literature. In addition, also to expand the information about currently known cases.

d. To estimate the return period of rare events that have the potential to create major disasters such as violent and deadly tornadoes.

e. To investigate atmospheric conditions associated with tornado occurrence in Poland and assess their forecasting possibilities within the use of numerical weather prediction (NWP) data.

Chapter 3

Databases

To achieve aims of the study following databases were used in the analysis.

3.1 European Severe Weather Database (severe weather reports)

An increasing number of severe weather reports in the media and more systematic efforts to collect them at the beginning of 21st century allowed for the development of ESWD, hosted by ESSL. The main objective of the ESWD is to collect and provide detailed and quality-controlled information on severe convective storm events over Europe. ESWD stores information about the location, time, intensity, and a description of the phenomena such as tornadoes, large hail and severe wind gusts, allowing researchers to use these reports in severe weather studies for Europe. For the purposes of this research, information about tornadoes reported over territory of Poland for years 1820–2015 was derived. In total, over 450 tornado reports from ESWD entered a quality control phase.

3.2 PERUN lightning detection network (lightning data)

Polish lightning detection network is operated by the Institute of Meteorology and Water Management − National Research Institute (IMGW-PIB), and since 2002 works operationally under the name of PERUN (from Slavik mythology the god of thunder and lightning). The system consists of nine SAFIR3000 (*Surveillance et Alerte Foudre par Interférométrie Radioélectrique*) total lightning automatic detection stations located in Białystok, Olsztyn, Toruń, Gorzów Wielkopolski, Kalisz, Częstochowa, Włodawa and Warszawa (Figure 1a). The system is able to detect CG and intra-cloud (IC) flashes. The detection efficiency and the location accuracy varies in the whole country. Bodzak (2006) estimated that network has 95%

detection efficiency over the entire area of Poland. Location accuracy below 1 km covers 38% area of the country while 77% is assigned to values below 2 km (Figure 1b). For the purposes of this research, information regarding CG lightning flashes for the years 2002–2013 was derived. In total, 4 952 203 CG lightning flashes were used to construct climatology.

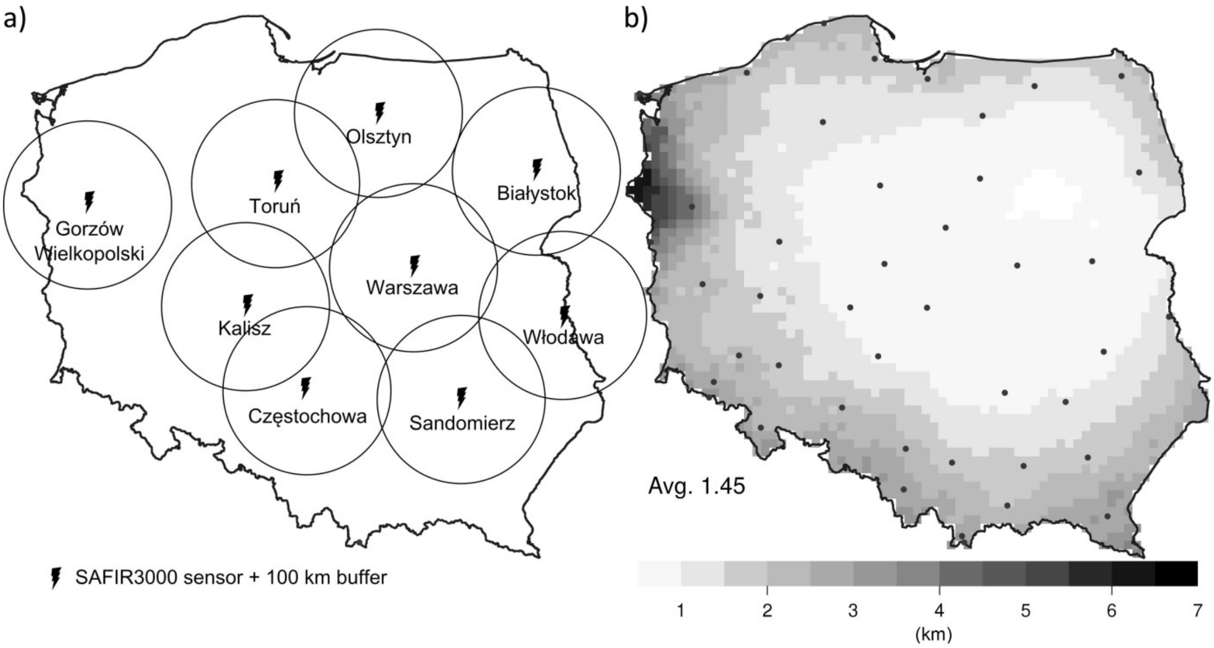


Figure 1. (a) SAFIR3000 lightning sensors location of the PERUN network with 100 km buffer zones. (b) Average CG lightning flash location accuracy (km) derived from PERUN database in the timeframe from 2002 to 2013. Computed in 10 km x 10 km grid cells. Dots denote main meteorological stations (44). Source: Taszarek et al. (2015).

3.3 NOAA National Climatic Data Center (thunderstorm reports)

Surface synoptic observations (SYNOP) were derived from the NOAA National Climatic Data Center (NCDC) daily summaries. For the purposes of the research, the information about thunderstorm occurrence over 44 meteorological station in the years 2002–2013 was derived. In total, 12 419 daily reports of thunderstorms (1 478 unique days with thunderstorms) were used in the analysis.

3.4 University of Wyoming (radiosonde measurements)

The rawinsonde measurements were derived from the sounding database of University of Wyoming and assigned as a proximity soundings to tornado events derived from ESWD. Soundings from 10 radiosonde stations in and around Poland were used (Figure 2): Wrocław (WMO ID: 12425), Legionowo (12374), Łeba (12120), Greifswald (10184), Lindenberg

(10393), Kaliningrad (26702), Praha (11520) Prostejov (11747), Poprad (11952) and Lviv (33393). For each sounding measurement, temperature, dew point, U and V wind vectors were interpolated in vertical in order to compute various thermodynamic and kinematic parameters. These were chosen on the basis of scientific literature related to the analysis of tornado environments in the United States and Europe (Rasmusen and Blanchard 1998, Thompson et al. 2003, Brooks et al. 2003b, Craven and Brooks 2004, Groenemeijer and van Delden 2007, Kaltenböck et al. 2009, Brooks 2009, Grünwald and Brooks 2011, Walczakiewicz et al. 2011, Thompson et al. 2012, 2013, Brooks 2013).

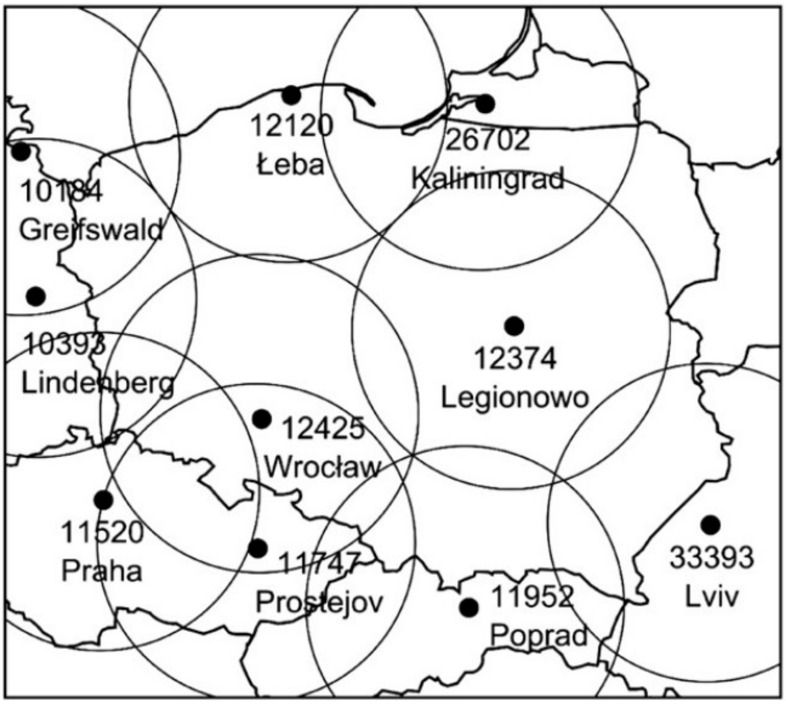


Figure 2. Location of radiosonde stations with WMO ID. Circles denote 400 km in diameter proximity range area. Source: Taszarek and Kolendowicz (2013).

3.5 Digital libraries (historial tornado reports)

Polish digital libraries contain original scans of various archival newspapers with a local and national coverage. For the purposes of this research, 12 digital libraries (Table 1) were used to browse historical sources from 19th and 20th century in search of tornado descriptions yet undocumented in a scientific literature. The highest number of archival newspaper editions was available for the second half of the 19th and first half of the 20th century. In total 26 new tornado cases were found while the information on 11 currently known was expanded. An example of a historical source containing tornado description from 22 May 1886 is shown in the figure 3.

Katastrofa w Krośnie.

Z ziemi górnoszląskiej, dnia 16-go maja.

W sobotę rozniosły pisma nasze prowincyonalne wieść o nieszczęściu, jakie w dniu 14-ym b. m. spotkało sąsiednie, bo tuż na północnem pograniczu ziemi nadodrzańskiej leżące, Krosno.

Powodem wypadku był tylokrotnie w ostatnich czasach wspominany i opisywany cyklon, strasznie pustoszący od niejakiego czasu kraje Stanów Zjednoczonych Ameryki północnej. Że po niezmiernych obszarach amerykańskich szaleć on może z niesłychaną gwałtownością, nic w tem dziwnego; w Ameryce zresztą wszystko na wielką odbywa się skalę, ale nie przypuszczaliśmy nigdy, żeby u nas z podobną siłą rozhulać się mogła trąba powietrzna.

Świadek naoczny tak opowiada katastrofę w Krośnie:

Rok 1886-ty bardzo boleśnie dał nam się we znaki: ostra i długa zima, wylewy, potem dotkliwe wiosenne przymrozki dużo wyrządziły szkody, ale niczem wszystko to w porównaniu z klęską, jaka teraz miasto nasze i okolicę dotknęła. Było to 14 go b. m. Pięknie złociło słońce uśmiechającą się życiem wiosennem przyrodę, wszystko rozkwitało uroczo pod wpływem ciepłego powietrza.—gdy nagle na zachodzie widnokręgu ukazały się chmury. Nikogo one zatrwożyć nie mogły; przeciwnie, witano je radośnie, bo spragniona ziemia potrzebowała deszczu i orzeźwienia. Ale robiło się coraz posępniej i coraz ciemniej, chmury podnosiły się coraz wyżej, a krótko przed 3-ią olbrzymia czarna ściana stanęła tuż za miastem i przechylać się na nie zdawała, szerząc mrok nocny wśród skwarnej duszności powietrza. I zaczęło niebawem szumieć i huczeć przeciągle, zerwał się wicher gwałtowny i zamienił się nagle—w tak niesłychaną burzę, tak się nad miastem i w mieście impetycznie skręcił i zwinął, tak zahuczał przerażająco wśród bicia piorunów, że przestrach ogarnął całą ludność. Straszliwy łomot napowietrzny, błyskawice, siekące ciemności, szum, wycie i huki przerażające, pioruny, grad,—wszystko to w jedną połączone było grozę. Ziemia się pod nogami trzęsła! Trwało to krótko. Cyklon pędził od południa-wschodu ku północnemu zachodowi.

Niebawem znowu zaczęło słońce odsłaniać pogodne oblicze i pokazało w całej okropności spustoszenie—dzieło kilkunastu minut. W mieście lament powstał wielki. Dość powiedzieć, że burza przewróciła wieżę wspaniałego maryackiego kościoła, krzyżem na dół zwaliwszy ją na zdruzgotane zabudowania pewnego przemysłowca i pogrzebawszy w gruzach kilkoro ludzi.

Straż ogniowa i załoga wojskowa rozbiegły się po mieście dla ratowania mieszkańców. Wszędzie rumowiska, masy cegieł, dachówek, belek, łat, okiennic, okien, drzew, szkła, sprzętów domowych... A jaki płacz i zgiełk, jakie szukanie i nawoływanie tych, których w czasie strasznej katastrofy niebyło w domu! Kominy fabryczne powywracane, z 500 domów poznoszone dachy i wiązania. Takimże uszkodzeniom uległy: kościół katolicki, szkoła, ratusz, gmach pocztowy i t. d.; 10,000 szyb wybitych, z pomnika kamiennego na rynku wierzchołek strącony. W domach meble i sprzęty połamane, lampy i naczynia potłuczone. Dziecko pewnego dekarza uniosła trąba wysoko w powietrze i zabiła. Najsilniejsze drzewa promenady miejskiej, na cmentarzu, po ogrodach i nad szosą powyrywane z korzeniami. W drukarni miejscowego tygodnika wszystkie okna powybijane, płyty drukarskie zniszczone, machina gruzami zasypana. Na rynku dwie ciężkie żelazne latarnie z ziemi wyrwane.

Sąsiednia wieś, Staresarnice (Alt-Rehfeld), także srodze ucierpiała; mało zabudowań uniknęło tam szkody; inne wsie, w równej bliskości, ale w innym kierunku położone, daleko mniej dotknięte.

Na Odrze rzuciła siła trąby jedną szkutę na drugą, przyczem obie utonęły, i zginęło pięć osób.

Na domiar utrapienia wieczorem gwałtownie deszcz zaczął padać: woda lała się strumieniami do domów, pozbawionych dachów i górnych sufitów, niszcząc ruchomy dobytek, towary i zapasy żywności.

Gdy noc nastała, nikt nie myślał o spoczynku. Rozlegały się wciąż płacze i jęki, a nie ustawała też praca około niesienia ratunku zasypanym gruzami.

Naliczono 5 ludzi zabitych na placach i ulicach; z pod gruzów wydobyto 3 trupy; ocalono 5 osób, mniej lub więcej niebezpiecznie poranionych.

Chc.

Figure 3. Description of a tornado on 14 May 1886 near Krosno Odrzańskie (in Polish). Source: *Gazeta Polska* newspaper, 22 May 1886.

Table 1. Digital libraries used in the analysis.

Original name	English name	Web address
Bałtycka Biblioteka Cyfrowa	Baltic Digital Library	http://bibliotekacyfrowa.eu/dlibra
Biblioteka Cyfrowa Uniwersytetu im. Marii Curie-Skłodowskiej	Marie Curie-Skłodowska University E-Library	http://dlibra.umcs.lublin.pl/dlibra
E-Biblioteka Uniwersytetu Warszawskiego	University of Warsaw E-Library	http://ebuw.uw.edu.pl/dlibra
Kujawsko-Pomorska Biblioteka Cyfrowa	Kuyavian-Pomeranian Digital Library	http://kpbc.umk.pl/dlibra
Łódzka Biblioteka Cyfrowa	Łódź Digital Library	http://bc.wimbp.lodz.pl/dlibra
Małopolska Biblioteka Cyfrowa	Lesser Poland Digital Library	http://mbc.malopolska.pl/dlibra
Podkarpacka Biblioteka Cyfrowa	Subcarpathian Digital Library	http://www.pbc.rzeszow.pl/dlibra
Portal Biblioteki Narodowej	Portal of the National Library	http://polona.pl/search/
Śląska Biblioteka Cyfrowa	Silesian Digital Library	http://www.sbc.org.pl/dlibra
Świętokrzyska Biblioteka Cyfrowa	Świętokrzyskie Digital Library	http://sbc.wbp.kielce.pl/dlibra
Wielkopolska Biblioteka Cyfrowa	Greater Poland Digital Library	http://www.wbc.poznan.pl/dlibra
Zachodniopomorska Biblioteka Cyfrowa	West Pomeranian Digital Library	http://zbc.ksiaznica.szczecin.pl/dlibra

3.6 Other sources (additional information on individual tornado cases)

An investigation of individual tornado cases was supported by web searches (media reports, social media, forum of the Polish Stormchasing Society), damage surveys, surface observations, lightning data, satellite data, radar data, aerial and global forest change project data (Hansen et al. 2013). In a few cases, archived synoptic weather charts and original scientific papers were derived from the library of the IMGW-PIB (e.g. Gumiński 1936, Rafałowski 1958, Salomonik 1960). For the purposes of a tornado case study from 14 July 2012, a 24-hour forecast was produced using a non-hydrostatic Weather and Research Forecasting Model (WRF) simulation with a spatial resolution of 15 km (Skamarock et al. 2005). The boundary and initial conditions were extracted based on the global simulation of the Global Forecast System (GFS; Yang et al. 2006) with a horizontal resolution of 0.5°.

Chapter 4

Methodology

Quality control assumptions and primary research methods used in each study are presented below.

4.1 Lightning data

A threat for severe thunderstorms is estimated by dividing days with thunderstorms according to the daily, monthly and annual sums of CG lightning flashes. Given measurements for years 2002–2013, results are presented in the form of tables, charts, and maps involving annual, monthly and hourly variation of CG lightning flashes. Temporal and spatial variability of polarity, peak current and percentage of nighttime flashes is involved as well. Data is limited to the geographical borders of Poland. Instead of strokes, only flashes are taken into account. According to the previous studies of Cummins et al. (1998) and Wacker and Orville (1999a,b) some of the CG positive lightning flashes with the peak current below 10 kA may be considered to be IC flashes, therefore database was also filtered out from these flashes.

4.2 Tornado data

A threat for tornadoes is estimated by collecting all available reports from years 1899–2014. Reports derived from the ESWD, forum of the Polish Stormchasing Society, and media reports are subjected to the quality control procedures which allow to filter suspicious cases and create a final database of 269 events. Cases are evaluated in terms of their credibility and intensity in *F*-scale, and divided on weak tornadoes, strong tornadoes and waterspouts. These are analyzed in terms of their temporal variability in years, months and time of the day. Spatial analysis include Kernel Density Estimation and statistics by Voivodeships of Poland. A comparison with American and European records is presented as well.

4.3 Deadly tornado data

A threat for deadly tornadoes is estimated by collecting all available reports from years 1820–2015. They are analyzed in terms of their intensity and temporal variability in decades, months and time of the day. Spatial analysis include statistics by Voivodeships of Poland and tornado damage tracks for selected cases. In addition, the most important factual information on each killer tornado case (as derived from the scientific literature and historical sources) is included. The return period is estimated by the statistical approximation including periodicity of significant and killer tornado cases.

4.4 Radiosonde data

Thermodynamic and kinematic conditions conducive to the tornado occurrence in Poland are defined by combining tornado reports from the ESWD and radiosonde measurements derived from the University of Wyoming sounding database. Proximity criteria allow to use certain sounding in the analysis if tornado event took place up to 3 hours prior to 6 hours after the sounding time (12 or 18 UTC), and no farther than 200 km away from the sounding site. A total of 97 cases including measurements from 10 sounding sites from years 1977–2012 are considered in the analysis. These are divided according to their intensity and environmental temperature. From each sounding profile, various thermodynamic and kinematic parameters are derived. In order to evaluate their forecasting value, tornado-related soundings are compared with thunderstorm and non-thunderstorm sounding profiles. Results are presented in the form of scatterplots and box-and-whisker charts.

4.5 Tornado prediction

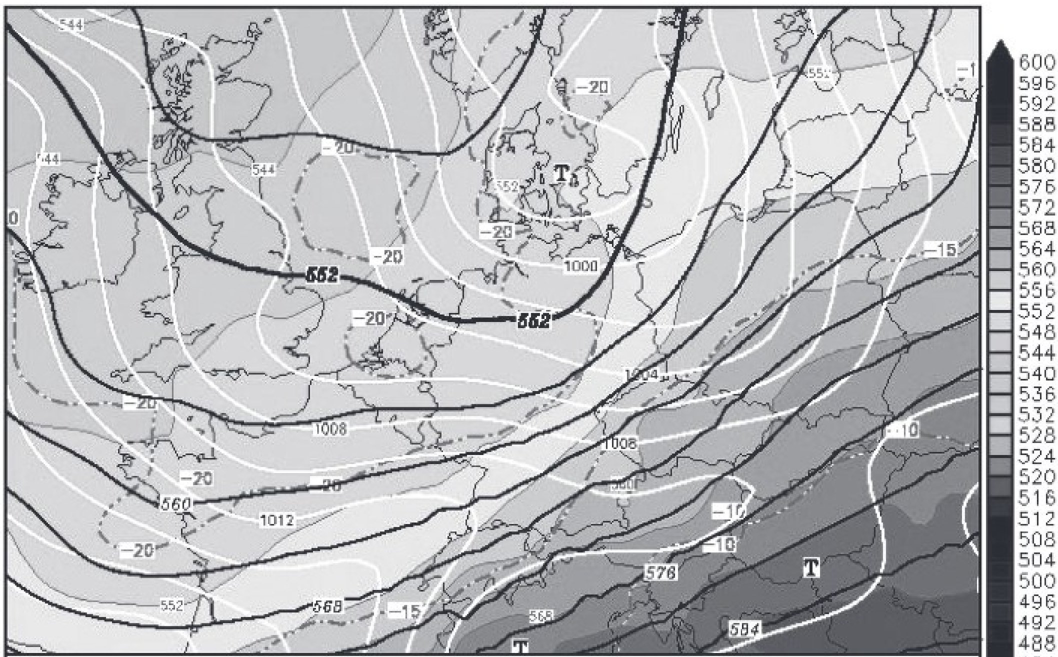
Possibilities to forecast tornadoes are evaluated by: reviewing scientific literature, analyzing available forecasting techniques, local climate characteristics and the prevalence of the tornadoes in Poland. Institutions performing convective forecasts and the severe weather awareness of the Polish society is evaluated as well. The analysis is presented in the form of the review.

4.6 Case study of 14 July 2012

A tornado event of 14 July 2012 is studied by analyzing the course of the event, synoptic and mesoscale meteorological conditions, and by assessing the possibilities of its short-term prediction. Damage survey, surface observations, lightning data, satellite data, radar data, aerial and global forest change project data are used to analyze the event. Possibilities of tornado prediction are assessed by performing an experimental WRF downscalling simulation based on 0000 UTC GFS grib 15 hours prior to the event. Tornado potential is estimated by the use of thermodynamic and kinematic indices, chosen on the basis of scientific literature related to tornado environments in the United States and Europe (the same as listed in the end of the section 3.4). A comparison with significant tornado cases of 20 July 2007 and 15 August 2008 is presented as well.

Chapter 5 (Appendix A)

Forecasting the possible emergence of tornadoes in Poland



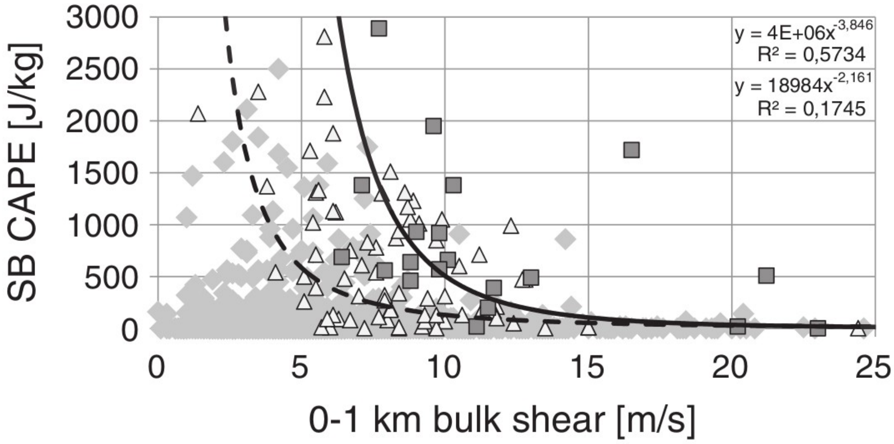
500 hPa Geopotencjał [gpdam] oraz Temperatura [^{O}C], Ciśnienie [hPa], względna Topografia [gpdam]
Sobota, 14-07-2012 12 UTC (GFS 0,5^{0}) (Analiza) www.wetter3.de

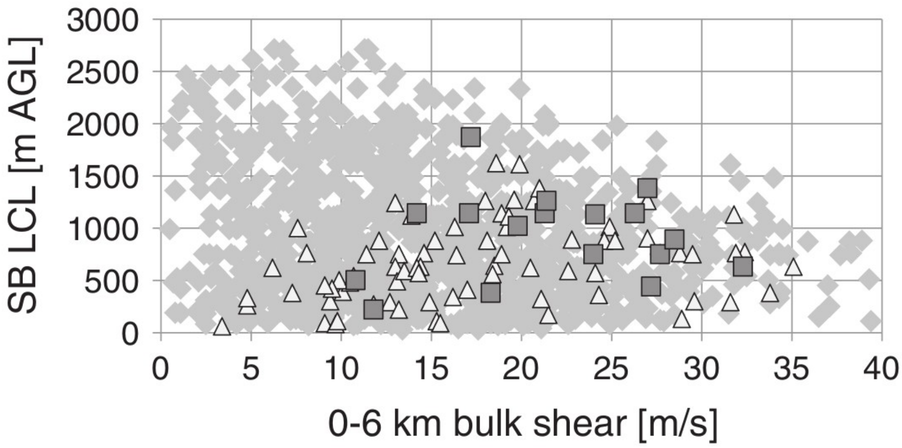
500 hPa Geopotential [gpdam] and Temperature [^{O}C], Pressure [hPa], relative Topography [gpdam]
Saturday, 14-07-2012 12 UTC (GFS 0,5^{0}) (Analysis) www.wetter3.de

Przegląd Geograficzny, 2013, Volume 85, pp 323–340

Chapter 6 (Appendix B)

Sounding-derived parameters associated with tornado occurrence in Poland and Universal Tornadic Index

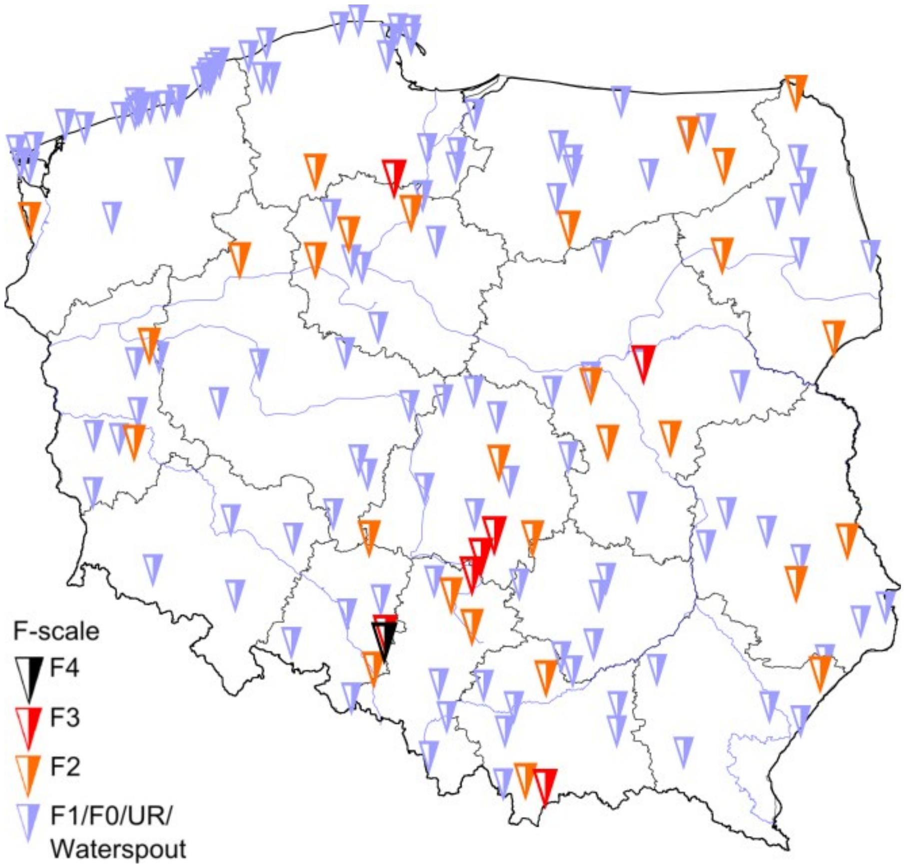




Atmospheric Research, 2013, Volume 134, pp 186-197

Chapter 7 (Appendix C)

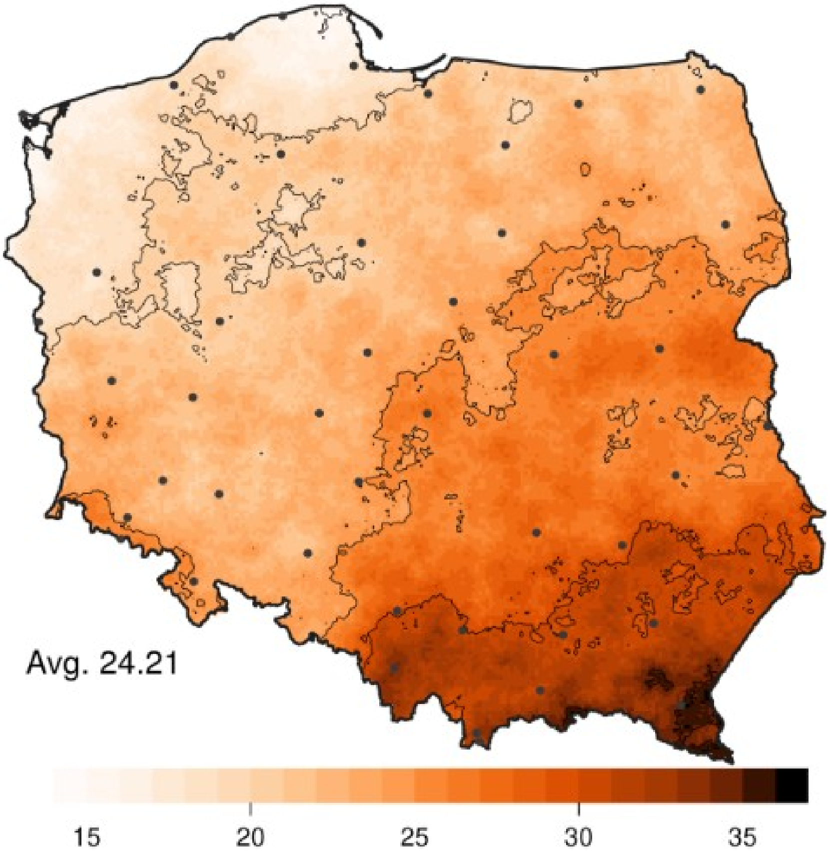
Tornado climatology of Poland



Monthly Weather Review, 2015, Volume 143, pp 702–717

Chapter 8 (Appendix D)

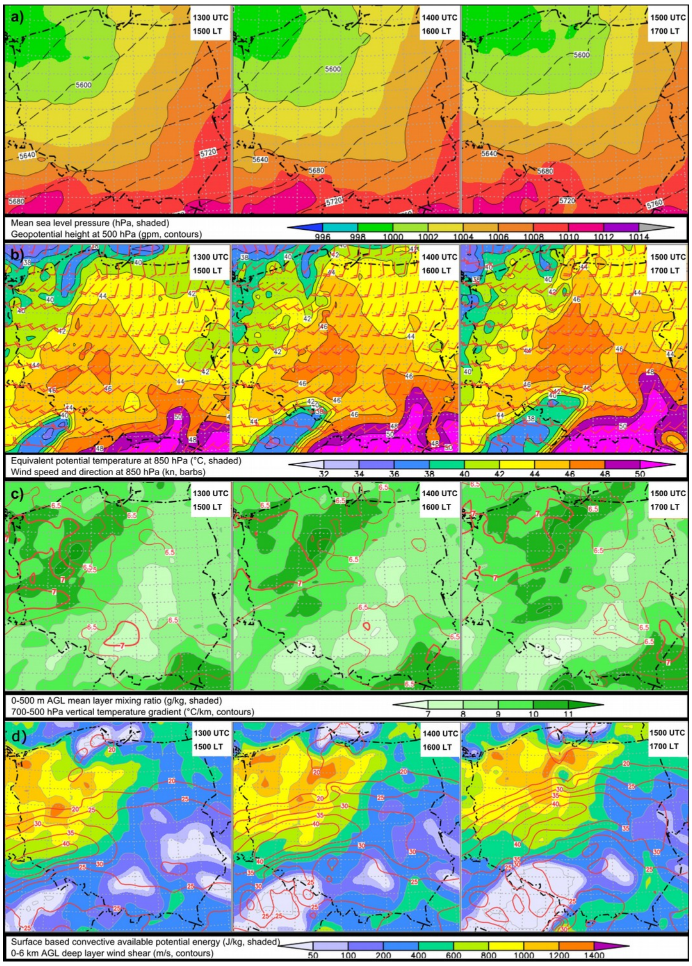
A cloud-to-ground lightning climatology for Poland



Monthly Weather Review, 2015, Volume 143, pp 4285–4304

Chapter 9 (Appendix E)

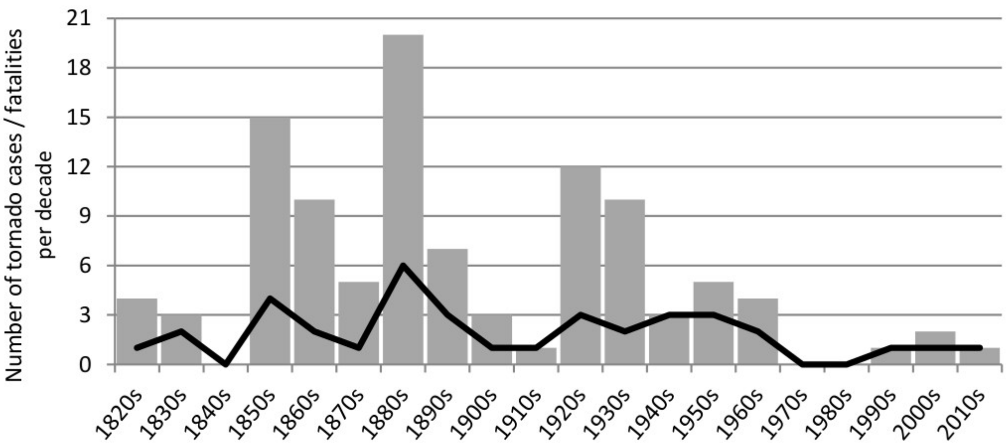
An isolated tornadic supercell of 14 July 2012 in Poland - a prediction technique within the use of coarse-grid WRF simulation



Atmospheric Research, 2016, Volume 178, pp 367–379

Chapter 10 (Appendix F)

Deadly tornadoes in Poland from 1820 to 2015



Monthly Weather Review, 2016 (in press)

Chapter 11

Summary of results

Below, the most important results regarding each topic are presented:

11.1 Thunderstorm climatology

a. The annual average of around 360 000 CG lightning flashes occur each year over Polish territory. This results in an average of 150 days with thunderstorms appearing anywhere in Poland.

b. The average annual number of days with a thunderstorm within a particular location increases from the northwest to the southeast of Poland with the lowest values along the coast of Baltic Sea (15−20 days) and the highest in the Carpathian Mountains (30−35 days).

c. The spatial distribution of the mean annual CG lightning flash density varies from 0.2 to 3.1 flashes km^{-2} yr^{-1} reaching the lowest values along the coast of Baltic Sea and the highest in the southwest-northeast belt from the Kraków-Częstochowa Upland to the Masurian Lake District.

d. Majority of CG lightning flashes are detected during the daytime with the peak at 1400 UTC and the minimum at 0700 UTC. While the activity of less severe thunderstorms drops after 1700 UTC, intense thunderstorms remain active until the late evening hours.

e. Most intense thunderstorms occur from May to August and peak in July as the most intense month (an average of 4 days with at least 10 000 CG lightning flashes).

f. Very intense thunderstorms are capable of producing locally in only one day more CG lightning flashes that on average occur during the whole year in this particular place. The highest values of maximum daily CG lightning flash density are observed in the central and eastern parts of the country.

g. Approximately 15% of all CG lightning flashes occur during nighttime hours.

h. An increase in the frequency of mesoscale convective systems (MCS; Houze 2004) and the percentage of nighttime CG lightning flashes has been observed in the recent years.
i. During years 2002–2013, 26 June 2006 turned out to be the day with the highest number of detected CG lightning flashes (73 549).
j. Almost 97% of all CG lightning flashes had negative current reaching the highest average monthly values in February (55 kA) and the lowest in July (24 kA). The percentage of positive CG lightning flashes was the lowest from May to October (from 2 to 3%), while from November to April it amounted from 10 to 20%.

11.2 Tornado climatology

a. Polish tornado records suffer from the strong underreporting of weak tornado cases. After the foundation of the Polish Stormchasing Society in 2008, the quality of tornado reporting has considerably improved.
b. 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. Violent tornadoes occur once every one or two decades.
c. An average of 1–2 killer tornadoes with 5 fatalities may be depicted for each decade. It is estimated that around 5–10% of significant tornadoes in Poland cause fatalities, while the average number of fatalities per any significant tornado amounts to roughly 0.27.
d. The majority of deaths and injuries due to tornadoes in Poland were associated with people being lifted or crushed by collapsed buildings (usually wooden barn). Most of these cases took place in rural areas but some tornadoes did hit urban areas, causing a higher number of fatalities.
e. The most deadly tornado in a Polish history occurred on 14 May 1886 at around 1230 UTC in Krosno Odrzańskie in Lubusz Voivodeship and killed 13 people (Figure 4).
f. Tornadoes occur most likely from May to September with July as the peak month for tornadoes forming over land, and August for waterspouts. They are the most frequent between 1500 and 1800 UTC, whereas waterspouts peak between 0900 and 1200 UTC.
g. The highest number of significant tornado reports over the course of the last 200 years took place in the south-central part of the country. Taking into account also tornado reports in other parts of the country, an apparent correlation between tornado frequency and orography can be found.
h. Tornadoes are prone to occur together with southwestern and western airmass advections.

Figure 4. Damage in Krosno Odrzańskie due to tornado on 14 May 1886. Source: the collection of the Piast Castle in Gliwice.

11.3 Tornado forecasting

a. Due to a very small scale of phenomenon, it is not possible nowadays to predict with great accuracy where and when tornado will take place. The phenomenon of a span of several hundred of meters is not captured by mesoscale NWP models in which a mesh size is a few kilometers. However, within the use of the same NWP models it is possible to predict the conditions conducive to the occurrence of supercells that can produce tornadoes.

b. Depending on the airmass temperature, tornadoes in Poland tend to present different environmental conditions. Warm airmass tornadoes feature with increased atmospheric instability and moderate vertical wind shear while cold airmass tornadoes are characterized by dynamic wind field (high vertical wind shear) and rather marginal instability.

c. Significant tornadoes are characterized by higher than in weak cases convective available potential energy (CAPE), deep layer wind shear (DLS), low-level wind shear, storm relative helicity, boundary layer's moisture content and the presence of low-level jet stream. Their occurrence is related to supercell thunderstorms that are possible to predict within the use of NWP models.

d. Weak tornadoes are characterized by increased CAPE released below 3 km above ground level, low lifted condensation level and weak vertical wind shear. They are mostly related to wind-shift boundaries with preexisting vertical vorticity and developing convection. Tornadoes forming this way are difficult in prediction.

e. The use of WRF downscaling model simulations may be supportive of predicting atmospheric conditions conducive to severe convective weather, including tornadic supercells.

f. An experimental 24-hour WRF simulations performed for tornado events of 20 July 2007, 15 August 2008 and 14 July 2012 shown that within the use of forecasting technique including certain convective parameters and convective precipitation filter, it was possible to indicate with a lead time of several hours areas where tornadoes may possibly form.

Chapter 12

Conclusions and discussion

The main objective of the research was to estimate spatial and temporal variability of thunderstorms and tornadoes in Poland. This aim was achieved by creating and analyzing a large database of almost 5 million CG lightning flashes and a database of over 450 tornado reports derived from the ESWD and media sources. A research performed on historical sources allowed to expand tornado database with 26 newly identified deadly tornado events and update information on 11 currently known cases.

The development of such studies become possible thanks to changes that took place in Poland in the last 10–15 years. These included the development of POLRAD and PERUN networks, increase in the exchange of weather information by the Internet, technological development of mobile devices, increase in severe thunderstorm monitoring, development of social media and a more systematic efforts to collect severe weather reports (the foundation of the ESWD and the Polish Stormchasing Society). However, it has to be accepted that due to only 12 years of lightning detection measurements and limitations regarding tornado reporting, obtained climatological results will always be uncertain and remain only an approximation of the real distributions. Nevertheless, knowing at least 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. For this reason, it is believed that results obtained within this research carry a practical value and may be used alike in operational forecasting as well as in future studies regarding severe thunderstorm occurrence in Poland.

Although some part of the results found within this research allowed to confirm results from previous severe weather related studies from United States and Europe, many new findings have been introduced. Perhaps one of the most important ones concerns discovery of numerous historical tornado cases that took place in the last 200 years and proved that Poland is threatened to the occurrence of even F4 tornadoes. This finding stays in the opposition to the popular statement that "*tornadoes in Poland are a new thing and become more frequent due to changing climate*". Obtained results indicate that this phenomenon is not new for Poland and that numerous significant and killer tornadoes occurred in the past. High-quality European tornado observations that began only in the late 2000s also do not allow to determine any climate trends regarding tornado occurrence. Therefore, it is not possible to clearly determine if the frequency of tornadoes increases or not due to changing climate.

The second important finding concerns the study on CG lightning climatology that is the first of this type ever performed for Poland. Although the occurrence of the thunderstorms basing on human observations has been previously studied by Bielec-Bąkowska (2003) and Kolendowicz (2006), this study introduced new and unique findings regarding annual, monthly, diurnal and spatial lightning activity. In the opposition to the studies based on data from meteorological stations (that are sparsely distributed in space and perform measurements usually only once per hour), lightning data allows to analyze thunderstorm characteristics with a greater extent of details, especially involving the intensity of thunderstorms. One of the most important result indicates that severe thunderstorms occur most likely in the southwest-northeast belt from the Kraków-Częstochowa Upland to the Masovian Lowland (Figure 5a).

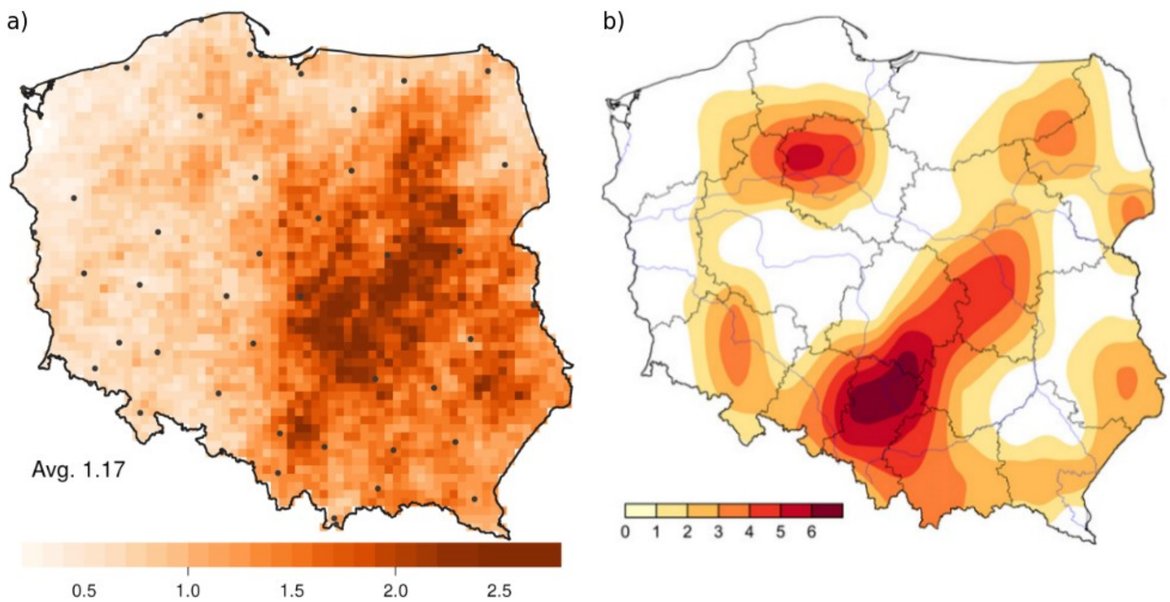


Figure 5. (a) The average annual number of CG lightning flashes per km^2, based on lightning data derived from PERUN network for period 2002 to 2013. Dots denote main meteorological stations (44). Source: Taszarek et al. (2015). (b) The number of significant tornado (F2+) reports per 100x100 km area in 1899–2013 timeframe estimated using kriging. Source: Taszarek and Brooks (2015).

Almost the same conclusion was found in the study regarding a spatial distribution of significant tornadoes over the course of the last 100 years (Figure 5b). In addition, studies on the large hail occurrence by Kłokowska and Lorenc (2012), Taszarek and Suwała (2012) and Pilorz (2015) also indicated this area (and the south-eastern part of Poland) as a vulnerable for the thunderstorms producing large hail. This supports the theory that aforementioned area may be somehow conducive to the occurrence of thunderstorms (probably supercells) producing severe convective phenomena. However, more studies involving the analysis of thermodynamic and kinematic conditions (from the climatological point of view), are needed to confirm this theory.

Another important finding concerning lightning data indicates that diurnal course of CG lightning flashes varies depending on the geographical location. Although the average percentage of nighttime flashes for the whole country amounts around 15%, values in the western and southwestern part of the country ranges from 30 to 40% (Figure 6). This is presumably due to a more frequent occurrence of intense MCSs, which enter Poland from Germany and Czech Republic in the late evening hours. These appear less likely in the eastern part of the country where mostly daytime convection develops. Such findings are one of the first ever obtained for Poland.

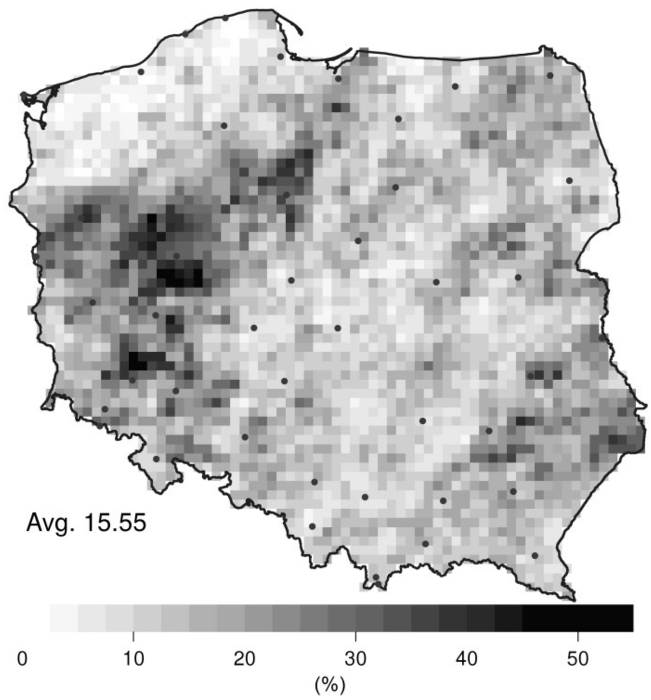


Figure 6. The average percentage of CG lightning flashes occurring during the nighttime (sun angle <-12°). Computed in 10 km x 10 km grid cells. Based on lightning data derived from PERUN network for period 2002 to 2013. Dots denote main meteorological stations (44). Source: Taszarek et al. (2015).

The results obtained on atmospheric conditions conducive to tornado occurrence in Poland mostly line up with the previous such analyses performed for United States. (e.g. Rasmusen and Blanchard 1998, Thompson et al. 2003, Craven and Brooks 2004) and Europe (Groenemeijer and van Delden 2007, Kaltenböck et al. 2009). However, they also introduce new findings regarding tornado occurrences depending on the temperature of the airmass with warm airmass tornadoes favored by high CAPE and moderate shear environments, and cold airmass tornadoes favored by low CAPE and high shear environments. This indicates that forecasters, should pay an attention to various atmospheric configurations while performing tornado prediction, and not focus only on one certain pattern.

An analysis regarding possibilities of tornado prediction, indicates that thanks to the POLRAD network and NWP models (which from year to year become increasingly better), it is possible in Poland to issue tornado forecasts and real-time warnings. However, due to lack a special system that would allow to share such an information quickly and efficiently to the public, rather low frequency of tornadoes in Poland, and still low severe weather awareness of the Polish society, one may question the need of such a system and procedures. Perhaps unjustly. Based on the records from the entire period of study, it is estimated that an average of 20 significant and 1–2 deadly tornadoes occur each decade in Poland. Each year Poland experiences 150 days with the thunderstorm including 10 with at least 10 000 CG lightning flashes. Approximately 10 people die due to severe thunderstorms each year. For these reasons, the author believe that the consideration of a real-time severe thunderstorm and tornado warning procedures in Poland (similar to those performed by the National Weather Service in U.S.) should be taken into account. This way people would have a possibility to receive a highly credible information about a possible danger in their surroundings, and shortly before the incident, take action to protect their lives. Such a solution is technically possible and can contribute significantly to the improvement of safety. We can neither prevent nor control the occurrence of severe thunderstorms, but because human safety is the most important issue, we should be able to do everything in order to inform people, in advance, about upcoming danger. Numerous high-impact killer tornadoes that occurred over the last 200 years, indicate that similar events are highly likely to appear in the future. The question is whether we will be able to protect people when the next such an event is going to happen.

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Appendix A

Bibliographic record:

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http://dx.doi.org/10.7163/PrzG.2013.3.2

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Author contribution statement:

M.T. designed the study, acquired and analyzed data, made figures, wrote the manuscript, improved the final version of the manuscript.

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2013, 85, 3, s. 353–371

Możliwości prognozowania trąb powietrznych w Polsce

Forecasting the possible emergence of tornadoes in Poland

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Zarys treści. Artykuł zawiera ocenę obecnych możliwości prognozowania trąb powietrznych w Polsce. Autor dokonuje przeglądu literatury związanej z mechanizmami powstawania trąb powietrznych oraz klimatycznymi uwarunkowaniami tego zjawiska w Polsce. Na podstawie aktualnych osiągnięć nauki oraz sposobów obecnie wykorzystywanych przez synoptyków, opisuje 3 metody (numeryczne modele pogody, nowcasting oraz sondowania atmosferyczne), używane przy wydawaniu ostrzeżeń oraz prognozowaniu trąb powietrznych. Na ich podstawie, autor wyznacza 4 poziomy operacyjne, na których możliwe jest wydawanie prognoz i ostrzeżeń dotyczących możliwości powstania trąby powietrznej. Analiza wykazała, że Polska dysponuje odpowiednią infrastrukturą radarową do szczegółowego monitorowania echa radarowego związanego z superkomórką, jednak ze względu na małą skalę zjawiska nie ma jeszcze rozwiniętych specjalistycznych systemów ostrzegania.

Słowa kluczowe: trąba powietrzna, niebezpieczne zjawiska meteorologiczne, Polska, prognozowanie, superkomórka, tornadogeneza.

