Sounding-Derived Parameters Associated with Convective Hazards in Europe

MATEUSZ TASZAREK

Department of Climatology, Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University, Poznań, and Skywarn Poland, Warsaw, Poland

HAROLD E. BROOKS

NOAA/National Severe Storms Laboratory, Norman, Oklahoma

BARTOSZ CZERNECKI

Department of Climatology, Institute of Physical Geography and Environmental Planning, Adam Mickiewicz University, Poznań, Poland

(Manuscript received 3 October 2016, in final form 15 December 2016)

ABSTRACT

Observed proximity soundings from Europe are used to highlight how well environmental parameters discriminate different kind of severe thunderstorm hazards. In addition, the skill of parameters in predicting lightning and waterspouts is also tested. The research area concentrates on central and western European countries and the years 2009–15. In total, 45 677 soundings are analyzed including 169 associated with extremely severe thunderstorms, 1754 with severe thunderstorms, 8361 with nonsevere thunderstorms, and 35 393 cases with nonzero convective available potential energy (CAPE) that had no thunderstorms. Results indicate that the occurrence of lightning is mainly a function of CAPE and is more likely when the temperature of the equilibrium level drops below −10°C. The probability for large hail is maximized with high values of boundary layer moisture, steep mid- and low-level lapse rates, and high lifting condensation level. The size of hail is mainly dependent on the deep layer shear (DLS) in a moderate to high CAPE environment. The likelihood of tornadoes increases along with increasing CAPE, DLS, and 0–1-km storm-relative helicity. Severe wind events are the most common in high vertical wind shear and steep low-level lapse rates. The probability for waterspouts is maximized in weak vertical wind shear and steep low-level lapse rates. Wind shear in the 0–3-km layer is the best at distinguishing between severe and extremely severe thunderstorms producing tornadoes and convective wind gusts. A parameter WMAXSHEAR multiplying square root of 2 times CAPE (WMAX) and DLS turned out to be the best in distinguishing between nonsevere and severe thunderstorms, and for assessing the severity of convective phenomena.

1. Introduction

Each year in Europe, severe thunderstorms pose a direct threat to human life and create an impact on critical infrastructure and personal property. From 2010, according to the European Severe Weather Database (ESWD; Dotzek et al. 2009), around 9000 severe weather incidents associated with severe thunderstorms are reported each year in Europe (Groenemeijer and Kühne 2014). These result in an annual average of 100 fatalities and 500 injures due to tornadoes, large hail, severe wind gusts, and lightning. Bearing in mind the prevalence of the thunderstorms across Europe (Anderson and Klugmann 2014) and the threat they pose (Brooks 2013), it is vital to effectively predict them and warn people in advance.

To predict deep moist convection (DMC) and severe thunderstorms, weather forecasters commonly use a set of a thermodynamic and kinematic parameters derived from numerical weather prediction (NWP) models. Numerous studies have assessed the value of such parameters in predicting thunderstorms and individual severe convective weather phenomena such as tornadoes, large hail, and severe wind gusts. Johns and Doswell (1992) defined three main ingredients that are necessary for DMC: 1) boundary layer moisture, 2) conditional instability, and 3) a lifting mechanism that

---

Corresponding author e-mail: Mateusz Taszarek, mateusz.taszarek@amu.edu.pl

DOI: 10.1175/MWR-D-16-0384.1

initiates convection. The studies of Weisman and Klemp (1982), Doswell and Evans (2003), and Thompson et al. (2003, 2012, 2013) indicated an additional fourth ingredient, vertical wind shear, that is responsible for organizing convection to make it more capable of producing severe weather phenomena. Except for the lift, three of these ingredients can be examined in atmospheric soundings.

Pioneering studies on sounding-derived parameters associated with severe convective storms originated in the United States in the 1950s and 1960s (Fawbush and Miller 1952, 1954; Beebe 1955, 1958; Darkow 1969). In later years, of relevance to us, Rasmussen and Wilhelmson (1983) found that thunderstorms with tornadoes appear to form in high shear, high convective available potential energy (CAPE) environments, while thunderstorms without tornadoes form in low CAPE, low shear environments. Using soundings from a global reanalysis dataset, Brooks et al. (2003) found that high CAPE, high shear environments were associated with thunderstorms producing severe weather. Increased severe thunderstorm probability in high CAPE, high deep layer shear (DLS) environments was also found in the studies of Rasmussen and Blanchard (1998), Craven and Brooks (2004), Groenemeijer and van Delden (2007), Brooks (2009, 2013), Taszarek and Kolendowicz (2013), and Púčik et al. (2015).