Wstęp

Tornado – czyli gwałtownie wirująca kolumna powietrza, rozciągająca się w pionie od poziomu kondensacji chmury *cumulonimbus* aż do powierzchni ziemi (Edwards i inni, 2004) w polskiej nomenklaturze nazywane jest „trąbą powietrzną". Zjawisko to było notowane praktycznie na każdym kontynencie oprócz Antarktydy. Powstaje najczęściej w strefach ścierania się dwóch zróżnicowanych termicznie oraz wilgotnościowo mas powietrza, co jest charakterystyczne dla strefy umiarkowanej. Największe nasilenie tego zjawiska pod względem ilościowym oraz jakościowym występuje w rejonie Wielkich Równin Stanów Zjednoczonych, gdzie wilgotne i ciepłe masy powietrza znad Zatoki Meksykańskiej spotykają się z chłodniejszymi i bardziej suchymi masami powietrza znad Gór

http://dx.doi.org/10.7163/PrzG.2013.3.2

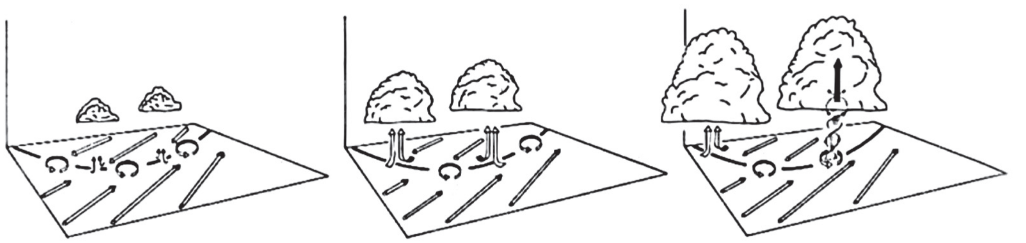
Skalistych (Concannon i inni, 2000). Z danych National Oceanic Atmospheric Administration (NOAA) wynika, że w stanach takich jak Kansas czy Teksas zjawisko jest dosyć powszechne (ponad 100 rocznie) i istotnie zagraża życiu ludzi. Jego siłę określa się w skali zniszczeń, jakie powoduje wiatr o określonej prędkości. Najczęściej używa się skali Fujity (Fujita, 1971) oraz TORRO (Meaden i inni, 2007). W Polsce funkcjonuje również 3-stopniowa skala dostosowana do polskich warunków, zaproponowana przez H. Lorenc (2012). W Polsce tornada osiągają największą aktywność w okresie od maja do sierpnia, w godzinach 16.00–20.00 (Taszarek, 2012). Według H. Lorenc (2012) największe prawdopodobieństwo ich wystąpienia notuje się w sierpniu (7%) oraz lipcu (5%). Średnia wieloletnia – to około 4 incydenty rocznie, jednak w ostatnich latach notuje się wzrost nawet do 10–12 przypadków rocznie (Lorenc, 2012; Taszarek, 2012). Najwięcej zjawisk trąby powietrznej pojawia się w pasie od Wyżyny Krakowsko-Częstochowskiej aż po Podlasie, obszar ten nazywany jest „szlakiem przemieszczania się trąb powietrznych w Polsce" (Lorenc, 2012) bądź też „polską aleją trąb powietrznych" (Taszarek, 2012). Amerykanie od wielu lat badają mechanizmy odpowiedzialne za powstawanie trąb powietrznych (Davies-Jones i inni, 2001) i rozwijają systemy ich wczesnego wykrywania oraz ostrzegania (Stensrud i Gao, 2010). W Polsce nie posiadamy jeszcze takich systemów, gdyż trąby powietrzne występują rzadko i zazwyczaj nie generują tak dużego zagrożenia jak w Stanach Zjednoczonych. Dramatyczne przypadki z ostatnich lat: 20.07.2007 (Bebłot i inni, 2008; Parfiniewicz, 2009), 15.08.2008 (Lorenc i inni, 2008; Bebłot i inni, 2010) oraz 14.07.2012 r., kiedy wystąpiły trąby powietrzne o sile F3 w skali Fujity i spowodowały śmierć ludzi wskazują jednak, że warto rozważyć, jakie są w Polsce obecne możliwości prognozowania i ostrzegania przed tym zjawiskiem. Celem artykułu nie była ocena i weryfikacja ilościowa dotychczas stosowanych procedur i prognoz trąb powietrznych, ale przegląd stosowanych metod i instytucji, które takie prognozy wykonują. Kwestia prognozowania trąb powietrznych wbrew powszechnej opinii jest w Polsce nowa i dotychczas Instytut Meteorologii i Gospodarki Wodnej nie posiadał odpowiednich systemów ani procedur do wydawania ostrzeżeń o trąbie powietrznej, trudno więc dokonać oceny wykonanych prognoz.

Mechanizm powstawania

Podstawą wszelkich prognoz jest znajomość procesów fizycznych jakie odpowiadają za powstawanie danego zjawiska. Dotychczas nie poznano wszystkich elementów tornadogenezy, ale aktualna wiedza pozwala na wyjaśnienie wielu aspektów powstawania trąb powietrznych. Prekursorami badań nad mechanizmem ich powstawania byli Amerykanie, którzy mieli szerokie możliwości obserwowania tych zjawisk. Obecna teoria mówi, że do powstania trąby powietrznej potrzebne jest wystąpienie pionowej wirowości powietrza, która po rozciągnięciu może uzyskać rozmiar trąby powietrznej (Markowski i Richardson, 2009). Taka wirowość może mieć różną genezę. J.M. Davies-Jones i inni (2001) wyróżnili dwa podstawowe mechanizmy.

Trąby powietrzne niezwiązane z mezocyklonem

Pierwszy jest związany z obecnością pionowej wirowości powietrza w rejonach horyzontalnego uskoku wiatru, czyli strefach, gdzie wiatr w płaszczyźnie poziomej nagle zmienia kierunek (Wakimoto i Wilson, 1989; Wilczak i inni, 1992). Takimi strefami mogą być granice frontu chłodnego, strefy konwergencji, linie szkwałowe (Carbone, 1982; Lorenc, 2012), bądź też lokalne turbulencje związane z ruchami w obrębie chmury konwekcyjnej. Horyzontalne uskoki wiatru w takich strefach powodują występowanie pionowych rotorów powietrza o różnej skali, od małych – przy lokalnej turbulencji do dużych – w przypadku frontu chłodnego. Ich wirowość jest zazwyczaj cyklonalna i cechuje ją nietrwałość. Sytuacja ulega zmianie, kiedy nad rotorem pojawia się chmura z silnymi ruchami wnoszącymi (ryc. 1). Powoduje to rozciąganie rotoru w pionie, co wiąże się ze zmniejszaniem jego średnicy, zwiększaniem prędkości kątowej i wreszcie obniżeniem ciśnienia w centrum (Markowski i Richardson, 2009). Przy sprzyjających warunkach wir może osiągnąć wielkość trąby powietrznej i rozciągać się pomiędzy poziomem kondensacji a powierzchnią ziemi. Trąby powietrzne



Ryc. 1. Schemat powstawania trąb powietrznych niezwiązanych z mezocyklonem w strefach konwergencji

The formation of a non-mesocyclonic tornado along a convergence line

Źródło / Source: Wakimoto i/and Wilson (1989).

powstałe w ten sposób nazywane są trąbami lądowymi lub wodnymi (ang. *landspout*, *waterspout*; Bluestein, 1985) i mogą uzyskać prędkość w leju do około 200 km h^{-1} osiągając zazwyczaj siłę F1. Trwają od kilkunastu sekund do kilku-kilkunastu minut. Występują najbardziej powszechnie, ale ze względu na małe rozmiary oraz częste „wtopienie" w struktury frontowe, są jednocześnie bardzo trudne do wykrycia w systemach radarowych (Lorenc, 2012). Ze względu na krótki cykl życia oraz powodowanie umiarkowanych zniszczeń, ich detekcja ma operacyjnie małe znaczenie (fakt, że w momencie wykrycia najczęściej już nie istnieją, ogranicza podejmowanie jakichkolwiek działań).

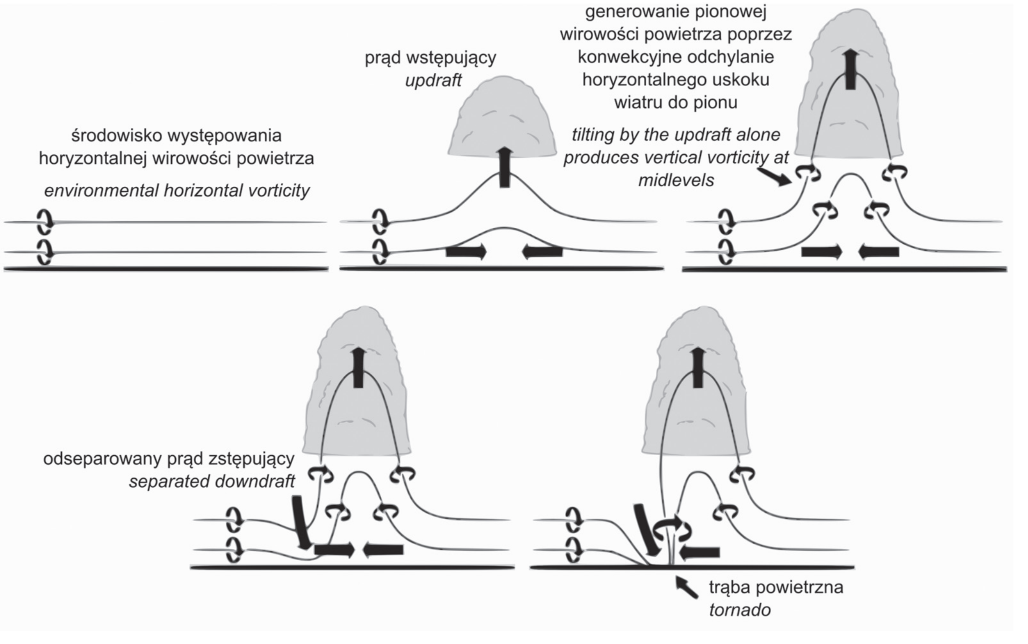
Superkomórkowe trąby powietrzne

Drugi mechanizm powstawania trąb powietrznych związany jest z obecnością mezocyklonu – wirującej w osi pionowej rozbudowanej chmury *cumulonimbus* zwanej superkomórką (Browning, 1964). Superkomórki występują w środowisku podwyższonych pionowych uskoków prędkościowych oraz kierunkowych wiatru, które warunkują powstawanie rotorów wirujących w osi poziomej. Przy obecności silnej konwekcji, rotory te odchylane są w kierunku pionowym i powodują wirowanie całego układu (Lorenc, 2012). Istnienie mezocyklonu związane jest również z odseparowaniem prądów wstępujących i zstępujących. Zapewnia to chmurze burzowej stały dostęp do energii w postaci ciepłego i wilgotnego powietrza, gdyż jego napływ nie jest ograniczany prądami zstępującymi. Ze względu na znaczne prędkości w wyższych partiach atmosfery (obecność prądu strumieniowego), rdzeń konwekcyjny mezocyklonu zazwyczaj pochylony jest zgodnie z kierunkiem wiatru z wyższych partii troposfery. Zagrożenie zejściem trąby powietrznej występuje wtedy, kiedy odseparowany prąd zstępujący w tylnej części chmury „odetnie" główny rdzeń mezocyklonu od poziomego rotoru przy powierzchni ziemi (ryc. 2).

Przy znacznie obniżonym poziomie kondensacji i obecności chmury stropowej, wir po osiągnięciu powierzchni ziemi obniża ciśnienie w swoim centrum i staje się trąbą powietrzną. Superkomórki są odpowiedzialne za zdecydowaną większość silnych i niszczycielskich trąb powietrznych (Doswell i Burgess, 1993). W Polsce tornada związane z superkomórkami mogą osiągać siłę nawet do F4 w skali Fujity (Gumiński, 1936). Występują jednak w środowisku o bardzo charakterystycznych warunkach kinematycznych i termodynamicznych, które w skali synoptycznej można przewidzieć. W systemach radarowych dają zazwyczaj charakterystyczne odbicie, co znacznie zwiększa szanse na ich detekcję. Ich cykl życia w warunkach polskich może trwać nawet do godziny (przypadek z 14.07.2012) – umożliwia to podjęcie działań w celu ostrzeżenia mieszkańców znajdujących się na trajektorii takiej superkomórki.

Badania klimatologiczne

Badania klimatologiczne nad trąbami powietrznymi pełnią równie ważną rolę jak badania nad mechanizmami ich powstawania. Szczególnie istotne są opracowania, w których analizuje się parametry fizyczne pochodzące z sondowań atmosferycznych. Niektóre prace analizują również dane pochodzące z numerycznych modeli pogody, porównując je z występowaniem trąb powietrznych. Prekursorami tego typu badań byli Amerykanie (Rasmusen i Blanchard, 1998; Rasmusen, 2003; Thompson i inni, 2004; Craven i Brooks, 2004), którzy jako pierwsi wyznaczyli parametry charakterystyczne dla środowisk sprzyjających trąbom powietrznym. W Europie podobne badania prowadzili A. Haklander i A. van Delden (2003), P.H. Groenmeijer i A. van Delden (2007), S. Grünwald i H.E. Brooks (2011). W Polsce klimatologiczne analizy występowania trąb powietrznych wykonali S. Walczakiewicz i inni (2011), H. Lorenc (2012) oraz M. Taszarek (2012). Pojedyncze przypadki najsilniejszych trąb powietrznych



Ryc. 2. Schemat powstawania superkomórkowej trąby powietrznej
The formation of a supercell tornado
Źródło / Source: Markowski i/and Richardson (2009).

były analizowane przez H. Lorenc i innych (2008), G. Bebłot (2008), J.W. Parfiniewicz (2009) oraz G. Bebłot i innych (2010). Wyniki tych badań pozwalają nam nie tylko stwierdzić, kiedy i gdzie najczęściej występują trąby powietrzne, ale również określić parametry termodynamiczne i kinematyczne, które można zastosować w numerycznych modelach pogody jako predyktory. Przykładami wskaźników, które powstały w ten sposób i są dedykowane prognozowaniu trąb powietrznych są: Significant Tornado Parameter (Thompson i inni, 2002), Non-supercell Tornado Parameter (Baumgardt i Cook, 2006), Szilagyi Waterspout Index (Keul i inni, 2009), Energy Helicity Index (Davies, 1993) czy też Universal Tornadic Index (Taszarek i Kolendowicz, 2013).

Możliwości prognozowania i ostrzegania

Obecna infrastruktura techniczna oraz wiedza dotycząca trąb powietrznych, pozwala wyróżnić trzy metody, które wykorzystuje się przy prognozowaniu tych zjawisk.

Numeryczne modele pogody

Pierwszą, najbardziej prężnie rozwijaną, jest analiza numerycznych modeli pogody, które są symulatorem procesów fizycznych zachodzących w atmosferze. Wykorzystuje się w nich dynamikę ruchu cząsteczki oraz procesy termodynamiczne jakim podlega. Dzięki numerycznym modelom pogody możemy uzyskiwać informacje dotyczące stanu atmosfery w najbliższych kilkudziesięciu godzinach. Modele takie działają w różnych skalach przestrzennych: mikroskali, mezoskali oraz skali synoptycznej.

Mikroskala

Trąba powietrzna jest zjawiskiem lokalnym, często o średnicy kilkudziesięciu metrów, dlatego do jej analizy powinno się używać dokładnych modeli z rozmiarem siatki kilkunastu metrów. Niestety ruch cząstek w takiej skali jest niezwykle trudno opisać, gdyż wymaga uwzględnienia ogromnej ilości detali, konieczne są więc specyficzne metody i uproszczenia. Sprawiają one, że uzyskane wyniki w skali kraju nie są na tyle wiarygodne, aby skutecznie prognozować trąby powietrzne. Obecnie nie ma na świecie modeli mikroskalowych, które obejmowałyby tak duże obszary i były wykorzystywane operacyjnie.

Mezoskala

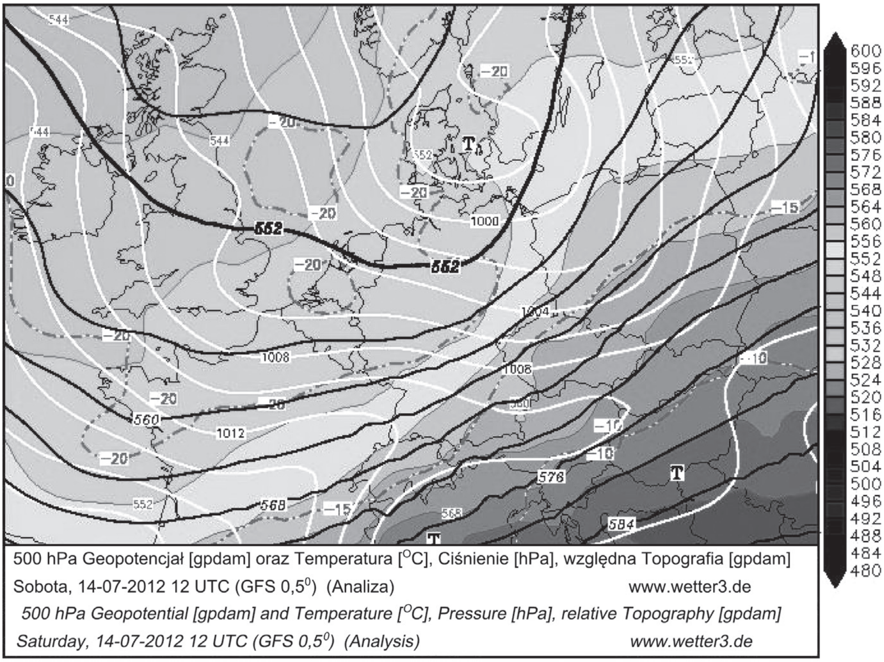
Znacznie lepsze wyniki osiąga się przy użyciu modeli globalnych oraz mezoskalowych. Zastosowanie tutaj znajdują głównie parametry kinematyczne oraz termodynamiczne, w tym wskaźniki kompozytowe, które określają jak bardzo środowisko sprzyja formowaniu trąb powietrznych. Do prognozowania trąb mezocyklonicznych (superkomórkowych) wykorzystuje się takie parametry jak CAPE (*convective available potential energy*), DLS (*deep layer shear*), LLS (*low-level shear*), czy też 0–1 km SRH (*storm relative helicity*, Miller, 1967; Droegemeier i inni, 1993; Craven i Brooks, 2004; Groenmeijer i van Delden, 2007; Taszarek, 2012). Natura trąb niezwiązanych z mezocyklonem jest bardziej skomplikowana i trudniejsza do określenia. Możemy jednak przyjąć, że ich formowaniu sprzyjają podwyższone parametry 0–3 km CAPE oraz pionowy gradient temperatury w dolnym kilometrze trospofery (Groenmeijer i van Delden, 2007; Taszarek, 2012). W obu przypadkach regułą jest również występowanie obniżonych poziomów kondensacji (LCL – *lifted condensation level*) i poziomu swobodnej konwekcji (LFC – *level of free convection*) (Craven i Brooks, 2004; Groenmeijer i van Delden, 2007; Taszarek, 2012) oraz niskich deficytów punktu rosy (Walczakiewicz i inni, 2011; Taszarek, 2012). Umiarkowaną skuteczność prognozowania trąb powietrznych w mezoskali wykazują wskaźniki kompozytowe opracowane na bazie klimatologii trąb powietrznych dla Stanów Zjednoczonych: Significant Tornado Parameter (Thompson i inni, 2002) oraz dla Polski: Universal Tornadic Index (Taszarek i Kolendowicz, 2013). Obecnie prognozowanie przy użyciu modeli mezoskalowych jest najbardziej powszechną metodą oceny środowiska pod kątem potencjału do generowania trąb powietrznych.

Skala synoptyczna

W prognozowaniu trąb powietrznych modele globalne pozwalają w skali synoptycznej określać obszary narażone na występowanie chwiejności termodynamicznej, uskoków wiatru oraz prądu strumieniowego. Sytuacja taka występuje wtedy, gdy mamy do czynienia z krótką falą baryczną w dolnej troposferze oraz rozległą (wraz z prądem strumieniowym) w górnej troposferze (Walczakiewicz i inni, 2011) (ryc. 3). Trąby powietrzne powstają zazwyczaj na południowy wschód od wierzchołka takiej fali. Powietrze w górnych warstwach troposfery w takiej strefie ulega dywergencji i warunkuje pojawianie się głębokiej konwekcji (Doswell, 2001). Jeżeli w takich strefach pojawiają się również silne pionowe uskoki kierunkowe oraz prędkościowe wiatru, mogą wytworzyć się struktury superkomórkowe. Podobna sytuacja wystąpiła w dniu 14 lipca 2012 r., kiedy na południowy wschód od centrum niskiego ciśnienia nad Danią wystąpiła chwiejność termodynamiczna, a nad Polską przechodził front chłodny. Obecność prądu strumieniowego oraz silnych uskoków wiatru spowodowała wystąpienie superkomórki oraz związanej z nią trąby powietrznej, która pojawiła się w rejonie Borów Tucholskich. Według Lorenc (2012) oraz Walczakiewicz i innych (2011) występowanie frontu pofalowanego oraz chłodnego poprzedzonego kilkudniową słoneczną pogodą z rozmytym polem barycznym sprzyja powstaniu trąb powietrznych. Prognozowanie w skali synoptycznej jest niestety w dużym stopniu zgeneralizowane i nie oferuje takiej dokładności jak modele mezoskalowe.

Nowcasting

Nowcasting, czyli prognozowanie pogody „na teraz", polega na wykorzystaniu aktualnych danych teledetekcyjnych (zdjęcia satelitarne, zobrazowania radarowe), depesz meteorologicznych oraz informacji pochodzących od lokalnych obserwatorów burz. Aktualne zdjęcia z satelity geostacjonarnego dają możliwość określenia obszarów inicjacji konwekcji, wierzchołków chmur *cb* oraz wyznaczania ich trajektorii. W prognozowaniu trąb powietrznych najbardziej użyteczne są radary dopplerowskie, dające możliwość wykrycia lokalnej wirowości powietrza w postaci mezocyklonu (Doswell i Burgess, 1993). Szczególnie istotna jest



Ryc. 3. Sytuacja baryczna nad Europą Środkową w dniu 14.07.2012 dla godziny 12.00 UTC wyliczona przez numeryczny model globalny GFS. Krótka fala w dolnej troposferze, białe linie – ciśnienie zredukowane do poziomu morza oraz rozległa fala w górnej troposferze, czarne linie – geopotencjał 500 hPa (archiwum wetter3.de)

The synoptic situation over Central Europe on July 14th 2012 for 12.00 UTC, as calculated using the GFS global numerical weather model. Mean sea-level pressure denoting short wave is marked using white lines, while 500 hPa geopotential height denoting the long wave is marked using black lines (wetter3.de archive)

identyfikacja sygnatury „*hook-echo*” (Stout i Huff, 1953), która według obserwacji amerykańskich w 84% przypadków związana jest z wystąpieniem trąby powietrznej (Forbes, 1981). Prognozowanie tą metodą w dużym stopniu zależy od wiedzy synoptyka i systemów jakimi dysponuje. Umożliwia wydawanie prognoz i ostrzeżeń o większej szczegółowości, gdyż uwzględnia czynniki lokalne i aktualne dane o pogodzie. Pomimo zawansowanych modeli numerycznych, nowcasting jest obecnie najlepszą metodą krótkoterminowego prognozowania i ostrzegania przed niebezpiecznymi zjawiskami konwekcyjnymi. Przy użyciu odpowiedniej technologii radarowej służącej wykrywaniu mezocyklonów, możliwe jest ustalenie określonej trajektorii komórki burzowej i zawiadomienie ludności na kilkanaście do kilkudziesięciu minut przed pojawieniem się zagrożenia. Należy jednak pamiętać, że dane z systemu radarowego są dostępne z około 10-minutowym opóźnieniem (wynika to z pomiaru i przetworzenia danych jakie musi radar wykonać), co istotnie skraca czas na reakcję, a w niektórych przypadkach uniemożliwia podjęcie działania. Amerykanie w celu wydłużenia czasu reakcji stosują system *warn-on forecast*, w którym zobrazowanie radarowe superkomórek jest diagnozowane i prognozowane przy użyciu numerycznego modelu (Yussouf i Stensrud, 2010; Stensrud i Gao, 2010; Stensrud i inni, 2009).

Sondowania atmosferyczne

Sondowania atmosferyczne związane z trąbami powietrznymi są wykorzystywane w badaniach do analizy warunków w jakich owe zjawiska powstają (Groenemeijer i van Delden, 2007; Walczakiewicz i inni, 2011; Taszarek, 2012). Można je więc wykorzystywać również do analizowania aktualnych warunków i estymacji ryzyka pojawienia się trąby powietrznej w danym regionie. Prognozowanie przy użyciu sondowań atmosferycznych opiera się na określeniu parametrów termodynamicznych i kinematycznych dla charakterystycznej masy powietrza oraz ustaleniu kierunku i siły wiatru na poziomie przenoszenia (700 hpa – zima, 500 hpa – lato). W ten sposób możliwe jest ustalenie, dokąd w określonym czasie przemieści się dana masa powietrza. Oczywiście okres ten nie może być długi, gdyż zależnie od warunków lokalnych i pory dnia, parametry fizyczne powietrza zmieniają się i po pewnym czasie dane pomiarowe przestają być reprezentatywne. Sondowania w Polsce w okresie największej aktywności trąb powietrznych (od maja do sierpnia) wykonywane są o godzinie 14.00 czasu lokalnego – w zestawieniu z największą aktywnością trąb powietrznych w ciągu dnia (od 16.00 do 18.00) daje to możliwości wykorzystania ich w metodzie nowcasting. W estymacji warunków sprzyjających powstawaniu trąb powietrznych wykorzystuje się te same parametry, które zostały opisane wcześniej. Użycie ich w radiosondażach może być bardziej wartościowe niż w modelach mezoskalowych, gdyż pokazują parametry zmierzone, a nie modelowe. Ich wadą jest jednak mała szczegółowość prognoz ze względu na nierównomierne i bardzo rzadkie rozmieszczenie stacji pomiarowych. Przykład sondowań z 12.00 UTC z miejscowości Poprad oraz Wiedeń z dnia 15.08.2008 (seria trąb powietrznych w środkowej Polsce – wysokie wskaźniki tornadowe) pokazuje, że dane radiosondażowe są ważnym źródłem informacji dla synoptyka i stanowią wartościowe uzupełnienie danych modelowych, które można wykorzystać w prognozie.

Prognozowanie w Polsce

Najbardziej efektywne prognozy powstają wtedy, gdy łączy się wszystkie opisane metody. Synoptycy powinni opierać się nie tylko na danych modelowych lub radarowych, ale kompleksowo analizować problem. Niezależnie od stopnia rozwinięcia modelowania matematycznego najważniejszy jest więc czynnik ludzki – osoba, która dzięki swojej wiedzy i intuicji będzie w stanie zebrać wszystkie dostępne dane oraz opracować ostateczną prognozę, a w razie zagrożenia wydać ostrzeżenie.

IMGW

W Polsce tymi zagadnieniami zajmuje się Państwowy Instytut Meteorologii i Gospodarki Wodnej (IMGW). Ma on dostęp do specjalistycznej infrastruktury, która pomaga śledzić oraz wykrywać procesy konwekcyjne. W skład systemów teledetekcji naziemnej wchodzą systemy PERUN oraz POLRAD. System PERUN składa się z dziewięciu sensorów SAFIR3000 przeznaczonych do wykrywania elektrycznej składowej fali elektromagnetycznej, a tym samym do detekcji i lokalizacji wyładowań atmosferycznych doziemnych oraz chmurowych. System POLRAD składa się z 8 radarów Dopplerowskich, których zadaniem jest lokalizacja zawieszonych w atmosferze hydrometeorów oraz rozpoznanie i analiza zachodzących w nich zjawisk. Sygnał radarowy może posłużyć do opracowania rozmaitych produktów dających możliwość wykrywania oraz prognozowania groźnych zjawisk konwekcyjnych. Do wykrywania komórek sprzyjających powstawaniu trąb powietrznych można wykorzystać pola rozkładu prędkości radialnych (pozwalające wykryć mezocyklon) oraz odbiciowość niższych elewacji umożliwiając wykrycie struktury hook-echo. Możliwa jest analiza danych zarówno wzdłuż określonej elewacji (PPI) jak i z określonej wysokości (CAPPI). Dodatkowo dostępne są produkty kompozytowe, takie jak SWI (*Severe Weather Indicator*) czy też TVD (*Tornado Vortex Detection*). Trzeba się również zgodzić z wypowiedzią Zdzisława Dziewita (Tuszyńska, 2012), że „efektywne rozpoznanie trąb powietrznych możliwe jest w odległości do 40–50 km od radaru, w większej odległości skazani jesteśmy na wnioskowanie na podstawie zjawisk towarzyszących i skazani na dużą ilość fałszywych alarmów". IMGW ma również dostęp do dokładnego modelu mezoskalowego COSMO (siatka 2,8 km), w którym możliwe jest wykorzystywanie rozmaitych parametrów termodynamicznych oraz kinematycznych w prognozach krótko- i średnioterminowych do prognozowania podatności środowiska na generowanie trąb powietrznych. Wskazane przez model mezoskalowy regiony zagrożone zejściem trąby powietrznej implikują dokładniejszą analizę radarową komórek burzowych przechodzących przez te obszary. Ostrzeżenia o groźnych zjawiskach meteorologicznych w 3-stopniowej skali wydaje CBPM (centralne biuro prognoz meteorologicznych) do 24 h przed ich pojawieniem się. W przypadku spodziewanych trąb powietrznych IMGW wydaje okazjonalnie oświadczenia o spodziewanym zjawisku na dzień przed nim. Ponadto ostrzeżenia oraz prognozy przekazywane są do Centrów Zarządzania Kryzysowego oraz instytucji odpowiedzialnych za podjęcie działań związanych ze spodziewanym zagrożeniem. W Warszawie w okresie wiosennym i letnim, pracuje dodatkowo grupa burzowych specjalistów, których celem jest monitoring i diagnoza procesów konwekcyjnych na terenie Polski.

ESTOFEX

Prognozy z uwzględnieniem możliwości pojawienia się trąby powietrznej na obszarze Polski wydaje grupa ESTOFEX (European Storm Forecast Experiment). Ogranicza się do prognoz 24-godzinnych, w których wyznacza zagrożone obszary na obszarze Europy oraz opisuje spodziewane zjawiska konwekcyjne (grad, wyładowania atmosferyczne, trąby powietrzne, silne podmuchy wiatru) w 3-stopniowej skali zagrożenia. Prognozy oparte są głównie na rozmaitych parametrach termodynamicznych i kinematycznych obliczanych przez numeryczne modele globalne, analizowane przez pracujących tam synoptyków. Produkty ESTOFEXU cechuje wysoki poziom sprawdzalności, jednak ze względu na brak użycia metod nowcastingowych, zespół nie wykrywa bezpośredniego zagrożenia, a raczej wskazuje na obszar, gdzie takowe może wystąpić.

Skywarn Polska

Zarówno nowcastingiem, jak i prognozami mezoskalowymi, zajmuje się europejskie stowarzyszenie Skywarn z polskim oddziałem „Polscy Łowcy Burz". Instytucja ta wykorzystuje ogólnodostępne dane pochodzące z numerycznych modeli globalnych i mezoskalowych oraz dane teledetekcyjne. Podobnie jak ESTOFEX, Skywarn Polska wykonuje mezoskalowe prognozy 24-godzinne z 3-stopniową skalą zagrożenia zjawiskami konwekcyjnymi (grad, wyładowania atmosferyczne, trąby powietrzne, silne podmuchy wiatru) oraz prowadzi na bieżąco nowcasting, wydając ostrzeżenia dla poszczególnych powiatów. Okresowo Skywarn Polska wydaje również średnioterminowe prognozy konwekcyjne, gdzie uwzględnia możliwość pojawiania się trąb powietrznych. Polscy łowcy burz mają także dostęp do szerokiego grona obserwatorów-pasjonatów, którzy monitorują sytuację w poszczególnych regionach kraju oraz zapewniają dokumentację zjawisk atmosferycznych. Nie posiadają niestety dostępu do zaawansowanych produktów radarowych oraz zintegrowanego i zaawansowanego systemu ostrzegania, który pozwalałby szybko zawiadamiać odpowiednie instytucje państwowe oraz mieszkańców znajdujących się na trasie niebezpiecznych komórek burzowych.

Poziomy prognozowania

Analiza obecnej wiedzy na temat tornadogenezy, dostępu do danych o pogodzie oraz możliwości krajowego prognozowania, pozwoliła wyznaczyć 4 poziomy, na których może odbywać się prognozowanie trąb powietrznych (tab. 1).

Poziom pierwszy funkcjonuje głównie w skali synoptycznej i wykorzystuje modele globalne. Daje możliwości wskazania rozległych obszarów, w których mogą wystąpić niebezpieczne zjawiska konwekcyjne, do 48 godzin przed ich pojawieniem się. Ze względu na skomplikowane procesy fizyczne jakim podlega

Tabela 1. Poziomy prognozowanie trąb powietrznych w Polsce

Tornado forecasting levels in Poland

Poziom *Level*	Okres prognozy / ostrzeżenia *Time of forecast / warning*	Produkt użyty *Used product*	Elementy prognozy / ostrzeżenia *Forecast / warning ingredients*	Szansa na przewidze-nie *Chance for prediction*	Możliwość ostrzeżenia *Warning-possibili-ties*	Szczegóło-wość pro-gnozy *Forecast-details*
1	48 h–24 h	model globalny *global model*	określanie środowiska sprzyjającego powstawaniu trąb powietrznych przy użyciu parametrów termodynamicznych i kinematycznych	niska	wysoka	niska
			defining an environment conducive to the formation of tornadoes by using thermodynamic and kinematic parameters	*low*	*high*	*low*
2	24 h–3 h	model globalny oraz mezoskalowy i sondowania atmosferyczne	określanie środowiska sprzyjającego powstawaniu trąb powietrznych przy użyciu parametrów termodynamicznych i kinematycznych	niska	umiarko-wana	umiarko-wana
		global or mesoscale model and atmospheric soundings	*defining an environment conducive to the formation of tornadoes by using thermodynamic parameters and kinematic*	*low*	*moderate*	*moderate*
3	3 h–30 min	zobrazowanie radarowe *radar data*	określanie trajektorii i monitoring komórek burzowych w strefach zagrożenia wyznaczonych przez model mezoskalowy	umiarko-wana	niska	wysoka
			determining and monitoring the trajectory of convective cells invulnerable zones pointed by the mesoscale model	*moderate*	*low*	*high*
4	30 min–0 min	zobrazowanie radarowe *radar data*	skręcające komórki burzowe z sygnaturami *hook-echo*, *v-notch*, detekcja mezocyklonu i zjawisk towarzyszących na produktach radarowych, symulacje radarowe	wysoka	bardzo niska	bardzo wysoka
			torsional convective cells with hook-echo and v-notch signatures, detection of mesocyclone and accompanying conditions on the radar products, radar simulations	*high*	*very low*	*very high*
–	0 min	widoczny lej kondensacyjny *visible tornado*	informacja od świadków zdarzenia *information from the witnesses of the event*	–	–	–

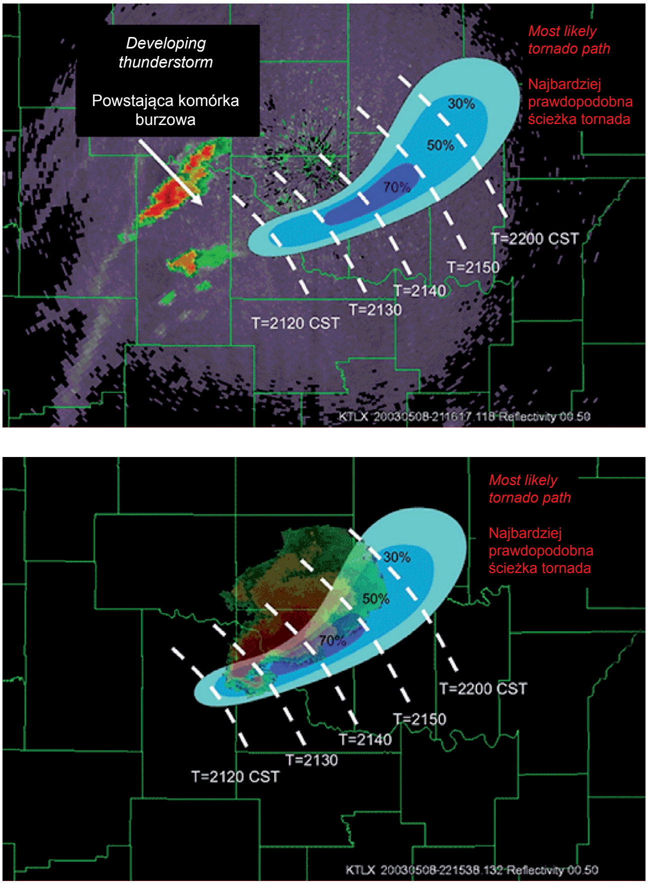
Opracowanie własne. / Author's own elaboration.

troposfera, niezwykle trudno jest dokładnie przewidzieć pogodę z 48-godzinnym wyprzedzeniem, dlatego sprawdzalność prognoz jest relatywnie niska.

W następnym poziomie oprócz modeli globalnych korzysta się z dokładniejszych modeli mezoskalowych, które w interwale czasowym do 24 godzin oferują bardziej szczegółowe i wiarygodne dane; wzrasta wtedy dokładność i sprawdzalność prognoz. Tutaj możliwe jest jeszcze efektywne poinformowanie mieszkańców poprzez formułowane w mediach ostrzeżenia o potencjalnie niebezpiecznych zjawiskach. Właśnie na tym poziomie przede wszystkim funkcjonuje obecne prognozowanie w Polsce (ESTOFEX, IMGW, Skywarn Polska).

Trzeci poziom opiera się na monitorowaniu powstałych komórek burzowych i nowcastingu, w którym dokładność i rzetelność prognoz oraz ostrzeżeń wzrasta. Taki monitoring prowadzi stowarzyszenie Skywarn Polska, które wykorzystując ogólnodostępne dane wydaje ostrzeżenia dla powiatów. Niestety, ze względu na brak rozwiniętych systemów informowania mieszkańców, niewielkie są możliwości dotarcia z ostrzeżeniem do osób znajdujących się na trajektorii niebezpiecznych komórek burzowych. IMGW przy użyciu własnych systemów teledetekcyjnych również prowadzi nowcasting. Grupa burzowych specjalistów w Warszawie monitoruje na bieżąco zjawiska konwekcyjne, a synoptycy w regionalnych biurach prognoz meteorologicznych wydają ostrzeżenia o możliwości wystąpienia niebezpiecznych zjawisk.

Ostatni, 4 poziom, wymaga dostępu do zaawansowanego systemu radarowego i umożliwia wydawanie ostrzeżeń z wysokim prawdopodobieństwem detekcji (84% w przypadku *hook-echo*, Forbes, 1981). Taki dostęp posiada IMGW, jednak nie dysponuje odpowiednim systemem ostrzegania mieszkańców w tak krótkim czasie. Na tym poziomie doskonale radzą sobie specjaliści ze Stanów Zjednoczonych, którzy po wielu latach doświadczeń związanych z tornadami, rozwinęli specjalne systemy prognozowania zobrazowania radarowego (ryc. 4), które potrafią wydłużyć czas na reakcje nawet do 20 minut (Yussouf i Stensrud, 2010; Stensrud i inni, 2009; Stensrud i Gao, 2010). Dzięki temu uzyskuje się dodatkowy czas na poinformowanie mieszkańców systemami ostrzegania (komunikaty w TV, radio, telefony komórkowe, syreny alarmowe). Mieszkańcy są informowani, jak reagować na ostrzeżenia oraz kiedy najczęściej można się ich spodziewać. Dodatkowo NOAA NWS przeprowadza specjalistyczne szkolenia dla obserwatorów burz, którzy w przypadku zaobserwowania niebezpiecznego zjawiska konwekcyjnego informują o tym służby meteorologiczne – w wielu przypadkach skraca to czas konieczny na wydanie odpowiednich ostrzeżeń.



Ryc. 4. Prognoza prawdopodobieństwa trąby powietrznej wykonana za pomocą systemu „*warn-on-forecast*" NOAA NWS
A tornado probability forecast generated by the "warn-on forecast" system of the NOAA NWS
Źródło / Source: www.nssl.noaa.gov

Podsumowanie

Aktualne badania pozwalają wyróżnić dwa mechanizmy powstawania, które generują dwa typy trąb powietrznych: trudniejsze do przewidzenia, ale słabsze trąby powietrzne niezwiązane z mezocyklonem oraz znacznie silniejsze i łatwiejsze do przewidzenia trąby powietrzne związane z występowaniem mezocyklonu w postaci superkomórki. Współczesne badania klimatologiczne wykazują, że trąby powietrzne w Polsce występują najczęściej w okresie od maja do sierpnia w godzinach od 16.00 do 20.00 i mogą generować zjawiska o sile do F3/F4 w skali Fujity. Obecne możliwości pozwalają na prognozowanie środowisk sprzyjających generowaniu trąb powietrznych przy użyciu zarówno numerycznych modeli globalnych i mezoskalowych, jak i aktualnych sondowań atmosferycznych z wykorzystaniem parametrów termodynamicznych oraz kinematycznych. Funkcjonujące w Polsce systemy PERUN oraz POLRAD pozwalają na prowadzenie nowcastingu i umożliwiają identyfikację mezocyklonu oraz struktury *hook-echo* potencjalnie związanej z trąbą powietrzną. Prognozowaniem trąb powietrznych dla obszaru Polski zajmuje się IMGW oraz Skywarn Polska, wykonując prognozy mezoskalowe oraz prowadząc nowcasting. Europejska organizacja ESTOFEX wykonuje dodatkowo krótkoterminowe prognozy konwekcyjne obejmując nimi obszar Polski. Trąby powietrzne nie są w Polsce tak powszechne jak w Stanach Zjednoczonych, ale ich rosnąca aktywność powoduje, że wzrasta potencjalne zagrożenie dla ludzkiego życia i należy podjąć odpowiednie kroki, aby rozwinąć metody wczesnego ostrzegania ludności. Zaproponowane poziomy wydawania ostrzeżeń przed trąbą powietrzną mają na celu usystematyzowanie działań jakie się podejmuje w prognozowaniu tego zjawiska. Obecnie w Polsce ostrzeganie przed zjawiskiem trąby powietrznej funkcjonuje na poziomach drugim i trzecim, ale dokładność i sprawdzalność prognoz na tym etapie jest stosunkowo niska. IMGW posiada odpowiednią infrastrukturę radarową do monitorowania echa związanego z superkomórką na poziomie czwartym. Obecnie czas na reakcję jest jednak zbyt krótki, aby informacja dotarła do mieszkańców na czas, nie funkcjonują systemy, które mogłyby szybko rozesłać informacje o zagrożeniu do znacznego grona odbiorców. Pilna jest więc potrzeba wprowadzenia odpowiednich systemów ostrzegania (np. przy użyciu telefonów komórkowych) oraz rozwój numerycznej prognozy zobrazowania radarowego w celu wydłużenia czasu na wydanie ostrzeżenia. Nie bez znaczenia jest również uświadamianie mieszkańców, jak odpowiednio interpretować ostrzeżenia i jak się zachowywać w sytuacji niebezpieczeństwa. Trzeba także pamiętać, że ze względu na małą skalę zjawiska i bardzo dynamiczny przebieg, nie jest tymczasem możliwe przewidzenie z dużym wyprzedzeniem, kiedy i gdzie pojawi się trąba powietrzna. Zjawisko o rozpiętości kilkudziesięciu metrów nie jest wychwytywane przez mezoskalowe modele pogody, w których gęstość siatki wynosi kilka kilometrów. Obecne prognozowanie opiera się głównie na określaniu warunków sprzyjających powstawaniu takiego zjawiska i probabilistycznemu oszacowaniu zagrożenia.

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MATEUSZ TASZAREK

FORECASTING THE POSSIBLE EMERGENCE OF TORNADOES IN POLAND

This paper assesses current possibilities for tornado forecasting to take place in Poland. To that end, the author reviews current research relating to the mechanisms of tornadogenesis and tornado climatology in Poland. It is noted that tornado activity peaks in the May-August period, and between 4 pm and 8 pm. While the long-term average incidence of tornadoes stands at about 4 incidents per year, recent years have seen an increase in activity to 10–12 cases per year. Today we can distinguish two mechanisms responsible for tornadogenesis: the mesocyclonic and the non-mescyclonic. The first mechanism applies to typical strong tornadoes associated with the presence of a mesocyclone (supercell), in which updrafts and downdrafts are separated. This tornado type can last for several hours and is much more readily detected and predicted, since the environment in which it is created is very characteristic. The second tornado type, often called the landspout, is less dangerous, but more difficult to predict. On the basis of current achievements in science in general, and meteorological methodology in particular, the author describes 3 methods applied in tornado prediction, i.e. numerical weather models, nowcasting, and atmospheric soundings. On the basis of this, he then sets four operational levels for tornado forecasting. The first level is mostly based on global numerical weather models, and provides for the issuing of forecasts on the basis of analysed thermodynamic and kinematic parameters associated with tornadoes. The second level is similar, but also includes analysis of local mesoscale numerical weather models, as well as current atmospheric soundings. The third level is characterized mainly by the use of teledetection data with a view to identifying and monitoring convective cells. The last level in turn sees specialized radar products used in mesocyclone, hook-echo detection.

In Poland, the most important institution dealing with convective issues is the Institute of Meteorology and Water Management (IMGW), which has access to the specialised infrastructure helping it to track and detect convective processes. This consists of the POLRAD remote sensing system (meteorological radar), as well as PERUN (lightning detection). The warnings for dangerous meteorological phenomena are on a 3-point scale, and are given by the BPM (regional meteorological forecasting office). In addition, warnings and forecasts are provided to Crisis Management Centres and institutions responsible for from the reactions to emerging threats. ESTOFEX (the European Storm Forecast Experiment) issues forecasts daily, and forecasts expected convective phenom-

ena using a 3-point severity scale (for hail, lightning, tornadoes and strong winds). The products of ESTOFEX have a high level of verifiability, though the lack of nowcasting means that they do not detect any direct threat, instead indicating hazardous areas.

The Institution that deals with both nowcasting and mesoscale forecasting is Skywarn, the European association whose Polish branch is "PolscyŁowcyBurz". Skywarn Poland uses publicly-available data - global numerical weather models and remote sensing. Skywarn Poland engages in mesoscale forecasting using a 3-point scale for convection phenomena hazards (hail, lightning, tornadoes and strong winds), also providing nowcasting analysis and issuing up-to-date warnings for individual regions. Analysis shows that effective warning issuance for the occurrence of tornadoes enjoys greatest accuracy on the second and third levels, albeit with the accuracy and verifiability of the forecasts remaining relatively low at this stage. Poland has the technical possibilities to monitor effectively the radar echoes associated with tornadic supercells on the fourth level. However, due to the limited incidence of tornado phenomena in Poland, specialized warning systems are lacking, ensuring that the achievable reaction time is too short for timely warnings to be issued to the public.

Appendix B

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M.T. designed the study, acquired and analyzed data, performed computations, made figures, wrote the manuscript, improved the final version of the manuscript.

L.K. designed the study, analyzed the data, improved the final version of the manuscript.

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Sounding-derived parameters associated with tornado occurrence in Poland and Universal Tornadic Index

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ABSTRACT

This study is mainly devoted to operational meteorology, to improve tornado forecast in Poland and create a Universal Tornadic Index formula. A study is focusing on climatology of sounding-derived parameters associated with tornadoes in Poland and their potential value for tornado forecasting. The data was collected from soundings made in 10 stations in and around Poland which were closely in time and space connected with tornado occurrence. The main aim of the study was to analyze the thermodynamic and kinematic parameters derived from soundings and formulate an index. The information about tornado incidents was taken from media reports and the European Severe Weather Database for the years 1977–2012. Total of 97 tornado cases were divided according to their strength for significant (F2/F3), weak (F0/F1) and unrated cases, and also according to their environmental surface temperature, for warm (>18 °C) and cold (<18 °C) tornadoes. As it turned out, depending on the temperature, tornadoes tended to present different environmental conditions for tornadogenesis. In warm cases, the most important factor was instability while for cold cases it was dynamic wind field. It was also proven that significant tornadoes in Poland occur in conditions accompanied by high moisture content, moderate instability and high wind shear conditions. The results of this study were used to create a Universal Tornadic Index designed to forecast activity in warm and cold, and weak and strong tornadic environments. The quality of this index was tested for the period with increased tornado activity in Poland from 2008 to 2010.

1. Introduction

Present synoptic meteorology is mostly based on numerical weather models which are a set of mathematical equations using basic physical principles and simulating how weather will change in the following hours or days. The input for the numerical models is partly data taken from atmospheric soundings which give information about the temperature, moisture content and wind strength in the vertical profile of the troposphere, therefore the better we will understand soundings connected with particular severe weather the better we will be able to predict them.

Thermodynamic and kinematic parameters which may be derived and calculated from the atmospheric soundings can be good predictors of severe weather phenomena. Many studies have been made on creating various types of parameters such as storm indicators, instability indexes, water content parameters, wind parameters and others. Simple ones use ambient temperature and dew point at different heights. Examples are the convective potential k-index (KI; George, 1960) and storm strength total totals (TT; Miller, 1967). More complicated parameters use parcel theory which is based on parcel lifting and takes into account adiabatic transformations. Examples of such parameters are convective available potential energy (CAPE; Miller, 1967), lifted index (LI; Galway, 1956) and Showalter index (SI; Showalter, 1953). More complex composite parameters such as significant tornado parameter (STP; Thompson et al., 2003), energy helicity index (EHI; Davies, 1993) or significant severe parameter (SSP; Craven and Brooks, 2004) are composed

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from several other parameters and were created for forecasting specific phenomena such as a tornado, hail or a supercell (Browning, 1964).

In addition to these parameters, a number of studies have been devoted to compare soundings data and severe weather occurrence. Grünwald and Brooks (2011) compared sounding parameters from reanalysis data and the strength of tornadoes in Europe and the U.S. and revealed differences in lifted condensation level (LCL) and CAPE distribution, suggesting that in the U.S. tornadoes are formed in higher CAPE and lower LCL environments. Studies of Rasmussen and Blanchard (1998), Craven et al. (2002) and Brooks et al. (2003) found that CAPE with high wind shear is a good discriminator between severe thunderstorms with tornadoes and nontornadic thunderstorms. Craven and Brooks (2004) have analyzed vertical lapse rates, CAPE, downdraft CAPE (DCAPE), LCL and vertical wind shear on the example of U.S. tornadoes, thunderstorms and hailstorms and proposed a strong tornado parameter. The skill of various forecast parameters as predictors of severe weather in Europe has been recently studied by Haklander and van Delden (2003), Groenemeijer and van Delden (2007) and Kaltenböck et al. (2009). Groenemeijer and van Delden (2007) and Kaltenböck et al. (2009) found that LCL is not as good a tornadic environment discriminator as in the U.S. but high values of 0–1 km wind shear and 0–1 km storm relative helicity (SRH; Droegemeier et al., 1993), can indicate tornado hazard. In Poland not many studies have been devoted to analyzing tornado environments.

As Rasmussen and Blanchard (1998) state, baseline climatology of forecast parameters is needed to support forecasters in qualifications whether for example SRH or CAPE is "marginal" or "large". Without known climatology of sounding parameters dedicated for various regions it is difficult to state which values of parameters are conductive for tornado risk.

In this study, we will analyze wind shear, SRH, CAPE and moisture content parameters derived from 97 proximity soundings connected with tornado reports in Poland from 1977–2012 for unrated, weak (F0/F1), significant (F2/F3), cold (sounding surface T <18°C) and warm (sounding surface T >18°C) tornado cases (damage ratings estimated in F-scale, Fujita, 1971). The goal is to determine operational tornado climatology of these parameters and establish how they can affect tornado strength and how they are dependent on temperature. We are also interested in examining conditions for unrated cases which will confirm Grünwald and Brooks (2011) that cases that have not been assigned damage ratings are likely to be weak (F0/F1). Two different patterns of environmental conditions for "cold" and "warm" tornadoes will be discussed.

The obtained database will help to create a Universal Tornadic Index (UTI) dedicated for forecasting weak, significant, cold and warm central European tornadic environments. The quality of the index will be tested on 1097 proximity soundings days for years 2008–2010. Parameters obtained from these soundings will also be used to compare with previously analyzed tornadic soundings. The motivation for this study was to better understand the environment in which tornadoes occur in Poland and improve their forecasting by creating an index which will be used in mesoscale model by the Polish Institute of Meteorology and Water Management. We also drew a hypothesis that, depending on the surface temperature, the combination of instability and wind shear parameters in tornado cases changes. This allows us to distinguish two different environments in which tornadoes are formed (Fig. 5.3.1).

2. Theory

The subject of this study is the analysis of sounding-derived parameters in the relationship to the occurrence of tornadoes in Poland. In order to better select and understand analyzed parameters it is worthwhile to briefly introduce mechanism of tornadogenesis. Generally tornadogenesis requires that large vertical vorticity arises at the ground (Markowski and Richardson, 2009). Referring to the mechanisms which are responsible for tornado creation we can distinguish few sources for causing rotation. Davies-Jones et al. (2001) distinguished two main types, non-mesocyclonic tornadoes that are formed with pre-existing vertical vorticity and mesocyclonic tornadoes that are formed with deep rotating updraft below supercells.

2.1. Non-mesocyclonic tornadoes

These tornadoes are relatively weak and are formed within preexisting vertical vorticity (Davies-Jones et al., 2001). They develop early in the storm lifecycle (Burgess et al., 1993). Waterspouts and landspouts (Bluestein, 1985) are initiated when a developing convective updraft is stretching shallow vertical vortices above the surface. They start to be formed when convergence boundaries such as outflow boundaries, fronts and wind-shift lines are present, and form vertical "rolls" which initiate vorticity. They consist of updrafts sufficiently strong to stretch up vortex and form a tornado.

Doppler radar studies show that landspout and waterspout pre-existing vorticity is a result of horizontal shearing instability in convergence boundaries, where winds blow from various directions and cause air turbulence (Wakimoto and Wilson, 1989; Wilczak et al., 1992). Multicellular structures, such as clusters and lines, work in the same way in spawning weak tornadoes but have a tendency to collide convergence boundaries, merging and strengthening pre-existing vorticity (Holle and Maier, 1980). In this mechanism, near the ground convergence resulting in vertical vorticity collides and under the action of updraft, stretches vortex to tornado size (Markowski and Richardson, 2009). Climatologically these type of tornadoes are characterized by increased instability in the lowest part of the troposphere, updraft sufficient to stretch up vortex (presence of low level steep lapse rates and high CAPE released below 3 km AGL) and presence of wind-shift boundaries to initiate surface veering (Caruso and Davies, 2005; Davies, 2006).

2.2. Mesocyclonic tornadoes

Mesocyclonic tornadoes are connected with strong rotating updraft which is present in supercells. Supercells are responsible for the vast majority of strong and violent tornadoes (Doswell and Burgess, 1993). Most researchers assume that tornadoes greater than F2 are mostly produced by supercells, which are connected with deep moist convection (Doswell, 2001). These tornadoes are more likely to have contact with the surface for several minutes or even for hours. Much research has been devoted to analyzing the environment of supercells. Many studies have now been devoted to the examination of wind shear influence on convective cells and tornadogenesis. Barnes (1970), Rotunno (1981), Davies-Jones (1984), and Markowski and Richardson (2009) point to the role of horizontal wind shear in mesocyclonic tornado formation. Supercells consist of four main ingredients which are necessary to produce a tornado: an unstable air parcel (presence of positive CAPE) which creates strong updraft, strong deep layer wind shear (DLS) to separate updrafts and downdrafts, strong low level wind shear (LLS) to create horizontal vorticity, and high low level moisture content to provide low cloud base (LCL).

The existence of LLS under convective cell causes the air to start spinning horizontally and create rotors. The stronger the wind shear, the stronger is the velocity of the rotor (Monteverdi et al., 2001; Brooks and Craven, 2002). Strong convection in an unstable environment causes the rotors to begin tilting and provides vertical rotation to updraft (Barnes, 1970; Rotunno, 1981; Davies-Jones, 1984; Markowski and Richardson, 2009). Rotunno and Klemp (1985) point out that horizontal vorticity can also be produced by the storm itself in baroclinic processes. These processes play a big role in creating vertical vorticity, especially when environmental horizontal vorticity is lacking (Markowski and Richardson, 2009). A magic factor which starts tornado formation is rear flank downdraft (RFD) (Fujita, 1975; Burgess et al., 1977; Markowski et al., 2002). It cuts off tilted horizontal vorticity and starts vertical vorticity at the surface. Climatological studies of tornadic supercells (Rasmussen and Blanchard, 1998; Rasmussen, 2003) noticed that SRH, which refers to the sudden growth of wind strength and direction in the lowest 1 km of the troposphere works well in distinguishing mesocyclonic tornadic environments.

3. Material and methods

In order to achieve the aim of the study, it was necessary to analyze radiosonde data close in time and space to a reported tornado event. Therefore, two datasets were needed to provide analysis. Firstly, a tornado events database with the information about the localization, estimated strength and date. And secondly, a database with soundings measurements from stations in and around Poland.

3.1. Tornado events

A total of 166 tornado events (excluding gustnado, funnel cloud and dust devil) from the area of Poland for the years 1977–2012 were collected from the European Severe Weather Database (ESWD) (Groenemeijer et al., 2004; Groenemeijer, 2009; Dotzek et al., 2009), the Polish Institute of Meteorology and Water Management, and media reports. In ESWD all reports with status QC1 (report confirmed) and QC2 (event fully verified) were investigated. Additionally for years 1977–1999, all events with status QC0 (as received) and QC0+ (plausibility check passed) were taken into account. This is explained by lesser proof degree of reported tornadoes and a relatively small dataset of tornado reports before 2000. In recent years, more people involved in this topic provide better documentation of these phenomena — cases from the 80's and 90's are not as well documented and require more investigation.

3.2. Soundings

For tornado reports, soundings from 10 radiosonde stations (Fig. 3.2.1) in and around Poland were used: Wrocław (12,425), Legionowo (12,374) and Łeba (12,120) (Poland), Greifswald (10,184) and Lindenberg (10,393) (Germany), Kaliningrad (26,702) (Russia), Praha (11,520) and Prostejov (11,747) (Czech Republic), Poprad (11,952) (Slovakia) and Lviv (33,393) (Ukraine). Not all stations were available during all analyzed period. Lviv and Kaliningrad provided soundings for the 70s and 80s. Greifswald, Prostejov and Lindenberg were available from the 90s. Good continuity of data was ensured by Wrocław, Legionowo and Praha stations. Unfortunately, not all soundings in the proximity of tornado events were available to use. Some of them were uncompleted while the others were not done in that

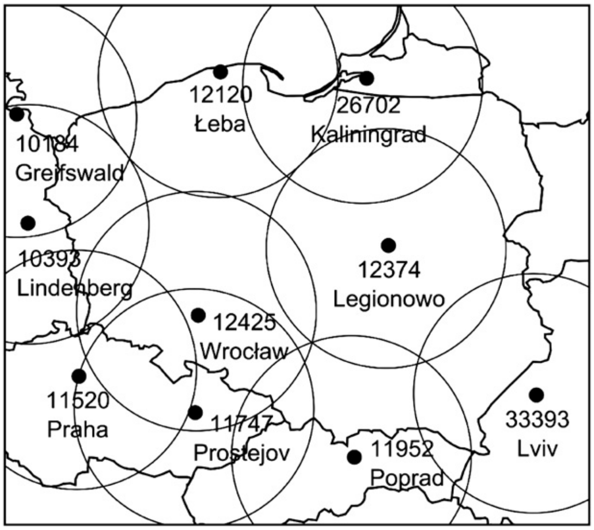

Fig. 3.2.1. Map showing location of radiosonde stations with WMO ID, which measurements were used in a study, circles denote 400 km diameter proximity range area.

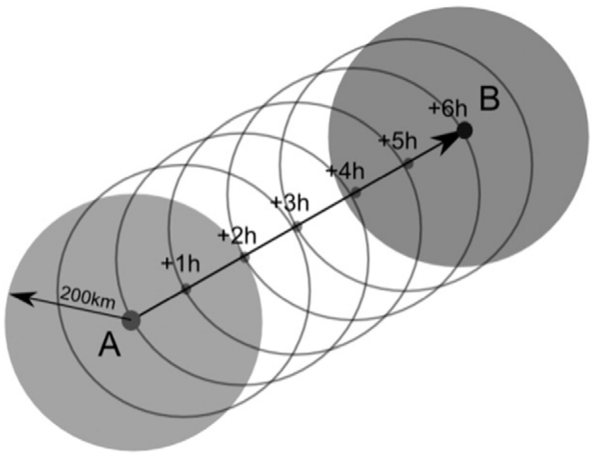

Fig. 3.2.2. The displacement of air mass moving in NE direction in time and space. Point A is a localization of sounding station with 200 km radius range of representative air mass. Point B is an area where the tornado occurred and where air mass from point A passed the way within 6 h.

day and time. The vast majority of tornado events occurred during the day, therefore most soundings were collected from 12 and 18 UTC.

The selection of an appropriate station from which the data was used was essential to obtain reliable results, therefore proximity assumptions (Darkow, 1969; Darkow and Fowler, 1971; Brooks et al., 1994; Rasmussen and Blanchard, 1998) were designated. Assumptions established that the data from the soundings could be taken if inflowing or outflowing air mass relative to tornado event was on the line in which, in the radius of 200 km, the sounding station was located (Fig. 3.2.2). Direction of advection was taken from the 500 hPa pressure layer of the sounding. In the assumption of time, the tornado event was included when it occurred no later than 6 h and no sooner than 3 h after and before sounding. These kind of assumptions did not provide perfect results and obviously could contain errors. We have to reckon with the fact that data which entered analysis could slightly dismiss from reality. This could include temporary and spatial variabilities of the air mass within the environment of an event (Doswell, 1982; Davies-Jones, 1993; Brooks et al., 1994; Grünwald and Brooks, 2011). When more than one sounding was meeting assumptions, the one with the largest 0–1 km bulk shear was chosen.

3.3. Quality control and event categorization

With such a specific phenomenon which is a tornado, one must assume that the database may have errors that can affect study results. It has to be taken into account that some observations have been influenced by the wish of seeing a tornado rather than real observations. Some other reports may have been wrongly recorded and the date or place could be mistaken, others had simply no certain date. It is possible also that although the phenomenon has occurred, with given atmospheric circulation and given day, none of the soundings was reliable enough to cast the state of the atmosphere where the tornado has been created. In an attempt to eliminate false reports each of the soundings included in this study was analyzed in terms of tornadic potential, and in the case of suspicion — excluded. This included: excluding zero CAPE soundings, excluding soundings which did not meet assumptions of proximity, excluding cases where on satellite images there were no clouds during a reported tornado event, including only 1 sounding per day (in example ESWD reports 9 tornado cases on 15.08.2008). In case of suspicious soundings (marginal CAPE, marginal wind shear, strong capping inversions) we have been precisely investigating tornado reports in terms of available data about the damage, witnesses, photography, place and date, and in case of suspicion that it was not a tornado (or possibility that sounding did not catch a representative air mass), excluding it from analysis (most for reports from 80s and 90s).

After passage through quality check and proximity assumptions, a total of 97 soundings (tornado days) were included in an analysis, 22 rated F2/F3 were assigned as significant tornado group, 21 rated F0/F1 were assigned as weak tornado group and the remaining 54 where damage ratings have not been assigned, as unrated group (Table 3.3.1). If one day was experiencing few tornadoes with different strength category, the sounding used in the analysis was assigned to the highest category. We have also divided separately all cases into groups with sounding surface temperature below 18°C (39 cold tornado cases) and with sounding surface temperature above 18°C (58 warm tornado cases). The reason for this division was that during the analysis, tornado cases depending on temperature were showing patterns concerning the relationship between CAPE and wind shear. This categorization aimed to highlight the parameters that are responsible for the differentiation of tornado strength and type. Soundings intended for quality check of Universal Tornadic Index, non-tornado, non-thunderstorm and thunderstorm days were taken from Wrocław station for each 12 UTC sounding from 2008 to 2010. The reason for this was that these were the most active tornado years in all the analyzed period, and Wrocław station was most often used for analysis. A total of 966 soundings ("null" days) have been chosen as not associated with a tornado and thunderstorm, and 90 (thunderstorm days) have been chosen as associated with a thunderstorm and not a tornado (based on daily SYNOP reports from Wrocław meteorological station).

Table 3.3.1
Sounding categories used in this study.

Category	Number of soundings (days)
No-tornado, no-thunderstorm	966
Thunderstorm, no-tornado	90
Tornadoes with sounding surface temperature <18 °C	39
Tornadoes with sounding surface temperature >18 °C	58
Unrated tornadoes (UR; reports that have been not assigned damage ratings)	54
Weak tornadoes (assessed damage on F0/F1)	21
Significant tornadoes (assessed damage on F2/F3)	22

3.4. Parameters and calculations

For all chosen soundings a total of 9 parameters were calculated (Table 3.4.1). Selection of parameters was strongly influenced by previous studies (Rasmussen and Blanchard, 1998; Craven and Brooks, 2004; Groenemeijer and van Delden, 2007; Grünwald and Brooks, 2011). Since we are mainly analyzing tornado cases in order to create an index, the idea was to check and establish climatology for previously

Table 3.4.1
Parameters computed from soundings.

Parameter	Shortcut	Units
Surface based convective available potential energy	SB CAPE	J/kg
Surface based convective available potential energy (released below 3 km above ground level)	SB 0–3 km CAPE	J/kg
Surface based lifting condensation level height (above ground level)	SB LCL	m AGL
Average mixing ratio below 500 m above ground level	AMR500	[g/kg]
0–1 km wind shear (magnitude of vector difference)	LLS	m/s
0–6 km wind shear (magnitude of vector difference)	DLS	m/s
0–1 km storm relative helicity	0–1 kmSRH	m^2/s^2
Upper jet stream (400–200 hPa layer)	UJS	m/s
Lower jet stream (800–500 hPa layer)	LJS	m/s

tested parameters recognized as associated with distinguishing tornadic environments. However, compared with previous studies we decided to analyze in addition average mixing ratio (AMR) calculated from 500 m above ground level (AGL) mean layer and presence of upper and lower jet stream (marked as present or absent). Threshold values for the upper jet were set on 35 m/s (400–200 hPa layer) and for the lower jet 25 m/s (800–500 hPa layer). Parcel parameters that have been used here (LCL, CAPE, 0–3 km CAPE) were based on a parcel that is lifted from surface (surface based). Wind shear has been expressed as the vector difference between the horizontal winds at 10 m AGL and 1 km AGL treated as low-level shear (LLS) and 10 m AGL and 6 km AGL treated as deep-layer shear (DLS). SRH for 0–1 km layer has been calculated for right-moving supercells using the ID-method developed by Bunkers et al. (2000). It is important to mention that negative values of SRH obtained in this analysis have been treated as 0, and we assume that the majority of tornado cases in this study is connected with right-moving cells.

Obtained results calculated for various sounding categories (Table 3.3.1) were presented in box-and-whiskers plots representing dataset distribution of particular parameters. Top cross and bottom cross fields denote 90th and 10th percentiles. Boxes extend from 25th to 75th percentiles, values in the middle indicate median values. Lack of overlap between categories suggests statistical differences and should be paid attention. Some parameters were also combined in scatterplot charts where significant tornadoes (F2/F3) were marked as squares, unrated and weak tornado cases have been combined into one category and marked as triangles. In the same chart cold tornado cases were marked as open circles while warm tornado cases were marked as grey circles. Non-tornado cases in both charts were marked as grey diamonds. Regression lines calculated for weak (dashed line) and significant (solid line) tornado categories were calculated using exponential regression line. They have been imposed on the chart in order to present at which parameter combination, the environmental potential for a weak and strong tornado increases.

4. Results

4.1. Instability

A parameter which shows energy of positively buoyant parcel — CAPE, demonstrated a diversity in F-scale cases,

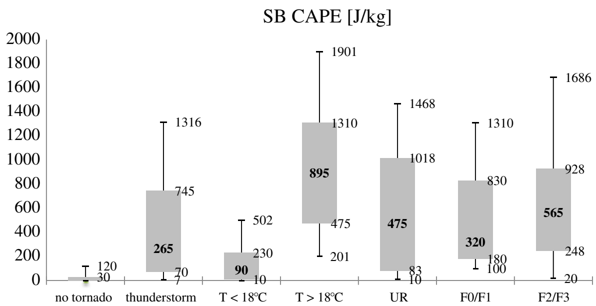

Fig. 4.1.1. Box-and-whiskers plot of the surface based convective available potential energy [J/kg]. The box extends to the 25th and 75th percentiles and the whiskers show the 90th (top part) and the 10th (bottom part) percentile values. Middle values denote medians.

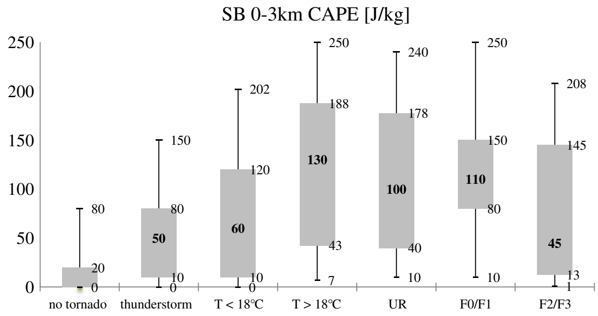

Fig. 4.1.2. As in Fig. 4.1.1 except for the surface based convective available potential energy released below 3 km AGL [J/kg].

amounting to higher values in stronger tornadoes and taking the median value 320 J/kg for weak cases (F0/F1) and 565 J/kg for significant cases (F2/F3) (Fig. 4.1.1). Median value in unrated cases (475 J/kg) was between these categories. There was considerable difference between cold and warm cases. Twenty-five percent of cold cases were accompanied by zero CAPE while twenty-five percent of warm cases had CAPE below the level of 475 J/kg. Median values were consecutively 90 J/kg and 895 J/kg and indicated that warm tornadoes tornadogenesis is more dependent on strong convection (comparing to thunderstorms category) which increases proportionally with the strength of a tornado. Inversely, convection in cold cases was practically negligible and was mainly located in the lower part of the troposphere (Fig. 4.1.2). Lower temperatures were not conductive for creating large instability in substantial part of the troposphere, therefore cold tornadoes needed an additional factor for tornadogenesis which in the next section will be described as a dynamic wind field. CAPE values in the no-tornado category were marginal and showed statistically significant difference between thunderstorm and tornado days.

Interesting results were found in CAPE released below 3 km AGL (Fig. 4.1.2). Firstly, differences between cold and warm cases were not as great as previously analyzed CAPE could indicate. Secondly, 25th percentile and median values of the F2/F3 tornado cases were significantly lower than in F0/F1 tornado cases. These relationships confirm the results obtained by Groenemeijer and van Delden (2007) that weak tornadoes are usually associated with increased 0–3 km CAPE parameter, since vortex stretching together with preexisting vertical vorticity is the reason why they form (Markowski and Richardson, 2009). Distribution of this parameter was also different in warm and cold tornado cases confirming again that warm cases are supported by stronger convection. 0–3 km CAPE was marginal in the no-tornado category and quite small in the thunderstorm category, distinguishing between weak (F0/F1) tornadic environments.

4.2. Moisture content

Tornadoes were generally formed in the environment with high moisture content in the lower troposphere. The results of LCL indicate that tornadoes are usually formed in low cloud base, from median 570 m AGL for weak cases up to 945 m AGL in significant cases (Fig. 4.2.1). Surprisingly, it can be assumed that LCL height increases proportionally with

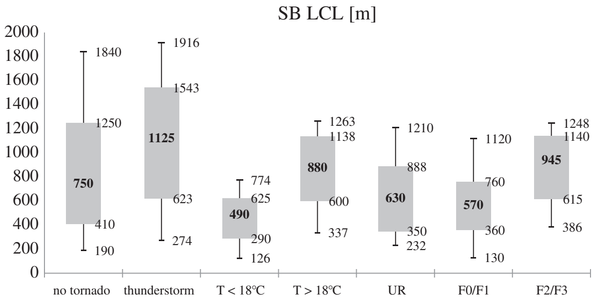

Fig. 4.2.1. As in Fig. 4.1.1 except for the surface based lifted condensation level [m].

F-scale. This result does not confirm previous studies from the Netherlands which indicated a reverse tendency (Groenemeijer and van Delden, 2007), but shares similar conclusions as Grünwald and Brooks (2011). In cold and warm tornado cases there is a large statistical difference. Higher LCL is found in warm cases, the 75th percentile of cold category is on the level of the 25th percentile of warm category. This can be related to relative humidity which during warm summer days is generally lower than during spring and autumn (at which times cold tornadoes tend to occur). The dataset of the unrated category in this parameter was pretty much similar to the weak F0/F1 cases. The no-tornado category ranged mainly from 410 m (25th percentile) to 1210 m (75th percentile), while in thunderstorm soundings, LCL was measured approximately 200 m higher. The statistical difference between ordinary storms and tornado cases suggests that tornadoes are generally formed in an environment with reduced LCL.

At the subsurface layer, medians of average mixing ratio calculated from the mean 500 m AGL layer ranged from 9.1 g/kg for weak cases up to 10.6 g/kg in significant cases (Fig. 4.2.2). Again there was considerable difference in warm and cold tornado cases ranging medians from 7 g/kg in cold category and almost 11 g/kg in warm category. There was also a large difference between no-tornado and thunderstorm soundings suggesting that this parameter is quite good in distinguishing thunderstorm environments. Dataset distribution in thunderstorms was very similar to tornado categories, excluding cold cases which involved an interesting conclusion that cold tornadoes are not always associated with thunderstorm.

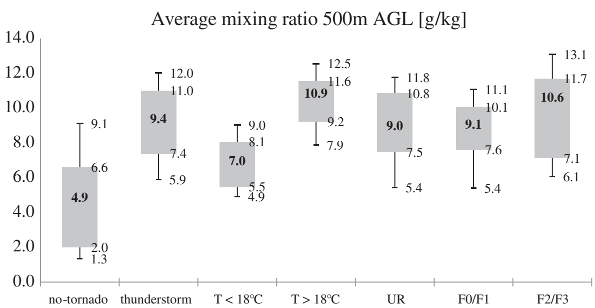

Fig. 4.2.2. As in Fig. 4.1.1 except for the average mixing ratio in mean 500 m AGL layer [g/kg].

It can be concluded that tornadoes generally form in an environment with high moisture content and their severity increases proportionally with the amount of water vapor in the lower troposphere. Because higher temperatures can store larger amounts of moisture and therefore release more latent heat which increases instability, we can state that tornado severity increases with increasing AMR500 values.

4.3. Wind shear, storm relative helicity and jet stream

Interesting results involved wind shear and storm relative helicity. Either in the lowest or in the middle part of the troposphere, wind shear obtained increased values for tornado cases and indicated a very dynamic environment. This suggests that presence of wind shear generally plays an important role in tornadogenesis. Analyzing it more accurately it can be seen

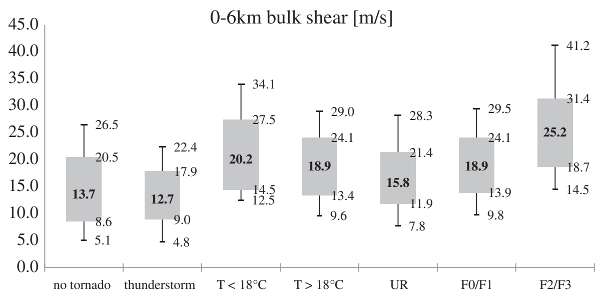

Fig. 4.3.1. As in Fig. 4.1.1 except for the 0–6 bulk wind shear [m/s] (magnitude of vector difference).

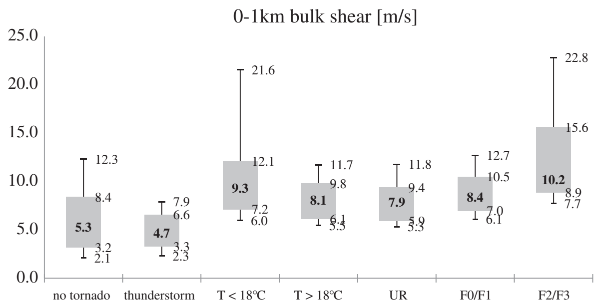

Fig. 4.3.2. As in Fig. 4.1.1 except for the 0–1 bulk wind shear [m/s] (magnitude of vector difference).

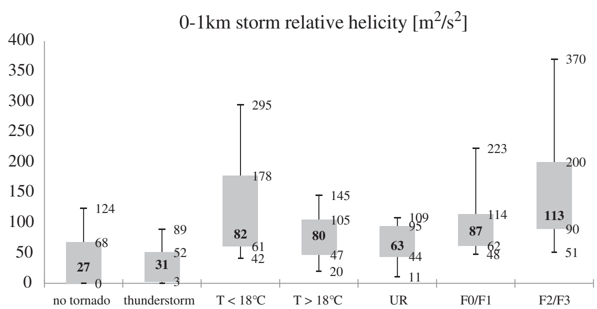

Fig. 4.3.3. As in Fig. 4.1.1 except for the 0–1 km storm-relative helicity [m^2/s^2].

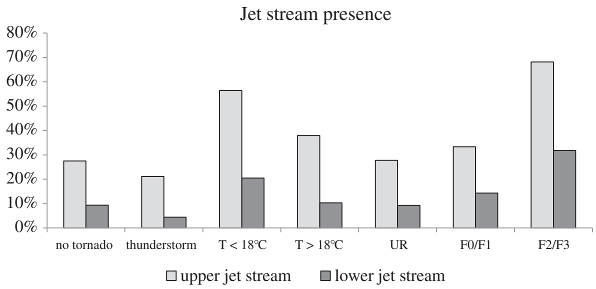

Fig. 4.3.4. The percentage of the upper and lower jet streams in analyzed cases. Threshold values for the upper jet were set on 35 m/s (400–200 hPa layer) and for the lower jet 25 m/s (800–500 hPa layer).

that much like in deep layer shear (DLS, 0–6 km) (Fig. 4.3.1) and low level shear (LLS, 0–1 km) (Fig. 4.3.2), bulk shear increases proportionally with F-scale, taking median values of significant tornadoes on the same level of 75th weak tornadoes percentile. Generally the higher values these parameters were reaching the higher was the severity of the tornado. Not without significance is also the fact that the median value of significant tornadoes exceeds 20 m/s. Based on the research of Weisman and Klemp (1982), Davies and Johns (1993), Rasmussen and Blanchard (1998), Markowski et al. (1998), Bunkers et al. (2000), Craven (2000), Doswell and Evans (2003) which stated that the median of DLS amounting to 20 m/s indicates a supercell presence, we can conclude that the majority of F2 and F3 cases was supercell tornadoes with a distinctive difference from weaker cases (probably non-mesocyclonic tornadoes).

In cold and warm cases, the diversity was not as high as in previous parameters. However wind shear in cold environment was generally higher which is opposite to CAPE findings. It may suggest that insofar as CAPE played an important role in warm cases, in cold cases this role is assigned mainly to strong wind shear and rather low instability. These conditions are usually called low cape–high shear environments that are often responsible for creating severe damage (Carbone, 1982; Forbes, 1985). It must be remembered that the majority of analyzed tornado cases in this study demonstrated increased values of LLS and partly confirmed the research of Craven and Brooks (2004) and Groenemeijer and van Delden (2007) that high LLS can distinguish between significant tornadic and thunderstorm nontornadic environments. In Fig. 4.3.2 it can be seen that 75% of no-tornado and 90% of thunderstorm soundings are on the same level as 25% of significant F2/F3 tornado cases, which confirm that this parameter can be a good strong tornado forecast tool, and is more distinctive than DLS. Other tornado groups demonstrated stronger overlapping with no-tornado category but their medians were still higher by approximately 3 m/s. Similar findings as above have also been found in the 0–1 km storm relative helicity parameter, in which distribution was almost the same as LLS. This allows us to also treat 0–1 kmSRH as a good tornado forecasting parameter (Fig. 4.3.3).

In addition, assuming that tornado strength increases proportionally to wind shear, unrated reports due to dataset similarity to weak cases, suggest that they should be treated as weak tornadoes.

Analysis of jet stream presence suggests that it played a considerable role in tornado occurrence. As it can be seen on Fig. 4.3.4, upper jet stream was present in approximately 35% of unrated and weak cases, and its presence was rising together with F-scale, up to 70% for the significant tornado category. This indicated that strong air flow in the upper troposphere can affect the strength of a tornado. There was also a difference between warm and cold tornado cases which once again suggests that dynamic air flow in cold tornado cases is an important factor in increasing the potential for tornadogenesis within an environment with marginal instability. The same findings were also found for lower jet which was, however, occurring less frequently. Comparing these results to no-tornado and thunderstorm days we can conclude that similar upper and lower jets occurred more often in tornado cases. But since the no-tornado dataset is large, there is not necessarily a good distinction between tornadic and non tornadic environments.

4.4. Parameter combinations

Examining low level shear and surface based convective available potential energy in the scatterplot on Fig. 4.4.1 we can see that depending on temperature, tornadoes tend to form in two different atmospheric conditions. First, which refers to warm cases (open circles), are characterized by increased instability and moderate wind shear conditions. Second, which is connected with cold cases (grey circles), display the tendency to marginal instability but stronger wind shear. On scatterplot charts we can also see the distribution of the cases depending on F-scale. Surprisingly significant tornadoes can form in both environmental types mentioned above. They demonstrate high instability or high wind shear but most

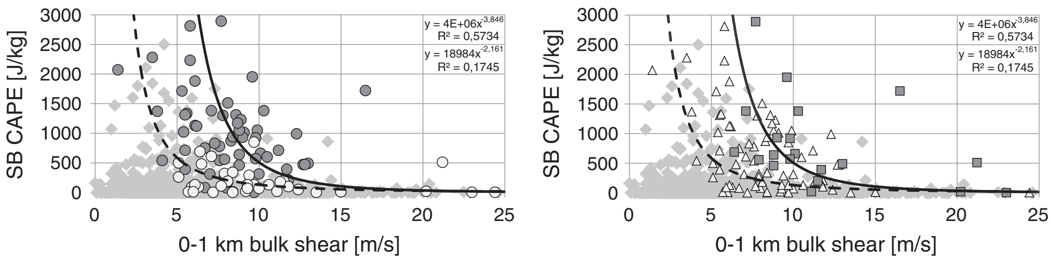

Fig. 4.4.1. Scatter plot of tornado and no-tornado events with respect to surface-based convective available potential energy [J/kg] versus low level shear [m/s]. On the left chart, warm tornado cases with surface temperature over 18 °C were marked by grey circles while cold tornado cases with surface temperature below 18 °C by open circles. On the right chart, weak and unrated tornado cases were marked by open triangles while significant tornado cases by grey squares. Solid line denotes exponential regression line for significant cases, while dashed line denotes exponential regression line for weak and unrated cases. Grey diamonds denote no-tornado and thunderstorm soundings.

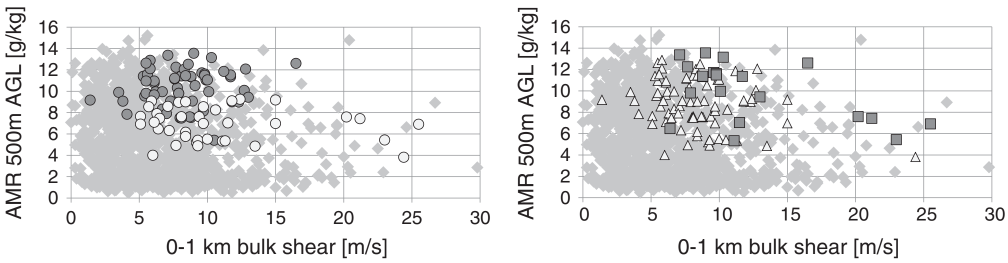

Fig. 4.4.2. As in Fig. 4.4.1 except for the mean average mixing ratio from 500 m AGL layer [g/kg] versus low level shear [m/s].

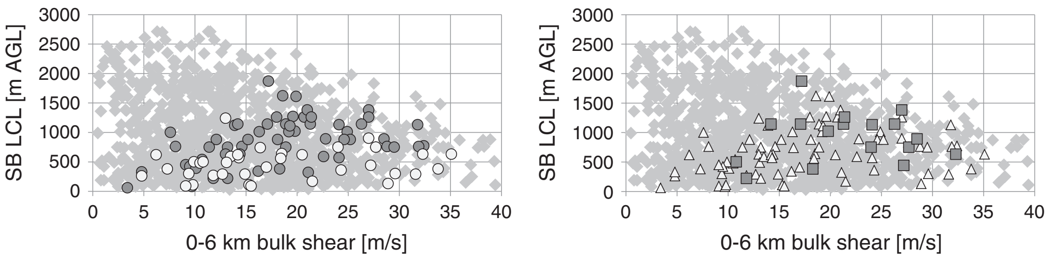

Fig. 4.4.3. As in Fig. 4.4.1 except for the surface based lifting condensation level [m AGL] versus deep layer shear [m/s].

often a moderate combination of these parameters. Despite the fact that the majority of strong cases occurs in warm conditions, in cold highly sheared environment, insignificant instability can result in a strong tornado. This dependence is shown on the chart by calculating exponential regression lines for significant tornadoes (solid line) and weak and unrated tornadoes (dashed line). This gives opportunity to estimate tornado strength with given wind shear and instability conditions. In moderate LLS environment (5–10 m/s) CAPE has higher than in high wind shear environment influences on the strength of the possible tornado (higher CAPE–stronger tornado). On the other hand, LLS parameter which exceeds 15 m/s together with the presence of even low but positive CAPE, gives an increased likelihood that if a tornado will form, it will be possibly strong.

On the second scatterplot chart LLS was examined with moisture content represented by AMR500 (Fig. 4.4.2). As we can see, tornadoes appear to occur with high moisture content accompanied by increased LLS. Relative to no-tornado and thunderstorm soundings they represent quite distinctive areas in the chart. From the chart we can conclude that conditions accompanied by AMR500 below 4 g/kg and LLS below 5 m/s are not very conductive for tornadogenesis, since only a few weak cases have been reported with these parameters (Fig. 4.4.2).

The last scatterplot represents a combination of LCL against DLS (Fig. 4.4.3). The area where tornado cases are distributed on the chart relative to no-tornado and thunderstorm cases is also slightly characteristic. Increased DLS values are assisted by reduced condensation levels, usually below 1000 m AGL, especially in cold tornado cases. We can also conclude that environmental conditions with LCL over 1500 m and DLS below 18 m/s provide virtually zero chances for tornado formation (Fig. 4.4.3).

5. Universal Tornadic Index

One of the aims of this study was to create a Universal Tornadic Index (UTI) algorithm dedicated for distinguishing central European conditions conductive for tornado occurrence. The challenge was addressed to create a formula that should be:

- adjusted to central European tornado conditions
- sensitive to an environment which produces weak non-mesocyclonic tornadoes
- able to detect warm as well as cold tornado types
- increasing with increasing probability for a significant mesocyclonic tornado

The index idea was mainly designed to be used in forecasting by using atmospheric soundings. It should determine how the environmental conditions are conducive to the formation of a tornado and hence what potential strength the tornado can reach. Based on the results obtained in this paper, initial assumptions connected with characteristic parameters for given category were adopted:

- weak/unrated tornadoes (high: 0–3 km CAPE, 0–1 kmSRH, LLS, AMR500, low: LCL)
- significant mesocyclonic tornadoes (high: CAPE, 0–1 kmSRH, LLS, DLS, AMR500, low: LCL)

• cold type tornadoes (high: LLS, 0–1 kmSRH, low: LCL, marginal instability)
• warm type tornadoes (high: CAPE, 0–3 km CAPE, 0–1 kmSRH, LLS, AMR500, low: LCL)

5.1. Index formula

The authors, adhering to an established assumptions, matched an appropriate combination of selected parameters and adjusted it to the database obtained in this study. Ultimately, a final formula with assumptions has been established:

$$UTI = \frac{\left\{\left[\frac{\text{CAPE J/kg} * 1\ \text{kmSRH m}^2/s^2}{200} * \frac{5(\text{DLS m/s}-20) + \left(\frac{2000-\text{LCL m}}{10}\right)}{100}\right] + 3\,\text{km CAPE J/kg} + \frac{1\ \text{kmSRH m}^2/s^2}{4}\right\}}{1000} * \frac{\text{LLS m/s}}{12} * \frac{\text{AMR500 g/kg}}{10} \qquad (5.1.1)$$

if 0–1 km SRH<0 m^2/s^2, then 0-1 km SRH equals 0
if LCL >1500 m, then UTI equals 0
if CAPE = 0 J/kg, then UTI equals 0.

The equation in the first square brackets is mainly responsible for distinguishing mesocyclonic tornadoes and their strength. Adding to this value a CAPE released below 3 km is there to highlight an environment conductive for non-mesocyclonic weak tornadoes. The same thing with 0–1 kmSRH, but for cold cases. Finally all equations are multiplied by the LLS part, since as it was found in analysis, all tornado cases are supported by an increased value of this parameter. In addition, multiplication by the AMR500 part turned out to be effective in reducing false alarms during winter time and in underlining the strength of a tornado. An assumption that only positive values of 0–1 kmSRH are taken into account was to avoid an erroneous indication of the index. However, 0–1 kmSRH in this equation can be used for both right-moving and left-moving supercells. Second assumption concerning LCL height was to avoid false alarms, because the vast majority of analyzed tornadoes had LCL below 1500 m AGL (Fig. 4.4.3), the same was with zero CAPE.

Since we can assume that some of the reports included in this study might not be tornadoes, additional application of the index is not only to detect conditions favorable for tornadogenesis but also to detect conditions that cause damage comparable to them.

5.2. Quality check

UTI has been calculated for all previously analyzed cases (Fig. 5.3.1). As we can see, all types including cold tornadoes are detectable for the index and distinguish between no-tornado and thunderstorm soundings. Moreover, values of the index increase together with the increasing strength of tornadoes.

Obviously, the sensitivity of the UTI might result in an increased number of false alarms throughout the entire year. Therefore, in order to establish how many false alarms it generates and what is the most important to determine operational significance — its quality has been tested on the example of 1097 days during the 3 active tornado years (2008–2010) in Poland. In this period, ESWD with QC0, QC0+, QC1, QC2 reports, indicated 41 tornado days for which proximity soundings were used. The remaining 1056 soundings were collected from Wrocław 12UTC. In addition, 8 days in which serious damage was recorded, but it was unclear whether it was a tornado, were excluded from the analysis. UTI forecast value thresholds have been examined in detection statistics

Table 5.2.1
Statistics for detection of tornadoes with following thresholds of UTI.

UTI	Hit	Miss	False alarm	Null-event	POD	FAR	CSI	TSS	ETS
0.10	34	7	86	962	0.83	0.72	0.26	0.75	0.24
0.30	24	17	23	1028	0.59	0.49	0.38	0.56	0.36
0.50	14	27	9	1038	0.34	0.39	0.28	0.33	0.26
0.75	10	31	3	1045	0.24	0.23	0.23	0.24	0.22
1.00	8	33	2	1046	0.20	0.20	0.19	0.19	0.18

UTI — Universal Tornadic Index
Hit — tornado was forecast and did occur
Miss — tornado was not forecast but did occur
False alarm — tornado was forecast but did not occur
Null-event — tornado was not forecast and did not occur
POD — Probability of Detection
FAR — False Alarm Ratio
CSI — Critical Success Index
TSS — True Skill Statistics
ETS — Equitable Skill Score.

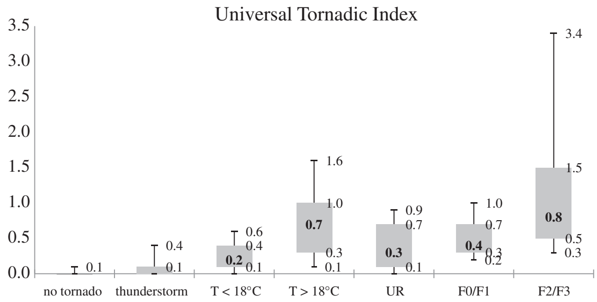

Fig. 5.3.1. As in Fig. 4.1.1 except for the Universal Tornadic Index.

calculated by using 2 × 2 contingency tables (see Doswell et al., 1990 and Wilks, 2006 for further details). Results are presented in Table 5.2.1. As we can see, the best forecasting performance represented by CSI is ranged between 0.3 and 0.5 values of UTI. It is also worth mentioning that UTI values over 0.7 provide low FAR. Low level of POD in UTI over 0.5 can be explained by the large number of weak tornadoes which in assumptions of the index are taking lower values of UTI and are located below 0.5.

6. Conclusions and discussion

Results obtained in the analysis partly confirm previous studies, and introduce new findings. Inspection of 97 soundings connected with tornado occurrence in Poland for years 1977–2012 and 1056 no-tornado and thunderstorm soundings yielded the following results:

- Depending on the temperature, tornadoes tend to present different environmental conditions. Cases with surface temperature over 18 °C feature with increased atmospheric instability and moderate wind shear while cases with surface temperature below 18 °C are characterized by dynamic wind field and rather marginal instability. Among these types statistical differences are also found in lifted condensation level (LCL) and moisture content (AMR500).
- Significant tornadoes occur in both warm and cold tornado cases but most of them are characterized by warm type. They are associated with higher than in weak cases CAPE, DLS, LLS and 0–1 kmSRH which is consistent with the findings of Rasmussen and Blanchard (1998), Thompson et al. (2003), Craven and Brooks (2004), Groenemeijer and van Delden (2007) and Kaltenböck et al. (2009), and increased moisture content (AMR500). Comparing to weak cases they feature with higher LCL which is in accordance with the study of Grünwald and Brooks (2011) but opposite to Groenemeijer and van Delden (2007) and Kaltenböck et al. (2009). The median value of DLS in significant tornadoes exceeded 25 m/s which on the basis of previous research Weisman and Klemp (1982), Davies and Johns (1993), Rasmussen and Blanchard (1998), Markowski et al. (1998), Bunkers et al. (2000), Craven (2000), and Doswell and Evans (2003) suggests tornadogenesis connected with mesocyclone.
- Weak tornadoes are accompanied by increased CAPE released below 3 km AGL and lowered cloud base (LCL) which with a combination of LLS and 0–1 kmSRH can discriminate between no-tornado and thunderstorm cases. Characteristics of this category suggest non-mesocyclonic tornadogenesis since low LCL and large 0–3 CAPE provide updraft sufficient to stretch up pre-existing vertical vorticity (Markowski and Richardson, 2009). Also, decreased values of DLS (median 18.9 m/s) partly exclude mesocyclones.
- The unrated tornado category shares similar statistical distribution as the weak category which confirms the study of Grünwald and Brooks (2011), that typically unrated tornadoes are short-lived and as a result did not cause enough damage to be rated.
- All tornadic categories are typically well distinguished by increased LLS and 0–1 kmSRH accompanied by presence of instability and lowered cloud base.
- The strength of the tornado increases together with increasing wind shear and moisture content
- Tornadoes are often supported by the presence of the upper jet stream. Low leveled jet stream is mainly connected with significant tornadoes.
- A Universal Tornadic Index distinguishes between tornadic and no-tornadic environments and detects warm as well as cold tornado cases. The values of the index increase together with an increasing probability for a significant tornado. In Poland, the operational significance of UTI should pay attention when the index exceeds values of 0.3–0.5.

Climatological values obtained in this study do not provide that if a forecaster will use threshold values in real-time data, he will be able to specify whether a tornado will occur. These results rather suggest that tornadoes can be formed in two different environments (cold and warm). The determination of whether environment parameters are favorable for a tornadogenesis has been made in creating a UTI parameter. Currently it is strongly recommended to use UTI only in the central European region and by analyzing atmospheric soundings.

Experimental usage of the UTI in the mesoscale weather prediction COSMO model in the Polish Meteorological and Water Management Institute for tornado case studies, suggests that the operational significance of UTI should be adjusted to the numerical model since a high-resolution grid provides more detailed data than soundings and thus, generates higher values of the index.

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Appendix C

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M.T. designed the study, acquired and analyzed data, performed computations, made figures, wrote the manuscript, improved the final version of the manuscript.

H.E.B. designed the study, analyzed data, improved the final version of the manuscript.

Tornado Climatology of Poland

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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

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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 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 (Marcinoniene 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; Rafałowski 1958; Parczewski and Kluźniak 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 km^2) 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

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

Category	Criteria
Historical reports (1899–1998)	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
Recent observations (1999–2013)	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 imaginary and radar data were provided.

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 as a tornado case.

Another assumption linked to credibility is that only reports from ESWD with status QC1 (report confirmed) and QC2 (event fully verified) were used in the analysis for the recent period (1999–2013). Reports with status QC0+ (plausibility check passed) have been investigated additionally and, if a funnel cloud in contact with the surface was observed, these reports have been also included (Table 1). In the case of suspicious reports, we have used other available data (satellite images, radar data), the existence of straight-line wind damage, witnesses, photography, and excluded those reports without corroborating evidence from the analysis.

Since, in the historical dataset (1899–1998), the quality of tornado reports is lower than in recent observations and this timeframe is not included in probabilistic estimates, we have taken a different approach to quality control assumptions. All reports with the status QC0+ were included for analysis. This is justified by a relatively low percentage of confirmed reports and the lower possibility of independent documentation that precludes the events from reaching the quality standard of QC1 in ESWD. In more recent observations, QC0+ reports are mostly associated with insufficient damage or come from a suspicious source. In the historical period, these reports rather result from too limited access to information. The dataset of tornado reports before 2000 is relatively small and, in many cases, some information related to tornado occurrence is missing. In cases when the exact day was uncertain, but the month was available, a report was only included in annual distribution analysis. A similar approach was used for inclusion in the analysis of the diurnal cycle. Cases with no location information have been excluded from any analysis.

d. Database categorization

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, inhomogenities 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).

TABLE 2. Tornado cases by F scale included in the analysis and definition of the categories.

F scale	Historical reports (1899–1998)	Recent observations (1999–2013)	Category	Total
Unrated cases	70 (65%)	31 (19%)		
F0	0 (0%)	4 (2%)	Weak tornadoes	169 (63%)
F1	7 (6%)	57 (36%)		
F2	16 (15%)	28 (17%)		
F3	11 (10%)	7 (4%)	Significant tornadoes	66 (24%)
F4	3 (3%)	1 (1%)		
Waterspouts	1 (1%)	33 (21%)	Waterspouts	34 (13%)
Total	108 (100%)	161 (100%)	—	269 (100%)

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 10 000 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

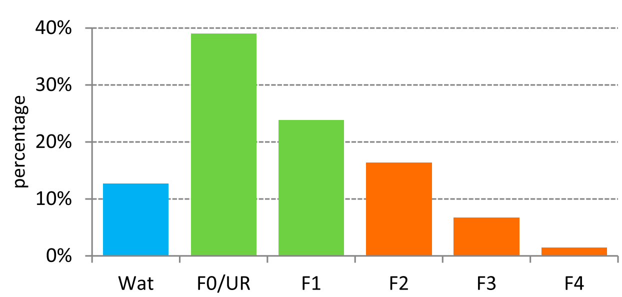

FIG. 1. Percentage of tornadoes by F scale and waterspouts that occurred in Poland in 1899–2013 [weak (green) and significant (orange)]. Waterspout (Wat) and unrated (UR).

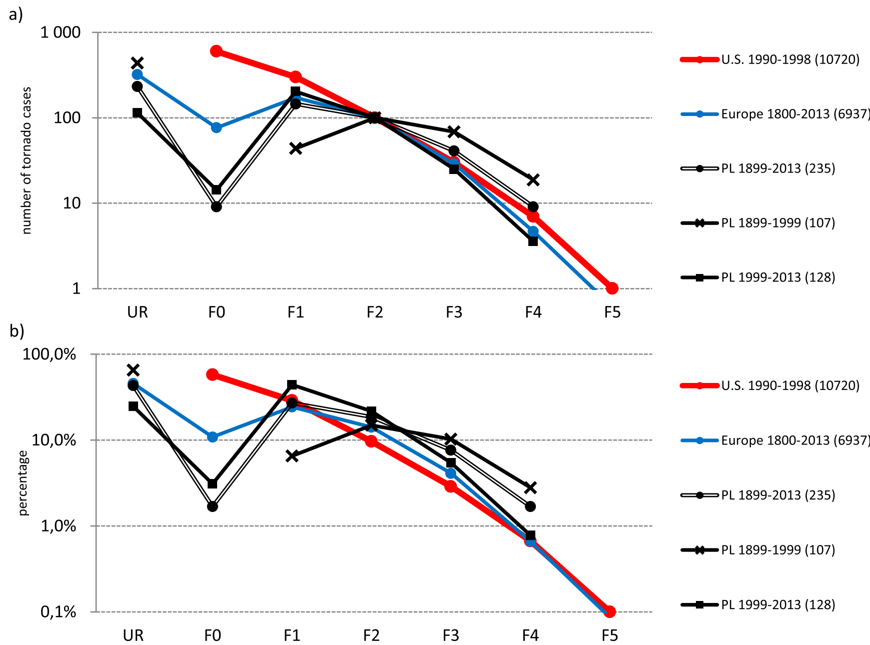

FIG. 2. (a) Tornado cases by F scale and unrated cases for Poland (PL), Europe, and the United States. Please note that reports have been normalized to 100 F2 tornadoes. (b) Percentage of tornado reports by F scale and unrated cases for Poland, Europe, and the United States.

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

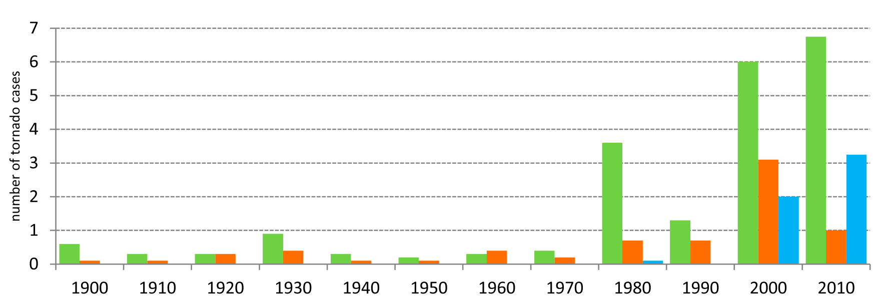

FIG. 3. Annual average of the tornado reports [weak tornadoes (green), significant tornadoes (orange), and waterspouts (blue)] in the decades in Poland. The last decade includes 4 years (2010–13).

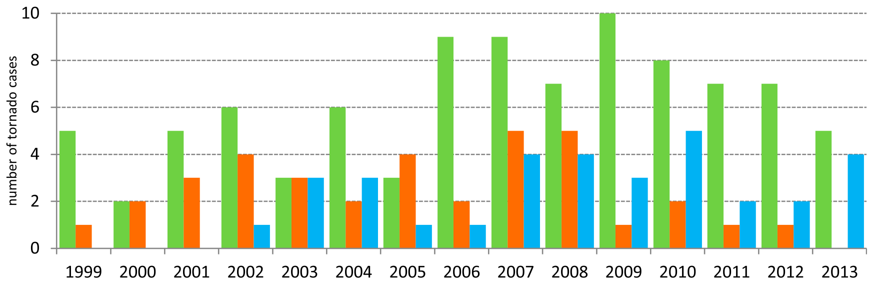

FIG. 4. Annual number of tornado cases [weak tornadoes (green), significant tornadoes (orange), and waterspouts (blue)] in Poland in a recent observations dataset.