The analysis of environmental parameters for particular weather phenomena revealed that in addition to CAPE and DLS, each severe thunderstorm phenomenon has specific accompanying conditions that make them more likely to occur. A low lifting condensation level (LCL) together with an increased low-level wind shear (LLS) and storm-relative helicity (SRH), was found to be favorable for tornadic supercells and for estimating tornado intensity (Rasmussen and Blanchard 1998; Thompson et al. 2003; Craven and Brooks 2004; Groenemeijer and van Delden 2007; Kaltenböck et al. 2009; Grünwald and Brooks 2011; Taszarek and Kolendowicz 2013; Púčik et al. 2015). Grünwald and Brooks (2011) found also that tornadoes in Europe usually form in a lower LCL and CAPE environments than those occurring in the United States, probably due to LCL and CAPE being on average lower in Europe from the climatological point of view.

Tornadoes occurring over water surface (waterspouts), which usually form without a deep mesocyclonic circulation, were found to be mostly associated with weak low-level wind shear, steep low-level lapse rates, preexisting low-level vertical vorticity, and thermodynamic instability strong enough to sustain updrafts and convection (Markowski and Richardson 2009; Szilagyi 2009; Keul et al. 2009; Renko et al. 2016). However, as Renko et al. (2016) suggested, waterspouts can occur in a wide variety of meteorological conditions making their forecasting very difficult.

To produce large hailstones (+2 cm), an updraft in the convective cloud must be strong enough to sustain a mass of the hailstones in their most efficient hail-formation layer (above 0°C isotherm height). According to recent studies on large hail occurrence, such conditions are most often found in a significant CAPE, moderate shear, or moderate CAPE, high shear environments (Edwards and Thompson 1998; Craven and Brooks 2004; Groenemeijer and van Delden 2007; Kaltenböck et al. 2009; Smith et al. 2012; Berthet et al. 2013; Púčik et al. 2015). The updrafts in supercell thunderstorms can be enhanced because of the interaction with the updraft and the environmental wind shear (Brooks and Wilhelmson 1993). Thus, these are the most prone for producing large and very large (+5 cm) hailstones. Groenemeijer and van Delden (2007) and Púčik et al. (2015) also showed that a high LCL may be contributing to the occurrence of the large hail.

Although parameters for large hail and tornadoes are associated with relatively consistent environments, this is not true for severe convective wind gusts, which can occur in a wide variety of environments. These can be associated with high shear, high CAPE supercells and long-lived squall lines producing widespread damaging wind gusts (Coniglio et al. 2004; Celiński-Mysław and Matuszko 2014), but also with weak shear local downbursts and microbursts (Fujita 1990). Numerous severe wind gusts may also appear within a high shear, low CAPE windstorms with strong horizontal pressure gradients and synoptic-scale forcing where wind gusts are amplified by convection (Przybylinski 1995; Evans and Doswell 2001; Clark 2009; Evans 2010; Gatzen 2011; Gatzen et al. 2011; Púčik et al. 2015).

In this study, we examine a set of parameters and test their skill in predicting particular severe weather phenomena. We consider the ingredients associated with tornadoes, large hail, and severe wind gusts, and estimate their likelihood in a given set of parameters. This information may be valuable to forecasters that use thermodynamic and kinematic parameters to predict severe thunderstorms in NWP models. Thanks to probability plots with a given combination of parameters, it is possible to better estimate threat for the occurrence of severe thunderstorms. Numerous studies from the United States using radiosonde and reanalysis dataset addressed similar research questions. In Europe, a similar study has been recently performed by Púčik et al. (2015) with sounding measurements and Kaltenböck et al. (2009) with ECMWF simulated