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

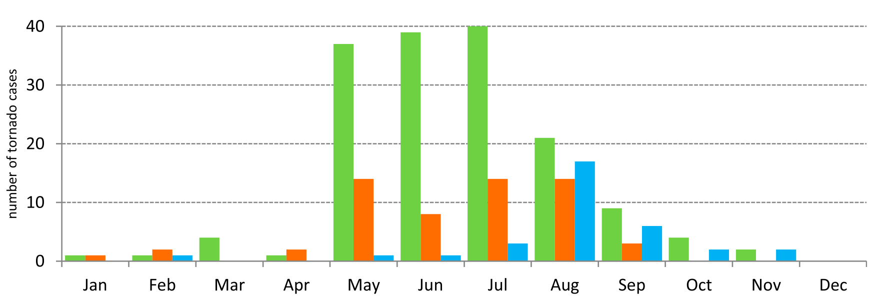

FIG. 5. Monthly distribution of all tornado cases [weak tornadoes (green), significant tornadoes (orange), and waterspouts (blue)] in Poland in 1899–2013.

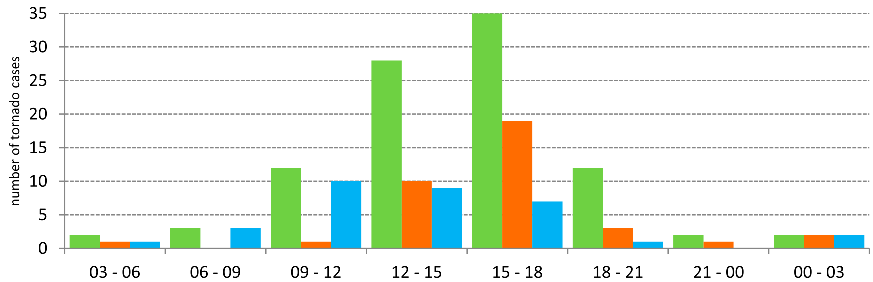

FIG. 6. Diurnal distribution of all tornado cases [weak tornadoes (green), significant tornadoes (orange), and waterspouts (blue)] in Poland in 1899–2013 (time in UTC).

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 (Szilard 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 occurence per day in any particular month

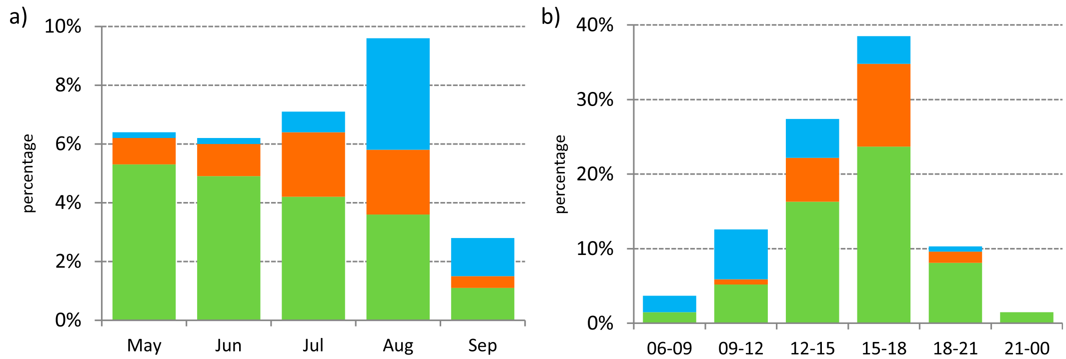

FIG. 7. (a) Daily probability of at least one tornado [weak tornadoes (green), significant tornadoes (orange), and waterspouts (blue)] anywhere in Poland during the tornado season (May–Sep). (b) Hourly probability for the tornado during the tornado season (May–Sep) in a tornado day anywhere in Poland (based on the 1999–2013 tornado reports).

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,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 $50 \times 50\,\mathrm{km}^2$ 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. 8e) 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 $10\,000\,\mathrm{km}^2$ 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

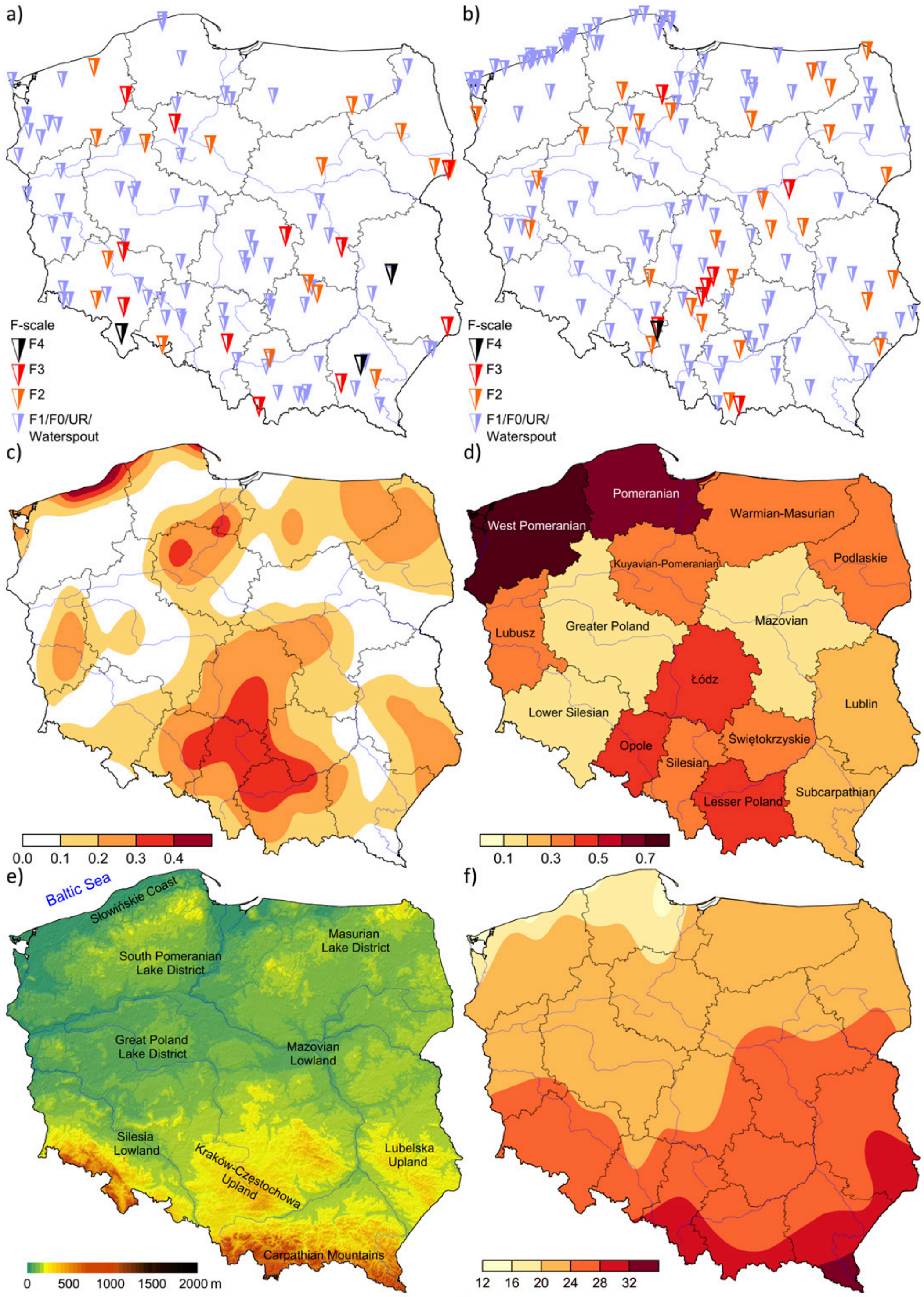

FIG. 8. Geographical distribution of tornado cases in Poland plotted by the F scale as in the legend (a) from 1899–1998 historical reports, and (b) 1999–2013 recent observations. (c) Average annual number for tornadoes (weak, significant, waterspout) in $50 \times 50\,km^2$ area estimated using kriging, and (d) in provinces with values normalized to $10\,000\,km^2$ (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).

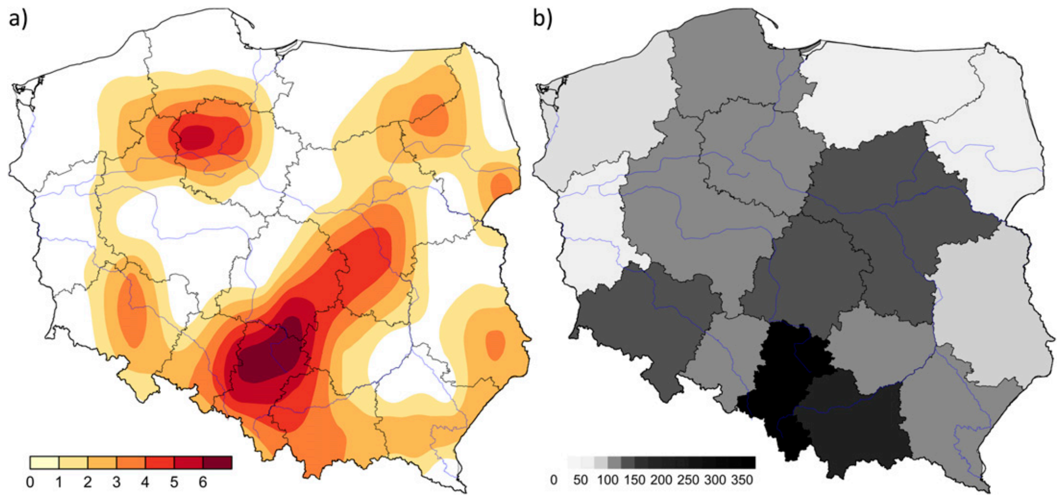

FIG. 9. (a) The number of significant tornado (F2+) reports per $100 \times 100\,km^2$ area in 1899–2013 timeframe estimated using kriging, and (b) population density in provinces [average number of people $(km^2)^{-1}$] in 2013.

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 $10\,000\,km^2$ 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

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

Province	Area (km^2)	No. of tornadoes (1999–2013)	Annual avg No. of tornadoes	Avg annual No. of tornadoes normalized to $10\,000\,km^2$ area
West Pomeranian	22 896	28 (4)*	1.87 (0.26)*	0.82 (0.12)*
Pomeranian	18 293	17 (8)*	1.13 (0.53)*	0.62 (0.29)*
Lesser Poland	15 108	10	0.67	0.44
Łódź	18 219	12	0.80	0.44
Opole	9 412	6	0.40	0.42
Lubusz	13 984	8	0.53	0.38
Silesian	12 294	7	0.47	0.38
Warmian-Masurian	24 191	13	0.87	0.36
Świętokrzyskie	11 627	6	0.40	0.34
Kuyavian-Pomeranian	17 969	9	0.60	0.33
Podlaskie	20 180	9	0.60	0.30
Subcarpathian	17 844	6	0.40	0.22
Lublin	25 155	8	0.53	0.21
Mazovian	35 579	10	0.67	0.19
Greater Poland	29 826	8	0.53	0.18
Lower Silesian	19 948	4	0.27	0.13

* Excluding waterspouts.

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

Category	Tornado recent observations in Poland (1999–2013)	
	No.	Periodicity
Waterspout	33	2–3 yr^{-1}
F0/UR	35	2–3 yr^{-1}
F1	57	3–4 yr^{-1}
F2	28	1–2 yr^{-1}
F3	7	1 for 2 yr
F4	1	1 for 15 yr
F5	—	—
All	161	8–14 yr^{-1}

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 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.

Date	Time (UTC)	Location	Total damage path (km)	Fatalities	Intensity
20 Jul 1931	Daytime	Lublin	20*	6	F4–F5*
20 May 1960	1400 (± 3 h)	Rzeszów	19*	3	F4*
15 Aug 2008	1500	Częstochowa	52	2	F3–F4
15 May 1958	Daytime	Rawa Mazowiecka	27*	2	F3–F4*
14 Jul 2012	1500	Bory Tucholskie	42	1	F3
20 Aug 1946	Daytime	Kłodzko	10*	0	F4*
25 Jul 1977	Daytime	Strzałkowo	*	0	F3–F4*

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.)

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; Setvák et al. 2003; Szilard 2007; Sioutas 2011; Rauhala et al. 2012, Groenemeijer and Kühne 2014; Antonescu and Bell 2015).

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

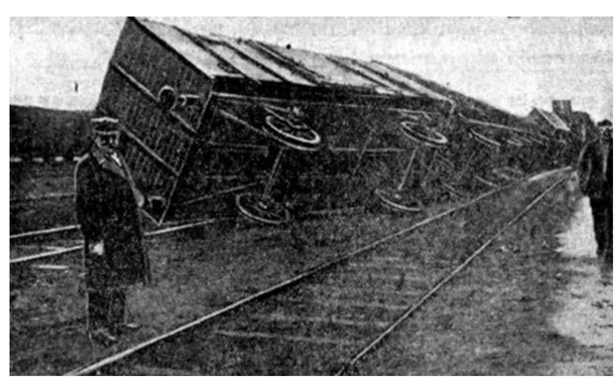

FIG. 11. Overturned railway wagons associated with tornado that passed through Lublin on 20 Jul 1931 [Source: *Światowid* newspaper, No. 31 (364)-01.08.1931.].

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.

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M.T. designed the study, acquired and analyzed data, wrote the manuscript, made figures, improved the final version of the manuscript.

B.C. acquired and analyzed data, performed computations, made figures, improved the final version of the manuscript.

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A Cloud-to-Ground Lightning Climatology for Poland

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ABSTRACT

This research focuses on the climatology of cloud-to-ground (CG) lightning flashes based on PERUN lightning detection network data from 2002 to 2013. To present various CG lightning flash characteristics, 10 km × 10 km grid cells are used, while for estimating thunderstorm days, circles with radii of 17.5 km in the 1 km × 1 km grid cells are used. A total of 4 328 892 CG lightning flashes are used to analyze counts, density, polarity, peak current, and thunderstorm days. An average of 151 days with thunderstorm (appearing anywhere in Poland) occurs each year. The annual number of days with thunderstorms increases southeasterly from the coast of the Baltic Sea (15–20 days) to the Carpathian Mountains (30–35 days). The mean CG lightning flash density varies from 0.2 to 3.1 flashes $km^{-2} yr^{-1}$ with the highest values in the southwest–northeast belt from Kraków-Częstochowa Upland to the Masurian Lake District. The maximum daily CG lightning flash density in this region amounted to 9.1 $km^{-2} day^{-1}$ (3 July 2012). The monthly variation shows a well-defined thunderstorm season extending from May to August with July as the peak month. The vast majority of CG lightning flashes were detected during the daytime (85%) with a peak at 1400 UTC and a minimum at 0700 UTC. Almost 97% of all CG lightning flashes in the present study had a negative current, reaching the highest average monthly values in February (55 kA) and the lowest in July (24 kA). The percentage of positive CG lightning flashes was the lowest during the summer (2%–3%) and the highest during the winter (10%–20%).

1. Introduction

Thunderstorms pose a direct risk to human lives and property. In the United States, in addition to flash-flood phenomena, cloud-to-ground (CG) lightning flashes are among the leading causes of weather-related fatalities (Holle et al. 1999; Curran et al. 2000). On average 10 people are killed in Poland each year by CG lightning flashes, as shown by the data from the Polish National Institute of Statistics. According to the European Severe Weather Database (ESWD; Groenemeijer et al. 2004; Dotzek et al. 2009), between 2012 and 2014 Poland experienced more than 100 damaging lightning events that killed 17 people.

CG lightning flashes are also associated with economic losses; they affect high-voltage power lines, cause forest and infrastructure fires, and also result in transportation disruptions (Wierzchowski et al. 2002; Sasse and Hauf 2003; Larjavaara et al. 2005; Mäkelä et al. 2013). Knowing the spatial and temporal distribution of thunderstorms can improve weather forecasting, and also can help urban planners, insurance companies, and the public to be better prepared (Brooks et al. 2003a).

For decades the main climatological research into thunderstorm spatial and temporary occurrence was based on observations at meteorological stations. Although human observations allow one to analyze long-term changes in the number of thunderstorm days [100-yr climatologies: Changnon and Changnon (2001); Bielec-Bąkowska (2003)], they cannot estimate the intensity of thunderstorms (Rakov and Uman 2003). Storms with either one lightning strike or thousands of flashes are reported as one thunderstorm. This however

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can be examined using lightning detection that allows one to count the number of flashes on particular days and in particular locations.

CG lightning flash climatologies based on data from ground-based lightning detection networks have been developed for some European countries.

a. Central Europe

Based on data recorded between 1992 and 2001 from the Austrian Lightning Detection and Information System (ALDIS), Schulz et al. (2005) showed that thunderstorms are most likely to occur from May to September, especially over the southern part of Austria, where the topographical and meteorological conditions are most favorable (flash density up to 4 flashes $km^{-2} yr^{-1}$, computed within 1 km × 1 km grid cells). Using the same grid resolution in the climatology of lightning characteristics within central Europe, Wapler (2013) estimated the highest CG lightning flash density to be in southern Germany, with more than 30 flashes $km^{-2} yr^{-1}$. In the Czech Republic, the number was estimated across 20 km × 20 km grid cells and found to average 1–3 CG lightning flashes $km^{-2} yr^{-1}$ each year (Novák and Kyznarová 2011).

b. Southern Europe

A 10-yr period (1992–2001) of lightning data derived from the Spanish Lightning Detection Network (SLDN) was analyzed over 0.2° × 0.2° grid cells by Soriano et al. (2005). They found that the lightning density is mainly related to the topography and the atmospheric circulation, with the maximum found over the Pyrenees and along the coast of Catalonia (density up to 2 flashes $km^{-2} yr^{-1}$). The CG lightning flash climatology for Portugal (Santos et al. 2012) revealed that thunderstorms are most likely in May and September between 1600 and 1800 UTC. The maximum CG lightning flash density estimated on the 0.1° × 0.1° grid cells was up to 0.6 flashes $km^{-2} yr^{-1}$. In Italy, Biron (2009), taking into account CG lightning flash data over 10 km × 10 km grid cells from the Italian National Meteorological Service Lightning Network (LAMPINET) between 2005 and 2007, concluded that Lake Como, Sardinia, the Gulf of Trieste, and Naples, Liguria, and the central Apennine have the highest average annual CG lightning flash densities. The highest CG flash density, up to 9 flashes $km^{-2} yr^{-1}$, computed over 0.02° × 0.03° grid cells, was also found in northeastern Italy by Feudale et al. (2013).

c. Northern Europe

In Scandinavia, the Nordic Lightning Information System (NORDLIS) was used by Mäkelä et al. (2014) to construct a CG lightning flash climatology spanning 2002–11. The average daily number of ground flashes peaked in mid-July and early August while cold season (October–April) thunderstorms were most frequent over the sea. At 0.2° × 0.2° grid resolution, Sonnadara et al. (2006) estimated for Sweden the maximum CG lightning density up to 0.4 $km^2 yr^{-1}$ and highlighted that the main thunderstorm season extends from June to August. Daily CG lightning flash densities in the contiguous United States and Finland across 20 km × 20 km grid cells, as well as the relationship between thunderstorm days and CG lightning flash density, were analyzed by Mäkelä et al. (2011). Enno (2011) investigated the lightning climatology of Estonia for the period 2005–09 and estimated that for 10 km × 10 km grid cells the maximum lightning density was 1 flash $km^{-2} yr^{-1}$.

d. Eastern Europe

The lightning climatology of Romania, as derived from the Romanian National Lightning Detection Network (RNLDN), was studied by Antonescu and Burcea (2010). The analyses of the years 2003–05 and 2007 revealed that most of the CG lightning flashes occur over the southern slopes of the central meridional Carpathians (density of up to 3 flashes $km^{-2} yr^{-1}$ computed within 20 km × 20 km grid cells) from May to September.

e. Poland

For Poland such a study has been not performed yet. However, integrated European lightning climatologies have been developed with the use of the Arrival Time Differencing Network (ATDnet) for the years 2008–13 (Anderson and Klugmann 2014), and the Vaisala Global Lightning Dataset (GLD360) and the European Cooperation for Lightning Detection (EUCLID) dataset for 2011 (Pohjola and Mäkelä 2013). The results show that the lowest lightning flash density was located along the coast of the Baltic Sea while the highest was placed over the southeastern and south-central parts of the country (density of over 3 flashes $km^{-2} yr^{-1}$ in the GLD360 and EUCLID networks, and 4 flashes $km^{-2} yr^{-1}$ in ATDnet).

The Polish PERUN lightning detection network (Łoboda et al. 2009), which was introduced in 2002, presented the possibility of performing a national analysis. Therefore, by using the data from this network the main aim of this paper is to present a CG lightning flash climatology for Poland. This is a first of its kind study to be performed in Poland and is a contribution to the European CG lightning climatology. Previously, national thunderstorm characteristics in Poland were studied only with the use of surface synoptic observation (SYNOP) reports. Bielec-Bąkowska (2003), Kolendowicz (2006, 2012), and Czernecki et al. (2015) estimated that within a particular location, from 15 to 33 thunderstorm days occur on average every year in Poland.

The paper is organized as follows. Section 2 describes the data and methods used in this study. The results concerning spatial, annual, monthly, and diurnal distributions of lightning count, density, polarity, peak current and thunderstorm days are presented in section 3. The last section contains a summary and concluding remarks.

2. Data and methods

In this section we describe the PERUN lightning detection network, its structure, detection techniques, detection efficiency, location accuracy, quality of the data, and quality control assumptions. We also discuss computational methods that we use to produce maps with thunderstorm days and characteristics of CG lightning flashes.

a. Lightning data

The lightning detection network in Poland is operated by the Institute of Meteorology and Water Management–National Research Institute (IMGW–PIB), and since 2002 has worked operationally under the name of PERUN (the god of thunder and lightning in Slavic mythology). The system consists of nine Surveillance et Alerte Foudre par Interférométrie Radioélectrique (SAFIR3000) total lightning automatic detection stations located at Białystok, Olsztyn, Toruń, Gorzów Wielkopolski, Kalisz, Częstochowa, Włodawa, and Warszawa (Fig. 1a). The network center's central processor (CP) unit is situated at IMGW–PIB headquarter in Warszawa.

With the use of interferometry in the band of very high frequency (VHF), sensors perform angular localization of thunderstorm electric activity for both CG and intracloud (IC) flashes. For measurements of various electrical parameters and discrimination between different types of discharges, detections are also performed at low frequencies (LFs). The system uses a direction-finding (DF) technique (Krider et al. 1980). The system is capable of detecting up to 100 events per second (Betz et al. 2009). Further information on lightning detection techniques and their limitations may be found in MacGorman and Rust (1998) and Rakov and Uman (2003).

To construct a climatology of CG lightning flash, we use PERUN data from 2002 to 2013. The R software package (R Core Team 2014) was used for our computational purposes. The PERUN database contained the information concerning the time of the event (milliseconds), the place [World Geodetic System (WGS-84) map projection], uncertainty related to detection (m), the type of discharge (CG or IC), polarity, peak current estimation (kA), and multiplicity. We reprojected the original WGS-84 projection into a meter-based Polish CS92 (EPSG:2180) coordinate system. The basic unit of detection was strokes; however, in the case of a multistroke flash, we considered only the first located stroke and its current. This meant that in the statistics we included only flashes instead of strokes.

As in previous studies on lightning climatologies (e.g., Antonescu and Burcea 2010; Feudale et al. 2013; Mäkelä et al. 2014), we considered only CG lightning flash data and excluded IC flashes. This can be justified by the relatively low detection efficiency and low quality of IC lightning data, which may yield unreliable climatological results. According to the previous studies of Cummins et al. (1998) and Wacker and Orville (1999a,b), some of the CG positive flashes with the peak current below 10 kA may be considered to be IC flashes; therefore, we also filtered out our data from these flashes and they have been removed. They accounted for around 1.5% of all CG flashes and around 33% of all positive CG flashes in our database.

Since the network is able to detect flashes that may appear far from the Polish border (e.g., numerous cases of lightning detections over Kazakhstan), the data have also been limited to the administrative borders of Poland.

b. Detection efficiency and location accuracy

The spatial distribution of the SAFIR3000 sensors is not homogenous in space; therefore, the detection efficiency and the location accuracy vary across the whole country. Bodzak (2006) estimated that PERUN network has a 95% detection efficiency over the area of Poland and that it is particularly high at distances of up to 100 km from the sensor. Considering the 100-km buffer zones around the SAFIR3000 sensors (Fig. 1a), we can define that the highest detection efficiency is located in the central-eastern part of the country while the lowest falls over the coastal zone and the northwestern and southwestern parts of the country.

Bodzak (2006) stated that the PERUN network reveals the lightning location accuracy in the whole country to be below 1 km. However, by analyzing uncertainty related to lightning location accuracy derived from our database (Fig. 1b), we can estimate that only

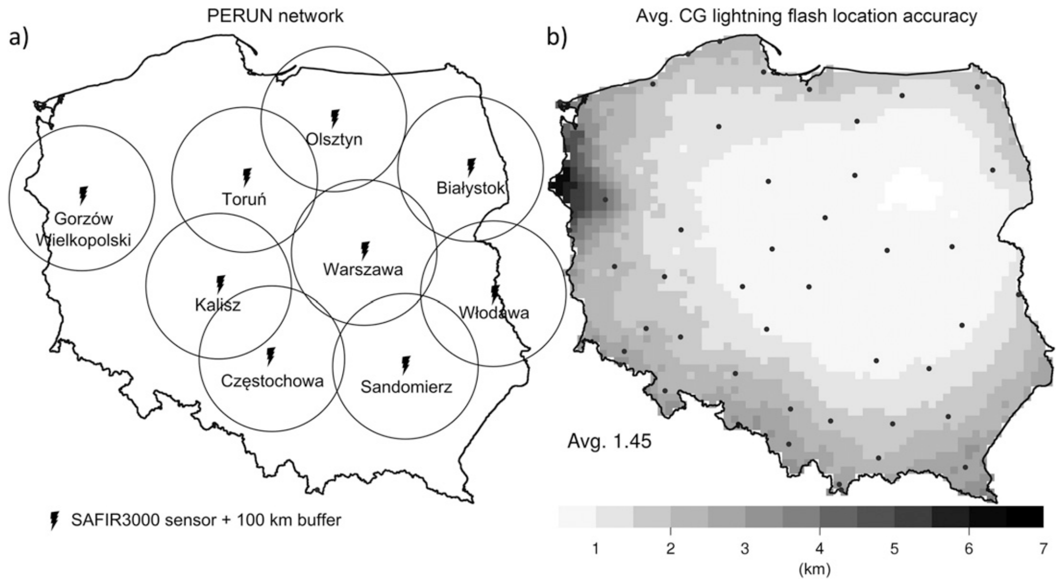

FIG. 1. (a) Locations of SAFIR3000 lightning sensors in the PERUN network with 100-km buffer zones. (b) Average CG lightning flash location accuracy (km) derived from the PERUN database during 2002–13. Computed in 10 km × 10 km grid cells. Dots denote main meteorological stations (44).

38.3% of the country has such a value while the location accuracy of less than 2 km covers almost 76.6%. It can be observed that the spatial distribution of the location accuracy is proportional to the density of the SAFIR3000 sensors (Figs. 1a,b). In the places where the distances between the sensors are smaller than 100 km (70.7% area of the country), the location accuracy is better. The lowest location accuracy (>6 km) falls on the northwestern parts of the country, where the distances to the sensors located in the central-eastern part of the country are the highest (Fig. 1b).

The spatial differences in sensor density suggest that climatological results obtained in the coastal and western regions may be slightly affected by unequal detection efficiency, especially if we take into account low-peak current strokes (Mäkelä et al. 2014). In the climatological examinations the study area should be considered when determining the steady detection efficiency and the location accuracy ratio; however, no correction was made as we analyzed only the measured values.

The performance of the network did not change significantly over the analyzed time frame. In 2009 one sensor (in Toruń) was switched off because of the renovation. There were also some small changes in the configuration of the system (induced after the manufacturer's recommendations) while in late 2009 the manufacturer's support of SAFIR3000 sensor types was stopped. In 2012 IMGW–PIB managed to renovate sensors in the network and thus increased the quality of the lightning detections throughout the whole system. Although the detection efficiency and the location accuracy varied somewhat, these changes were small and did not significantly affect the detection efficiency or the location accuracy. The interannual changes in the average location accuracy deviated from the average value up to 17% in 2002 and 2004 while in the remaining years these deviations were lower than 10%.

c. *Map computations*

Diendorfer (2008) showed that a reliable accuracy for flash density can be achieved when on average of more than 80 flashes occurs in each grid cell. Therefore, most of the modern CG lightning flash climatologies typically use 10 km × 10 km, 20 km × 20 km, or 0.2° × 0.2° (approximately 20 km × 20 km) grid cells (e.g., Soriano et al. 2005; Sonnadara et al. 2006; Tuomi and Mäkelä 2008; Biron 2009; Antonescu and Burcea 2010; Mäkelä et al. 2011; Enno 2011; Santos et al. 2012). In this study we use a resolution of 10 km × 10 km for the grid cells (100 km^2 area), and following the study of Diendorfer (2008), we believe that it is the most appropriate for our database (an average of 117 flashes in a grid cell).

To compute thunderstorm days derived from the PERUN database, we considered the flashes in the circle with the radius of 17.5 km from the center of the 1 km × 1 km grid cells. The higher resolution was chosen here to provide more-detailed and smoothed

TABLE 1. Statistics for 2002–13 CG lightning flashes derived from the PERUN lightning detection network. Data have been limited to the administrative borders of Poland.

Category	No. of flashes	Percentage	Avg yr^{-1}
Total	4 328 892	100.0	360 741
Negative	4 201 622	97.1	350 135
Positive	127 270	2.9	10 605
During daytime ($>-12°$ sun angle)	3 678 756	85.0	306 563
During nighttime ($<-12°$ sun angle)	650 136	15.0	54 178

results. To compute such maps, it was necessary to include additional lightning data within a 17.5-km buffer zone away from the Polish borders. The same method used in this study to compute thunderstorm day characteristics has also been used in other studies (Novák and Kyznarová 2011; Wapler 2013; Mäkelä et al. 2014). We used the value of 17.5 km since for Poland it was proven by Czernecki et al. (2015) to provide the best overlap of thunderstorm days derived from the human observations with those estimated within the use of lightning detection data (at least two CG lightning flashes in the circle).

We used SYNOP reports from 44 meteorological stations derived from NOAA/National Climatic Data Center (NCDC) daily summaries for the same period as the data from the PERUN database (2002–13). In total, we distinguished 12 419 daily reports with thunderstorms (1478 unique days with thunderstorms).

3. Results

In this section we first present the statistics for the CG lightning flash data limited to the administrative borders of Poland and we also estimate the intensity of the thunderstorms. In section 3b, we present the spatial distribution of the lightning flash densities and thunderstorm days on different time scales, as these parameters have been frequently used in past CG lightning flash climatologies. Section 3c is devoted to the percentage of nighttime CG lightning flashes. The polarity and peak current characteristics are presented in section 3d.

a. Data statistics

In total, 4 952 203 CG lightning flashes were derived from the PERUN database for the years 2002–13 while 4 328 892 of the flashes were limited to the administrative borders of Poland in order to compute country-scale statistics (Table 1). Among these, almost 97% were negative CG lightning flashes while 3% corresponded to a positive lightning charge. With the use of latitude, longitude, date, and exact time of the detection (counted in seconds), we calculated the angle of the sun for each record and divided the data for detections during the daytime (sun angle $\geq -12°$) and nighttime (sun angle $< -12°$). The value of 12° was used on the basis of NOAA's astronomical term for nautical dawn [''This is the time at which the sun is 12 degrees below the horizon in the morning. Nautical dawn is defined as that time at which there is just enough sunlight for objects to be distinguishable;'' NOAA/NWS (2015)] in order to focus on daytime and nighttime as it is perceived by the human eye. As it turned out, 85% of all flashes in our database were detected during the day while 15% occurred during the nighttime.

To estimate the intensity of thunderstorms, we used daily sums of flashes. We did not include in the analysis days with only one detected lightning flash because of the possibility of false detection and thus unreliable climatological results (these kinds of single discharges may originate either from electromagnetic noise of anthropogenic origin or be lightning from large distances reflected by the ionosphere). Depending on the number of diurnal flashes, we have distinguished in our database thunderstorm days (lightning anywhere in Poland) with more than 1 flash (1815 days), 10 flashes (1354 days), 100 flashes (980 days), 1000 flashes (542 days), and 10 000 flashes (123 days), which gave an annual average of 151 days with a thunderstorm occurring anywhere in Poland (Table 2).

There were 438 days during which the number of CG lightning flashes was between 101 and 1000. These days accounted for only 3.8% of all flashes in the database while 123 days with their daily CG lightning flashes counts exceeding 10 000 consisted represented 60% of all of the lightning data (Table 2). Moreover, thunderstorms on only the 10 days with the highest daily number of CG lightning flashes (Table 3) generated in total 545 071 CG lightning flashes, which accounted for 12.6% of the whole analyzed dataset. Six of these days appeared during the years 2011–13. At this point it is also worth mentioning that the majority of thunderstorm outbreaks occurred in July, the peak month (7 cases in the top 10 days and 41 cases in the top 100 days). The second-most intense month was June with 2 cases in the top 10 days and 26 in the top 100 days. August places third, with 1 case in top the 10 days and 22 in the top 100 days.

b. Average annual number of thunderstorm days

The average annual number of thunderstorm days (Fig. 2b) with at least two CG lightning flashes increases generally from the northwest to the southeast with the lowest values along the Baltic Sea coast (15–20 days)

TABLE 2. Statistics for days during 2002–13 with detected CG lightning flashes derived from the PERUN lightning detection network. Data have been limited to the administrative borders of Poland. Days with one detected lightning flash have been omitted.

No. of flashes	No. of days	Percentage	No. yr^{-1}	No. of flashes	Percentage	No. yr^{-1}
2–10	461	25.40	38	1598	0.04	133
11–100	374	20.61	31	13 172	0.30	1230
101–1000	438	24.13	37	164 218	3.79	13 684
1001–10 000	419	23.09	35	1 571 504	36.30	130 958
>10 000	123	6.78	10	2 578 400	59.56	214 866
SYNOP reports	1478	81	123			

and the highest in the Carpathian Mountains (30–35 days). The mean annual number of thunderstorm days averaged for the whole country amounted to 24.21 and was reasonably close to the value of 24.3 obtained from SYNOP reports for Poland by Kolendowicz (2012) through long-term observations (1951–2010). Similar results for the spatial distribution of thunderstorm days in the years 1885–2000 were also found by Bielec-Bąkowska (2003).

c. *Average annual CG lightning flash density*

The spatial distribution of the mean CG lightning flash density over 10 km × 10 km grid cells varied from 0.2 to 3.1 flashes $km^{-2} yr^{-1}$ (Fig. 2c). Similar densities were also observed in, for example, Austria, Spain, Romania, and the Czech Republic (Schulz et al. 2005; Soriano et al. 2005; Antonescu and Burcea 2010; Novák and Kyznarová 2011). In Poland, the lowest values were found over the Baltic Sea while the highest occurred in the middle-eastern part of the country [southwest (SW)–northeast (NE) belt from Kraków-Częstochowa Upland to Masurian Lake District; Figs. 2a,c]. Although the previous climatological study of Taszarek and Brooks (2015) pointed to exactly the same area as the most vulnerable for tornado occurrence, this pattern does not overlap with the spatial distribution of thunderstorm days. Such a distribution may be presumably correlated with PERUN's spatial lightning detection efficiency, which is the highest in the middle-eastern part of the country and thus accounts for more flash detections (Bodzak 2006; Figs. 1a,b). However, the results of the European lightning density analyses obtained by Anderson and Klugmann (2014) through the use of ATDnet for the years 2008–13, by Pohjola and Mäkelä (2013) from GLD360 and EUCLID for the year 2011, and by the Blitzortung network (Wanke 2011) for the year 2011 pointed exactly to the same region in Poland where the highest CG lightning flash density occurred.

d. *Maximum daily CG lightning flash density*

The analysis of the maximum daily number of CG lightning flashes per kilometer squared revealed the places where the most intense or multiple thunderstorms occurred within one day (Fig. 2d). The maximum daily CG lightning flash density varied from 0.2 to 9.1 $km^{-2} day^{-1}$ (3 July 2012; Table 3). This meant that very intense thunderstorms were capable of producing locally in only one day more CG lightning flashes that on average occur during the whole year (Fig. 2c). These kinds of storms are most likely related to mesoscale convective systems (MCSs; Houze 2004)—thunderstorms that are capable of producing large numbers of CG lightning flashes. The maximum daily density of the CG lightning flashes is the highest in the belt from Kraków-Częstochowa Upland to Masurian Lake District (Fig. 2a), similar to the average annual CG lightning flash density (Fig. 2c). Another similar pattern was also found in the large-hail report distribution in the study by Taszarek and Suwała (2015).

The spatial distribution of CG lightning flashes in the 10 days with the highest number of detected CG lightning flashes in our dataset (Table 3, Fig. 3) revealed that the thunderstorm activity was often covering more than half of the country, with 4–8 locations having CG lightning flash density exceeding 3–5 $km^{-2} day^{-1}$. The maximum CG lightning flash density during these days

TABLE 3. Top 10 days with the highest daily number of CG lightning flashes detected by the PERUN lightning detection network from 2002 to 2013. Data have been limited to the administrative borders of Poland.

Date	No. of CG lightning flashes	Avg flash density (km^2)	Max flash density (km^2)
26 Jun 2006	73 549	0.24	6.56
3 Jul 2012	65 656	0.21	9.11
15 Aug 2008	64 029	0.21	3.69
31 Jul 2005	61 456	0.20	5.83
20 Jul 2011	54 675	0.18	3.51
7 Jul 2012	48 234	0.16	2.91
1 Jul 2012	47 985	0.15	6.57
14 Jul 2011	44 765	0.14	6.03
29 Jul 2005	44 698	0.14	6.24
21 Jun 2013	40 024	0.13	8.36

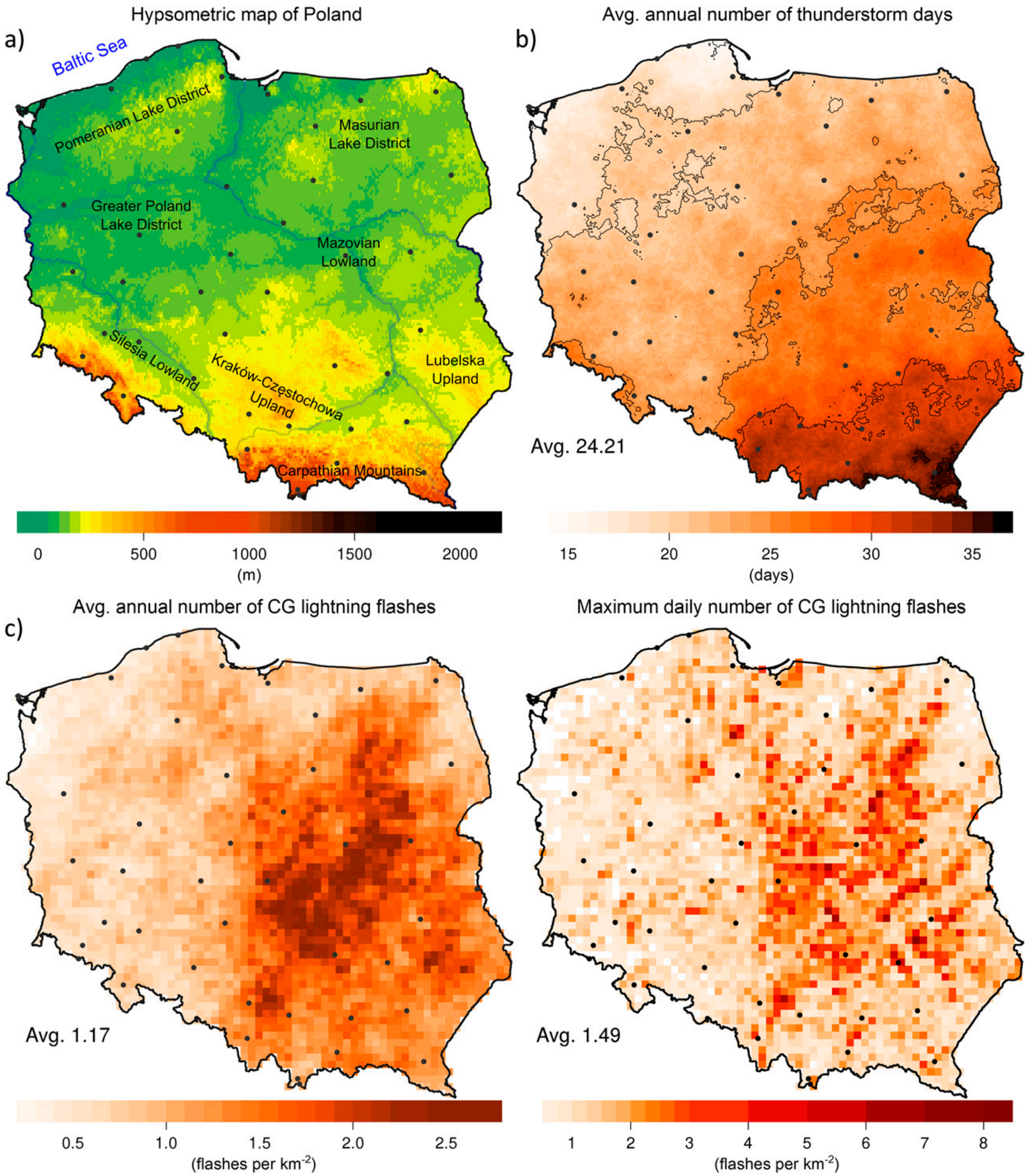

FIG. 2. (a) Hypsometric map of Poland based on Shuttle Radar Topography Mission Global Coverage (SRTM3) data (Farr et al. 2007). (b) The average annual number of thunderstorm days during 2002–13. Lightning location data are computed within a radius of 17.5 km from the bin center (within a surface area of 962 km^2) in 1 km × 1 km grid cells. (c) The average annual number of CG lightning flashes km^{-2}. (d) The maximum daily number of CG lightning flashes km^{-2}. Lightning densities are computed for 10 km × 10 km grid cells. Based on lightning data derived from the PERUN network for the period 2002–13. Dots denote main meteorological stations (44).

varied from 3 to 9 $km^{-2} day^{-1}$ (Table 3). These days also indicate that the belt from Kraków-Częstochowa Upland up to the Masurian Lake District is the most vulnerable region in terms of the occurrence of intense thunderstorms in Poland.

e. Annual variations in CG lightning flash density and thunderstorm days

The yearly variations in the total annual numbers of CG lightning flashes show a notable variability, with an average of 360 741 CG lightning flashes per year (Fig. 4) and a spatial average of 1.17 flashes $km^{-2} yr^{-1}$ (Fig. 5). The years 2011 and 2012 were characterized by increased thunderstorm activity, with more than 500 000 CG lightning flashes per year (spatially 1.8 flashes $km^{-2} yr^{-1}$). For thunderstorms, the years 2004 and 2009 were the least active and produced only 200 000 CG lightning flashes each year (spatially 0.6 flashes $km^{-2} yr^{-1}$). Most of the annual peak CG lightning densities (>8 flashes $km^{-2} yr^{-1}$) were observed in the middle and the eastern parts of the country. The highest value occurred in 2012 near the Masurian Lake District and exceeded 12 flashes $km^{-2} yr^{-1}$.

The interannual number of thunderstorm days (occurring anywhere in Poland), with at least two flashes, varied from 133 (2007) to 171 (2002), with an average of 151 per year (Fig. 6). Human observations performed at meteorological stations indicated a lower frequency (an average of 123 days per year) and were similar to the data sample of thunderstorm days with at least 10 flashes (an average of 113 per year; Fig. 6).

The spatial distribution of thunderstorm days in particular years indicated that in almost every year more than 30 thunderstorm days occurred in the southern and southeastern parts of the country (Fig. 7). The highest value (58 days) observed in 2002 also occurred in the same region. The rest of the country was characterized by a greater differentiation, from 5 to even 50 thunderstorm days (Masurian Lake District in 2010). The annual number of thunderstorm days averaged across the whole area of the country amounted to 19.3 in 2008 with up to 27.5 in 2012 (Fig. 7). In the long-term climatology based on the SYNOP reports (Kolendowicz 2012; Czernecki et al. 2015), this value varied between 18 in 1976 and up to 32 in 1963 (based on the average from 44 meteorological stations). Bearing this in mind, the thunderstorm activity analyzed in this paper did not differ from the overall climatological values.

f. Percentage of nighttime CG lightning flashes

Interesting results are found when we take into account the percentage of CG lightning flashes occurring

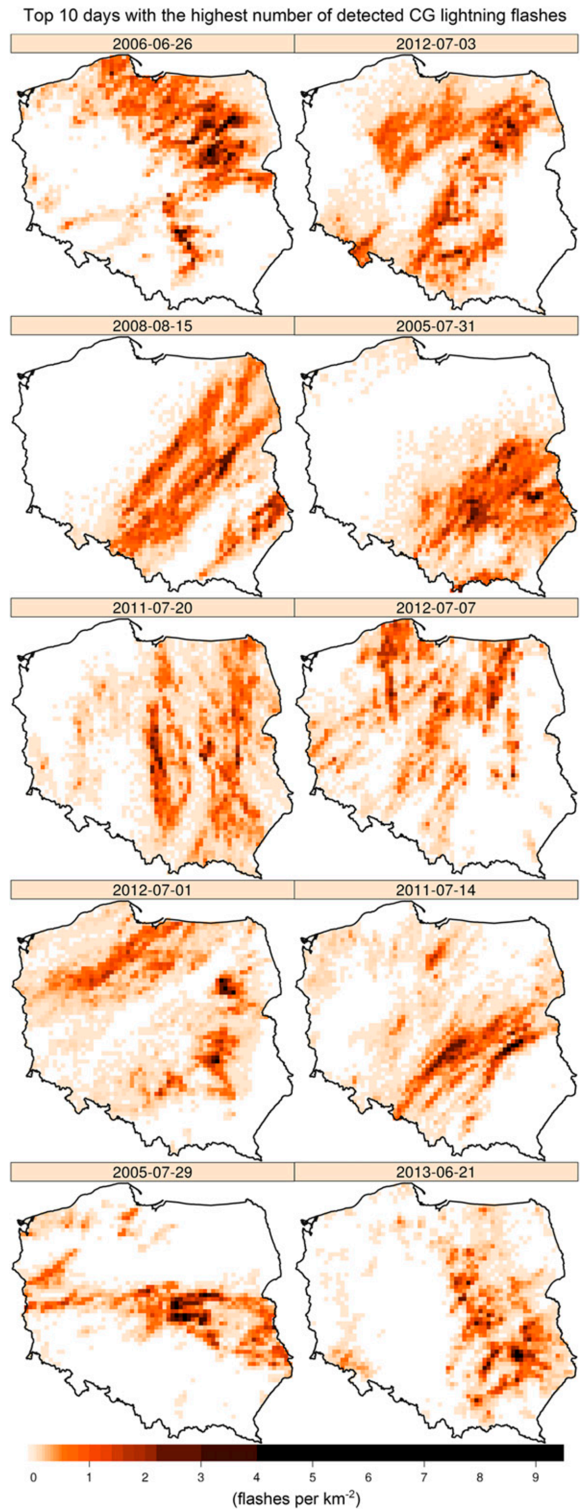

FIG. 3. The number of CG lightning flashes km^{-2} in 10 days with the highest number of detected CG lightning flashes (as in Table 3). Computed for 10 km × 10 km grid cells. Based on lightning data derived from the PERUN network for the period 2002–13.

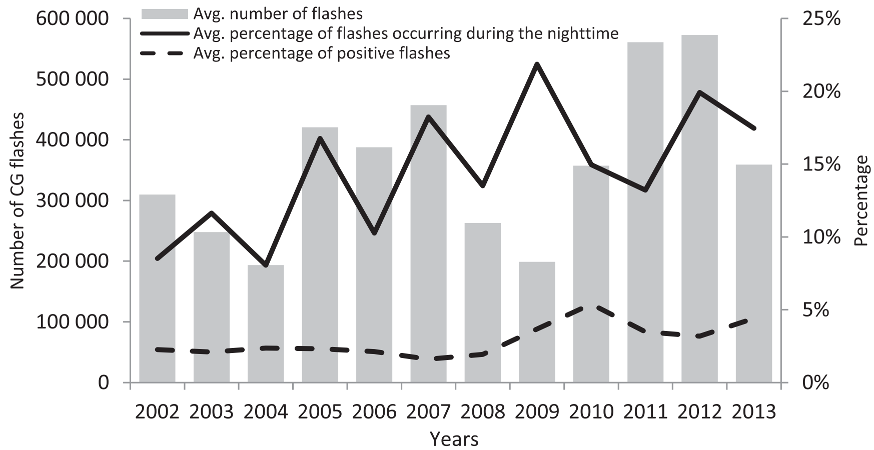

FIG. 4. Annual CG lightning flash count (bars), percentage of CG lightning flashes occurring during the night (black solid line), and percentage of positive CG lightning flashes (black dashed line). Based on lightning data derived from the PERUN network for the period 2002–13. Data have been limited to the administrative borders of Poland.

during the night (sun angle $< -12°$; section 2d). We can observe an increase in CG lightning flashes occurring during the night from an average of 12% during the years 2002–07 to as much as 17% during the years 2008–13, with the peak in 2009 (22%; Fig. 4). It is difficult to explain such an increase, but since it is a percentage value, we doubt the fact that changes in network's performance could affect it. It is possible that in these years conditions were more conducive for providing higher thermodynamic instability during the evening hours. Thunderstorm clouds could then last longer and produce more lightning during the night, especially in the form of MCSs (Nesbitt et al. 2000; Virts et al. 2013). The presence or absence of a few MCSs in a single year due to synoptic-scale factors that naturally vary from year to year could have dominated an average lightning count on many time and spatial scales.

The spatial distribution of the percentage of CG lightning flashes occurring during the nighttime varied in most of the area from 2% to 20% (Fig. 8). The exception was the midwestern and the southwestern parts of the country, where this value exceeded 45%. In the days with the highest number of CG lightning flashes in this region (e.g., 1 July 2012, 2 July 2012, 5 July 2012, 7 July 2012, 22 August 2012, 4 August 2013, and 29 July 2013), we can see that the majority of the flashes were produced by MCSs that were passing through this area during the nighttime hours (not shown). The majority of these cases had a very characteristic pattern. Thunderstorms during the daytime initiated over Germany and/or the Czech Republic and then moved northeasterly/easterly in the form of MCSs that were entering to the west and southwestern parts of Poland in the evening and nighttime hours. We also consider this pattern as one of the reasons why the annual percentage of CG lightning flashes during the nighttime has been higher in recent years (Fig. 4). MCSs that usually last until the late evening hours were more frequent in recent years and, thus, resulted in a higher percentage of nighttime flashes. The same effect was also observed in the studies of Nesbitt et al. (2000) and Virts et al. (2013), where long-lived MCSs were affecting the daily lightning cycle and increasing the percentage of CG lightning flashes during the nighttime.

The percentage of nighttime CG lightning flashes was highest during winter months and peaked in January (90%). The lowest percentage of nighttime flashes was in the early summer (11%), and from that point it was increasing each month through October (46%; Fig. 9). This could be justified by the advection of cold air masses during the late summer that over relatively preheated ground provided higher thermodynamic instability during the nighttime.

g. *Monthly variations of CG lightning flash density and thunderstorm days*

The monthly variations in CG lightning flash frequency clearly show a well-defined thunderstorm season extending from May to August with July as a peak month (an average of 137 024 CG lightning flashes per year with a maximum flash density in central Poland of up to 20 km^{-2} $month^{-1}$; Figs. 9 and 10). Similar thunderstorm seasons have also been found in recent European CG lightning flash climatological studies (e.g., Antonescu and Burcea 2010; Novák and Kyznarová

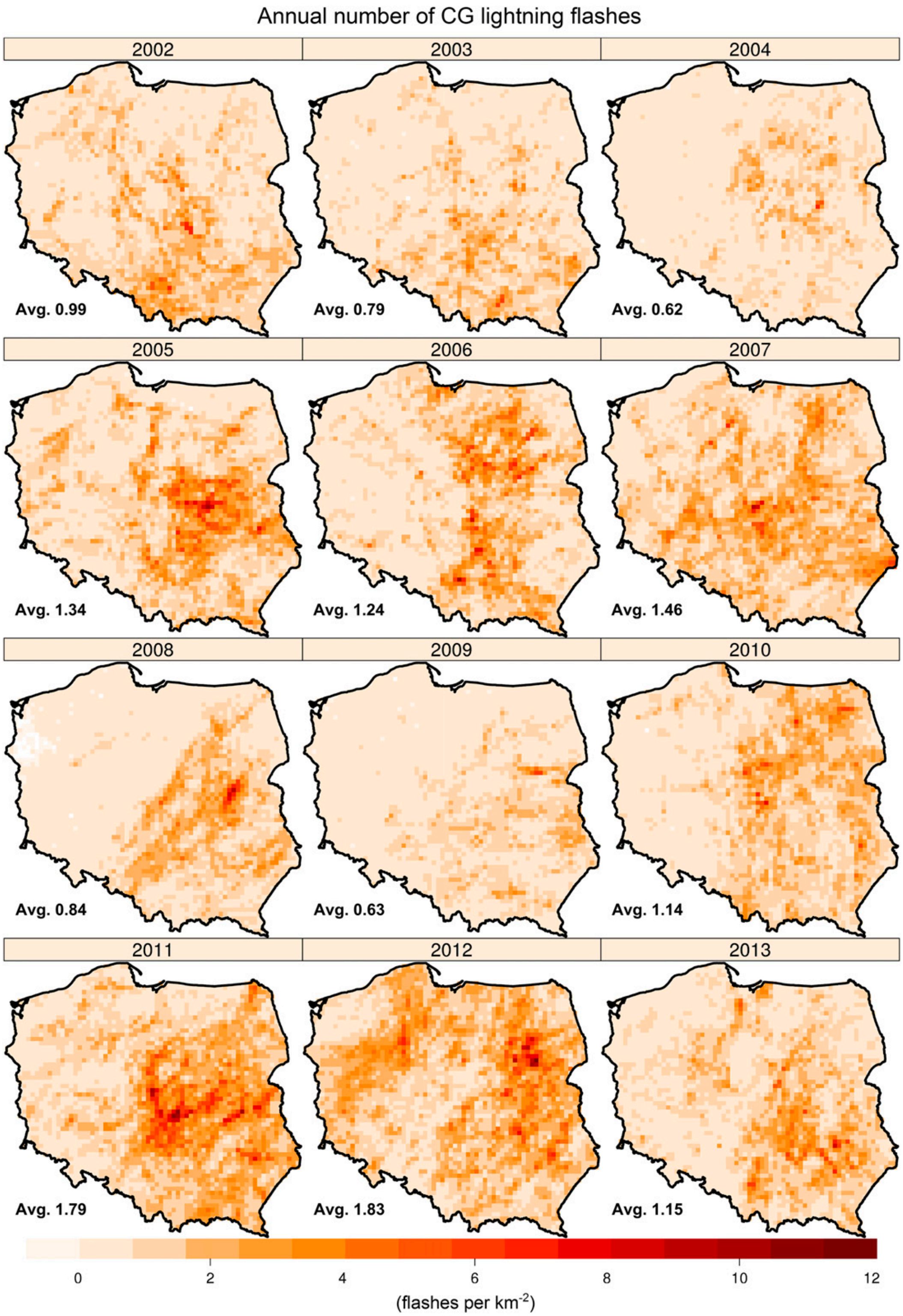

FIG. 5. Annual number of CG lightning flashes km^{-2} during the years 2002–13. Computed for 10 km × 10 km grid cells. Based on lightning data derived from the PERUN network.

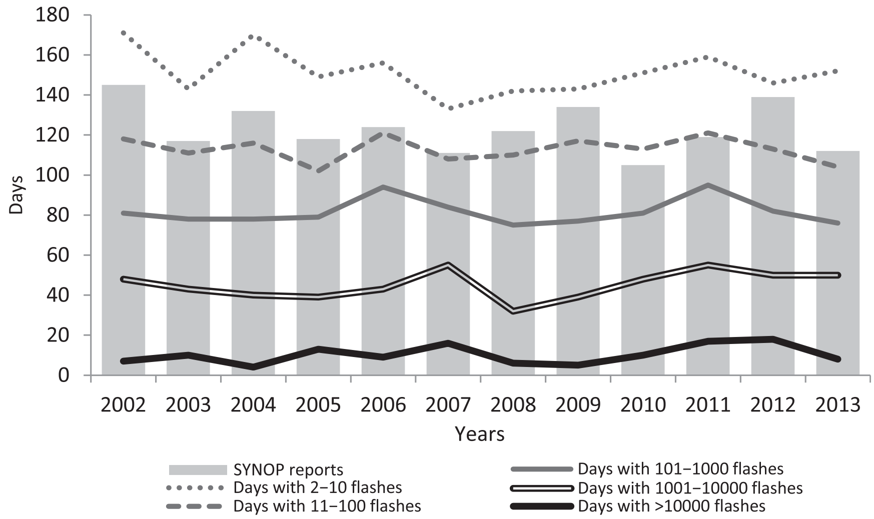

FIG. 6. Annual number of days with detected thunderstorms from SYNOP (44 stations) reports (bars), and annual number of days with the following number of CG lightning flashes detected: >1 (gray dotted line), >10 (gray dashed line), >100 (gray solid line), >1000 (black empty line), and >10 000 (black solid line). Based on lightning data derived from the PERUN network for the period 2002–13. Data have been limited to the administrative borders of Poland.

2011; Feudale et al. 2013; Wapler 2013; Mäkelä et al. 2014). The spatial distribution of the CG lightning flash density in June–August was the highest in the belt from Kraków-Częstochowa Upland up to the Masurian Lake District.

The analysis of thunderstorm days reveals that the daily probability for thunderstorm occurrence anywhere in Poland from May to August exceeds 76% (>23 days with thunderstorm in each month; Fig. 11) with the July as a peak month (87%; 27 days). In April and September this probability decreases to 40% (12 days) while during cold months it varies from around 5% (February; 2 days) to 25% (October; 8 days).

While days with at least 2 CG lightning flashes occur all year round, the days with at least 10 CG lightning flashes occur mainly from March to October, and those with at least 100 CG lightning flashes occur from April to September. Most of the intense thunderstorm days with at least 10 000 CG lightning flashes appear during May–August and the number peaks in July (an average of 4.2 days yr^{-1}), the most intense month (Fig. 11).

The monthly number of thunderstorm days averaged across the whole country (Fig. 12) varied from 0.03 (December) to 0.32 (October), thus giving daily probabilities for thunderstorm occurrences in a particular location (in a circle within the radius of 17.5 km, ~962 km^2) from 0.1% to 1%. Substantially higher probabilities exceeding 14% (4.4 days) extended from May to August with the peak in July (21%, 6.6 days). In transitional months, the probability amounted to 3% in April (0.9 days) and 4% in September (1.2 days).

From April to August thunderstorms were most frequent in the continental southeastern part of the country (Fig. 12). Studies by Riemann-Campe et al. (2009) and Brooks et al. (2003b) revealed that strong diurnal heating during these months and overlap with the boundary layer's high moisture content often results in high convective available potential energy (CAPE) environments in this part of the country and, thus, provide good conditions for thunderstorms.

h. Hourly variations of CG lightning flashes

The hourly distribution of CG lightning flashes overlaps well with the diurnal cycle of convective activity, which generally depends on the boundary layer's temperature and moisture content. The highest CG lightning flash activity peaks at 1400 and 1500 UTC (1600 and 1700 LT during summer months), whereas a flat minimum lies between 2300 and 0900 UTC (0100 and 1100 LT during summer months; Fig. 13). Exactly the same distribution was also found in other lightning climatological studies (e.g., Antonescu and Burcea 2010; Wapler 2013; Virts et al. 2013; Mäkelä et al. 2014).

Regardless of the number of CG lightning flashes during the day, thunderstorm activity always starts to increase around 1000 UTC (1200 LT during summer months). We also note that the intense thunderstorms

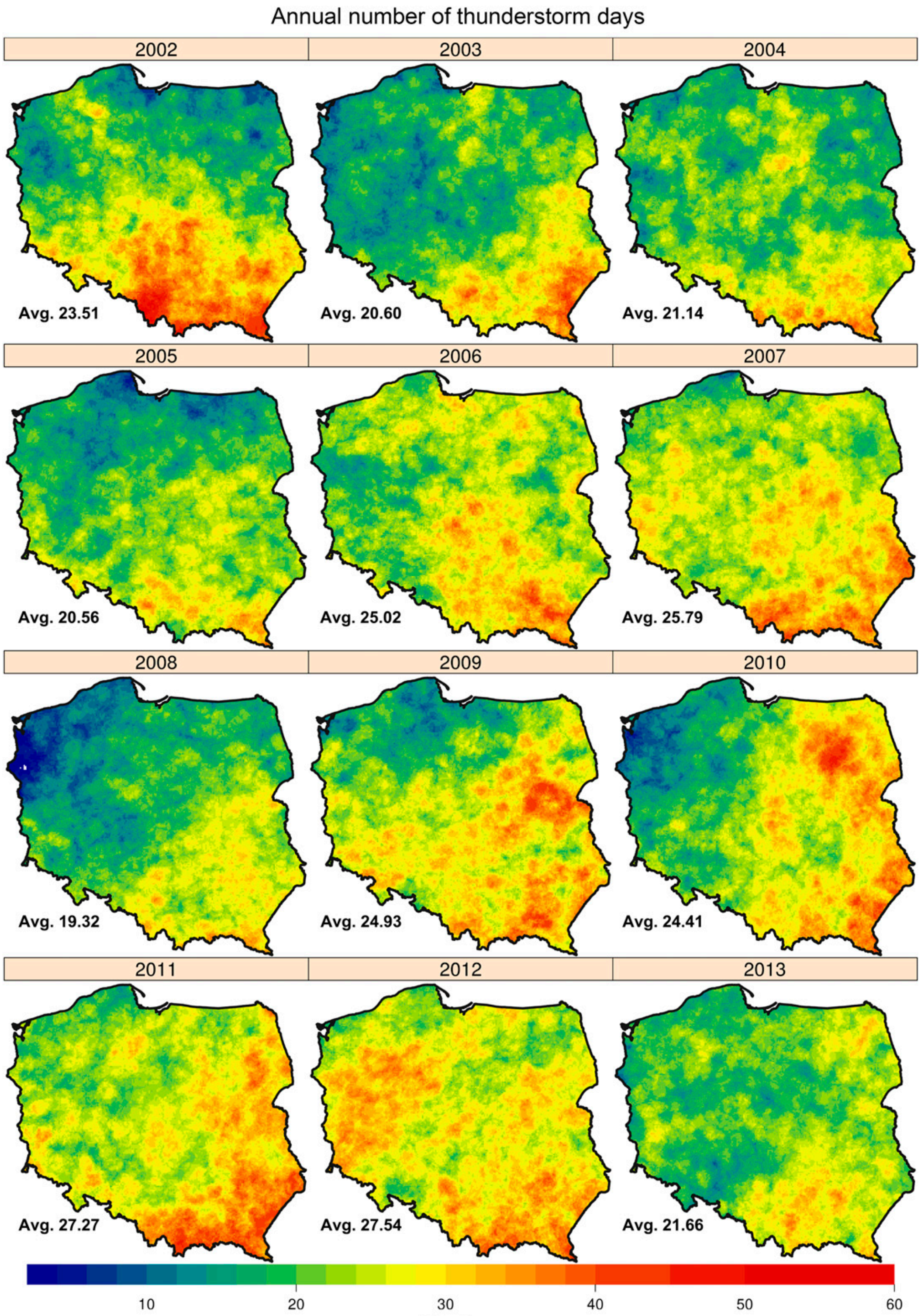

FIG. 7. Annual number of thunderstorm days in 2002–13. Lightning location data are computed within a radius of 17.5 km from the bin center (within a surface area of 962 km^2) in 1 km × 1 km grid cells. Based on lightning data derived from the PERUN network.

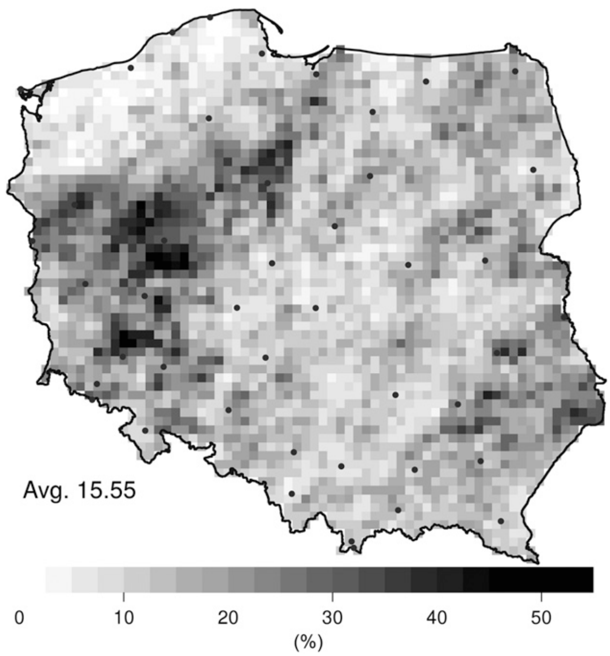

FIG. 8. The average percentage of CG lightning flashes occurring during the nighttime (sun angle $<-12°$; section 3a). Results are computed for 10 km × 10 km grid cells. Based on lightning data derived from the PERUN network for the period from 2002 to 2013. Dots denote the main meteorological stations (44).

with more than 10 000 CG lightning flashes per day are still very active in the late evening hours [1700–2100 UTC (~1900–2300 LT) during summer months] while at the same time the activity of thunderstorms in days with fewer than 1000 CG lightning flashes sharply decreases (Fig. 13).

i. *Polarity and peak current of CG lightning flashes*

The percentage of positive CG lightning flashes was the lowest from May to October (around 2%–3%), while from November to April it ranged from 10% to 20% (Fig. 9). Positive flashes occur when the positive charge region in the thunderstorm cloud is closer to the ground compared to the typical scenario (Mäkelä et al. 2014). Therefore, shallow convection that is more likely during cold seasons may provide a higher percentage of positive CG lightning flashes (Williams 2001). A higher percentage of positive CG lightning flashes during the wintertime was also reported by Clodman and Chisholm (1996), Orville and Huffines (2001), Soriano et al. (2005), and Antonescu and Burcea (2010).

In a spatial sense, the percentage of positive CG lightning flashes varied in most of the area from 1% to 4% while in the northwestern, midwestern, and northeastern parts of the country it locally exceeded 6% (Fig. 14a). It is difficult to explain such a distribution; however, it is possible that during the analyzed period these areas experienced a few intense thunderstorms with inverted polarity (Williams 2001) that increased the percentage in a climatological sense. Orville and Silver (1997) pointed out that as the distance from a sensor of a CG lightning flash increases, only CG lightning flashes with higher peak current are detected. Therefore, positive CG lightning flashes that usually have a greater peak current than negative ones produce a higher percentage of CG-positive lightning flashes at long distances from a sensor. Such a pattern was found in Antonescu and Burcea (2010) but in our database this dependency only partially explained the

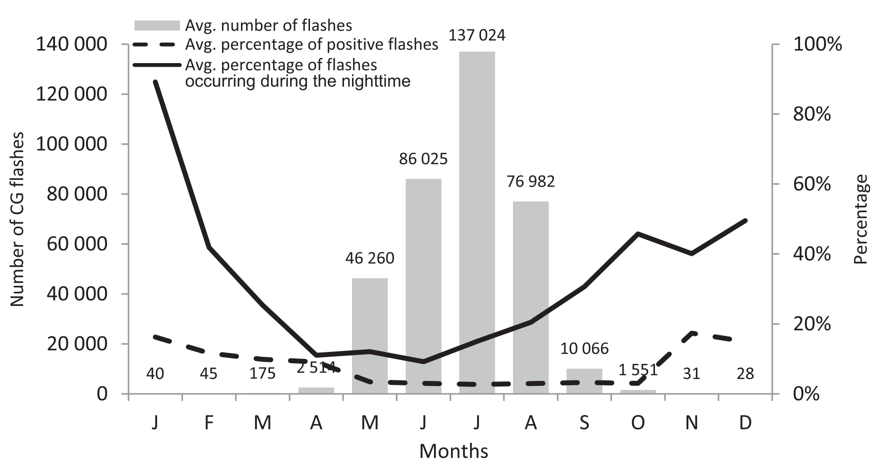

FIG. 9. Monthly annual mean number of CG lightning flashes (bars), percentage of CG lightning flashes detected during the nighttime (black solid line), and percentage of positive CG lightning flashes (black dashed line). Based on lightning data derived from the PERUN network for the period from 2002 to 2013. Data have been limited to the administrative borders of Poland.

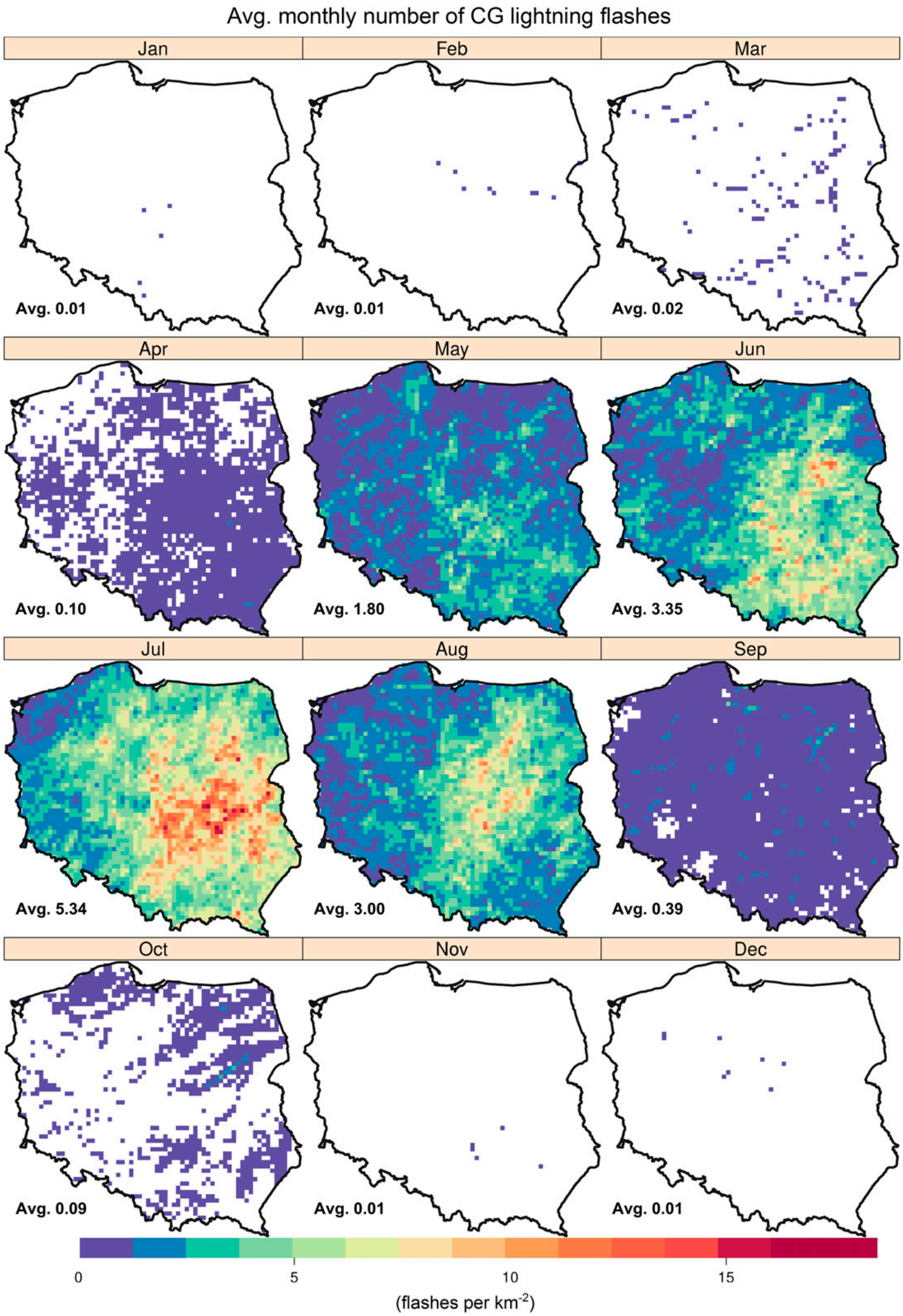

FIG. 10. Average monthly number of CG lightning flashes km^{-2} during the years 2002–13. Computed for 10 km × 10 km grid cells. Based on lightning data derived from the PERUN network.

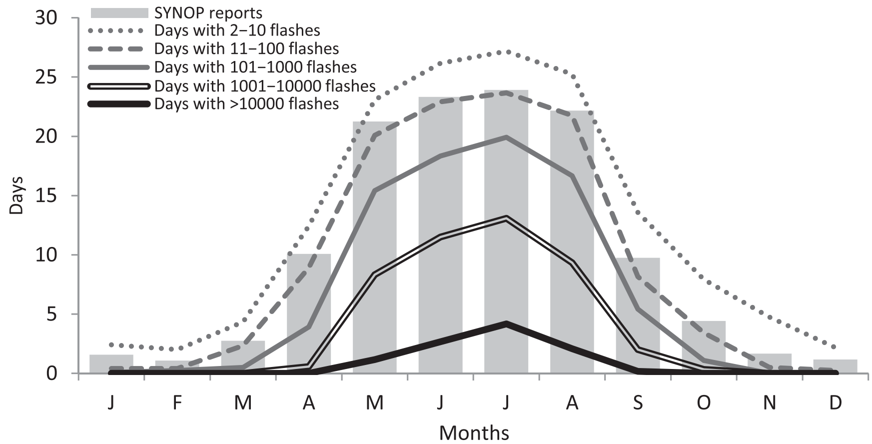

FIG. 11. Monthly mean number of days with a detected thunderstorm from SYNOP (44 stations) reports (bars), and the number of days with CG lightning flashes detected: >1 (gray dotted line), >10 (gray dashed line), >100 (gray solid line), >1000 (black empty line), and >10 000 (black solid line). Based on lightning data derived from the PERUN network for the period from 2002 to 2013. Data have been limited to the administrative borders of Poland.

spatial distribution of the positive CG lightning flash percentage.

A high correlation with network's lightning detection efficiency was found in a spatial pattern of an average negative peak current (Fig. 14b). Lowest values (15–25 kA) overlapped with the area of the high PERUN's lightning detection efficiency (Fig. 1a). This can be explained by the fact that the closer the lightning is to the sensor, the lower the current of the lightning that can be detected will be (Orville and Silver 1997). The highest average peak current values (40–60 kA) that were observed along the coast of the Baltic Sea were presumably due to larger peak electric fields over the highly conductive sea surface (Orville et al. 2011).

In the monthly distribution of the average peak current of negative flashes (not shown) the highest values peaked in February (55 kA) with the lowest attributable to July (24 kA). The electrical field that initiates the lightning is presumably higher in lower temperatures and therefore produces on average flashes with higher peak currents (Brook 1992). The similar patterns in the monthly distribution of average peak current of negative flashes were also observed in the studies of Brook (1992), Orville and Huffines (2001), Soriano et al. (2005), and Antonescu and Burcea (2010).

4. Summary and final remarks

In contrast to SYNOP reports, CG lightning flash data provide a basis for climatologies that resolve variations in thunderstorm occurrence on different time scales with great accuracy. The main aim of this study was to present the first CG lightning flash climatology of Poland. Although PERUN's lightning detection efficiency and the location accuracy are not homogenous in a spatial sense, the analysis of 4 952 203 CG lightning flashes derived from the PERUN database for the period 2002–13 yielded numerous conclusions. The most important are listed below.

1) The average annual number of days with a thunderstorm at a particular location generally increases from the northwest to the southeast, with the lowest values along the coast of the Baltic Sea (15–20 days) and the highest in the Carpathian Mountains (30–35 days). This is consistent with studies forming the thunderstorm climatology of Poland that are based on SYNOP reports and long-term time frames (Bielec-Bąkowska 2003; Kolendowicz 2006, 2012).
2) The annual average of 360 741 CG lightning flashes occurs each year over Polish territory. This results in 151 days with a thunderstorm appearing anywhere in Poland. Approximately 15% of all CG lightning flashes occur during nighttime hours while around 3% are CG lightning flashes with a positive current.
3) An increase in CG lightning flashes occurring during the nighttime from an average of 12% in the years 2002–07 to as much as 17% in the years 2008–13 can be observed. This was presumably due to a more frequent occurrence of MCSs that in recent years (e.g., 1 July 2012, 2 July 2012, 5 July 2012, 7 July 2012, 22 August 2012, 4 August 2013, and 29 July 2013) produced large numbers of CG lightning flashes during the nighttime hours.
4) The spatial distribution of the mean annual CG lightning flash density in 10 km × 10 km grid cells

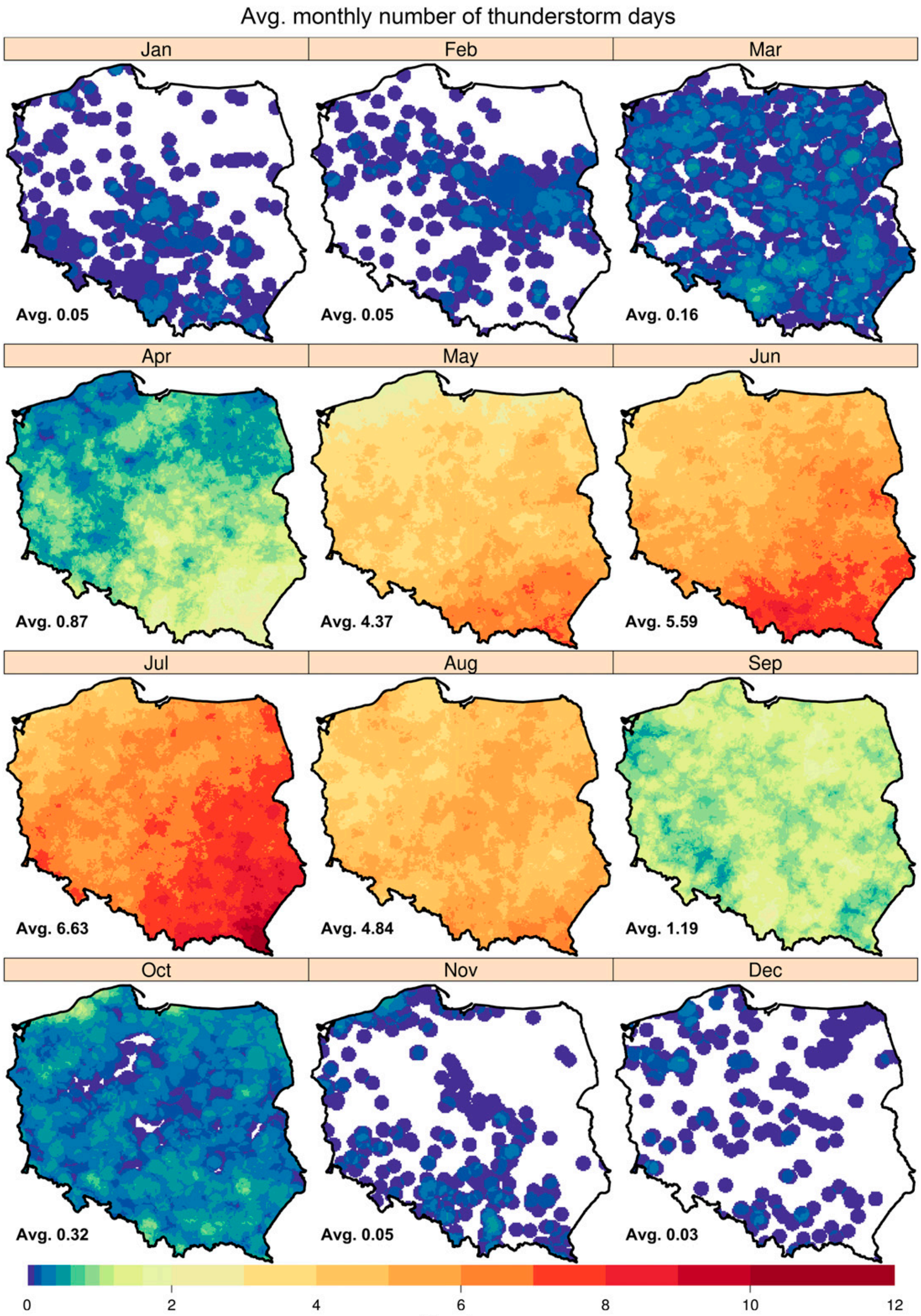

FIG. 12. Average monthly number of thunderstorm days during the years 2002–13. Lightning location data are computed within a radius of 17.5 km from the bin center (within a surface area of 962 km^2) for 1 km × 1 km grid cells. Based on lightning data derived from the PERUN network.

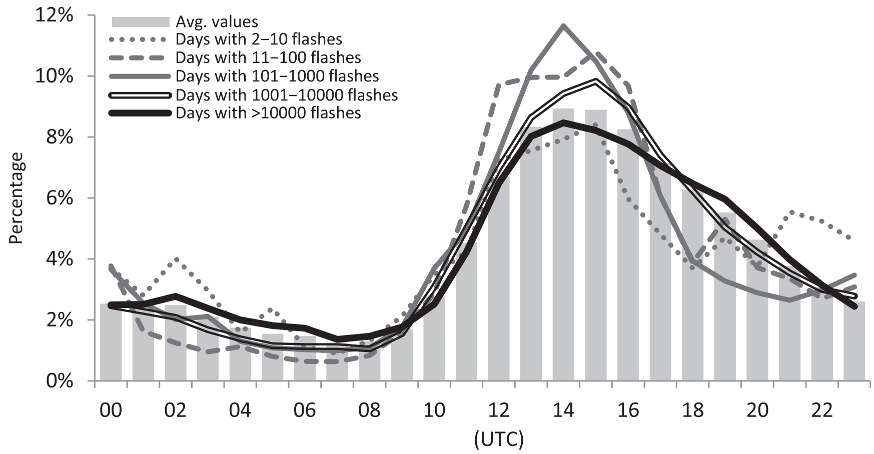

FIG. 13. Mean diurnal distribution of CG lightning flashes (percentage bars) with a time resolution of 1 h (UTC). Linear plots denote the diurnal distribution of CG lightning flashes on days when 2–10 (gray dotted line), 11–100 (gray dashed line), 101–1000 (gray solid line), 1001–10 000 (black empty line), and >10 000 (black solid line) flashes were detected. Based on lightning data derived from the PERUN network for the period 2002–13. Data have been limited to the administrative borders of Poland.

varied from 0.2 to 3.1 flashes $km^{-2} yr^{-1}$, reaching its lowest values along the coast of the Baltic Sea and its highest in the SW–NE belt from Kraków-Częstochowa Upland to the Masurian Lake District. Although this region partially coincides with the PERUN network's lightning detection efficiency, the same area with peak lightning density was obtained in the studies of Pohjola and Mäkelä (2013) and Anderson and Klugmann (2014).

5) The maximum daily CG lightning flash density varied from 0.2 to 9.1 $km^{-2} day^{-1}$ and meant that very intense thunderstorms were capable of producing locally in only one day more CG lightning flashes that on average occur during the whole year. The highest values of maximum daily CG lightning flash density were observed in the central and eastern parts of the country. The day with the highest number of CG lightning flashes during the whole analyzed period was 26 June 2006 (73 549 flashes).
6) The monthly variation in CG lightning flash frequency clearly showed a well-defined thunderstorm season extending from May to August with July as a peak month (an average of 137 024 CG lightning flashes per year with the maximum flash density in central Poland of up to 20 flashes per $km^{-2} month^{-1}$). The days with the most intense thunderstorms (days with over 10 000 CG lightning flashes) occur from May to August and peak in July (4.2 days $month^{-1}$) as the most intense month.
7) The vast majority of CG lightning flashes were detected during the daytime with the peak at 1400 UTC and the minimum at 0700 UTC. It was also noticed that the intense thunderstorms in days with more than 10 000 CG lightning flashes were still very active in the late evening hours (1700–2100 UTC) while at the same time the activity of thunderstorms in days with less than 1000 CG lightning flashes was sharply decreasing.
8) Almost 97% of all CG lightning flashes in our study had a negative current, reaching the highest average monthly values in February (55 kA) and the lowest in July (24 kA). The percentage of positive CG lightning flashes was the lowest from May to October (2%–3%), while from November to April the percentage ranged from 10% to 20%.
9) Compared to thunderstorm statistics in other parts of Europe, Polish thunderstorms have many similar features. The diurnal CG lightning flash peak around 1400 UTC with the thunderstorm high season extending from May to August was also found in CG lightning flash climatologies of Austria (Schulz et al. 2005), Spain (Soriano et al. 2005), Romania (Antonescu and Burcea 2010), Estonia (Enno 2011), the Czech Republic (Novák and Kyznarová, 2011), Germany (Wapler 2013), and Scandinavia (Mäkelä et al. 2014). Conversely, over the Mediterranean (especially the eastern part) the thunderstorm season shifts toward cold season months (October–March) with increased CG lightning flash activity during the nighttime hours (Altaratz et al. 2003; Virts et al. 2013).

Further research into this topic is necessary, especially concerning the atmospheric conditions during the days with the most intense thunderstorms.

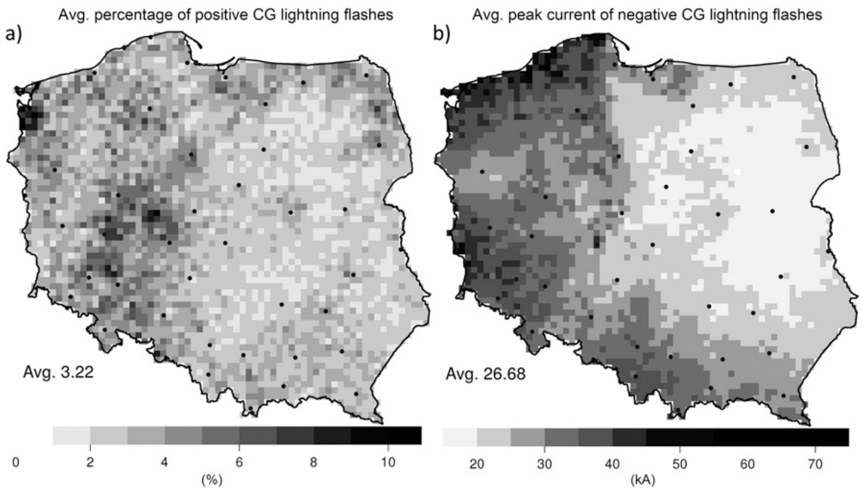

FIG. 14. (a) The average percentage of positive CG lightning flashes, and (b) the average peak current (kA) of negative CG lightning flashes. Results are computed for 10 km × 10 km grid cells. Based on lightning data derived from the PERUN network for the period from 2002 to 2013. Dots denote the main meteorological stations (44).

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Appendix E

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M.T. designed the study, acquired and analyzed data, performed computations, made figures, wrote the manuscript, improved the final version of the manuscript.

B.C. performed computations, made figures, improved the final version of the manuscript.

S.W. analyzed data, made figures, wrote the manuscript.

L.K. analyzed data, improved the final version of the manuscript.

A.M. analyzed data, performed computations.

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An isolated tornadic supercell of 14 July 2012 in Poland — A prediction technique within the use of coarse-grid WRF simulation

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ABSTRACT

On 14 July 2012 a shortwave trough with a cold front passed through Poland. A few tornadoes were reported in the north central part of the country within an isolated cyclic supercell. The cell moved along the thermal and moisture horizontal gradients and the support of a synoptic scale lift. An analysis allowed for setting up four tornado damage tracks in a distance of 100 km and with a total length of 60 km. Tornadoes damaged 105 buildings with predominant intensity of F1-F2/T3-T4 (maximum F3/T6) in Fujita/TORRO scale, caused 1 fatality, 10 injures and felled 500 hectares of Bory Tucholskie forest. The main aim of this article was to analyze this event and assess the possibilities of its short-term prediction. In order to achieve this, a model forecast data derived from WRF-ARW simulation with a spatial resolution of 15 km and initial conditions extracted from 0000 UTC GFS was used. An analysis yielded that the cell moved in the environment of a low lifting condensation level, rich boundary layer's moisture content and a steepening vertical lapse rates that provided the presence of a thermodynamic instability. A wind vectors tilting with height and an increased vertical wind shear occurred as well. A forecasting method that combined a Universal Tornadic Index composite parameter with a convective precipitation filter showed that convective cells at 1500 UTC in the north central Poland had a potential to become tornadic. Within the use of a proposed methodology, it was possible to issue a tornado forecast for the areas where an index pointed the risk.

1. Introduction

Tornadoes are one of nature's most powerful phenomena which can wreak havoc on life and property. For a long time in Poland, they have been regarded as strange and rare phenomena (Taszarek and Brooks, 2015). People generally assumed that tornadoes do not occur in Poland and that such phenomena were mainly limited to the Great Plains of the United States. Doswell (2003) described this situation as a self-fulfilling prophecy, in which denying the existence of tornadoes had resulted in no records being kept of such events, and, in the case where a tornado occurred, it was either not reported or considered an erroneous observation (Antonescu et al., 2016). However, beginning with the "Polish Millennium" flooding of 1997, severe weather phenomena have received more media attention. Awareness of severe weather risks has led to the development of the POLRAD Doppler radar (Jurczyk et al., 2008) and PERUN lightning detection (Loboda et al., 2009) networks. In recent years, mainly due to the significant tornadoes of 20 July 2007 (Parfiniewicz, 2009a, 2009b), 15 August 2008 (Popławska, 2014) and 14 July 2012 (Wrona and Avotniece, 2015) which were widely discussed in the media, tornado awareness increased in Poland. Currently, more attention from both scientific and social aspects is being devoted to the problem of tornado occurrences and the challenge of forecasting them in Poland.

According to the most recent studies, around 6–10 tornadoes occur in Poland each year, most frequently from May to September between 1500 and 1800 UTC (Taszarek and Brooks, 2015). However, despite the risk involved, official tornado warnings and forecasts are not issued for Poland (Rauhala and Schultz, 2009; Taszarek, 2013) except unofficial services such as ESTOFEX (Brooks et al., 2011) and Skywarn Poland (Walczakiewicz et al., 2011). The problem of polish tornadoes was also analyzed by Lorenc (2012) who provided a wind scale designed to rate severe wind events in Poland. Taszarek and Kolendowicz (2013) investigated sounding-derived parameters associated with tornado occurrence in Poland, and proposed a Universal Tornadic Index (UTI) — a composite parameter aimed at indicating atmospheric conditions conducive for tornado occurrence. A similar analysis but within the use of a smaller dataset was also performed by Walczakiewicz et al. (2011). The Polish tornado case studies were carried out by Sławiński (1877), Gumiński (1936), Rafałowski (1958), Parczewski

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Table 1
Selected details of simulation made by the WRF model and important physical settings used.

Model characteristic	Setting
Horizontal grid Resolution	15 km
Number of vertical layers (up to 5000 mb)	45
Simulation length	24 h, starting at 00 UTC
Time step	75 s
Model core	Advanced Research WRF (ARW), non-hydrostatic
Initial and lateral boundary	0.5° GFS
Cumulus parametrization scheme	Multi-scale Kain-Fritsch scheme: This scheme includes (a) diagnosed deep and shallow KF cloud fraction; (b) Scale-dependent Dynamic adjustment timescale for KF clouds; (c) Scale-dependent LCL-based entrainment methodology; (d) Scale-dependent fallout rate; (e) Scale-dependent stabilization capacity; (f) Estimation and feedback of updraft vertical velocities back to gridscale vertical velocities; (g) new Trigger function based on Bechtold method (Zheng et al., 2015).
Microphysics schemes	Lin et al. (1983) scheme: A sophisticated 5-class scheme that has ice, snow and graupel processes, suitable for real-data high-resolution simulations. Includes ice sedimentation and time-split fall terms.
Planetary Boundary Layer (PBL) scheme	Yonsei University scheme: Parabolic non-local-K mixing in dry convective boundary layer. Depth of PBL determined from thermal profile. Explicit treatment of entrainment. Diffusion depends on Richardson Number in the free atmosphere (Skamarock et al., 2005).
Land surface physics scheme	Noah Land Surface Model: Unified NCEP/NCAR/AFWA scheme with soil temperature and moisture in four layers. Vegetation effects included. Diagnoses skin temperature and uses emissivity. Provided heat and moisture fluxes to the PBL (Chen and Dudhia, 2001).
Urban canopy model	Off
Long and short wave radiation scheme	Rapid Radiative Transfer Model (RRTM; Mlawer et al., 1997).
Sea Surface Temperature support	Calculation of SST skin temperatures was OFF.
Orography	U.S. Geological Survey (USGS) Digital Elevation Model (30s)

and Kluźniak (1959), Kolendowicz (2002), Niedźwiedź et al. (2003), Parfiniewicz (2009a, 2009b), Chmielewski et al. (2013), Popławska (2014), and Wrona and Avotniece (2015). Although most of these papers provided important factual information (related to tornado occurrences) and analyzed the accompanying atmospheric conditions, virtually none of these examined the possibilities for prediction with the use of numerical weather prediction (NWP) model data.

Worldwide, numerous studies have assessed the use of Weather Research and Forecasting (WRF) model simulations in tornado predictions. Litta et al. (2010, 2012) used the WRF Non-hydrostatic Mesoscale Model (NMM) with spatial resolutions of 3 and 4 km and a period of 24 h (starting at 0000 UTC) to simulate meteorological conditions that led to the tornadoes of 15 August 2007 and 31 March 2009 in India. The WRF–NMM model with the combination of a short-range ensemble and a grid resolution of 4.5 km was also used in the case study of the 2 April 2006 U.S. tornado outbreak by Weiss et al. (2006). The simulations agreed with the observations and demonstrated the capacity for using a high-resolution WRF–NMM model in simulating and predicting such events.

The Advanced Research WRF model (WRF-ARW) with a grid resolution of 1.333 km was utilized by Matsangouras et al. (2011) in the analysis of a 12 February 2010 tornado in Greece. The model appeared capable of simulating an event with significant accuracy and a lead period of 18 h. Weisman et al. (2008) presented a summary of the 0–36-h explicit convective forecasts with the use of the WRF-ARW model (4 km grid resolution) during the 2003–2005 spring and summer seasons in the U.S. The summary pointed out that thanks to WRF-ARW, a significant value was added to the high-resolution forecasts in representing the convective system mode (e.g., for squall lines, bow echoes, mesoscale convective vortices) and the diurnal convective cycle. Convection-allowing configurations of the WRF-ARW model during the 2004 Storm Prediction Center – National Severe Storms Laboratory Spring Program – were also assessed in another study by Kain et al. (2006). Shafer et al. (2009, 2010a) evaluated WRF model simulations of tornadic and nontornadic outbreaks occurring during spring and fall in the U.S. The results showed that storm relative helicity (SRH), low-level wind shear (LLS), deep layer wind shear (DLS), and lifted condensation level (LCL) parameters, along with synoptic parameters such as

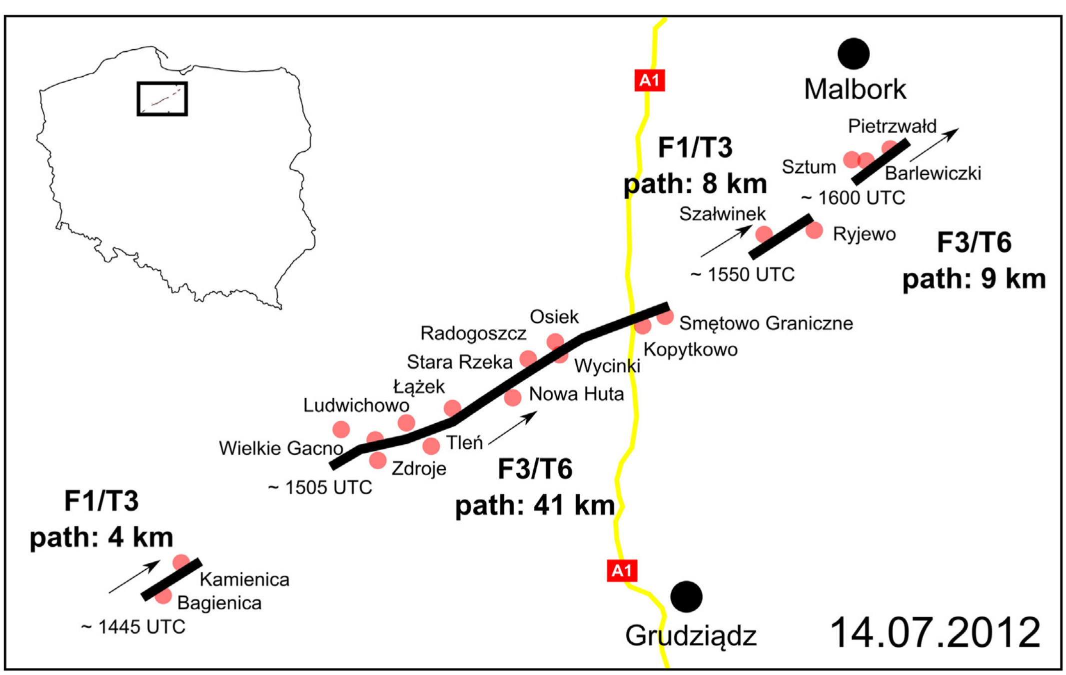

Fig. 1. Damage tracks of the 14 July 2012 tornadoes in a portion of north central Poland. Red dots indicate villages and towns where a tornado was reported. Arrows indicate the direction of tornado motion. Solid black lines denote tornado damage paths (with estimated maximum intensity in Fujita and TORRO scale). Yellow line denotes A1 highway. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Damage track in Bory Tucholskie forest due to tornado of 14 July 2012. Photography: Kacper Kowalski. Source: http://www.kacperkowalski.pl.

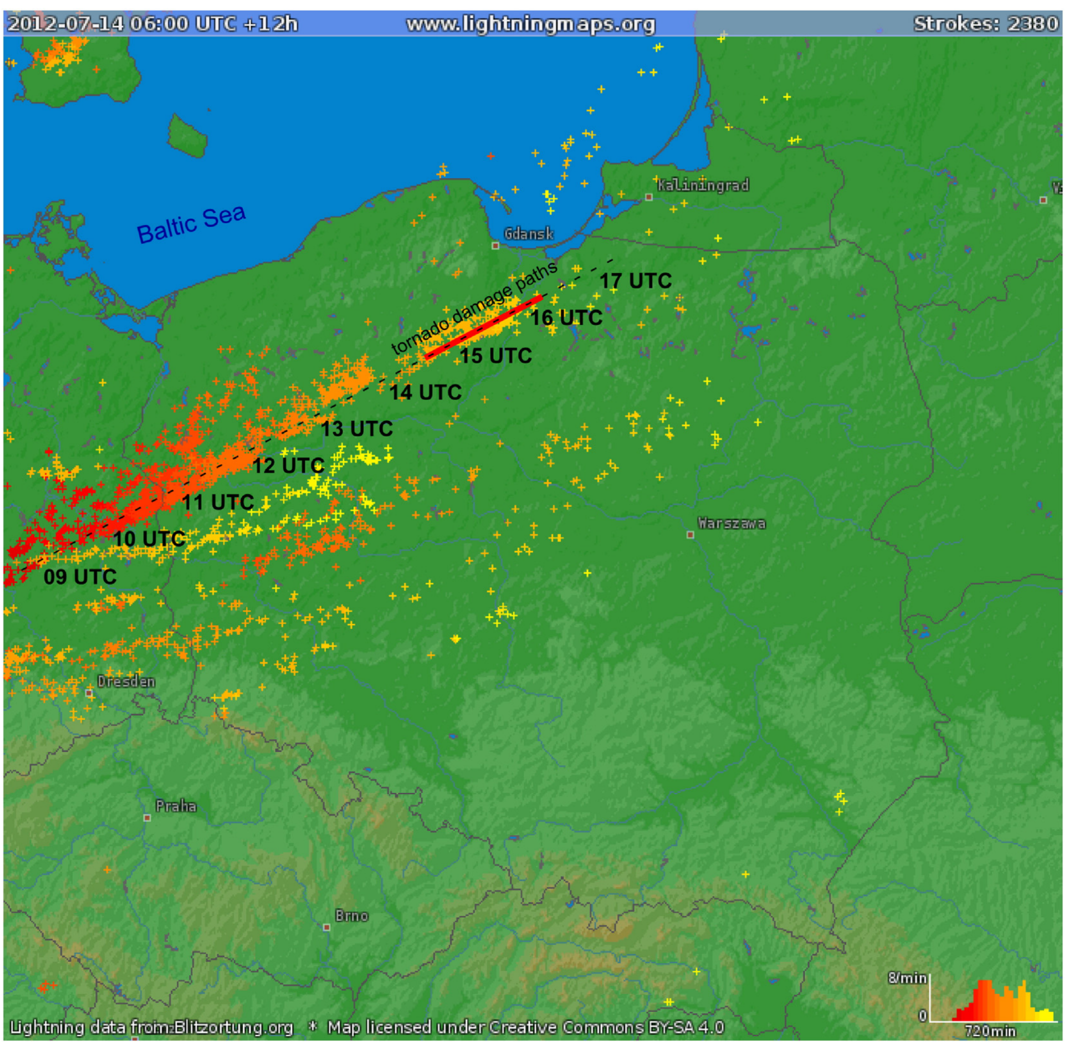

Fig. 3. Lightning captured by the blitzortung lightning detection network (Wanke, 2011) on 14 July 2012 between 0600 and 1800 UTC. Dashed lines indicate the POLRAD radar-based time and position of the thunderstorm. Red line indicates tornado damage paths. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

geopotential heights and mean sea level pressure, appeared to be the most helpful in distinguishing outbreak type; whereas thermodynamic instability parameters were noticeably less accurate and less skillful, primarily because of a strong seasonal dependence and convective modification in the simulations. Fierro et al. (2012) presented an assimilation of total lightning data to help initiate convection at cloud-resolving scales in a WRF-ARW model simulation in a case study of the 24 May 2011 Oklahoma tornado outbreak where large destructive tornadoes occurred. The results indicated that assimilation of the total lightning data for only a few hours prior to analysis time significantly improved the representation of the convection.