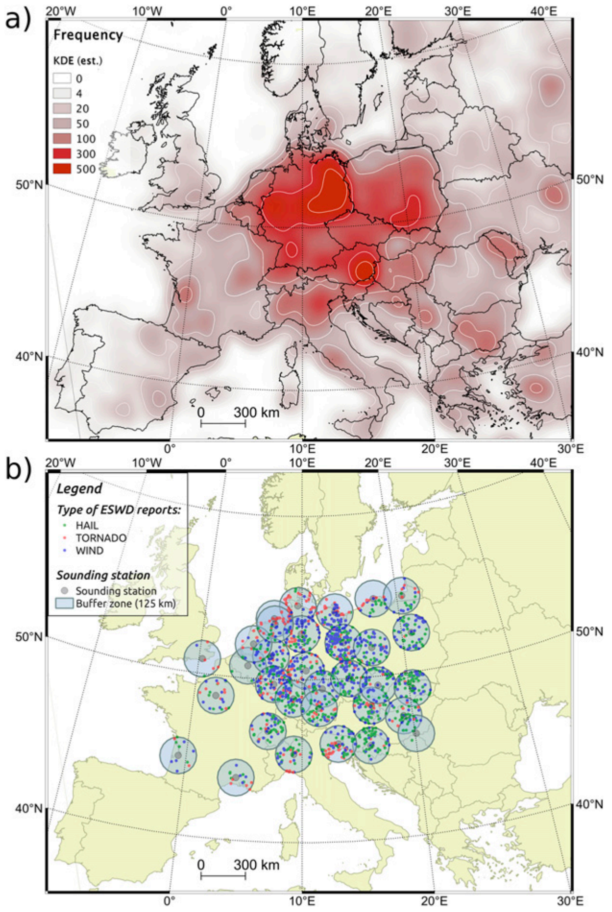

FIG. 1. (a) Kernel density estimation of March–October ESWD severe weather reports (tornadoes, large hail, convective severe wind gusts) in 2009–15 (sigma = 125 km), and (b) location of radiosonde stations with 125-km buffer zones and ESWD severe weather reports used in this study for analysis.

soundings. We use a different computational methodology, domain, and dataset timeframe, but with similar parameters allowing for comparison of our results. The main aims of our study cover two main aspects. First we want to highlight the parameters that discriminate best between nonsevere and severe thunderstorms. Second, we estimate how the intensity of the tornadoes, large hail, and severe convective wind gusts changes with a given set of parameters across the central and western European domain. In addition, we also test the skill of parameters in predicting lightning by comparing them with nonthunderstorm soundings.

2. Dataset and methodology

a. *Area of the study*

The research area covers parts of western and central Europe. According to lightning climatology studies for this area (Wapler 2013; Anderson and Klugmann 2014; Taszarek et al. 2015) thunderstorm high-season falls on summertime and extends from May to August with a peak in July. However, some thunderstorms also occur in transitional months in March/April and September/October. They are the least likely during wintertime from November to February.

Severe weather reports (tornadoes, large hail, severe convective wind gusts) derived from ESWD for the years 2009–15 indicate that their highest density fall on central Europe, northern Italy, and parts of France (Fig. 1a)—thus, the same area is chosen for our study. Although basing on ESWD data this place seems to be the most favorable European area for the occurrence of severe and extremely severe thunderstorms, it must be taken into account that due to spatial inhomogeneities in reporting, which correspond mainly to unequal distribution of severe weather observers, unequal population density, and language diversity, the true distribution of severe weather frequency may be unknown (Antonescu et al. 2016). According to Groenemeijer and Kühne (2014), the area of central Europe has a more uniform and reliable reporting in ESWD than the rest of Europe. Therefore, focusing on this region reduces a risk that analyzed soundings will be incorrectly considered as a nonsevere category.

b. *Severe weather reports database*

Severe weather reports were derived from ESWD for the years 2009–15. We started in 2009 for a variety of reasons. First, in this year quality control levels were incorporated by the European Severe Storms Laboratory (ESSL); therefore, it was possible to rate the credibility of the reports on a four-level scale: as received (QC0), plausibility check passed (QC0+), report confirmed (QC1), and event fully verified (QC2). Second, most of the national cooperating partners joined ESWD after 2010, thus increasing the number and a quality of the reports (Mr. Kühne 2015, personal communication). Third, the development of social media and an increase in people interested in severe weather that took place in recent years (e.g., the foundation of the Polish Stormchasing Society, Polscy Łowcy Burz) significantly increased the number of reports (often accompanied by a photograph of the event) as well.

For the purposes of this study we used only reports of large hail, tornadoes, and severe wind gusts with quality control levels QC1 and QC2. In addition, we also excluded hail reports with unknown hail diameter (or less than 2 cm), and severe wind gusts marked as nonconvective. Among tornado reports we included waterspouts as a separate category (a tornado reported over a water surface). Hail reports with diameter

TABLE 1. Sounding stations and the number of nonzero CAPE soundings used in the study.

WMO ID	Name	Country	0000 UTC	1200 UTC	1800 UTC
03882	Herstmonceux	United Kingdom	583	288	0
06260	De Blit	Netherlands	5	19	0
06458	Beauvechain	Belgium	293	25	0
06610	Payerne	Switzerland	693	1055	0
07145	Trappes	France	655	952	0
07510	Bordeaux Merginac	France	599	825	0
07645	Nimex-Courbessac	France	438	582	0
10035	Schleswig	Germany	628	875	0
10113	Norderney	Germany	550	625	0
10184	Greifswald	Germany	591	876	0
10200	Emden	Germany	0	14	0
10238	Bergen	Germany	575	936	993
10393	Lindenberg	Germany	680	962	1036
10410	Essen	Germany	690	938	0
10548	Meiningen	Germany	671	1032	0
10618	Idar-Oberstein	Germany	690	967	1033
10739	Stuttgart	Germany	714	1037	0
10771	Kuemmersbruck	Germany	694	991	0
10868	Muenchen	Germany	708	1016	0
11035	Wien	Austria	619	964	0
11520	Praha-Libus	Czech Republic	674	1086	540
11747	Prostejov	Czech Republic	388	809	0
11952	Poprad	Slovakia	533	907	0
12120	Łeba	Poland	605	743	0
12374	Legionowo	Poland	601	940	0
12425	Wrocław	Poland	548	910	0
12843	Budapest	Hungary	526	641	0
12982	Szeged	Hungary	569	136	0
14240	Zagreb	Croatia	626	982	0
16044	Udine	Italy	836	969	101
16080	Milano	Italy	894	972	0
26702	Kaliningrad	Kaliningrad Oblast	1	23	0
		Total	17 877	24 097	3703

between 2 and 4.9 cm along with severe wind gusts with measured wind speed below $33\,\mathrm{m\,s^{-1}}$ and F0–F1 tornadoes (estimated in an original F scale; Fujita 1971) were assigned to a severe thunderstorm category. Hailstones equal to or larger than 5 cm, severe wind speed gusts equal to or stronger than $33\,\mathrm{m\,s^{-1}}$, and tornadoes equal to or stronger than F2 were assigned to the extremely severe thunderstorm category.

c. *Sounding database and parameter computation*

The rawinsonde measurements were derived from the sounding database of University of Wyoming. For the years 2009–15 all available measurements for 0000, 1200, and 1800 UTC were downloaded for the stations from the area discussed in section 2a (Table 1, Fig. 1b). For each sounding we interpolated temperature, dewpoint, **U** and **V** wind vectors, and computed parameters listed in Table 2. For thermodynamic calculations, we used a mixed layer (ML) parcel through 0–500 m above ground level (AGL). This approach has some advantages and disadvantages compared to a surface-based (SB) parcel. ML parcel parameters are less variable in time and space and in general have lower values of CAPE than the SB version. However, in situations during the nighttime hours, especially when a shallow surface-based inversion exists, ML CAPE can be higher while SB version amounts zero. As suggested by Bunkers et al. (2002), ML CAPE was the most often used version in a previous studies investigating thunderstorm environments. Craven et al. (2002) also showed that mixed layer parcels more accurately estimated the cloud-base height. In addition to the choice of the parcel type, a virtual temperature correction was incorporated in our computations (for further details see Doswell and Rasmussen 1994). To compute storm relative helicity for the right-moving supercells (Davies and Johns 1993) we applied a Bunkers's storm motion vector (Bunkers et al. 2000).

d. *Thunderstorm database*

The information about thunderstorm occurrence as reported in SYNOP data was derived from the

TABLE 2. Parameters used in the study.