In this study, we analyze the case of a cyclic supercell (thunderstorm that has a deep and persistent rotating updraft, cf. Doswell and Burgess, 1993) that produced a few tornadoes in north central Poland on 14 July 2012. We perform the WRF-ARW model simulation for this case and assess the possibilities for short-term prediction within the use of an ingredient-based methodology (Doswell et al., 1996). We also present a forecasting technique that combines multiple parameters into one product, and provide an example of how operational meteorologists may base their tornado predictions on NWP data.

2. Dataset and methodology

The most important factual information related to the tornadoes of 14 July 2012 was derived from the European Severe Weather Database (ESWD; Dotzek et al., 2009) and Skywarn Poland (A. Surowiecki, 2015,

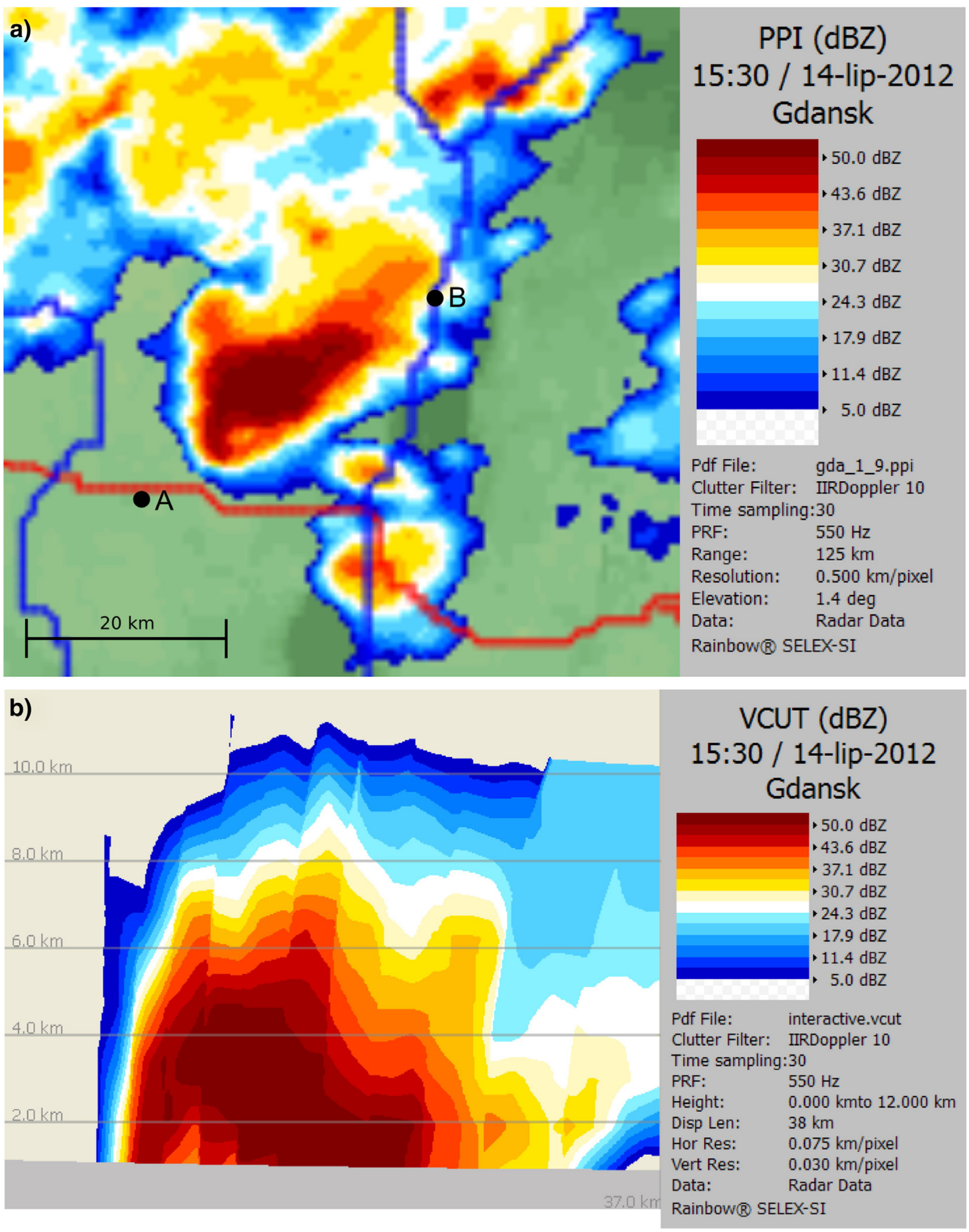

Fig. 4. (a) Radar PPI 1.4 deg. reflectivity (dBZ) derived from Gdańsk on 1530 UTC 14 July 2012 (hook-echo signature), (b) VCUT view of the supercell (SW–NE cross section between A and B). Source: POLRAD Doppler radar network, Polish Institute of Meteorology and Water Management — National Research Institute.

personal communication). We also supported our investigation by performing additional web searches (e.g. Grochala, 2014) for damage reports, eye-witnesses descriptions, and videos that allowed us to distinguish 4 separate tornado damage tracks.

The synoptic analysis charts from 14 July 2012 (0000 UTC) and 15 July 2012 (0000 UTC) were obtained from the Polish Institute of Meteorology and Water Management — National Research Institute (IMGW-PIB) archive. Radar data used to define the life cycle of the cell was obtained from the POLRAD Doppler radar network operated by IMGW-PIB. Lightning data was derived from the blitzortung lightning detection network at lightningmaps.org webpage archive (Wanke, 2011).

The network of weather stations was based on the 1200 and 1500 UTC SYNOP reports from 31 meteorological stations (portion of north-western Poland). We included observational data to discuss and determine horizontal boundaries which, as suggested by Markowski et al. (1998), Rasmussen et al. (2000), Bentley et al. (2002), and Giaiotti and Stel (2007), may be conducive for the occurrence of tornadoes given favorable thermodynamic and kinematic conditions.

We did not analyze proximity soundings since none of them in our opinion was reliable enough to capture the environment in which the tornado formed (especially considering the low levels). The 1200 UTC soundings performed in Lindenberg (WMO ID: 10,393) and Łeba (12,120) were located on the cool side of the cold front and did not represent the environment in which the tornadic cell formed. Soundings from the same time taken in the warm sector in Legionowo (12,374), Wrocław (12,425), and Kaliningrad (26,702) were distanced more than 200 km from the analyzed cell, which according to many proximity sounding studies, did not meet the criteria for the analysis (Rasmussen and Blanchard, 1998; Craven and Brooks, 2004; Groenemeijer and van Delden, 2007; Taszarek and Kolendowicz, 2013; Púčik et al., 2015).

In order to assess whether it was possible to issue a tornado forecast with the use of specific for this phenomenon's thermodynamic and kinematic parameters, a 24-hour forecast was produced using a mesoscale numerical weather prediction model (WRF-ARW 3.7) with a spatial resolution of 15 km (Skamarock et al., 2005). Although the model's simulations cannot resolve tornadoes explicitly, the use of meteorological covariates (in the form of thermodynamic and kinematic parameters) is necessary to determine whether or not the model is able to predict tornadoes (Shafer et al., 2010b). Since our aim was not to simulate the tornado itself (but rather conducive conditions), we decided to use a coarse-grid for this purpose. According to Shafer et al. (2009), the use of high-resolution simulations in such situations is not necessary since most of the tornado cases are related to synoptic scale processes that may well be represented in a smaller resolution. In our simulation, the boundary and initial conditions were extracted at 0000 UTC, with a horizontal resolution of 0.5° based on the global simulation of the GFS model (Global Forecast System; Yang et al., 2006). Detailed information related to model settings is presented in Table 1. Data assimilation of the GFS-based boundary conditions was made every 3 h. We analyzed the model output from the time steps just before and during the occurrence of the tornado (1300, 1400 and 1500 UTC).

Thermodynamic and kinematic parameters discussed in this paper were chosen on the basis of studies related to the analysis of characteristic tornadic environments. The studies performed for the U.S. by Rasmussen and Blanchard (1998) and Craven and Brooks (2004), for Europe by Groenemeijer and van Delden (2007), Grünwald and Brooks (2011), and Púčik et al. (2015), and for Poland by Walczakiewicz et al. (2011) and Taszarek and Kolendowicz (2013) all pointed out that mesoscale features such as increased DLS, low LCL, high boundary layer's moisture content (e.g. mixing ratio, dew point), high SRH and LLS overlapping with the presence of a convective available potential energy (CAPE) create favorable conditions for the occurrence of mesocyclone tornadoes (Davies-Jones et al., 2001).

With the use of an ingredient-based methodology, we analyzed the mentioned parameters in the WRF-ARW model output and discussed possibilities for tornado prediction. In addition, we also used UTI – a composite parameter designed on the basis of a Polish tornado database by Taszarek and Kolendowicz (2013) – to indicate areas where tornado favorable conditions overlap. Finally, we proposed a tornado forecasting method that combines UTI with exclusion of areas where accumulated convective precipitation predicted by the model was lower than 0.75 mm per hour.

3. Description of the event

In this section we provide the most important factual information related to the event. We present tornado damage tracks and analyze the evolution of the storm with the use of a lightning and radar data.

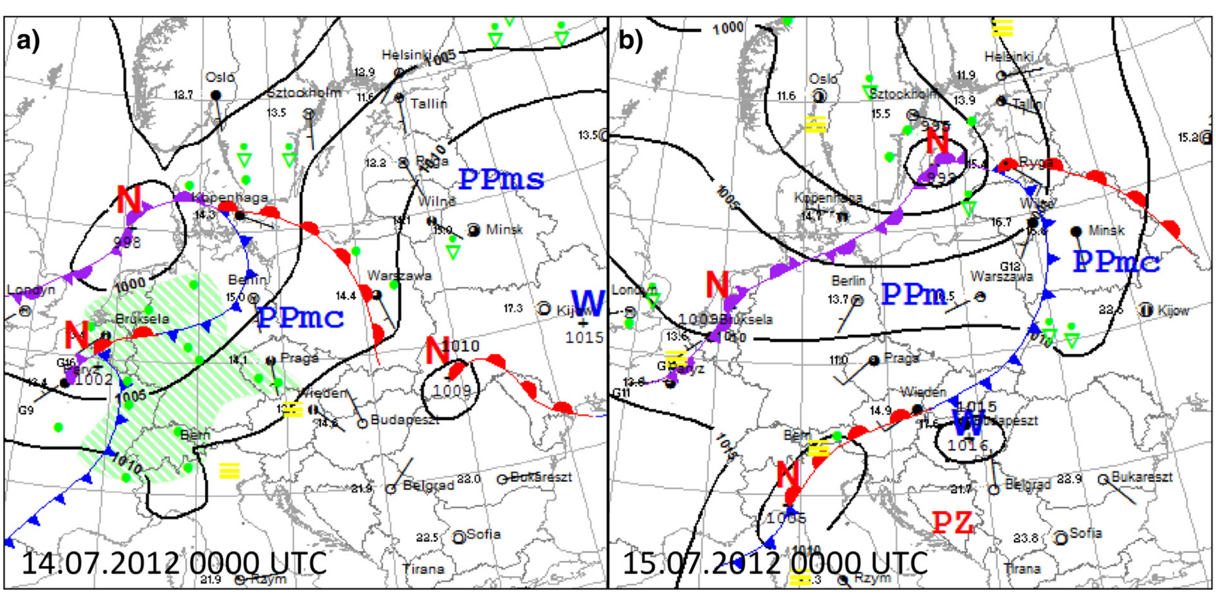

Fig. 5. Synoptic analysis charts of (a) 14 July 2012 0000 UTC and (b) 15 July 2012 0000 UTC. W — high pressure, N — low pressure, PPm — polar marine air mass, PPms — polar marine transitional air mass, PZ — tropical air mass.
Source: Polish Institute of Meteorology and Water Management — National Research Institute.

We also discuss the basics of a synoptic setup and provide surface observational data derived from SYNOP reports.

3.1. Tornado damage tracks

On 14 July 2012, an isolated cyclic supercell thunderstorm occurred in north central Poland and produced a few tornadoes near the Bory Tucholskie forest. An analysis of the radar data (IMGW-PIB archive), aerial photography, local damage survey (Skywarn Poland, Sieć Obserwatorów Burz), damage reports in media, and global forest change project data (Hansen et al., 2013) allowed for setting up four tornado damage tracks in a distance of 100 km (Fig. 1).

The first tornado touchdown was observed around 1445 UTC (1645 LT) near the village of Bagienica (φ 53.453 N, λ 17.785 E), and left a damage track of 4 km with a maximum intensity of F1 in the F-scale (Fujita, 1971) and T3 in the TORRO scale (Meaden et al., 2007). The second tornado occurred around 1505 UTC (1705 LT) northwest of Zdroje village (φ 53.598 N, λ 18.171 E), and from that point it was also reported in Ludwichowo, Zdroje, Wielkie Gacno, Tleń, Łążek, Nowa Huta, Stara Rzeka, Radogoszcz, Osiek, Wycinki, Kopytkowo, Smętowo Graniczne, and passed by the A1 highway (Fig. 1). In total, it left a damage path of 41 km with a maximum intensity of F3/T6. In Wycinki village, the tornado lifted a summer house into the air and due to this, one man was crushed to death.

The third tornado occurred around 1550 UTC (1750 LT) southwest of Szałwinek (φ 53.842 N, λ 18.870 E) and then moved to Ryjewo, leaving a damage path of 8 km. The maximum intensity was rated at F1/T3. The last tornado occurred around 1600 UTC (1800 LT) south of Sztum city (φ 53.921 N, λ 19.029 E) and left a damage path of 9 km, reaching a maximum intensity of F3/T6. For the last time, the last tornado was reported

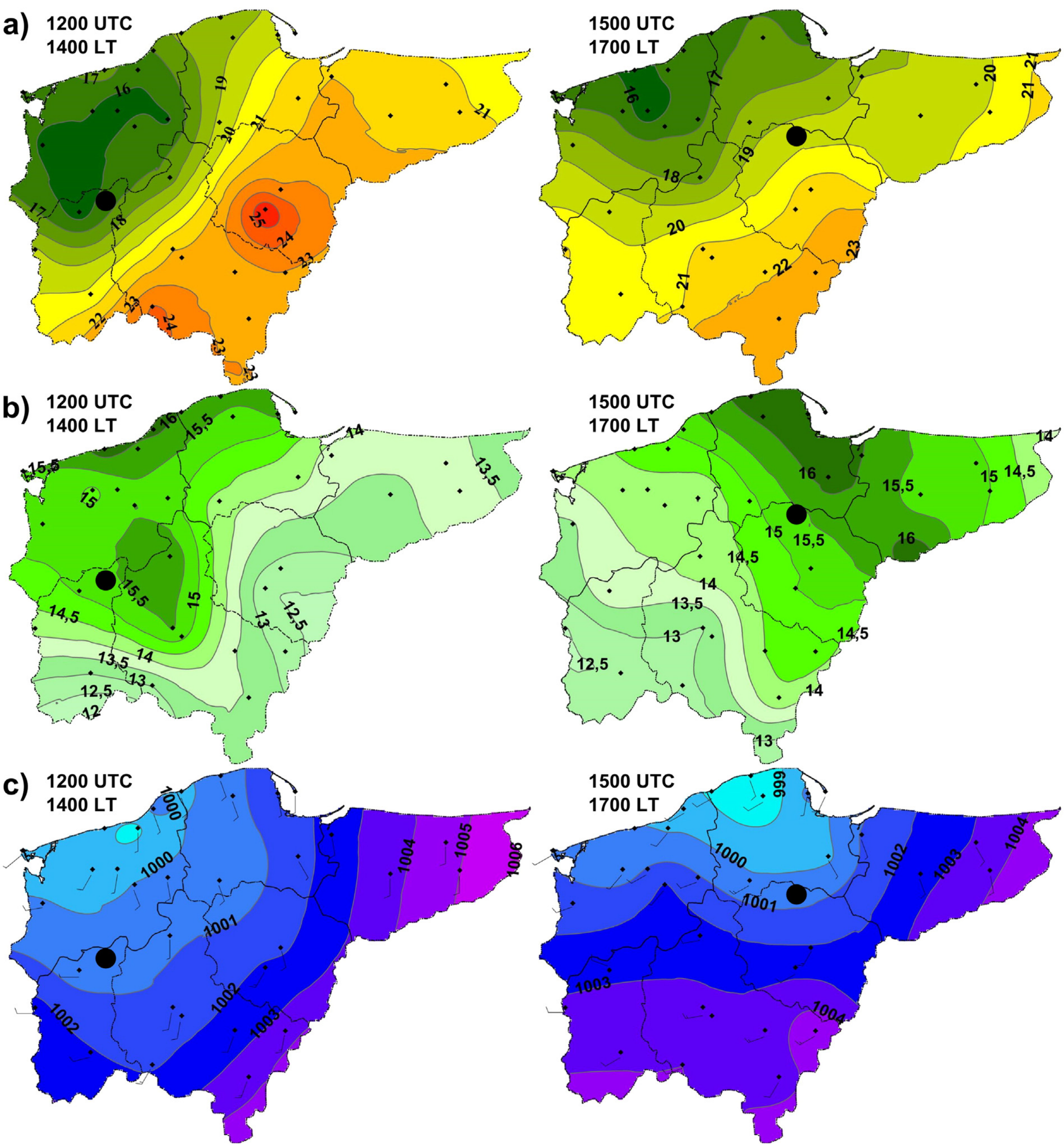

Fig. 6. Spatial distribution (kriging interpolation technique) of the (a) 2 m AGL temperature, (b) 2 m AGL dew point temperature, and (c) sea level pressure with 10 m AGL wind direction and strength on 14 July 2012 at 1200 UTC (left panel) and 1500 UTC (right panel) derived from SYNOP reports of 31 meteorological stations (small dots). The positions of the analyzed convective cell at 1200 and 1500 UTC were marked by a large dot sign.

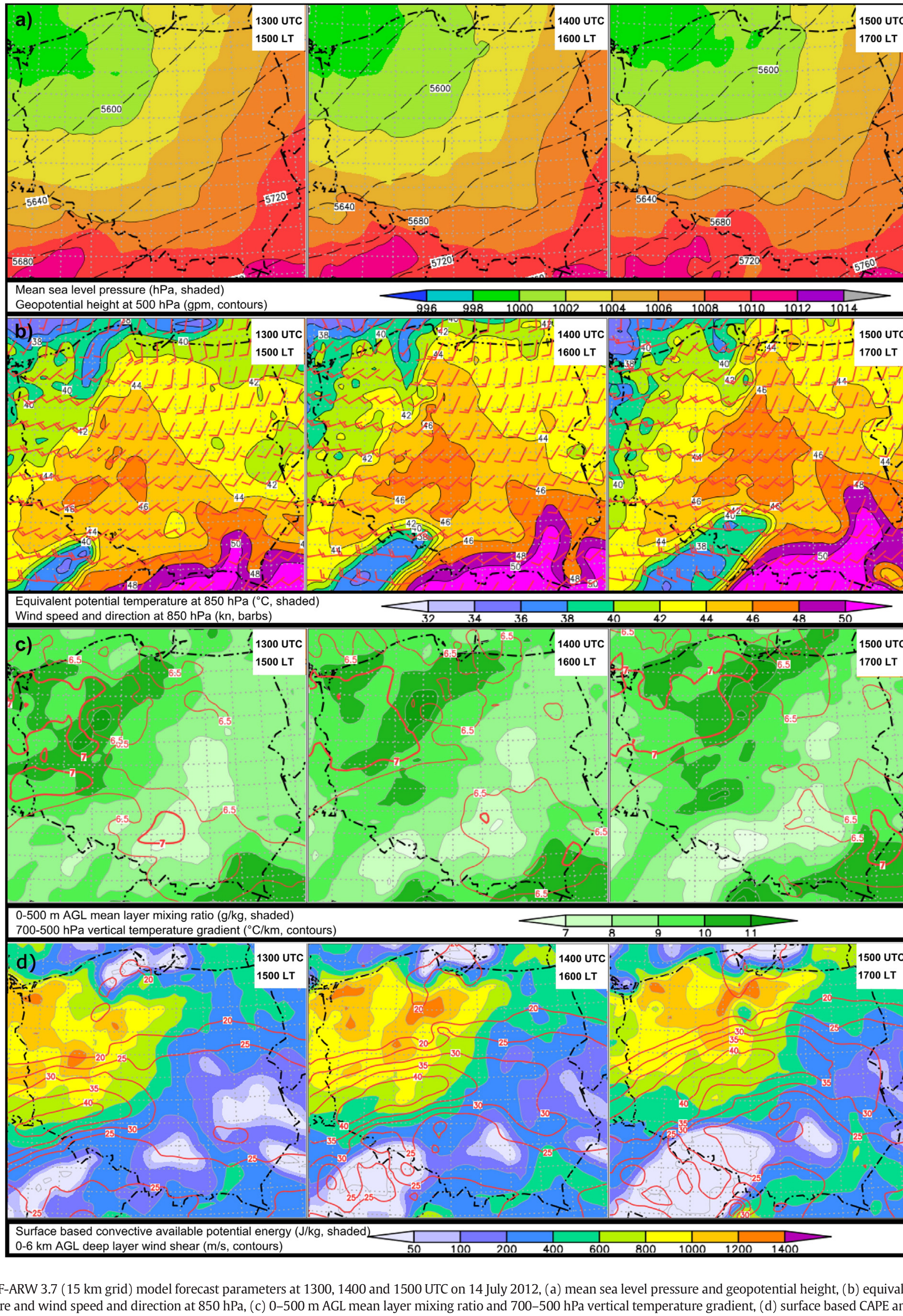

Fig. 7. WRF-ARW 3.7 (15 km grid) model forecast parameters at 1300, 1400 and 1500 UTC on 14 July 2012, (a) mean sea level pressure and geopotential height, (b) equivalent potential temperature and wind speed and direction at 850 hPa, (c) 0–500 m AGL mean layer mixing ratio and 700–500 hPa vertical temperature gradient, (d) surface based CAPE and DLS. Initial conditions were extracted from 14 July 2012 0000 UTC 0.5° GFS.

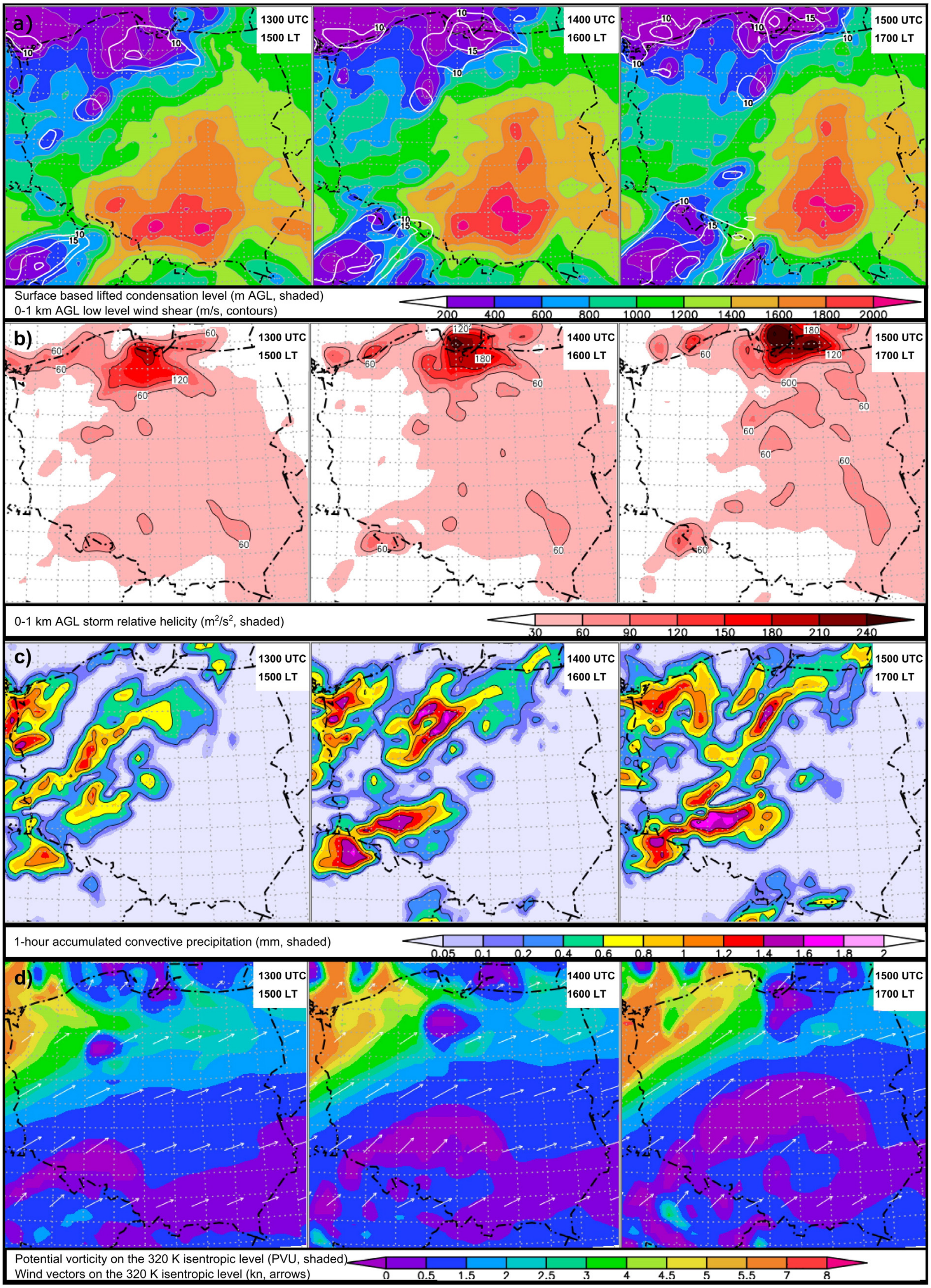

Fig. 8. WRF-ARW 3.7 (15 km grid) model forecast parameters at 1300, 1400 and 1500 UTC on 14 July 2012, (a) surface based LCL and LLS, (b) 0–1 km SRH, (c) 1-hour accumulated convective precipitation, (d) potential vorticity and wind vectors on the 320 K isentropic level. Initial conditions were extracted from 14 July 2012 0000 UTC 0.5° GFS.

around 1605 UTC (1805 LT) east of Pietrzwałd village (φ 53.571 N, λ 19.922 E) where it also vanished. Given the distance and time of the first and last tornado report, the average speed of the tornadoes was estimated at 80 km/h. In total, the tornadoes damaged 105 buildings (including a few that were severely damaged with a predominant intensity of F1-F2), caused 1 fatality, 10 injures, and felled 500 ha of Bory Tucholskie forest, leaving an impressive path with a maximum width of 700 m (Fig. 2).

3.2. Storm evolution

On the basis of the radar data analysis, we can ascertain that the thunderstorm started around 0900 UTC near Berlin. From that point, it began to move northeastwardly with a cyclic activity of presumably three isolated cells that were emerging and dying one after another. The thunderstorm entered Poland around 1100 UTC (1300 LT) near Słubice and passed near Gorzów Wielkopolski, Piła, Tuchola, and Malbork where around 1730 UTC (1930 LT) it finally weakened and decayed (Fig. 3). Within 7 h, it passed almost 500 km with an average speed of 70 km/h. Convective cells were electrically active along their entire path except for a section just before the first tornado's occurrence.

Radar-based characteristics of this cell were consistent with the Lemon and Doswell (1979) classical supercell conceptual model. At 1530 UTC (1730 LT), the radar located in Gdańsk (~50 km from the cell) recorded mesocyclone distinct features such as hook-echo, bounded weak echo region, and v-notch signatures (PPI 1.4°. reflectivity; Fig. 4a). The VCUT section (southwest–northeast cross section through the supercell; Fig. 4b) shows that the main reflectivity core which reached a level of 6 km above ground level (AGL) was tilted in accordance with the mid-level southwesterly flow, and the cell itself was 12 km AGL high. A forward-flank downdraft with a strong reflectivity area and heavy rain with large hail was located in the northeastern part of the supercell.

It is worth saying that during almost the entire life-cycle, the analyzed cell was isolated. According to Bunkers et al. (2006), 79% of these kinds of cells (supercells) tend to be long-lived (>4 h). This can partly explain the long life-cycle of the thunderstorm and four tornadoes that occurred within this one cell at a distance of 100 km. However, in this case it is difficult to clearly state from which part of the life-cycle the cell became a supercell with a deep persistent rotating updraft (Rotunno and Klemp, 1985). Numerous severe wind damage incidents (with strength of up to F1/T3) were already reported around 1310–1330 UTC (1510–1530 LT) in Trzcianka, Sarbia, Piła, and Kaczory (northern part of Greater Poland voivodeship) and could have been the first indications of a supercellular character.

3.3. Synoptic scale setup

On 14 July 2012, a low with 1000 hPa SLP and a cold polar air mass were centered over the North Sea at 0000 UTC (Fig. 5a). In opposition, southern and southeastern Europe was under the influence of a warm and moist air mass of tropical origin. A jet stream between these two air masses (at the level of 300 hPa with wind speeds of up to 60 m/s) stretched from the Iberian Peninsula, through southern France, northern Italy, Switzerland, southern Germany, Austria, Czech Republic, Slovakia, and Poland all the way to Belarus. During the afternoon and evening hours, a shortwave trough passed through Germany, Poland, and the Baltic countries. In the morning hours, a wave amplified the frontal boundary and Poland was under the influence of a warm sector. In the afternoon hours, a cold front with a deepening trough entered the western part of the country and, with almost a parallel flow along the frontal boundary, moved in a northeastern direction (Fig. 5b).

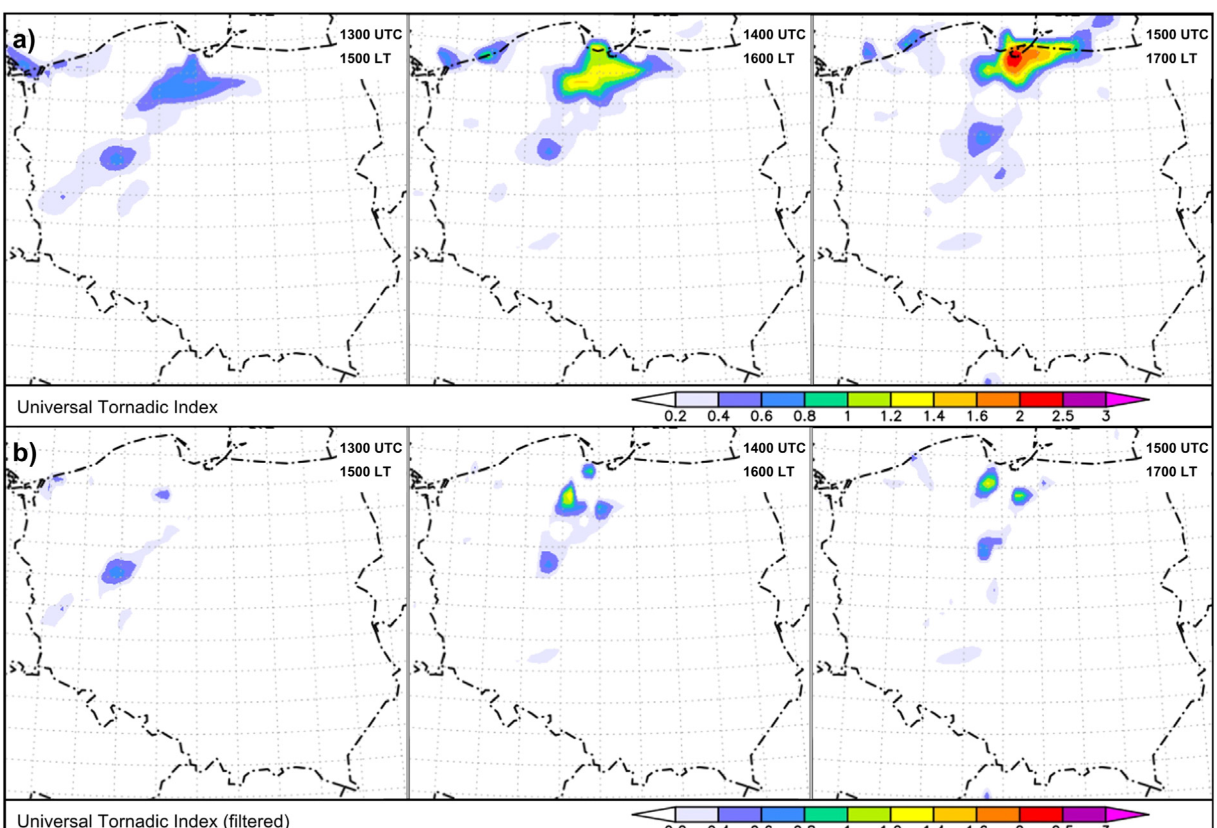

Fig. 9. WRF-ARW 3.7 (15 km grid) model forecast parameters at 1300, 1400 and 1500 UTC on 14 July 2012, (a) UTI (for further detail see Taszarek and Kolendowicz, 2013), (b) UTI filtered (if 1-hour accumulated convective precipitation <0.75 mm, then UTI = 0). Initial conditions were extracted from 14 July 2012 0000 UTC 0.5° GFS.

3.4. Surface observational data

Due to a frontal boundary, Poland was under the influence of a large horizontal temperature and moisture gradients. Maximum 2 m AGL temperature at 1200 UTC (Fig. 6a) was measured in a warm sector in Inowroclaw (26 °C) and Leszno (24 °C). At the same time, the lowest temperature was in a cold sector in northwestern Poland where a meteorological station recorded about 16 °C. Proportional dependence was also found in a 2 m AGL dew point (Fig. 6b). The lowest was recorded in a warm sector in southern Greater Poland, Lubusz and Kuyavian-Pomeranian provinces (~13 °C). The highest fell on Pomerania and southern Greater Poland provinces (~16 °C). When the cell strengthened and a tornado occurred, it topped the well-developed trough's axis along with the zone of low-level converging winds (Fig. 6c). The dew point depressions in the area where the tornadoes occurred were relatively small and amounted approximately to 4 °C. This provided low LCL (~500 m AGL) that was supportive for the formation of tornadoes.

It is worth pointing out that the strongest temperature and moisture horizontal gradients were in the southern Greater Poland where an analyzed convective cell was located at 1200 UTC. At 1500 UTC (i.e. when the first tornado occurred), these boundaries together with the cell shifted toward the northeast. As thermal and moisture gradients slightly decreased, the pressure gradient increased. The presence of such horizontal gradients, as suggested by Maddox et al. (1980), Markowski et al. (1998) and Rasmussen et al. (2000), may well be an important factor in the origin of mesocyclone vorticity. In addition, the low-level rotation in a mesocyclone, generated via tilting and stretching of a horizontal vorticity, is produced mainly in such boundaries (Markowski and Richardson, 2009). Interesting conclusions were also stated by Maddox et al. (1980, 2013) who pointed out that supercells moving along preexisting thermal boundaries tend to have longer damage tracks. In our case, this argument finds confirmation since an analyzed supercell that moved along such boundaries left significant (at least for the Polish conditions) damage tracks with a total length of around 60 km.

4. NWP data

In this section we present WRF-ARW 3.7 model data computed for +13, +14 and +15 h time steps (1300, 1400, 1500 UTC) from 0000 UTC 14 July 2012 initial conditions of a GFS. In the analysis we focus mainly on the area where the tornadoes occurred.

4.1. Circulation pattern

The model's forecast data indicated the same circulation pattern as previously described in Section 3. The trough's axis, where the cell of interest was located, moved northeastwardly together with the orientation of the mid-level jet (Fig. 7a). The maximum of equivalent potential temperature was located in the central part of the country, while the strong horizontal gradient on the west indicated an approaching cold front with an almost parallel mid-level flow (Fig. 7b). The cell of interest (and thus the tornado) moved within a strong horizontal gradient of the equivalent, potential temperature. Within this border and ahead of it, a southern low-level inflow of warm and moist air was found.

4.2. Thermodynamic instability and vertical wind shear

A boundary layer's mixing ratio exceeding 10 g/kg overlapped with the area where a steepening of the vertical lapse rates (~7 °C/km) took place (Fig. 7c). Such overlap of instability ingredients resulted in the surface-based CAPE, estimated by the model at up to 800–1200 J/

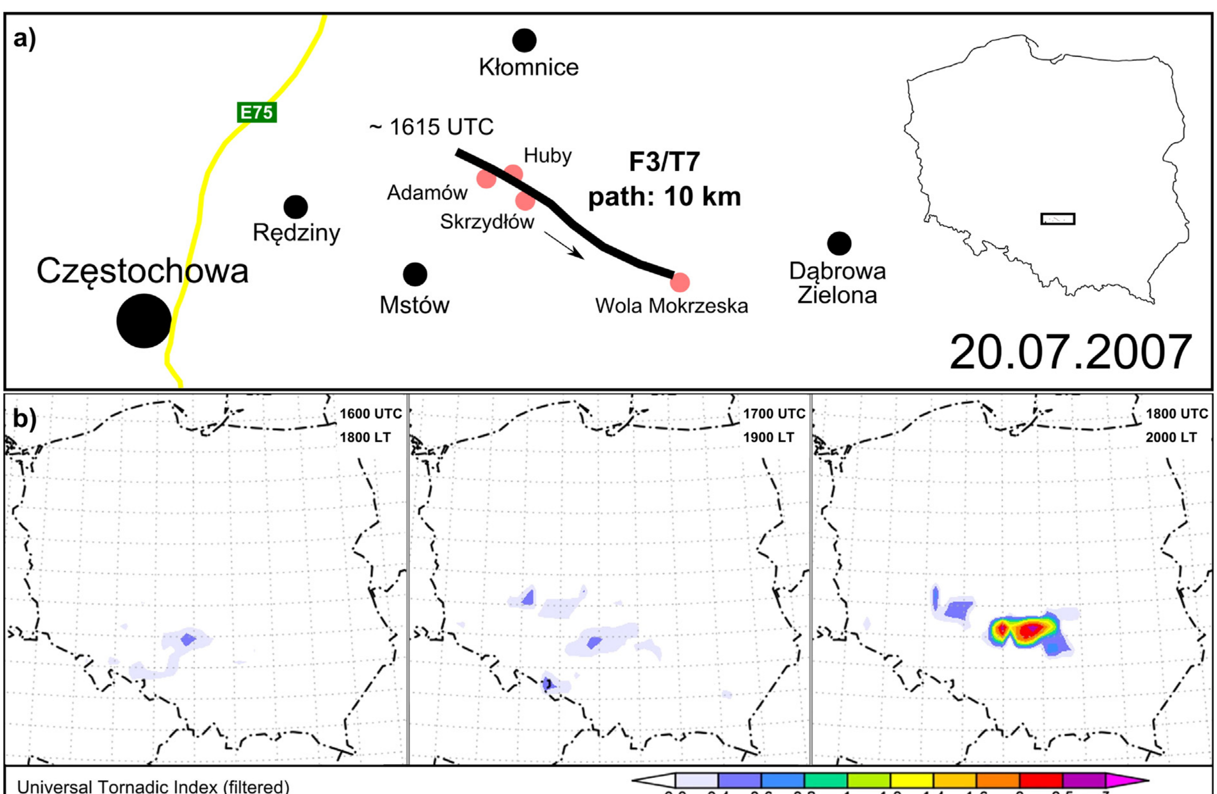

Fig. 10. (a) Damage track of the 20 July 2007 tornado in a portion of south central Poland. Red dots indicate locations where a tornado was reported. Solid black lines denote tornado damage path (with estimated maximum intensity in Fujita and TORRO scale). Arrow indicates the direction of tornado motion. Yellow line denotes European Route E75. (b) WRF-ARW 3.7 (15 km grid) model forecast UTI filtered (if 1-hour accumulated convective precipitation <0.75 mm, then UTI = 0) at 1600, 1700 and 1800 UTC on 20 July 2007. Initial conditions were extracted from 20 July 2007 0000 UTC 0.5° GFS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

kg. Although this value was moderate (Riemann-Campe et al., 2009), it occurred in an environment of ~20 m/s DLS (Fig. 7d) that according to a study by Doswell and Evans (2003) should be conducive to the occurrence of supercells. The importance of thermodynamic instability and a 20 m/s + DLS overlap in the context of significant F2 + tornado occurrence was also indicated by Taszarek and Kolendowicz (2013) and Púčik et al. (2015).

An LLS parameter, which implies the presence of a horizontal vorticity was also increased in the area where tornadoes occurred (Fig. 8a). A model indicated up to 10–15 m/s LLS with LCL lowered to 200–400 m AGL, which according to numerous sounding studies is also a favorable combination for the significant tornado occurrence (Rasmussen and Blanchard, 1998; Craven and Brooks, 2004; Grünwald and Brooks, 2011; Taszarek and Kolendowicz, 2013).

Not without significance was also the presence of an increased 0–1 km SRH which like LLS can also be treated as a good tornado forecasting tool (Groenemeijer and van Delden, 2007). The area with the highest values (up to 150–200 m^2/s^2 as indicated by the model) was located slightly ahead of our cell of interest (Fig. 8b). Nevertheless, the signal from the model indicated that the cell moved in the zone where the winds were tilting with height.

4.3. Convective initiation

In order to assess a lift on the synoptic scale (an important ingredient in terms of steepening of vertical lapse rate and the release of CAPE), we used an isentropic potential vorticity parameter with wind vectors on 320 K level. As shown by the model, the advection of a higher PVU (potential vorticity units) took place in north central Poland where the cell of interest occurred and received a triggering factor (Fig. 8d). Therefore, the model provided a signal in producing a convective precipitation and at 1400 UTC initiated two individual convective cells in our area of interest (Fig. 8c). This indicated that the overall pattern was conducive for the occurrence of deep moist convection (DMC) and hence the severe thunderstorms because all the basic ingredients

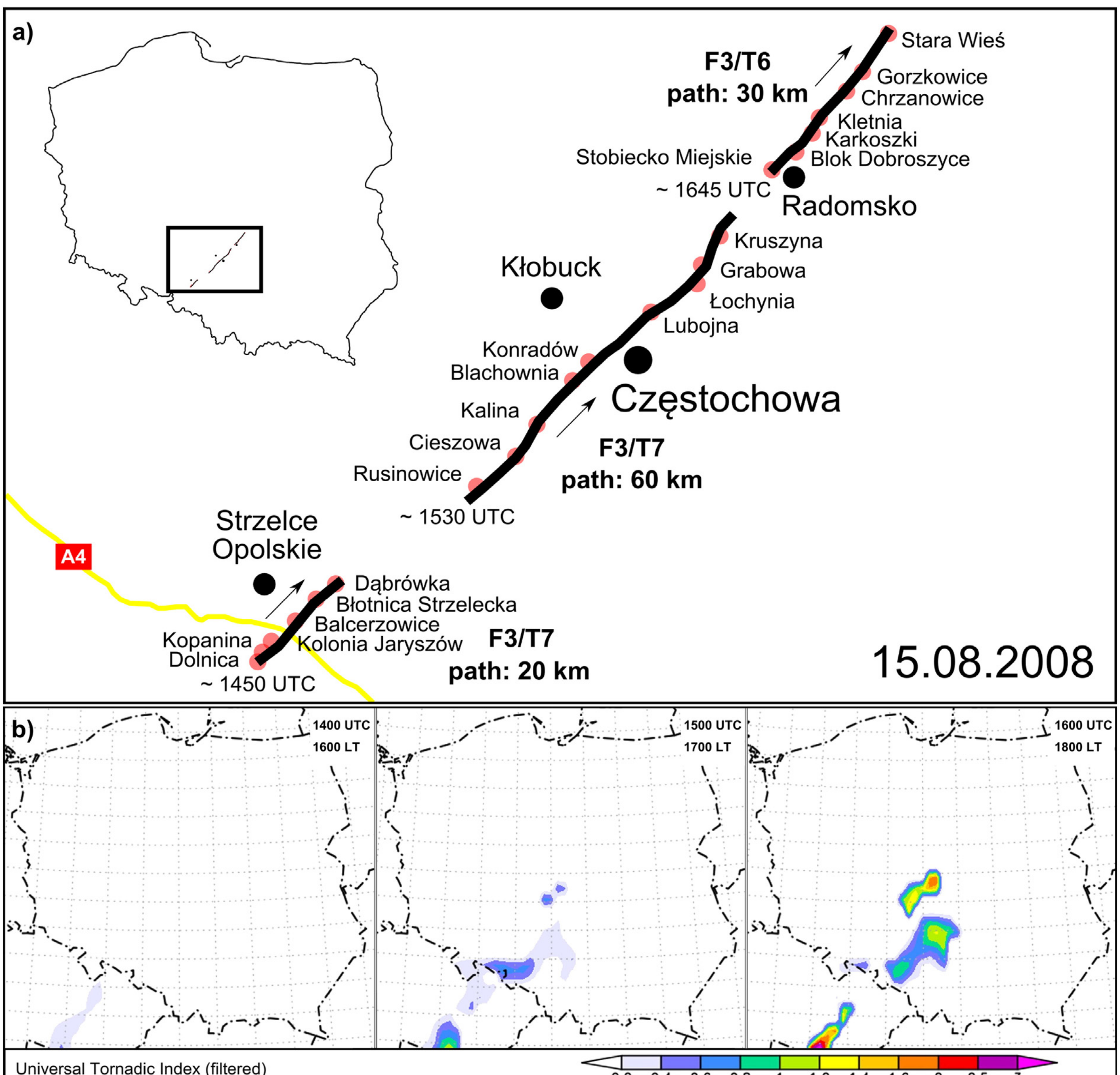

Fig. 11. (a) Damage tracks of the 15 August 2008 tornadoes in a portion of south central Poland. Red dots indicate locations where a tornado was reported. Solid black lines denote tornado damage paths (with estimated maximum intensity in Fujita and TORRO scale). Arrows indicate the direction of tornado motion. Yellow line denote A4 highway. (b) WRF-ARW 3.7 (15 km grid) model forecast UTI filtered (if 1-hour accumulated convective precipitation <0.75 mm, then UTI = 0) at 1400, 1500 and 1600 UTC on 15 August 2008. Initial conditions were extracted from 15 August 2008 1200 UTC 0.5° GFS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(instability, moisture, lift, vertical wind shear) were available during the passage of the shortwave.

4.4. Tornado potential forecast

In order to more precisely define where the atmospheric conditions were most conducive for tornado occurrence, we used a UTI index that when exceeding the values of 0.5 should indicate the presence of a significant tornado potential (Taszarek and Kolendowicz, 2013). When applied in our model data, it pointed out that tornadoes in the north central part of the country were possible if DMC would be involved (Fig. 9a).

In order to reduce false alarms and focus on areas where the model forecasts DMC, we filtered out the UTI values with 1-hour accumulated convective precipitation below 0.75 mm. In this way, we wanted to obtain information whereby the model is able to predict the tornado potential and the occurrence of convective cells (capable of producing tornadoes). With the use of this method, the final product (UTI filtered; Fig. 9b) indicated quite distinctively that the tornado potential existed with the northeastwardly moving cells which at 1500 UTC were forecast to be located in north central Poland (i.e. in the area where tornadoes actually occurred). It is also worth adding that the signal indicated by the index at 1300 UTC in western Poland overlapped with severe wind reports (with strength of up to F1/T3) that were reported in Trzcianka, Sarbia, Piła, and Kaczory around 1310–1330 UTC (Section 3.2).

4.5. Complementary case studies

As a supplement to this study, in order to test the value of the methodology already determined, we performed the same WRF-ARW model simulations and applied the same UTI filtered parameter to two famous Polish significant tornado cases from recent years; 20 July 2007 (Fig. 10a) and 15 August 2008 (Fig. 11a) that occurred in Poland in the late afternoon hours. These two cases similar as in the case from 14 July 2012 were characterized by the overlap of high thermodynamic instability and increased low and mid vertical wind shear during the passage of the westerly (20 July 2007) and southwesterly (15 August 2008) shortwave trough. Model simulations of UTI indicated that although the forecasted tornado potential had a temporal shift of around 1–2 h, the technique quite distinctively indicated the primary regions where the significant tornadoes occurred allowing their short-term prediction (Figs. 10b, 11b).

5. Concluding remarks and discussion

Worldwide, there have been numerous observational case studies analyzing the mesoscale environment of tornadic supercells (e.g. Hoxit and Chappell, 1975; Maddox et al., 1980; Bentley et al., 2002; Giaiotti and Stel, 2007; Maddox et al., 2013). These studies pointed out that mesoscale characteristics of the wind field, altered by horizontal boundaries such as thermal or moisture horizontal gradients, can be supportive of tornado occurrence. The analysis of a case from 14 July 2012 indicated that the convective cell classified as an isolated cyclic supercell in fact moved along such boundaries.

An analysis of the radar data, aerial photography, local damage survey, damage reports in media, and global forest change project allowed for the setup of four tornado damage tracks at a distance of 100 km with a total length of around 60 km. The tornadoes damaged 105 buildings with predominant intensity of F1-F2 (maximum F3), caused 1 fatality and 10 injuries, and felled 500 ha of Bory Tucholskie forest. We suspect that the cell reached a long life-cycle and left significant (at least for the Polish conditions) damage tracks due to being isolated from other cells.

This study confirmed findings from previous studies (Weiss et al., 2006; Weisman et al., 2008; Litta et al., 2010, 2012; Matsangouras et al., 2011) that the use of WRF model simulations may be supportive of severe convective storm prediction. A WRF-ARW model forecast data for the afternoon hours with a spatial resolution of 15 km and initial conditions extracted from 0000 UTC 14 July 2012 GFS output indicated that thermodynamic and kinematic parameters were conducive for tornado occurrence. With the use of a UTI composite parameter, it was possible to indicate areas where tornado favorable conditions overlapped. An experimental forecasting method that combined a UTI parameter with a filter based on excluding areas where a 1-hour accumulated convective precipitation estimated by the model was lower than 0.75 mm showed that convective cells at 1500 UTC in north central Poland had the potential to become tornadic. Given this knowledge and being aware that from a climatological standpoint the highest risk for tornadoes in Poland occurs between 1500 and 1800 UTC (Taszarek and Brooks, 2015), operational forecasters could suspect that isolated convective cells visible on the radar data may later become tornadic.

Although the presented technique demonstrated a potential in predicting tornadic environments, further studies concerning large datasets are necessary to define the operational significance of such methodology, particularly false alarm ratio and a probability of detection given particular index values. In our current understanding an operational significance of the index over central European area starts with a value of around 0.5 and together with increasing values, increases chances of a tornado with higher intensity. Values exceeding 3–5 spread over large area indicate possibility of the severe weather outbreak. In order to reduce false alarm ratio during wintertime, we suggest applying an additional filter of 100 J/kg CAPE. The main purpose of the index is to draw attention to the places where favorable tornadic conditions overlap. However, instead of using index itself, forecasters should be aware that the use of an ingredient-based methodology is the best way of understanding what is really happening in the atmosphere and the index should be treated as an additional tool.

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Deadly tornadoes in Poland from 1820 to 2015

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Abstract

Using historical sources derived from 12 Polish digital libraries, an investigation into killer tornado events was carried out. Although some of the cases took place more than 150 years ago, it was still possible to identify tornado phenomena and the course of events. Study has shown that historical sources contain dozens of tornado reports, sometimes with information precise enough to reconstruct the tornado damage paths. In total, 26 newly identified deadly tornado cases were derived from the historical sources and the information on 11 currently known was expanded. An average of 1-2 killer tornadoes with 5 fatalities may be depicted for each decade and this rate is decreasing over time. It was estimated that 5-10% of significant tornadoes in Poland have caused fatalities and the average number of fatalities per significant tornado was roughly 0.27. Most of the cases were reported in late July and early August. The majority of deaths and injuries were associated with victims being lifted or crushed by buildings (usually a wooden barn). Most of these cases took place in rural areas but some tornadoes hit urban areas, causing a higher number of fatalities. The spatial distribution of cases included maxima in the central lowland and south-central upland of Poland. In a noticeable fraction of cases (38%), large hail occurred either before or after passage of the tornado.

Keywords: tornado, history, fatalities, Poland

1. Introduction

Tornadoes are among the most spectacular natural hazards that can pose a significant threat to life and property, and thus attract a lot of media attention. However, probably due to the infrequent occurrence of high-impact tornadoes in Poland, tornado reports have not been officially kept as they are, for example, in the United States (U.S.). Therefore, it is not an easy task to create long-term climatological studies based on their occurrence, especially taking into account the temporal and spatial reporting inhomogeneities prevalent in Poland. These arise mainly from historical changes in the national borders, wars, political regimes, language diversity, and changing severe weather awareness.

For a long time, tornadoes in Poland were regarded by society as strange and rare phenomena reserved mainly for the territory of the U.S. (Dotzek 2001; Taszarek and Brooks 2015). Doswell (2003) described this situation as a self-fulfilling prophecy, in which denying the existence of tornadoes resulted in no record keeping of such events. However, tornado databases are likely to be more consistent over time, especially for intense spectacular events that cause significant property damage (Brooks and Doswell 2001; Verbout et al. 2006; Rauhala et al. 2012; Taszarek and Brooks 2015). This issue concerns especially deadly tornadoes that attract more public attention and are usually better documented in media reports. The studies on historical tornado cases in Europe (Wegener 1917; Groenemeijer and Kühne 2014; Antonescu et al. 2016) have shown that even old cases from previous centuries can be derived from archival sources.

On the basis of tornado reports in the European Severe Weather Database (ESWD; Dotzek et al. 2009) hosted by the European Severe Storms Laboratory (ESSL), Groenemeijer and Kühne (2014) estimated that tornadoes in Europe kill 45-60 people each decade (1900-2013 time frame). They suggested that due to problems related to tornado reporting the average fatality rate is probably higher and estimated the true value to be closer to 100-150.

For comparison, in the U.S., Ashley (2007) estimated the average number of tornado-related deaths per decade at 1000 since the 1880s, and 500 since the 1980s. Nowadays, 68%, 31%, and 1% of casualties are due to violent (F4-F5 at *F*-scale; Fujita 1971), strong (F2-F3), and weak (F0-F1) tornadoes, respectively.

Apart from numerous studies on tornado fatalities in the U.S. (e.g. Brooks and Doswell 2002; Merrell et al. 2005; Simmons and Sutter 2005, 2008; Ashley 2007; Ashley et al. 2008), little such research exists on killer tornadoes in Europe. In Poland, the climatology of tornadoes, taking into account the period 1899-2013, has been studied by Taszarek and Brooks (2015). However, while deadly tornado case studies exist (e.g. Gumiński 1936; Rafałowski 1958; Parczewski et al. 1959; Salomonik 1960; Chmielewski et al. 2013; Popławska 2014; Taszarek et al. 2016), a comprehensive study on tornado fatalities in Poland is absent, mainly due to the lack of reports or insufficient data on killer tornadoes. The ESWD data used in studies by Taszarek and Brooks (2015), Groenemeijer and Kühne (2014), and Antonescu et al. (2016) contained only a few such cases; thus, fatality records were underestimated.

To improve the database of tornado fatalities in Poland, the aim of this study was to investigate historical records from the 19^{th} and 20^{th} centuries. The analysis of such data is important to estimate the future threat of rare events that have the potential to create a major disaster (Doswell 2003). The 1820s were chosen as a starting point due to this time frame having the first available description of fatalities from tornadoes in Poland. Additionally, most of the archival sources in the digital libraries have been made available since the early 19^{th} century.

The paper is organized as follows: in section 2 the methodology related to collecting tornado reports, quality control issues, intensity estimation, and a short overview of historical tornado studies are presented. Section 3 contains the results of the analysis while the last section provides a discussion and concluding remarks. The most important factual information on each killer tornado case (as derived from the scientific literature and historical sources) is presented in the Appendix.

2. Database and methodology

a. Quality control assumptions

Cases with descriptions of considerable damage including fatalities provided no doubt that the described phenomenon was related to a tornado. In events with less severe damage, it was important to investigate whether the description may have been related to a severe straight line wind event such as a downburst (Fujita and Wakimoto, 1981). This issue concerned primarily the archival descriptions from the 19th and 20th century when the term "*tornado*" (Polish: *trąba powietrzna*) was not well recognized in Polish media sources. Although archival sources sometimes contained detailed descriptions regarding long, narrow damage tracks and/or eyewitnesses mentioning a rotating cloud sticking onto the earth's surface, the term "*strong hurricane*" was normally used. Conversely, some of the newspaper reports, especially from the late 20th and 21st century, started using the term "*tornado*" commonly when convection-related wind gusts caused strong damage to infrastructure (without any characteristic tornado damage indicators). These issues represented a source of uncertainty when classifying such events.

In a quality control process in which credibility ratings were assigned, the most important issue (besides the name of the phenomenon that was assigned by the newspaper) was the description of the event and the inflicted damage. Cases with fatalities due to severe storms as described in the newspapers which lacked eyewitness funnel cloud reports or information about physical processes characteristic of tornadoes (objects and people lifted in the air, narrow and long damage path, debris and trees scattered in different directions, great destruction etc.) were not considered. In cases where "*tornado*" (and/or a description suggesting the occurrence of a funnel cloud) was not mentioned but the report had information suggesting the presence of damage due to a vortex, a "*case uncertain*" rating was assigned. The same rating was also attributed to cases in which "*tornado*" or a visible funnel cloud was mentioned, but the overall information about the event and damage was too limited. Cases for which descriptions provided no doubt about the presence of a vortex phenomenon, (the presence of a funnel cloud along with the description of a typical tornado damage), received a "*case confirmed*" rating. The last credibility rating ("*case fully verified*") was assigned to cases in which damage was described in detail (usually in numerous sources), and where a reconstruction of the event along with the tornado damage track was possible.

To perform an additional quality control of the analyzed cases, 20th and 19th Century Reanalysis Data (Compo et al., 2011) was used for cases since 1870, mainly to check whether simulated synoptic-scale conditions were in general conducive to the occurrence of severe convective storms (e.g. an increased mid-level flow, the presence of a thermal boundary, the passage of a trough) on days with alleged tornadoes. Since the authors were aware of the spatial and temporal limitations of the reanalysis data, only the general synoptic pattern was taken into consideration. This in particular helped to ensure whether the event was plausible rather than excluding it from the analysis. In cases with suspicious or limited descriptions that in addition took place in an unfavorable synoptic pattern, a "*case uncertain*" rating was assigned. In addition, the geostrophic wind at 500 hPa was used to estimate the general motion of the thunderstorm (and of approximately the tornado) in cases where the description of the event did not allow for such an estimate. However, we acknowledge that the real tornado motion might have differed from this estimate due to left- or right-turning supercells.

b. Inhomogeneity factors

Numerous factors influenced tornado reporting and availability of reports in media sources. The most important ones refer to political and social contexts, Poland's changing borders, and world wars which resulted in the decline in interest in atmospheric phenomena. From 1795 to 1918, the territory of Poland was under German, Austrian and Russian occupation, and never gained independence. However, Polish nationality and the awareness of one's cultural identity remained. Numerous Polish newspapers operated on a regional scale. As Antonescu et al. (2016) suggested, development of national and regional newspaper-type publications was the main factor that influenced the spatial distribution and temporal evolution of tornado databases. In this study, regional libraries that covered almost the whole modern-day territory of Poland (except the southwestern and northeastern areas), were accessed. The highest number of archival newspaper editions was available for the second half of the 19th and first half of the 20th century. During the socialistic period from 1945 to 1989 any information on catastrophic events was difficult to find, thus resulting in a low number of tornado reports (Taszarek and Brooks 2015). A similar situation also happened in Romania (Antonescu and Bell 2015) and the Czech Republic (Setvák et al. 2003) during the 1970s and 1980s. The existence of tornadoes was not officially recognized and the word "*tornado*" was barred from both official meteorological and mass media reports (Antonescu et al. 2016).

Since 2000, advances in communication technologies and development of tornado databases and thunderstorm observer networks have led to a rapid surge in tornado reporting both in Poland (8-14 yr^{-1} Taszarek and Brooks 2015) and Europe as a whole (200-300 yr^{-1} Groenemeijer and Kühne 2014). This suggested that before 2000, tornadoes were strongly underestimated in Europe.

c. Collecting tornado reports

In 1917, Alfred Wegener, a German meteorologist, geophysicist, and pioneer polar researcher, in his work *Wind- und Wasserhosen in Europa* (Wind and Waterspouts in Europe), published one of the first collections of tornado records in Europe, where he included a few tornado cases from the territory of western Poland (in that time these areas belonged to the German Empire). His study was based mainly on tornado reports collected from a wide range of scientific literature and personal observations. The work of Wegener (1917) contained probably the oldest well-described killer tornado case that occurred over the current territory of Poland near Oleśnica on 11 September 1535. The tornado lifted wooden wagons, roofs, people, and even whole wooden houses. Over 60 masonry walls were demolished. According to original sources, 5 people died after being crushed under collapsed walls.

Tornado reports derived from the work of Wegener (1917), along with well-known Polish killer tornado cases from the 20th and 21st century described in scientific literature (20 July 1931, Gumiński 1936; 15 and 16 May 1958, Rafałowski 1958; 20 May 1960, Salomonik 1960; 15 August 2008, Popławska 2014; 14 July 2012, Taszarek et al. 2016) were reported to ESWD. This resulted in a total of 11 killer tornado cases. However, initially only six of these contained information about fatalities, among which three had incomplete statistics on victims. Thus, all cases required an additional study.

To look for tornado descriptions which are undocumented in scientific literature and expand information about currently known cases, archival sources from the 19th and 20th century were searched. This was done by browsing databases of several Polish digital libraries that contained original scans of various newspapers with local and national coverage (Table 1). These were studied using keyword searches like *trąba powietrzna, huragan,* and *orkan* (tornado, hurricane, and orcane). In some cases, an investigation was supported by performing web searches and obtaining original scientific papers in the library of IMGW-PIB (Polish

Institute of Meteorology and Water Management – National Research Institute). In total, 26 newly identified killer tornado cases that occurred in the territory of Poland during the 19th and 20th century were found.

Together with previous cases included in the ESWD, a total of 37 killer tornado cases are investigated in this paper. A summary of all cases with information about exact date, place, subjective estimate of strength on the *F*-scale (Fujita, 1971), damage path size, tornado motion, number of fatalities, assigned credibility rating, and cause of death is presented in Table 2.

d. Intensity estimation

As in ESWD, the original *F*-scale was used to rate the intensity of tornadoes on the basis of damage descriptions. However, due to very limited information about the inflicted damage in historical cases, instead of using a traditional F0-F5 scale, we defined less accurate categories that allowed for estimation of tornado intensity with some degree of approximation. Four categories (still using damage indications from the original *F*-scale) were used to rate cases: F1/F2 (tornadoes bordering on weak and strong intensity), F2/F3 (strong tornadoes), F3/F4 (tornadoes bordering on strong and violent intensity), and F4/F5 (violent tornadoes). For example, if a case was rated F2/F3, it was assumed that both intensities were possible, but it was unlikely that the case was weaker than F2 or stronger than F3. None of the damage descriptions allowed for an F0/F1 intensity rating. Joint ratings were not used for the recent tornado cases (15 August 2008 and 14 July 2012). where damage surveys were detailed enough to assign a particular *F*-scale rating.

3. Results

a. Credibility rating

A total of 37 cases from the period 1820-2015 were responsible for 106 fatalities, providing an average of 2.9 fatalities per case (Table 2). Among all, 9 cases (24% of the data) were classified as "*event fully verified*". That group consisted of 38 fatalities and included the most deadly case – the tornado of 14 May 1886 that passed through Krosno Odrzańskie and killed 13 people. The tornadoes were confirmed with relatively good credibility ("*case confirmed*" rating) in another 10 cases (27%). The "*case uncertain*" rating was assigned in 18 cases (49%) where tornadoes were likely, but the information was insufficient to ultimately confirm the event.

b. Decadal variation

Although the database contains no deadly tornadoes from the 1840s, 1970s and 1980s, an average of 1-2 killer tornadoes with 5 fatalities may be depicted for each decade based on the records from the entire period of analysis (Figure 1). It was hypothesized that the number of fatalities in the first half of the 19th century might have been higher, but the limited availability of historical sources from this period did not allow for investigation of more cases. The highest number of 20 fatalities and 6 killer tornadoes occurred in the 1880s, whereas the reporting "*gap*" was observed during the second half of the 20th century. A similar gap was also pointed out by Dotzek (2001), Holzer (2001), Setvák et al. (2003), Antonescu and Bell (2015), and Taszarek and Brooks (2015), and was justified as "*certainly artificial*", resulting in the weather service, journalists, and the general public ignoring such events. During the socialistic period, it was typical that tornadoes were virtually ignored - damage events were simply attributed to damaging wind gusts within convective storms, such that the term ‘‘*tornado*’’ was essentially forbidden (Setvák et al. 2003). After Poland transformed its political system in 1989, the situation changed and an increase in tornado reporting was observed (Taszarek and Brooks 2015).

The analysis showed that the average decadal number of tornado fatalities in Poland has decreased throughout time. Taking into account 40-year intervals, an average of 10.5 fatalities per decade in the years 1860-1899 decreased to 6.5 in the years 1900-1939 to 3.0 in the years 1940-1979 to only 1.2 in recent years (1980-2015). The last two values may be underestimated and be a result of underreporting issues during socialistic period. The same decrease since the 1930s was also observed in the U.S. (Ashley 2007). Simmons and Sutter (2005) have also shown that tornado casualties due to violent cases (F4-F5) have decreased significantly over the course of the 20th century. Doswell et al. (1999) and Brooks and Doswell (2002) suggested that this decline can be attributed to the advancement in tornado forecasting technology, improved communication, development of meteorological observer networks, better building construction techniques, development of a Doppler radar network, and the implementation of watch–warning processes. Sims and Baumann (1972) and Cohen and Nisbett (1998) pointed out that human perception and response to the threat of tornadoes may be influencing the number of fatalities across different regions. Complacency ("*It can't happen here!*") and detachment from the natural environment and a general failure to embrace warning information may also be important factors in explaining human behavior during tornado events, and hence the number of fatalities (Biddle, 1994). Authors speculate that the drop in fatalities over the decades in Poland may be due to advances in construction techniques and it is unlikely that the fatality rate will continue to decrease unless considerable improvements in tornado warnings are implemented.

In Poland, official tornado forecasts and warnings have never been performed by the IMGW-PIB (Rauhala and Schultz 2009; Taszarek 2013). Up until 1997 when the so-called Polish Millennium Flooding took place (Kundzewicz et al. 1999), severe weather awareness in Polish society was relatively low. In the 21st century numerous advances in severe thunderstorm forecasting (e.g. the foundation of the Polish Stormchasing Society and the development of PERUN lightning detection and POLRAD Doppler radar network, Jurczyk et al. 2008; Taszarek et al. 2015) have been introduced and supported the growth in severe weather awareness. However, this has not led to an elimination of tornado casualties as evidenced by recent killer tornado events (15 August 2008 and 14 July 2012).

c. Monthly and diurnal distribution

All tornado cases occurred during late spring and summer from April to August (Figure 2). The highest number of tornadoes (16) and fatalities (50) came from late July and early August. An increased number of killer tornado cases was also found in May when the highest number of strong/violent cases with 29 fatalities was reported. Early June consisted of only 2 reports. A similar pattern in significant (F2+) tornado occurrences (66 cases in the time frame 1899-2013) was also found by Taszarek and Brooks (2015).

The approximate time (+/- 1h) of the tornado occurrence was defined in 20 cases, while in another 13 cases it was possible to determine that the tornado occurred during daytime or evening hours. Among reports where the time was defined, the highest number of cases took place between 1400 and 1600 UTC. This is consistent with the findings of Groenemeijer and Kühne (2014), Taszarek and Brooks (2015), and Antonescu et al. (2016), who found that significant tornadoes in the central European region are most likely in the late afternoon.

d. Spatial distribution and tornado motion

Most of the cases (location denotes the most known or nearest place of fatality/fatalities caused by the tornado) took place in the central lowland and south-central upland part of Poland (Figures 3a,d). Similar areas were also denoted in previous studies on tornadoes in Poland as conducive to significant tornado occurrence (Walczakiewicz et al. 2011; Lorenc 2012; Taszarek and Brooks 2015). However, the spatial distribution of population density may play a significant role in these data. It is possible that a greater number of tornado reports and fatalities came from areas which were simply more populated, especially when the tornado hit urban areas (Figure 3c). In the provinces, the mean number of tornado cases per 100 years with values normalized to 10,000 km^2 was highest in the Silesian and Łódź Voivodeships (Figure 3b). The most deadly cases (18 July 1851, 14 May 1886, 31 May 1866, 15 August 1922; Table 2) occurred in the Mazovian, Lubusz, Silesian, and Świętokrzyskie Voivodeships.

From the use of reanalysis data and descriptions of the events, it was possible to define tornado motion in 34 cases. It is worth underlining that almost all cases containing information about the direction of a tornado movement agreed with the 500 hPa geopotential pattern obtained from the reanalysis data. A majority of cases were associated with SW (53%) and W (24%) airflow, while tornadoes occurring from S (12%) and SE (6%) directions were less frequent. Similar findings were obtained by Suckling and Ashley (2006) who found that almost 70% of U.S. tornadoes were associated with W and SW airflows.

e. Circumstances of death

It was possible to investigate the circumstances of death surrounding 87 of 107 fatalities. Almost 43% of the deaths happened outdoors while 44% were attributable to being inside buildings (Table 3). Around 13% of the deaths were associated with means of transportation such as boat, droshky or train. Cases in which people were lifted into the air were usually associated with being in open space and devoid of appropriate shelter. Only a small fraction of cases were associated with deaths due to being crushed by a falling tree, what is known to predominantly cause fatalities in straight line wind events according to ESWD records for Poland. In the U.S., as was suggested by Brooks and Doswell (2002), fatalities within vulnerable housing stock continue to provide a major obstacle in reducing overall tornado death rates. The majority of these cases take place in mobile homes (44% of all cases; Ashley 2007).

f. Intensity rate

A noticeable fraction of cases (38%) contained descriptions about accompanying large and very large hail before or after the passage of the tornado. This may suggest that tornadoes were predominantly associated with the presence of mesocyclones (convective cell that has a deep and persistent rotating updraft; Doswell and Burgess 1993; Davies-Jones et al. 2001), which are known to be distinctive in producing large hailstones (Van Den Heever and Cotton 2004; Donavon and Jungbluth 2007).

On the basis of damage descriptions, 8 cases were classified as weak/strong (F1/F2), 19 as strong (F2/F3), 7 as strong/violent (F3/F4), and 1 as violent (F4/F5) in terms of intensity. Two deadly tornado cases from the 21st century with an accurate damage survey were rated as F3. The average path length computed from all cases where this information was available (22 cases) amounted to 19.1 km (maximum 42 km, minimum 3 km), while the average path width (12 cases) was estimated at 737 m (maximum 2000 m, minimum 50 m). Similar average path characteristics were obtained from European records of F3 and F4 tornadoes (Groenemeijer and Kühne 2014).

From the use of significant tornado frequency as assessed by Taszarek and Brooks (2015) for Poland (around 1-3 per year), it can be estimated that approximately 400 significant tornadoes occurred in the period 1820-2015. Assuming that 29 to 37 cases in our study reached significant intensity, this would indicate that around 5-10% of significant tornadoes in Poland caused fatalities and the average number of fatalities per any significant tornado was about 0.27. Although a similar value (0.28) obtained by Groenemeijer and Kühne (2014) was assigned to F3 tornadoes, we hypothesize that due to incomplete knowledge on killer tornado cases in Poland and a presumably imperfect estimate in Taszarek and Brooks (2015), the true value is probably higher. Nevertheless, an estimation of 20 significant and 1-2 deadly tornadoes per decade, indicate that strong and deadly tornadoes are rather a rare phenomenon in Poland.

g. Comparison with other European countries

It is difficult to compare our results with other European countries because only a limited number of studies on deadly tornadoes have been published. In addition, even after the launch of ESWD, underreporting issues (especially considering Southern and Eastern European areas) have continued which limits the ability to compare databases between particular countries in a reliable way. However, as Groenemeijer and Kühne (2014) suggests, ESWD tornado data in central European countries (especially Germany) is more reliable and less susceptible to underreporting issues than the rest of Europe.

Considering ESWD deadly tornado records in the time frame 1820-2015 (Table 4) it can be defined that the highest number of deadly tornadoes (53) was reported in Germany (which deal probably with the lowest ratio of underreporting issues among all European countries). Both the total number of fatalities (an average of 2-3 casualties per tornado) and mortality of the most deadly tornado case (9 September 1913, Helgoland, 14 casualties) show a similarity with Polish records suggesting a similar killer tornado threat.

The highest number of fatalities and thus the most deadly tornadoes were recorded in Italy where 275 people have been killed. Although the number of killer tornadoes in Italy was lower than in Poland and Germany (probably due to underreporting issues), the mortality rate was much higher. A similar situation was also observed in France where 23 tornadoes were responsible for 130 fatalities, including one of the most deadly European tornado (19 August 1845, Montville, 70 casualties). Large numbers of fatalities (106) within just 18 tornadoes and a most deadly case in Ivanovo (6 September 1984, 69 casualties) was observed in western

Russia where population density is much lower than in central Europe and where tornado events are severely underestimated. Other countries such as Spain, Turkey, Austria, Netherlands and Romania demonstrated higher mortality rates than in Polish and German records, but due to small sample size and underreporting issues it is difficult to define how reliable these estimates are.

4. Summary and concluding remarks

Using historical sources derived from 12 Polish digital libraries and the time frame between 1820 and 2015, research to examine deadly tornado descriptions was conducted. Although some of the tornadoes occurred more than 150 years ago, it was still possible to identify them and the course of the events with relatively high credibility. This study has shown that historical sources contain dozens of tornado reports, sometimes with information precise enough to reconstruct tornado damage paths. Surprisingly, newspaper sources from the turn of the 19th and 20th century turned out to be of better quality than those from the socialistic period in the second half of the 20th century. In total, the Polish tornado climatology was expanded with 26 newly identified deadly tornado cases while the information on 11 currently known was updated. Although the analysis was under influence of temporal and spatial reporting inhomogeneities, several conclusions can be drawn.

1 An average of 1-2 killer tornadoes with 5 fatalities may be depicted for each decade and this rate is decreasing over time. It is estimated that around 5-10% of significant tornadoes in Poland cause fatalities, while the average number of fatalities per any significant tornado amounts to roughly 0.27.

2 The majority of deaths and injuries were associated with victims being being lifted or crushed by buildings (usually a wooden barn). Most of the killer tornadoes occurred in rural areas but some hit urban areas, causing a higher number of fatalities. Cases in which

people were lifted into the air were usually associated with being in open space and devoid of appropriate shelter.

3 Killer tornadoes occur from late April to late August with the peak activity in late July and early August. They are the most likely in the late afternoon. These findings agree with those of Groenemeijer and Kühne (2014), Taszarek and Brooks (2015), and Antonescu et al. (2016) on significant tornado occurrence in the central European region.

4 Most of the cases took place in the central lowland and south-central upland part of Poland. Although this finding overlaps partly with Taszarek and Brooks (2015), it is possible that our results may have been influenced by a diverse spatial range of regional newspaper archives and spatial distribution of population density.

5 A majority of cases were associated with SW and W airflows, which coincided with the results obtained for the U.S. by Suckling and Ashley (2006).

6 Lastly, a noticeable fraction of cases contained descriptions about accompanying large and very large hail. This suggested that tornadoes were predominantly associated with mesocyclones, which are known to be distinctive in producing large hailstones.

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Appendix

In this section the most important factual information related to deadly tornadoes analyzed in this study (Table 2) are presented. The reference below each case denotes the primary historical source of information on the event: name of the newspaper, release date and the shortcut of the digital library (Table 1).

1. 19th century

a. 30 June 1829, Turzyn (4 fatalities, case confirmed)

This case is probably one of the first reliable descriptions of a killer tornado in Poland. The tornado appeared in the vicinity of Wyszków in the Mazovian Voivodeship. A strong thunderstorm accompanied by hen's egg-sized hail passed through Wyszków at around 1700 UTC. The half-mile tornado brought down trees, swept away roof tiles, and severely damaged a timber barge on the Bug River. As a result, 4 people were drowned. The tornado left a damage path of approximately 10 km.

Gazeta Polska, 6 July 1829, EBUW

b. 15 May 1830, Szamotuły (1 fatality, case confirmed)

A quickly moving thunderstorm with a "*rotating column of air*" was observed in the evening hours in Kiekrz near Poznań in the Greater Poland Voivodeship. Damage path extended from Kiekrz through Piątkowo up to Szamotuły where one person was crushed under the rubble of a windmill. Newspaper sources mention a "*higher number of fatalities*" but do not specify the exact number. The tornado destroyed several buildings and killed a large number of animals. It moved from the southeast.

Powszechny Dziennik Krajowy, 2 June 1830, EBUW *c. 27 June 1833, Węgrzynów (2 fatalities, case uncertain)*

This case occurred in the vicinity of Wyszogród in the Mazovian Voivodeship. The newspaper source does not use the term “*tornado*“ but the tornado phenomenon can be identified on the basis of the damage description. The destruction was arranged in a clear narrow damage path with a length of 16 km. Roofs and trees were torn while weakly constructed farm buildings were damaged and destroyed. Two people died as a result of being crushed under a collapsed barn.

Kurjer Warszawski, 6 July 1833, EBUW

d. 12 May 1851, Charsznica (1 fatality, case confirmed)

A severe thunderstorm was reported in Charsznica near Miechów in the Lesser Poland Voivodeship. The phenomenon called “*tornado*” destroyed and/or damaged 45 houses, uprooted hundreds of trees, and killed 23 heads of cattle. One person died of an unknown cause while seven were injured. The tornado was preceded by large hail.

Goniec Polski, 1 June 1851, WBC

e. 18 July 1851, Bobrowniki (3 fatalities, case uncertain)

This case occurred in the neighborhood of Bytom in the Silesia Voivodeship. During a heavy storm that was called by a newspaper source “*hurricane*”, considerable damage was caused in several villages from Bobrowniki through Pyrzowice up to Zendek. The wind tore up roofs, snatched haystacks, and collapsed a few buildings. Three people died of unknown causes. The damage reports were arranged in a clear path of 15 km in length.

Goniec Polski, 31 July 1851, WBC

f. 18 July 1851, Szopienice (10 fatalities, case uncertain)

A second significant tornado event dated 18 July 1851 was described in the church archives of Dąbrówka Mała. As the local priest Górecki (1995) writes in his article, after a sunny and hot day, a strong tornado occurred in the afternoon hours and in a few seconds demolished the zinc smelter near Szopienice (the Silesia Voivodeship). As a result, 10 workers from Dąbrówka Mała were killed after being crushed under the rubble. Additional information can be found on the grave of the victims at the cemetery in Bogucice: "*On 18 July 1851, a tornado turned into rubble a zinc smelter and because of this the following workers were killed: Edward Kuczera, Wojtek Kasza, Grześ Opaszewski, Wincenty Woźniok, Andrzej Stalmach, Jan Kuczera, Józef Nędza, Franciszek Bieloch, Łukasz Janta, Feliks Opaszewski*". However, except for this mention, the information on this event is very limited.

g. 01 June 1853, Wieliczka (1 fatality, case confirmed)

As Mr. Fischer, an eyewitness to the event, recalls, during a hot and sultry day at around 1530 UTC, approaching dark clouds were observed southwest of Lednica Górna in the Lesser Poland Voivodeship. Around 1600 UTC, a "*bright baggy cloud with rotating funnel*" started to descend to the land surface. It quickly passed from Rożnowa to Zabawa, leaving a damage path at a width of around 50 meters. Trees, wooden piles, and people were lifted into the air. One child was killed but the circumstances remain unknown. The tornado was accompanied by a hailstorm.

Kurjer Warszawski, 7 June 1853, EBUW

Gazeta Codzienna, 11 June 1853, POLONA

h. 29 July 1862, Żerków (3 fatalities, case fully verified)

A good description of tornado refers to Żerków in the Greater Poland Voivodeship. In details it was described in priest Łukasiewicz's book about the history of the Żerków town (Łukasiewicz 1891). A tornado in the shape of a "*large grey wedge*" appeared at around 1400

UTC over the city and destroyed 30 buildings, tearing up roofs, uprooting trees, collapsing walls, and lifting furniture. One third of the town was destroyed. As Łukasiewicz (1891) writes, a "*large cloud causing havoc was rotating in a circle of about 2000 m diameter*". Thick brick walls were demolished and large trees were moved 200 m away. Fish and water sucked up from nearby ponds fell from the sky. The tornado moved to Raszewy on the NE of Żerków where it totally destroyed brick stables and barns. Several people were lifted or crushed in the building including three fatalities: a miller in a destroyed mill, a shepherd buried by the rubble of a collapsed barn, and a male who was lifted in the air. A large number of farm animals were also killed.

Gwiazdka Cieszyńska, 16 August 1862, SBC

Gazeta Polska, 4 August 1862, POLONA

i. 31 May 1866, Jarłuty (7 fatalities, 12 missing, case fully verified)

A fatal tornado case in Humięcino and Jarłuty near Ciechanowiec in the Mazovian Voivodeship was reported in several sources. A tornado with the look of a "*rotating spindle"* appeared in the afternoon hours near Jarłuty, falling numerous trees, destroying several buildings, and lifting animals. It was preceded by a potato-sized hailstorm that left a 9-inch layer of hail. Many people, trees, and items were lifted and carried at distances of up to 200 m. As a result, seven people were killed. Seventeen people were injured while 12 went missing. This suggests that the total number of fatalities was probably higher and that this case may be one of the most deadly tornado case in a Polish history. According to the descriptions, some of the injured and deceased experienced tearing of the limbs from the body which indicates a large force of the tornado. In addition, on the exact extension of the tornado's damage path, 20 km to the northeast, another tornado with a visible funnel and a damage track extending from Świniary to Budki was reported (Figure 4). Therefore, it is plausible that both cases at a distance of 45 km were produced by the same cyclic supercell.

Nadwiślanin, 8 June 1866, KPBC

Nadwiślanin, 17 June 1866, KPBC

Kurjer Warszawski, 19 June 1866, EBUW

Zorza Pismo Niedzielne, 26 June 1866, POLONA

j. 19 June 1871, Tuchola (5 fatalities, case uncertain)

According to a short newspaper note, extensive damage due to a tornado was caused in the Tucholski district in the Kuyavian-Pomeranian Voivodeship (exact place was not specified). The tornado demolished numerous houses and farm buildings including a sheepfold where it killed ”*around 1000 sheep*”. More than 2000 trees in a forest were damaged or uprooted. In one barn, 5 people died after being crushed under the rubble. This case is uncertain due to limited and ambiguous description. .

Gazeta Warszawska, 6 July 1871, EBUW

Gazeta Warszawska, 24 June 1871, EBUW

k. 12 August 1880, Nacesławice (1 fatality, case uncertain)

This incident took place in Nacesławice near Blaszki in the Łódź Voivodeship. A tornado tore up the roofs of several buildings, uprooted large trees, knocked down some parts of the forest, killed animals, and destroyed a sheepfold. As a result, a shepherd was crushed to death while two others were injured. Tornado was accompanied by large hail.

Gazeta Warszawska, 21 August 1880, EBUW

l. 15 August 1880, Rębowo (1 fatality, case confirmed)

Around 1430 UTC, a "*thick black rotating pillar in the shape of a funnel*" was seen over Kazimierz near Konin in the Greater Poland Voivodeship. In Rębowo, it demolished 7 houses and a windmill. One child was found dead, crushed under the wooden beams. Further, the tornado uprooted numerous trees, blew away a few roofs and barns in Bienieszewo, and sucked the water from a nearby pond before spilling it on the fields. The exact day of the event may be uncertain (up to one or two days).

Gazeta Warszawska, 20 August 1880, EBUW

m. 09 August 1881, Wronczyn (2 fatalities, case uncertain)

During a severe thunderstorm in Wronczyn near Poznań in the Greater Poland Voivodeship, a "*tornado*" appeared and destroyed a newly built barn. Two people working in the field during harvest died, crushed under a collapsed pea stack. This case is uncertain since there is no explicit description of the tornado damage.

Goniec Wielkopolski, 12 August 1881, WBC

n. 13 July 1884, Gostycyń (1 fatality, case uncertain)

This case occurred around 1730 UTC in Gostycyń near Tuchola in the Kuyavian-Pomeranian Voivodeship. As a newspaper source described it, a "*crazy storm with a tornado*" destroyed several farm buildings and damaged many roofs. A small building probably the size of a shed was lifted and dropped onto the roof of the inn. As a result, one woman was killed.

Gazeta Toruńska, 18 July 1884, KPBC

o. 14 May 1886, Krosno Odrzańskie (13 fatalities, case fully verified)

The most deadly tornado occurred in Krosno Odrzańskie in the Lubusz Voivodeship at around 1230 UTC. During a severe thunderstorm that came from the southwest, a tornado described as a "*dark cylinder cloud connected to the earth's surface*" caused massive destruction in the city (Köppen 1886; Von Bezold 1888). Archival sources speak of terrifying air howling, earth shaking, and hailstones exceeding 8 cm in diameter. Over 500 buildings were damaged or destroyed including a school, post office, St. Mary's church tower, and the town hall (Figure 5). More than 10,000 windows in the city were broken while some of the large trees were uprooted and lifted into the air. Bricks, tiles, beams, shutters, trees, glass, and industrial equipment were scattered throughout the whole city. Some people were lifted and carried considerable distances. As a result, five people died while another three were crushed under the rubble. Five people were drowned in the Oder River after their boat was hit by another boat that was lifted by the tornado. Tornado left a damage path of 30 km in length and 800-1200m in width (Figure 6).

Gazeta Polska, 22 May 1866, POLONA

p. 13 August 1888, Walewice (2 fatalities, case confirmed)

A large and powerful tornado with a significant hailstorm occurred on the right side of the Bzura River east of Łęczyca (Łódź Voivoideship) at around 1500-1600 UTC. It passed near Goślub, Rogaszyn Łazin, Borów, Walewice, and then moved toward Łowicz where it vanished (Figure 7). The tornado severely damaged a few buildings, tore up roofs, and destroyed parts of nearby forests. In Walewice, a tornado with a large force demolished in a couple of minutes a few buildings and an old forest park. Two people were killed, but the cause of death is not provided.

Słowo, 17 August 1888, POLONA

r. 24 July 1890, Modła (3 fatalities, 1 missing, case fully verified)

Numerous sources describe a tornado that occurred near Konin in the Greater Poland

Voivodeship at around 1300-1400 UTC. A tornadic thunderstorm passed through Łukom, Trąbczyn, Rzgów, Modła, Stare Miasto and Brzeźno, and left a narrow damage path (~ 200 m) of around 35 km in length (Figure 8). The tornado destroyed a few windmills and barns, damaged numerous buildings, killed several animals, uprooted and demolished thousands of trees, and broke off roofs carrying them at distances of a few hundred meters. Three people were found dead under the rubble of a brick barn in Modła. In Brzeźno, a man was lifted and was never found.

Kurjer Warszawski, 3 August 1890, POLONA

Kurjer Codzienny, 23 August 1890, POLONA

Gazeta Świąteczna, 17 August 1890, POLONA

Słowo, 29 July 1890, POLONA

s. 30 July 1895, Rudka (1 fatality, case uncertain)

This incident took place near Hrubieszów in the Lublin Voivodeship. During a "*thunderstorm with a whirlwind*", dozens of buildings were destroyed. One man was killed by a falling tree. The description of the event is insufficient to uniquely identify the phenomenon as a tornado.

Kurjer Warszawski, 24 August 1895, EBUW

t. 07 July 1897, Pytowice (3 fatalities, case confirmed)

A westerly moving tornadic thunderstorm caused a significant damage northwest of Radomsko in the Łódź Voivodeship. In Chorzenice and Holendry near Pajęczno, almost all the buildings were destroyed. Damage was also reported near Janki, Dubidze, Wiewiec, Wola Wiewiecka, Wola Blakowa, Lgota, Bieliki, Brudzice, and Pytowice. Many windmills and barns were destroyed while a "*thousand people lost their homes*". Three people were killed.

One by flying roof near Dubidze. The second near Pytowice after being lifted inside a cart (with two other people were seriously injured). The third victim was found near Holendry but the cause of death remains unknown. Walnut-sized hail destroyed large areas of crops, injured a few people and killed birds. Newspaper sources are not consistent when it comes to the number of fatalities and use of "*tornado*" term. Although the damage description is indicative of a strong vortex, the damage reports extending to a distance of 30 km and in some places 10 km wide may suggest an accompanying downbursts.

Gazeta Świąteczna, 25 July 1897, BCUW

Kurjer Warszawski, 17 July 1897, BCUW

Tydzień, 25 July 1897, ŁBC

2. 20th century

a. 27 June 1905, Kamienica (3 fatalities, case confirmed)

This incident occurred in Kamienica near Kartuzy in the Pomeranian Voivodeship, probably on 27 June 1905. An eyewitnessed tornado described as a "*pillar in the air"* damaged several houses breaking off roofs and lifting household and agricultural equipment. Three people were killed and several injured but the circumstances remain unknown.

Głos Śląski, 8 July 1905, POLONA

Głos Śląski, 13 July 1905, POLONA

b. 30 July 1912, Pobikry (1 fatality, case uncertain)

A tornado was reported in Pobikry village in the Podlaskie Voivodeship. According to a newspaper source, a "*whirlwind*" destroyed everything in its path, killing 24 cows and 4 horses. Large trees were uprooted and destroyed. One man died crushed under the rubble of a building while several people were seriously injured. Although a “*tornado*” term is mentioned in the newspaper report, this case is uncertain due to limited information on inflicted damage.

Kurjer Warszawski, 3 August 1912, POLONA

b. 15 August 1922, Jędrzejów (8 fatalities, case uncertain)

During a severe thunderstorm in the area between Jędrzejów and Olkusz in the Lesser Poland Voivodeship, a tornado occurred and broke off roofs and overturned railway wagons. In one village, 8 children were lifted into the air and thrown onto a field, causing their deaths. This case is uncertain due to limited information available.

Orędownik Ostrowski, 13 September 1922, KPBC

c. 27 April 1926, Rowiska (2 fatalities, case uncertain)

During a severe thunderstorm in the Masovian Voivodeship, a strong wind damaged a few hundred of buildings. The most intense damage was reported near Skierniewice in Rowiska where according to a newspaper source, a tornado occurred and completely destroyed a whole village, leaving behind a 10 km damage path. Severe damage was also reported in neighboring Maków, Krężce and Dąbrowice. The tornado uprooted and damaged large trees. Two children were lifted and killed. Although two media sources use “*tornado”* term and describe considerable damage, this case is uncertain due to ambiguous description.

Głos Polski, 29 April 1929, ŁBC

Lech Gazeta Gnieźnieńska, 30 April 1926, WBC

d. 04 July 1928, Jaktory (2 fatalities, case uncertain)

On this day, extremely severe thunderstorms with plausible quick-moving derecho (Hinrichs 1888) swept through the country from the west, causing 62 fatalities.

Meteorological sources indicated wind gusts exceeding 40 m/s in Bytom and Gliwice, and damage to almost 1000 buildings. Around 1200 UTC, a plausible tornado occurred near Radzymin in the Masovian Voivoideship. Tornado "*completely destroyed*" Jaktory village including brick buildings. As a result, two girls on the field were lifted and found dead on treetops. Information on this case is limited.

Słowo Pomorskie, 12 July 1928, BBC

Orędownik Ostrowski, 10 July 1928, WBC

e. 20 July 1931, Lublin (6 fatalities, case fully verified)

This case is unique because it passed through a considerable part of a large city with dense infrastructure, thereby causing a lot of damage. Also, it is one of the most famous tornado in Polish history since, according to a research article by Gumiński (1936), the wind that caused damage in Lublin (the Lublin Voivodeship) produced a dynamic pressure equivalent to a wind speed of between 110 and 145 m/s. If this estimate was correct, it would indicate an F5 intensity – the strongest tornado ever recorded in Polish history. Although winds destroyed 50 cm thick brick walls, overturned railway wagons (some of them were moved a few meters away from the rail), overthrew industrial chimneys and bent iron structures, this estimate is highly uncertain since no typical F5 damage was reported. Instead, F4 damage was plausible (Figure 9). The tornado appeared at around 1700 UTC southwest of Lublin and moved northeasterly along the Bystrzyca River as a "*dark mass in the shape of a funnel with rumbling and whistling wind*". Wooden buildings, sawmill and barns in the suburbs of Lublin were razed to the ground. The slaughterhouse, sugar factory and other industrial buildings had their metal roofs blown away and found a few kilometers further downwind. A city bus was lifted and smashed. The tornado left behind a narrow damage path with a length of approximately 20 km (Figure 10). It demolished Zemborzyce village and severely damaged Wrotków, Tatary, Wólka, Trzęsinów and Hajdów. The tornado caused in total 6 fatalities and over 100 injuries including several serious. One man died after being lifted and thrown against electric wires. Three people were lifted into the air while two others were crushed by falling debris.

Ziemia Lubelska, 21 July 1931, POLONA

Ziemia Lubelska, 22 July 1931, POLONA

Ziemia Lubelska, 23 July 1931, POLONA

Ziemia Lubelska, 30 July 1933, POLONA

Kurjer Warszawski, 22 July 1931, EBUW

Kurjer Bydgoski, 22 July 1931, WBC

Kurjer Bydgoski, 23 July 1931, WBC

Kurjer Bydgoski, 31 lipca 1931, WBC

f. 29 July 1936, Łążyn (4 fatalities, case confirmed)

This incident occurred near Chełmża in the Kuyavian-Pomeranian Voivodeship at around 1200 UTC. A tornadic thunderstorm damaged and destroyed hundreds of buildings including windmills and barns. The biggest damage was reported in the Łążyn, Dębiny, and Rzeczków villages where 80% of the buildings were destroyed. Four people died crushed under the rubble of collapsed buildings. In Łążyn, a church tower was knocked down. The tornado uprooted large trees and hurled roofs. As witnesses described, a "*whirlwind*" was preceded by a giant hen's egg-sized hail.

Kurjer Bydgoski, 30 July 1936, KPBC

Warszawski Dziennik Narodowy, 29 July 1936, EBUW

g. 21 July 1940, Borzymy (1 fatality, case uncertain)

The source information for this case is an eyewitness report. A tornado came from the southwest and hit the Borzymy village in the Warmian-Masurian Voivodeship. A single farm brick building was destroyed and parts of the roofs were whirled into the air. A farmer inside a building was found dead under the rubble. The dog of a farming family was blown away and found dead in the area of Grądzkie village 3 km further. One bus was thrown off the road. The damage path was estimated at 600 m in width and 10 km long. This case occurred presumably on 21 July 1940 but the exact date is uncertain.

Personal communication with Thilo Kühne

h. 13 June 1946, Zabrzeg (1 fatality, case uncertain)

According to information from a book on the history of Zabrzeg city in the Silesia Voivodeship (Wrzoł and Tyc, 1998), a "*tornado*" knocked down a sizeable part of the forest and broke off a few roofs. As a result of this incident, one person died from an unknown cause. The information on this case is limited and uncertain.

k. 20 August 1946, Stronie Śląskie (1 fatality, case confirmed)

A large and strong tornado occurred near Stronie Śląskie in the evening. "*A dark cloud with a loud noise*" occurred near Śnieżnik mountain and then moved northeast to the Czech Republic border. The wind was so powerful that large objects and animals were moved at a considerable distance. A large number of animals were killed. The tornado demolished telegraph poles, large trees, damaged Strachocin village and destroyed 3 other villages: Janowa Góra, Sienna, and Stronie Śląskie. The tornado left a large damage path of 10 km long and 1000 m wide in a spruce forest. One person was killed while 10 went missing. The total length of the damage path was estimated to be around 20 km (Figure 11).

Rzeczpospolita, 28 August 1946, BCUMCS

Rzeczpospolita, 26 August 1946, BCUMCS

i. 15 May 1958, Rawa Mazowiecka (2 fatalities, case fully verified)

A strong thunderstorm passed through central Poland in the evening hours. A large tornado was reported at Rawa Mazowiecka in the Masovian Voivodeship. The tornado demolished 52 buildings and damaged 75 which accounted for 40% of the town (Rafałowski 1958). Almost 90% of the buildings had their roofs blown away. Severe damage on the path of the tornado was also reported in Dziurdzioły, Petrynów, Julianów, Stare Pole, Czerwionka and Kaleń villages (Figure 12). 107 buildings in these villages were severely damaged. Two people died from unknown causes and over 100 were injured including 22 seriously.

Dziennik Polski, 16 May 1958, MBC

Głos Koszaliński, 16 May 1958, ZBC

j. 16 May 1958, Nowe Miasto nad Pilicą (1 fatality, case fully verified)

The day after the event in Rawa Mazowiecka, another tornadic thunderstorm occurred in the same region and caused significant damage and one fatality (Morawska 1959). A large funnel "*connecting earth with the cloud base*" was seen in the afternoon hours in Nowe Miasto nad Pilicą and was preceded by hen's egg-sized hailstones. A tornado lifted and overthrew a large bus with children that "*rolled a few times*" (Figure 13). It also lifted animals and people, and spilled fish from the nearby Pilica River onto the surrounding fields. The whole event lasted only a few minutes and left a damage path of 13 km in length (Figure 14). Almost 80% of all buildings were damaged, half of them severely. Large trees were uprooted or twisted. 17 people were injured including 8 seriously. Severe damage was also reported in Wólka Gostomska, Potycz and Brzostowiec villages where almost 50 buildings were demolished.

Dziennik Bałtycki, 17 May 1958, BBC

Dziennik Bałtycki, 19 May 1958, BBC

k. 23 July 1958, Swaty (2 fatalities, case uncertain)

This incident occurred during a series of severe thunderstorms on 23 July 1958. A peak intensity was reached in the vicinity of Ryki in the Lublin Voivodeship where a tornado was reported. In several villages, the tornado damaged tens of buildings. Two people died from unknown causes. Although "*tornado"* term is used in a newspaper report, this case is uncertain since only a scant description is provided.

Słowo Ludu, 25 July 1958, SWBC

l. 20 May 1960, Przeworsk (3 fatalities, case uncertain)

An extremely severe thunderstorm with probable downburst clusters and tornadoes passed through the Subcarpathian and Lublin Voivodeships in the late afternoon hours. According to numerous newspaper sources, 425 buildings were destroyed, thousands of buildings were damaged (600 severely), and 77 people were injured. The most severe damage was reported in Niechobrz, Racławówka and Przybyszówka villages near Rzeszów where the tornado was visible (Salomonik 1960). In these villages, almost 50% of the buildings were destroyed and the debris was scattered a few hundred meters away. In Niechobrz, metal pylons were ripped from concrete foundations. Severe damage was also reported in Przeworsk district where a strong wind derailed a train near Urzejowice village. As a result, 1 person died and 13 were injured including 8 severely. In Gorliczyna, one person died after being crushed by a tree. Another fatality was reported in Białoboki village due to unknown causes. Given the large number of damage reports in this area and the lack of typical tornado damage, it was not possible to determine tornado tracks even though funnels were reported. Given 35 m/s wind gust measured at the Rzeszów meteorological station and the widespread damage reports, it may be plausible that the damage and fatalities were due to a downburst cluster (Fujita and Wakimoto, 1981) or a derecho with embedded tornadoes.

Dziennik Polski, 20 May 1960, MBC

Dziennik Polski, 21 May 1960, MBC

Nowiny Rzeszowskie, 21 May 1960, PBC

Nowiny Rzeszowskie, 22 May 1960, PBC

Nowiny Rzeszowskie, 23 May 1960, PBC

Nowiny Rzeszowskie, 24 May 1960, PBC

m. 20 May 1960, Żulice (1 fatality, case uncertain)

This incident occurred probably within the same thunderstorm complex that passed through Rzeszów and Przeworsk districts. The most severe damage was reported southeast of Tomaszów Lubelski in the Lublin Voivodeship. Winds with a great force scattered to distant places roofs, chimneys, boards, and household equipment. Dozens of animals were killed in ruined barns. In Żulice village, two children were seriously injured and one died crushed under the rubble of the building. The whole village was destroyed while some of the debris was found 200 m away. Over 300 buildings in Ulhówek were demolished. Severe damage was also reported in Chodywańce and Chorążanka. Even though "*tornado*" term was used, it was not possible to determine the tornado damage track.

Nowiny Rzeszowskie, 21 May 1960, PBC

Nowiny Rzeszowskie, 22 May 1960, PBC

n. 08 July 1996, Suchodębie (1 fatality, case uncertain)

This event took place in Suchodębie village near Kutno in the Lódź Voivodeship at around 1700 UTC. After a series of thunderstorms throughout the day, a tornado described by a newspaper source as "*a swirling funnel"* came from the south and either destroyed or damaged 30 buildings, farm equipment, and cars. One man was killed as a result of being crushed by a broken-off roof.

Rzeczpospolita, 10 July 1996, [available online: rp.pl]

3. 21st century

a. 15 August 2008, Rusinowice (2 fatalities, case fully verified)

A series of significant tornadoes passed in the afternoon hours through the Opole, Silesian and Łódź Voivodeships, leaving behind a total damage track of 110 km in length and a maximum width of 1500 m. Severe damage was caused to 1624 buildings, forests, and infrastructure (Chmielewski et al. 2013). Two people died while 60 were injured. The tornadoes lifted cars, demolished brick walls, arched power poles, blew out buildings, and brought down trees (Figure 15). An analysis of the satellite, radar, aerial photography, damage survey, and global forest change project data (Hansen et al. 2013) made it possible to establish three tornado tracks (Popławska 2014; Figure 16). The deadly tornado occurred at around 1530 UTC in Rusinowice where one person died after being crushed inside a building. Another person was killed in Kalina by a falling tree. Before vanishing south of Łęg in the Silesian Voivodeship, the tornado left behind a damage path of 60 km with a highest intensity of F3.

b. 14 July 2012, Wycinki (1 fatality, case fully verified)

An isolated cyclic supercell occurred on 14 July 2012 on the border of the Kuyavian-Pomeranian and Pomeranian Voivodeships (Taszarek et al. 2016). An analysis of satellite, radar, aerial photography, damage survey, and global forest change project data allowed us to establish four tornado damage tracks (Figure 17). Tornadoes damaged 105 buildings, caused 1 fatality, 10 injuries, and felled 500 hectares of Bory Tucholskie forest leaving an impressive path with a maximum width of 700 m. The deadly tornado occurred at around 1500 UTC near Zdroje village, and up to Smętowo Graniczne left a 42 km damage path with the maximum intensity up to F3. It passed through Kałębie Lake (Figure 18) and then moved to Wycinki village where it lifted a summer house killing one man.

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List of tables

Table 1. Digital libraries used in the analysis.