Parameter	Abbreviation	Units
Parcel parameters		
0–500-m AGL mixed layer convective available potential energy	CAPE	$\mathrm{J\,kg^{-1}}$
0–500-m AGL mixed layer CAPE up to 3 km AGL	0–3-km CAPE	$\mathrm{J\,kg^{-1}}$
Parcel's max vertical velocity (square root of 2 × CAPE)	WMAX	$\mathrm{m\,s^{-1}}$
0–500-m AGL mixed layer lifted condensation level	LCL	m AGL
0–500-m AGL mixed layer equilibrium level	EL	m AGL
0–500-m AGL mixed layer equilibrium level temperature	EL temperature	°C
Moisture parameter		
0–500-m AGL mixed layer mixing ratio	MIXR	$\mathrm{g\,kg^{-1}}$
Temperature gradients		
800–500-hPa temperature lapse rate	LR85	$\mathrm{K\,km^{-1}}$
0–3-km AGL temperature lapse rate	LR03	$\mathrm{K\,km^{-1}}$
Kinematic parameters		
0–6-km AGL bulk shear (deep layer shear)	DLS	$\mathrm{m\,s^{-1}}$
0–3-km AGL bulk shear (midlevel shear)	MLS	$\mathrm{m\,s^{-1}}$
0–1-km AGL bulk shear (low-level shear)	LLS	$\mathrm{m\,s^{-1}}$
0–1-km AGL storm-relative helicity	0–1-km SRH	$\mathrm{m^2\,s^{-2}}$
Composite parameter		
DLS × WMAX	WMAXSHEAR	$\mathrm{m^2\,s^{-2}}$

NOAA/National Climatic Data Center (NCDC) database. We took into account any indicators for the thunderstorm occurrence, including past hour and current observation report. For the each sounding site, we included SYNOP reports from three meteorological stations that fully covered the timeframe of 2009–15 and were within 125 km of a sounding station. We have chosen the assumption of three stations per sounding station because in many cases it was difficult to find a higher number of available proximity stations with a good continuity of measurements. Because we wanted to obtain unbiased results for the whole domain (so the thunderstorm ''capture rate'' remained the same for each sounding site) we did not use a higher amount of meteorological stations where it was possible. We aimed to choose meteorological stations distributed evenly in space and not being too close to each other. In a few cases (e.g., Łeba, Wrocław), SYNOP reports were derived from the same meteorological station as a sounding site. If any of the meteorological stations reported a thunderstorm within the proximity range, the appropriate sounding was considered to be associated with a thunderstorm. If no thunderstorm report was available but a sounding had positive CAPE, it was assigned to a nonthunderstorm positive CAPE category and included in the study. All zero CAPE soundings were excluded from the study. We did this in order to focus only on environments that are conditionally unstable and eliminate possibly nonrepresentative soundings. Removal of zero CAPE soundings was often practiced in a proximity sounding studies in the United States (e.g., Rasmussen and Blanchard 1998; Craven and Brooks 2004; Brooks et al. 2003; Brooks 2009).

e. The definition of proximity

Previous studies have used a variety of proximity sounding distance thresholds. Because we had a large dataset of more than 10 000 reports, we decided to use a relatively strict assumption of 125 km. Initially, we tested our dataset within the thresholds of 200, 175, 150, 125, 100, and 75 km, and found that the best compromise between sample size and a quality of obtained results (differences between severe weather categories were better pronounced) led to a distance threshold of 125 km. In higher distances, differences between particular categories were less apparent.

In the temporal sense, we assigned soundings to particular weather phenomena if the event took place up to 2 h prior to 4 h after the sounding time (0000, 1200, 1800 UTC). These numbers were chosen as a compromise between the representativeness of the sounding measurements and the number of proximity soundings that would result for each category in our study.

f. Quality control

We were aware that in some cases, the sounding contained errors in measurement or the sounding would not be representative of the atmosphere in which the phenomenon occurred (this problem was discussed by Brooks et al. 1994). Therefore, in order to minimize issues related to unrepresentative soundings, and exclude soundings with erroneous unrealistic values, quality control was applied to the soundings. In the first step, we discarded all soundings that contained measurements of temperature, dewpoint, and wind on