Shortcut	Original name	English name	Web address
BBC	Bałtycka Biblioteka Cyfrowa	Baltic Digital Library	http://bibliotekacyfrowa.eu/dlibra
BCUMCS	Biblioteka Cyfrowa Uniwersytetu im. Marii Curie-Skłodowskiej	Marie Curie-Skłodowska University E-Library	http://dlibra.umcs.lublin.pl/dlibra
EBUW	E-Biblioteka Uniwersytetu Warszawskiego	University of Warsaw E-Library	http://ebuw.uw.edu.pl/dlibra
KPBC	Kujawsko-Pomorska Biblioteka Cyfrowa	Kuyavian-Pomeranian Digital Library	http://kpbc.umk.pl/dlibra
ŁBC	Łódzka Biblioteka Cyfrowa	Łódź Digital Library	http://bc.wimbp.lodz.pl/dlibra
MBC	Małopolska Biblioteka Cyfrowa	Lesser Poland Digital Library	http://mbc.malopolska.pl/dlibra
PBC	Podkarpacka Biblioteka Cyfrowa	Subcarpathian Digital Library	http://www.pbc.rzeszow.pl/dlibra
POLONA	Portal Biblioteki Narodowej	Portal of the National Library	http://polona.pl/search/
SBC	Śląska Biblioteka Cyfrowa	Silesian Digital Library	http://www.sbc.org.pl/dlibra
SWBC	Świętokrzyska Biblioteka Cyfrowa	Świętokrzyskie Digital Library	http://sbc.wbp.kielce.pl/dlibra
WBC	Wielkopolska Biblioteka Cyfrowa	Greater Poland Digital Library	http://www.wbc.poznan.pl/dlibra
ZBC	Zachodniopomorska Biblioteka Cyfrowa	West Pomeranian Digital Library	http://zbc.ksiaznica.szczecin.pl/dlibra

Table 2. Deadly tornadoes in Poland between1820 and 2015.

No	Date	Nearest city	Rating	Time (UTC)	Path length	Path width	Motion	Deaths	Credibility	Cause of death
1.	1829-06-30	Turzyn	F1/F2	1700	10 km	800 m	no data	4	case confirmed	*4 drowned in an overturned boat*
2.	1830-05-15	Szamotuły	F2/F3	evening	20 km	no data	SE-NW	1	case confirmed	*1 crushed in a building*
3.	1833-06-27	Węgrzynów	F2/F3	daytime	16 km	no data	SW-NE	2	case uncertain	*2 crushed in a building*
4.	1851-05-12	Charsznica	F2/F3	daytime	no data	no data	SW-NE	1	case confirmed	*unknown causes*
5.	1851-07-18	Bobrowniki	F2/F3	1430	15 km	no data	SW-NE	3	case uncertain	*unknown causes*
6.	1851-07-18	Szopienice	F2/F3	daytime	no data	no data	no data	10	case uncertain	*10 crushed in a building*
7.	1853-06-01	Wieliczka	F1/F2	1600	5 km	50 m	SW-NE	1	case confirmed	*unknown causes*
8.	1862-07-29	Żerków	F3/F4	1400	8 km	2000 m	SW-NE	3	case fully verified	*2 crushed in a building,* *1 lifted*
9.	1866-05-31	Jarłuty	F3/F4	1400	7 km	no data	SW-NE	7 (19?)	case fully verified	*7 lifted,* *12 people missing*
10.	1871-06-19	Tuchola	F2/F3	no data	no data	no data	SW-NE	5	case uncertain	*5 crushed in a building*
11.	1880-08-12	Nacesławice	F2/F3	daytime	no data	no data	SE-NW	1	case uncertain	*1 crushed in a building*
12.	1880-08-15	Rębowo	F1/F2	1430	7 km	no data	NE-SW	1	case confirmed	*1 crushed in a building*
13.	1881-08-09	Wronczyn	F1/F2	daytime	no data	no data	W-E	2	case uncertain	*2 crushed by falling debris*
14.	1884-07-13	Gostycyń	F1/F2	1730	no data	no data	W-E	1	case uncertain	*1 crushed by a falling debris*
15.	1886-05-14	Krosno Odrzańskie	F3/F4	1230	30 km	1200 m	SW-NE	13	case fully verified	*5 lifted,* *3 crushed in a building,* *5 drowned in an overturned boat*
16.	1888-08-13	Walewice	F2/F3	1530	25 km	no data	W-E	2	case confirmed	*unknown causes*
17.	1890-07-24	Modła	F2/F3	1300	35 km	200 m	W-E	3 (4?)	case fully verified	*3 crushed in a building,* *1 person missing*
18.	1895-07-30	Rudka	F2/F3	daytime	no data	no data	W-E	1	case uncertain	*1 crushed by a falling tree*
19.	1897-07-07	Pytowice	F2/F3	daytime	30 km	no data	W-E	3	case confirmed	*1 crushed by a falling debris,* *1 lifted in a droshky,* *1 unknown causes*
20.	1905-06-27	Kamienica	F2/F3	daytime	3 km	no data	N-S	3	case confirmed	*unknown causes*
21.	1912-07-30	Pobikry	F2/F3	no data	no data	no data	SW-NE	1	case uncertain	*1 crushed in a building*
22.	1922-08-15	Jędrzejów	F2/F3	no data	no data	no data	W-E	8	case uncertain	*8 lifted*
23.	1926-04-27	Rowiska	F2/F3	daytime	10 km	no data	S-N	2	case uncertain	*2 lifted*
24.	1928-07-04	Jaktory	F3/F4	1200	no data	no data	SW-NE	2	case uncertain	*2 lifted*
25.	1931-07-20	Lublin	F4/F5	1700	20 km	300 m	SW-NE	6	case fully verified	*3 lifted,* *2 crushed by a falling debris,* *1 lifted in a droshky*
26.	1936-07-29	Łążyn	F2/F3	1200	15 km	no data	SW-NE	4	case confirmed	*4 crushed in a building*
27.	1940-07-21	Borzymy	F2/F3	daytime	10 km	600 m	SW-NE	1	case uncertain	*1 crushed in a building*
28.	1946-06-13	Zabrzeg	F1/F2	daytime	no data	no data	S-N	1	case uncertain	*unknown causes*
29.	1946-08-20	Stronie Śląskie	F3/F4	evening	20 km	1000 m	SW-NE	1	case confirmed	*unknown causes*
30.	1958-05-15	Rawa Mazowiecka	F3/F4	1600	20 km	800 m	SW-NE	2	case fully verified	*unknown causes*
31.	1958-05-16	Nowe Miasto nad Pilicą	F3/F4	1530	13 km	200 m	SW-NE	1	case fully verified	*unknown causes*
32.	1958-07-23	Swaty	F1/F2	no data	no data	no data	S-N	2	case uncertain	*unknown causes*
33.	1960-05-20	Przeworsk	F2/F3	1200	no data	no data	SW-NE	3	case uncertain	*1 crushed in a derailed train,* *1 crushed by a falling tree,* *1 unknown causes*
34.	1960-05-20	Żulice	F2/F3	1300	no data	no data	W-E	1	case uncertain	*1 crushed in a building*
35.	1996-07-08	Suchodębie	F1/F2	1700	no data	no data	S-N	1	case uncertain	*1 crushed in a building*
36.	2008-08-15	Rusinowice	F3	1530	60 km	1000 m	SW-NE	2	case fully verified	*1 crushed in a building,* *1 crushed by a falling tree*
37.	2012-07-14	Wycinki	F3	1500	42 km	700 m	SW-NE	1	case fully verified	*1 crushed in a building*

Table 3. Fatalities due to tornadoes in Poland in the time frame 1820-2015.

Location	Reason	No. of fatalities	Total
being outdoors	hit by a falling debris	6 (7%)	37 (43%)
	crushed by a falling tree	3 (4%)	
	lifted	28 (32%)	
being in the building	crushed in a building	38 (44%)	38 (44%)
being in means of transportation	drowned due to overturned boat	9 (10%)	12 (13%)
	lifted in a droshky	2 (2%)	
	derailed train	1 (1%)	
	unknown causes	19	19

Table 4. Deadly tornadoes in chosen European countries in the time frame 1820-2015 (source: ESWD).

Country	No. of deadly tornadoes	No. of fatalities	Most deadly tornado		
			Date	Place	No. of fatalities
Italy	26	275	09.21.1897	Oria	55
Germany	53	119	09.09.1913	Helgoland	14
France	23	130	08.19.1845	Montville	70
Russia	18	106	06.09.1984	Ivanovo	69
Poland	37	106	05.14.1886	Krosno Odrzańskie	13
Spain	2	48	05.12.1886	Madrid	47
Turkey	9	39	07.28.1930	Edirne	20
Austria	5	39	07.10.1916	Wiener-Neustadt	35
Netherlands	7	37	06.10.1981	Moerdijk	16
Romania	5	24	05.13.1912	Breţcu	17
Greece	5	8	10.18.1934	Astakós	3

List of figure captions

Figure 1. A decadal number of tornado fatalities (bars) and killer tornadoes (linear plot) that occurred in Poland.

Figure 2. Annual distribution of killer tornadoes that occurred in Poland in years 1820-2015.

Figure 3. (a) Spatial distribution of deadly tornado cases in the time frame 1820-2015. The size of icon is matched to the number of fatalities (from 1 to 13). (b) Average number of killer tornado cases in provinces per 100 years normalized to 10 000 km^2. (c) Population density in sub-provinces (average number of people per km^2) in 2013. (d) Hypsometric map of Poland based on SRTM3 data (Farr et al. 2007).

Figure 4. Tornado damage tracks (solid black lines) with 500 m buffer zones (white polygons) on 31 May 1866.

Figure 5. Damage in Krosno Odrzańskie due to tornado on 14 May 1886. Source: Gazeta Polska newspaper, 22 May 1886.

Figure 6. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 14 May 1886.

Figure 7. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 13 August 1888.

Figure 8. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 24 July 1890.

Figure 9. F4 damage due to tornado on 20 July 1931. (a) Slaughterhouse in Lublin, and (b) brick cowshed in Tatary. Source: Gumiński (1936).

Figure 10. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 20 July 1931.

Figure 11. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 20 August 1946.

Figure 12. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 15 May 1958.

Figure 13. Tornado damage in Nowe Miasto nad Pilicą due to tornado on 16 May 1958 (photography: Marek Wisławski).

Figure 14. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 16 May 1958.

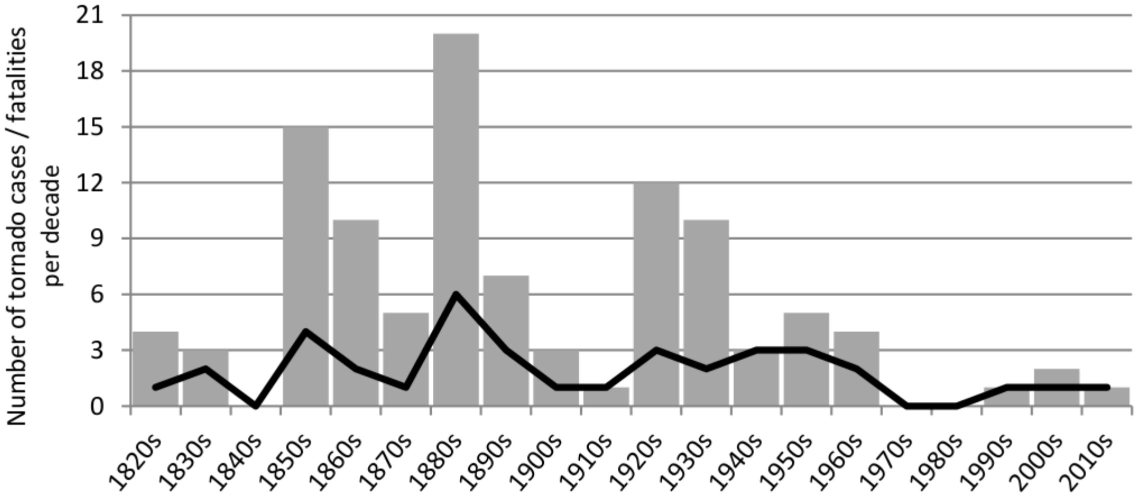
Figure 15. (a) Tornado damage near Balcerzowice (photography: Adam Hawałej), and (b) Sieroniowice (photography: Radosław Dimitrow) on 15 August 2008.

Figure 16. Tornado damage tracks (solid black lines) with 500 m buffer zones (white polygons) on 15 August 2008.

Figure 17. Tornado damage tracks (solid black lines) with 500 m buffer zones (white polygons) on 14 July 2012.

Figure 18. Tornado passing through Kałębie Lake near Wycinki on 14 July 2012 (photography: Benedykt Nawrotek).

969 ## List of figures



970

971 **Figure 1.** A decadal number of tornado fatalities (bars) and killer tornadoes (linear plot) that occurred in Poland.

972

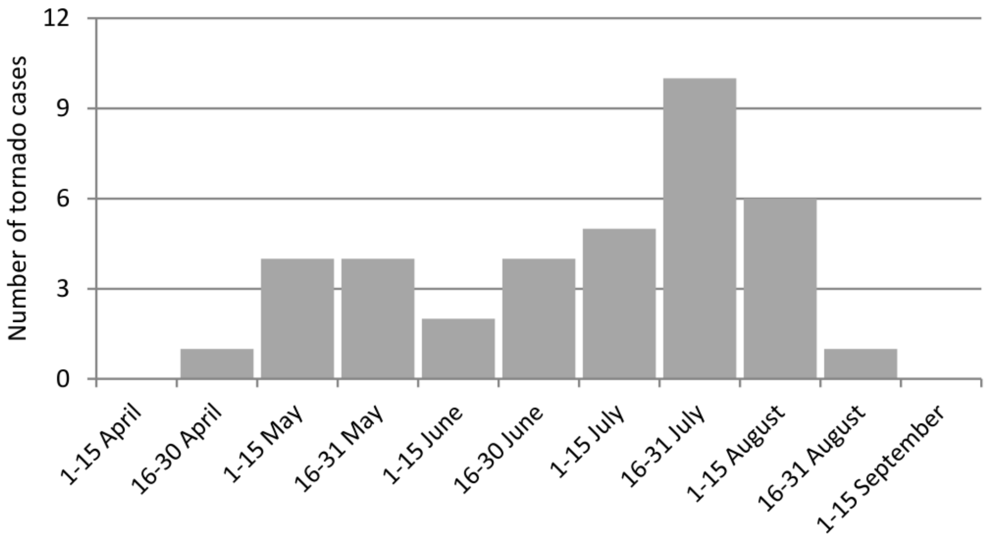


Figure 2. Annual distribution of killer tornadoes that occurred in Poland in years 1820-2015.

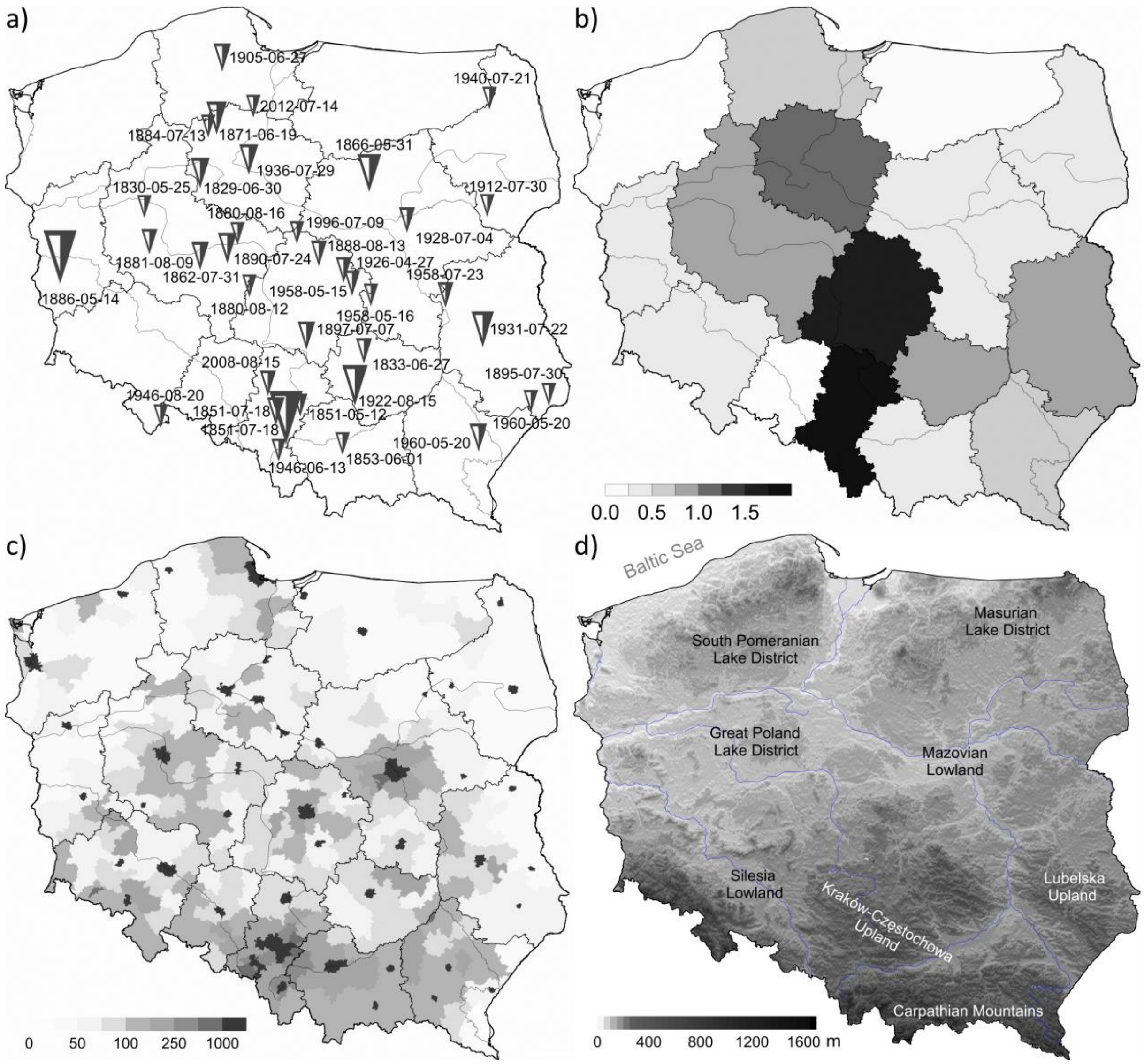


Figure 3. (a) Spatial distribution of deadly tornado cases in the time frame 1820-2015. The size of icon is matched to the number of fatalities (from 1 to 13). (b) Average number of killer tornado cases in provinces per 100 years normalized to 10 000 km^2. (c) Population density in sub-provinces (average number of people per km^2) in 2013. (d) Hypsometric map of Poland based on SRTM3 data (Farr et al. 2007).

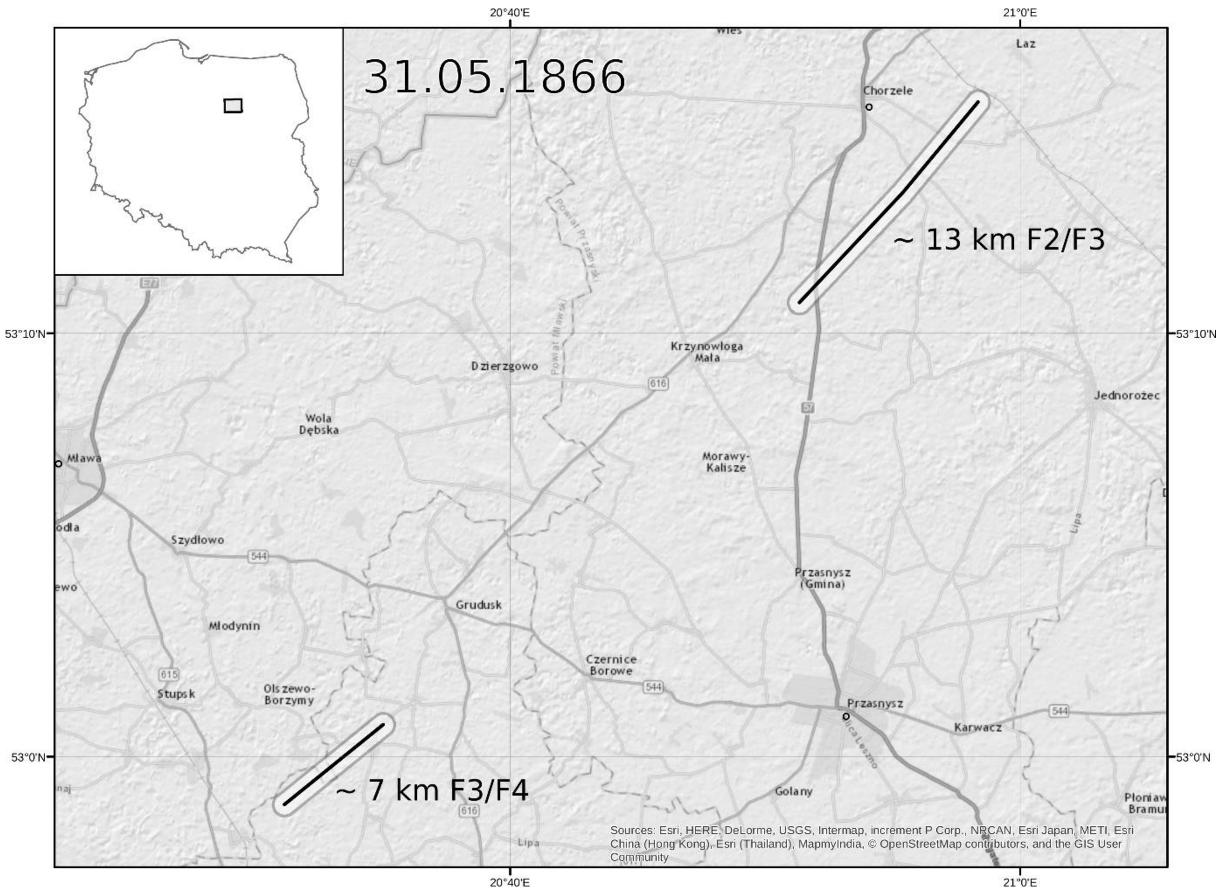


Figure 4. Tornado damage tracks (solid black lines) with 500 m buffer zones (white polygons) on 31 May 1866.

Figure 5. Damage in Krosno Odrzańskie due to tornado on 14 May 1886. Source: *Gazeta Polska* newspaper, 22 May 1886.

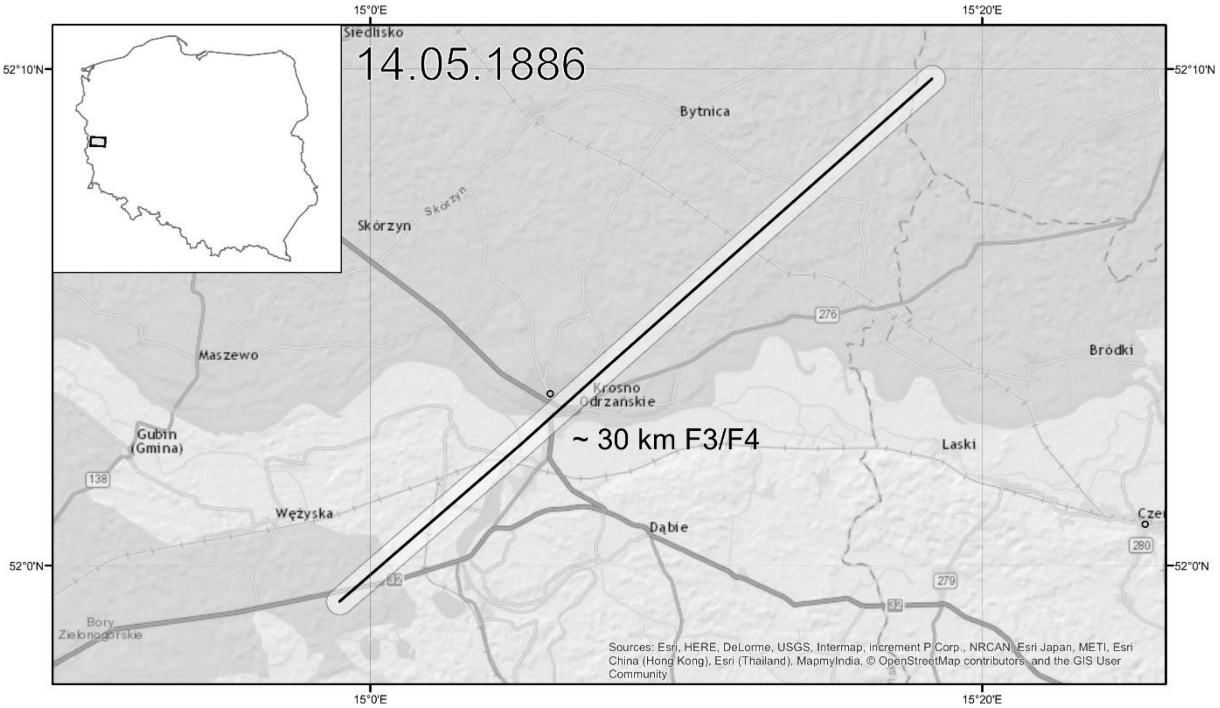


Figure 6. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 14 May 1886.

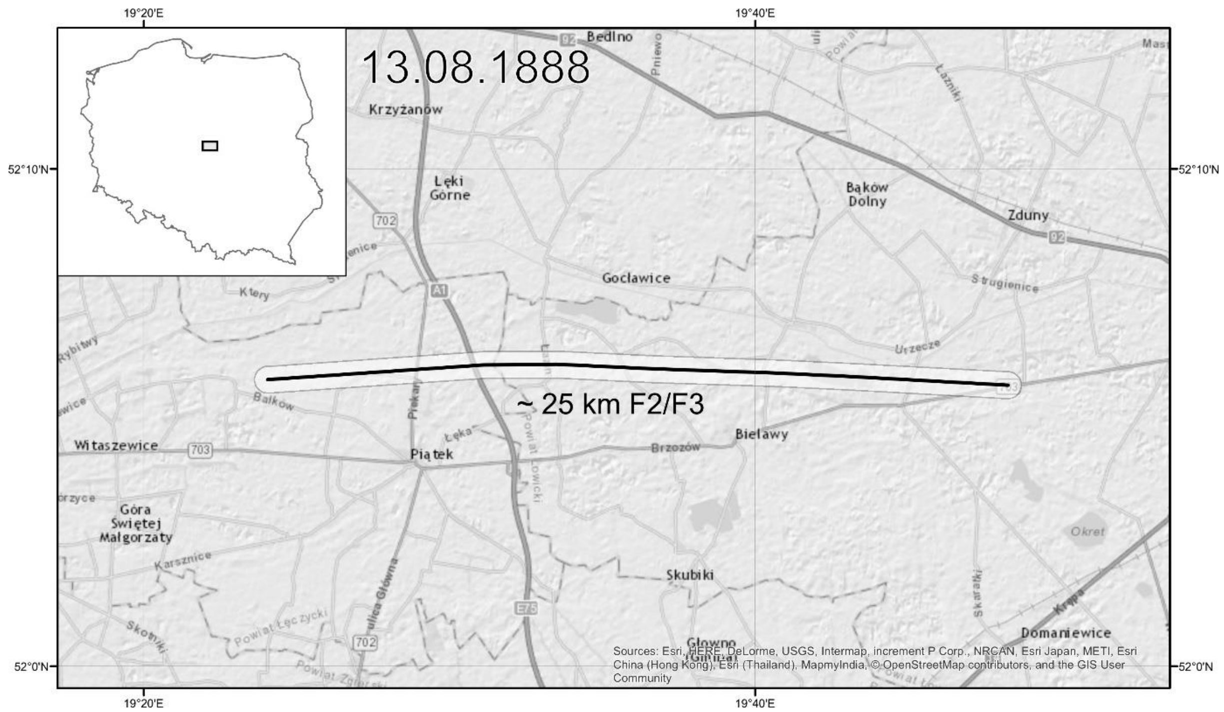


Figure 7. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 13 August 1888.

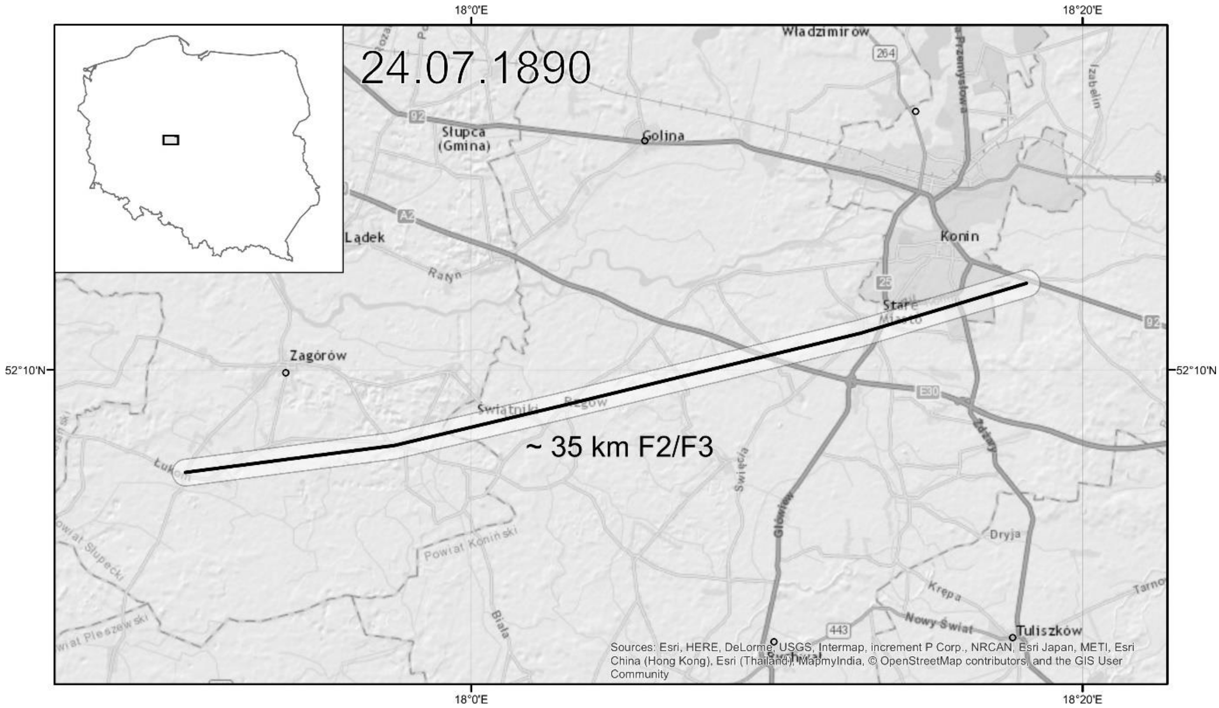


Figure 8. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 24 July 1890.

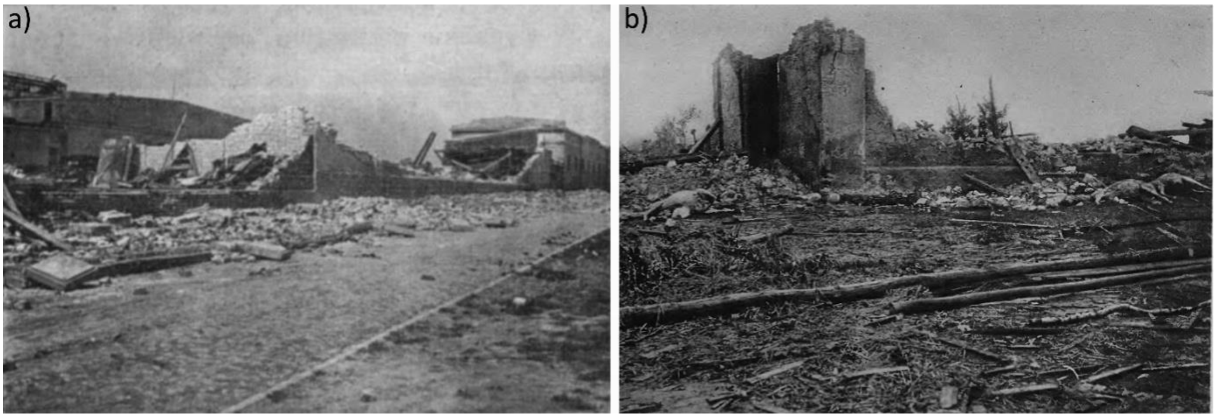


Figure 9. F4 damage due to tornado on 20 July 1931. (a) Slaughterhouse in Lublin, and (b) brick cowshed in Tatary. Source: Gumiński (1936).

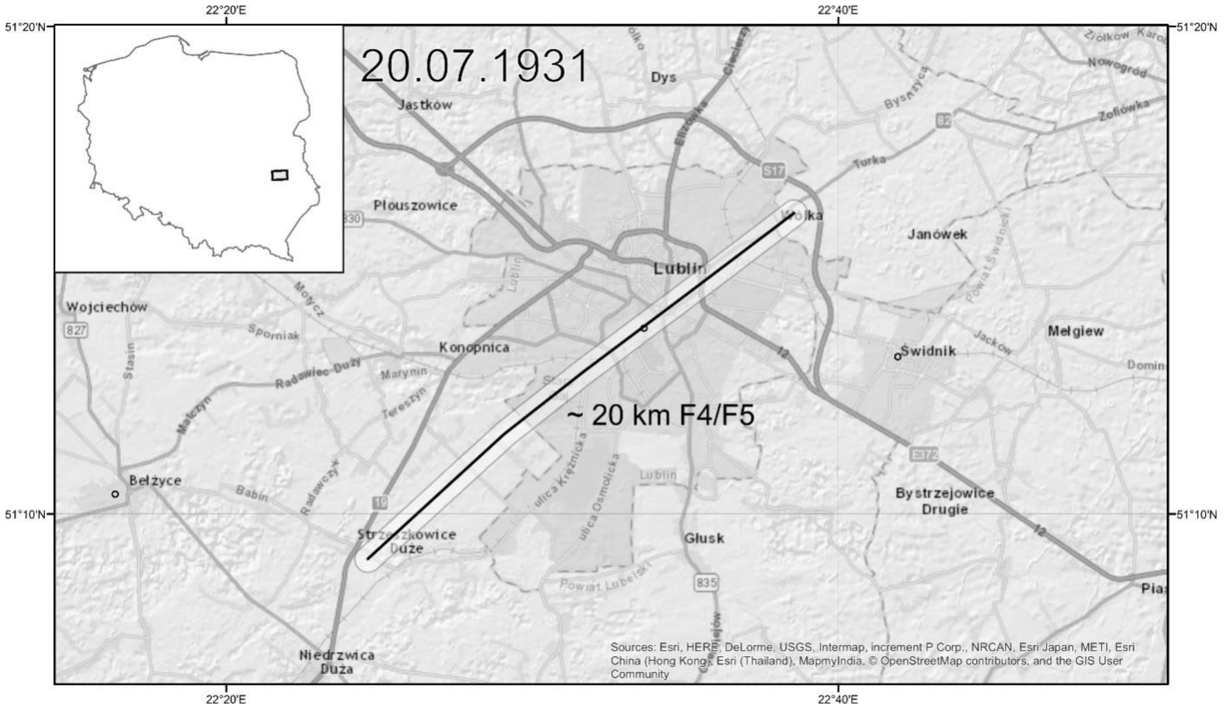


Figure 10. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 20 July 1931.

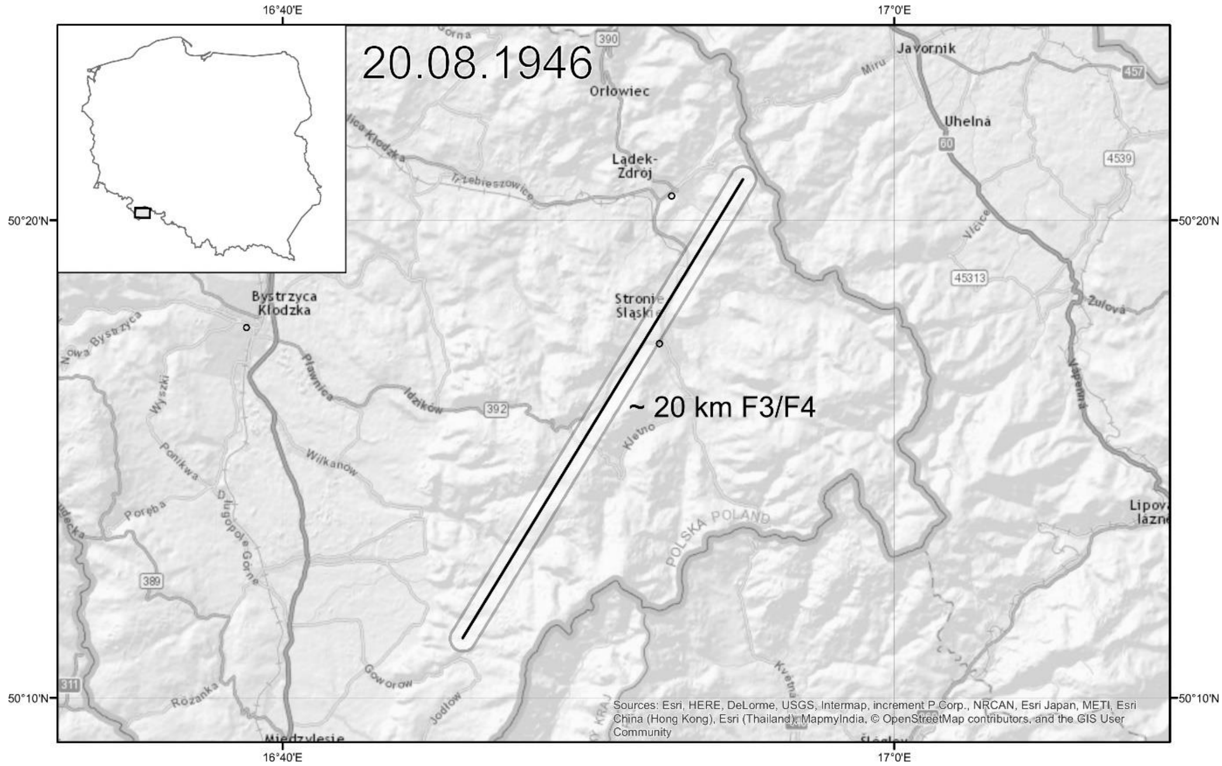


Figure 11. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 20 August 1946.

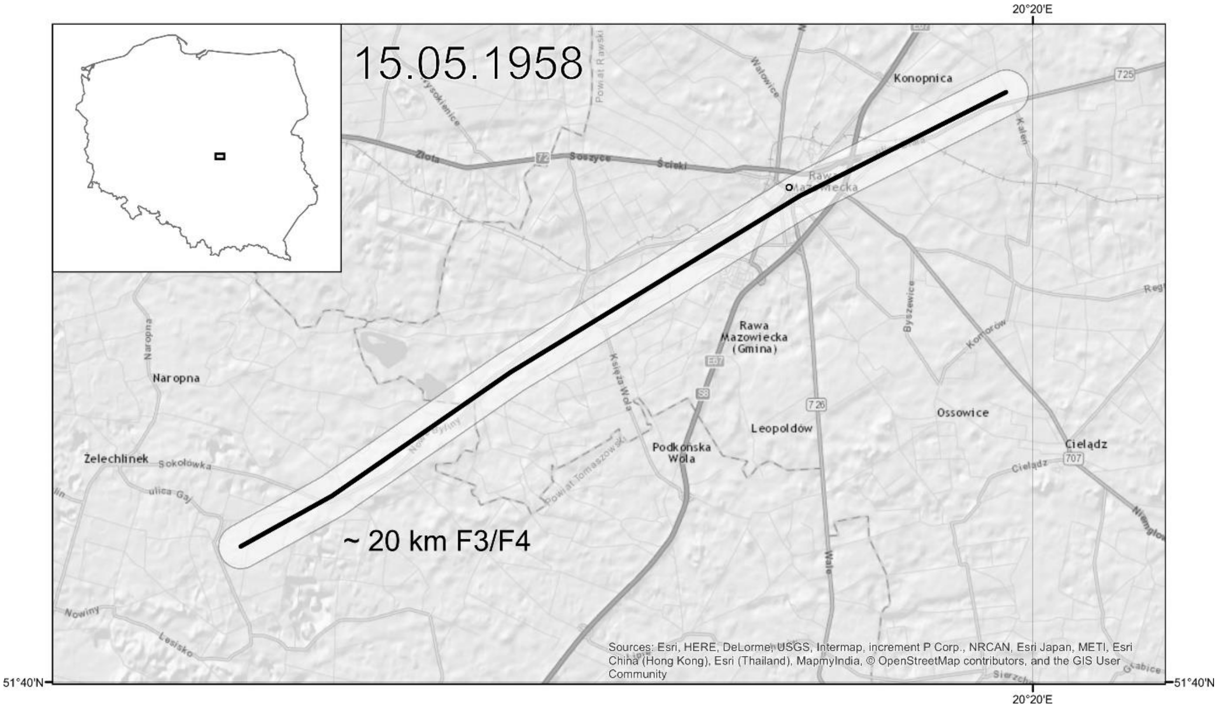


Figure 12. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 15 May 1958.

Figure 13. Tornado damage in Nowe Miasto nad Pilicą due to tornado on 16 May 1958 (photography: Marek Wisławski).

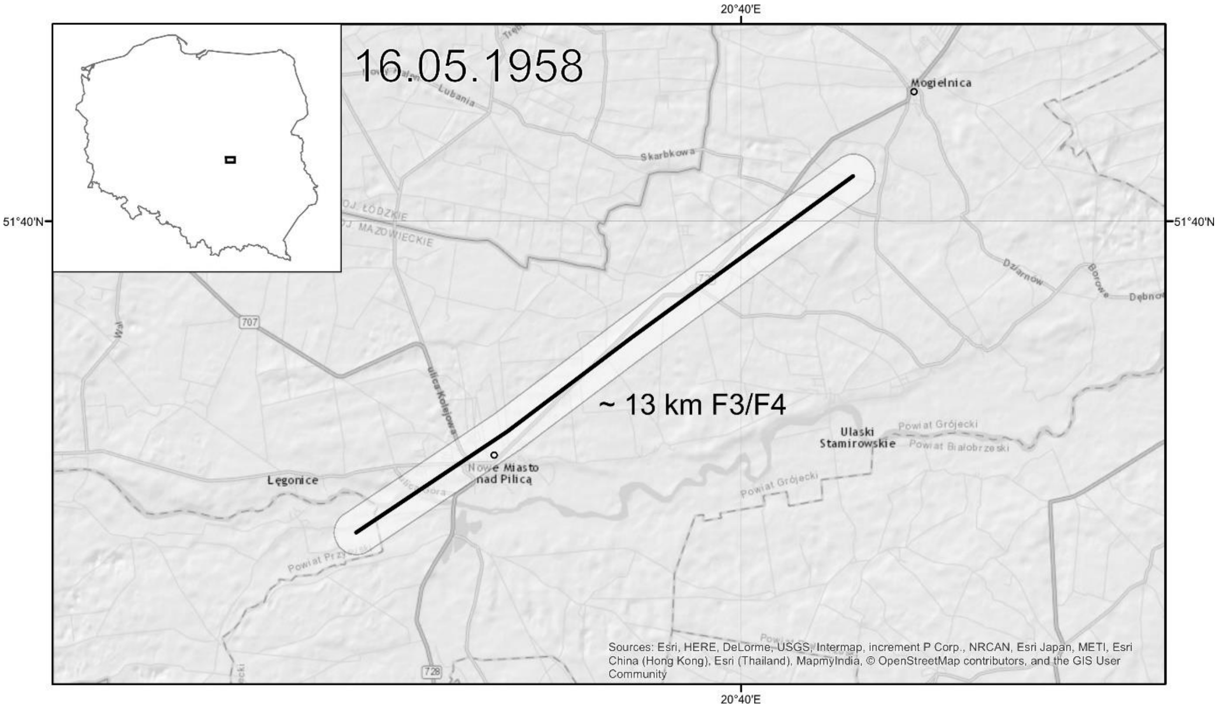


Figure 14. Tornado damage track (solid black line) with 500 m buffer zone (white polygon) on 16 May 1958.

Figure 15. (a) Tornado damage near Balcerzowice (photography: Adam Hawałej), and (b) Sieroniowice (photography: Radosław Dimitrow) on 15 August 2008.

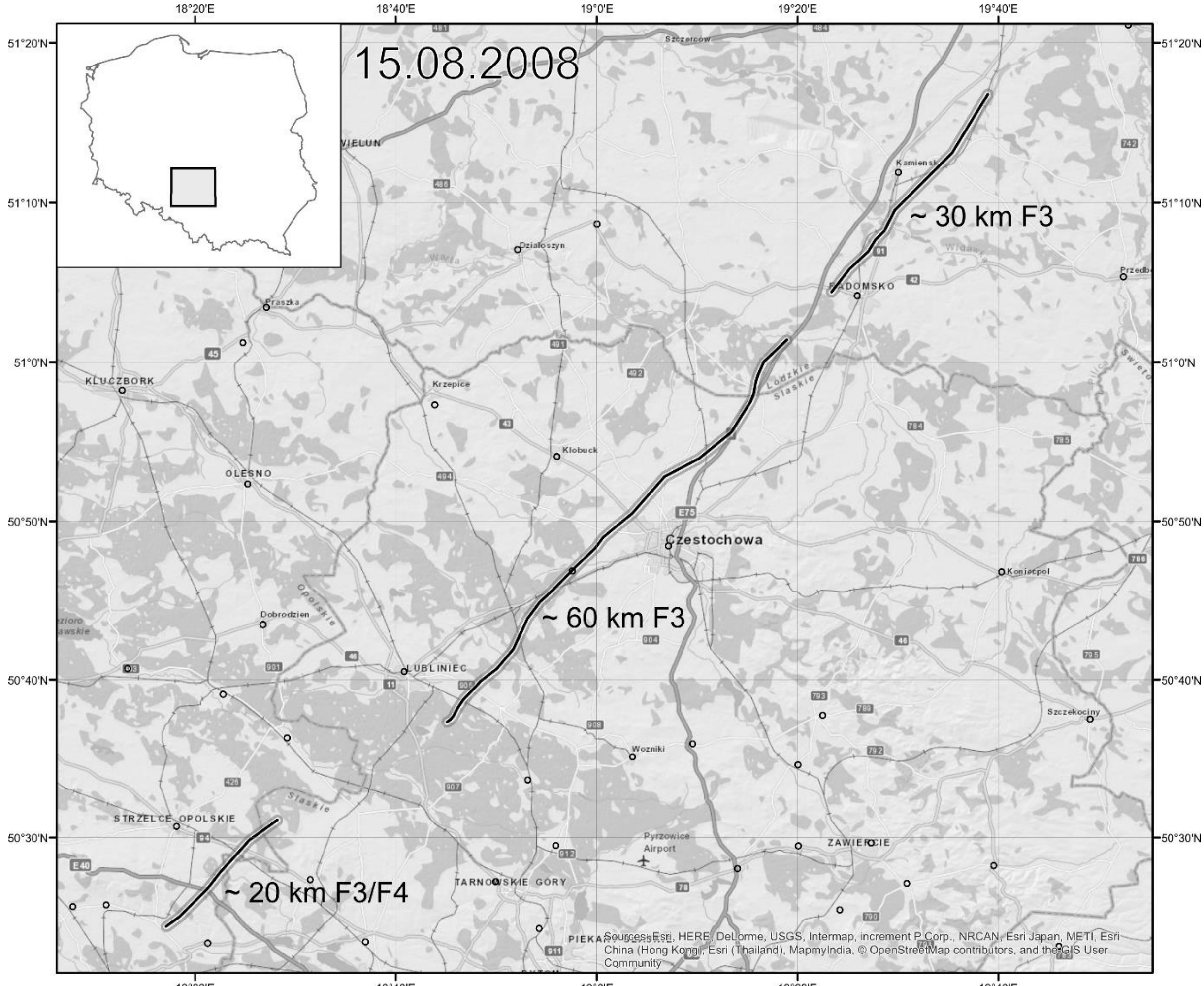


Figure 16. Tornado damage tracks (solid black lines) with 500 m buffer zones (white polygons) on 15 August 2008.

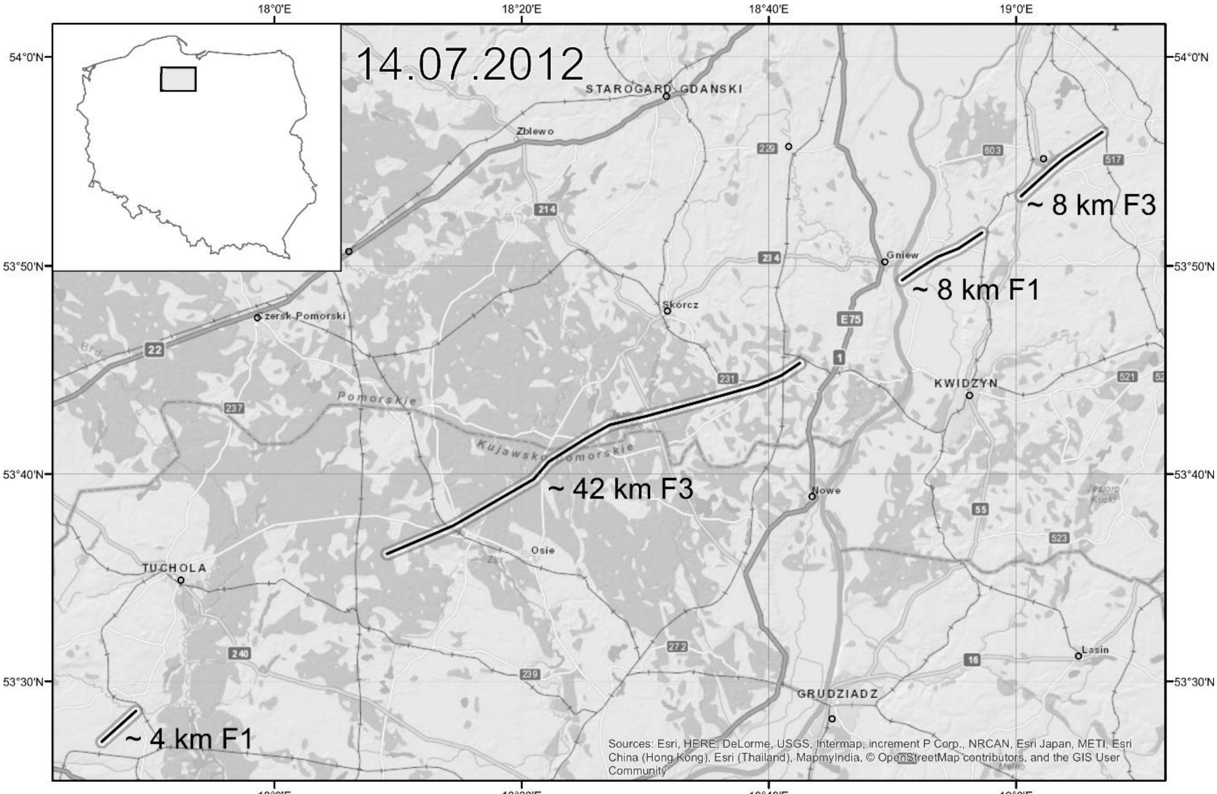


Figure 17. Tornado damage tracks (solid black lines) with 500 m buffer zones (white polygons) on 14 July 2012.

1028 **Figure 18.** Tornado passing through Kałębie Lake near Wycinki on 14 July 2012 (photography: Benedykt
1029 Nawrotek).