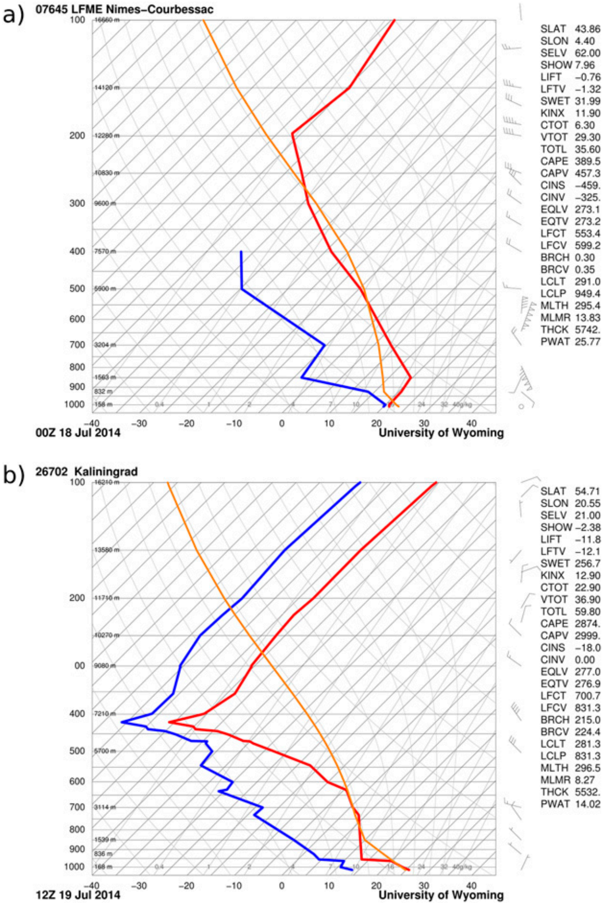

FIG. 2. Examples of erroneous sounding measurements derived in a quality control phase: (a) 800–600-hPa wind speed and (b) 600–400-hPa temperature lapse rate.

fewer than 10 pressure levels between ground and 10 km AGL. Next, we performed a manual quality control of the soundings with values of the computed parameters, and discarded those that resulted from obvious errors (e.g., Fig. 2). These corresponded mainly to checking soundings with LR85 $> 9\,\mathrm{K\,km^{-1}}$, LR03 $> 10\,\mathrm{K\,km^{-1}}$, DLS $> 70\,\mathrm{m\,s^{-1}}$, MLS $> 40\,\mathrm{m\,s^{-1}}$, LLS $> 30\,\mathrm{m\,s^{-1}}$, CAPE $> 5000\,\mathrm{J\,kg^{-1}}$, and MIXR $>$ $18\,\mathrm{g\,kg^{-1}}$. In addition, in order to remove severe wind reports that might have been not associated with DMC, we limited our database only from March to October and excluded wintertime in which thunderstorms in our study area are the least likely (Wapler 2013; Anderson and Klugmann 2014; Taszarek et al. 2015). In total, the final database consisted of 45 677 soundings: 169 associated with extremely severe thunderstorms, 1754 with severe thunderstorms, 8361 with nonsevere thunderstorms, and 35 393 with no thunderstorms but nonzero CAPE (Table 3). The highest number of soundings occurred in July, August, and June, respectively (Table 4).

g. *Probability plots*

To assess the probability for particular severe weather phenomenon given a combination of two environmental parameters, density distributions were produced. The distributions are estimated using a kernel density estimation technique (KDE; Silverman 1986) in a 100 × 100 grid matrix. The smoothing allows us to obtain a signal that is consistent with the underlying hypothetical true distribution of event for a given set of parameters (Grünwald and Brooks 2011). The sigma parameter for the Gaussian was chosen to be a one-third of the difference between minimum and maximum value of the given parameter. For example, if the distribution of mixing ratio values extended from 0 to $18\,\mathrm{g\,kg^{-1}}$, the sigma value associated with the Gaussian smoother was set on $6\,\mathrm{g\,kg^{-1}}$. This means that the overall distribution should be representative of the true distribution, but details have been smoothed out. Final probability plots were limited to the values of KDE for particular category higher than 10^{-4}. In this way we wanted to show only the results from the areas on the chart where the density of a sounding reports was sufficient enough to show meaningful results for relatively large sample sizes.

h. *Limitations of the approach*

The main limitation is related to the methodology in which nonsevere thunderstorm events were obtained. The use of SYNOP reports provides measurement only in certain points, in the observational range of around 17 km away from the meteorological station (Czernecki et al. 2016). However, when thunderstorms form, they usually cover much larger areas and move, thus significantly increasing the chances of capturing a thunderstorm event by the meteorological station. By comparing our thunderstorm events with lightning climatology (e.g., Taszarek et al. 2015), we estimate that around 30%–40% of thunderstorm events may be missed by using only human observations of thunderstorms. As a result, some part of soundings associated with nonsevere thunderstorm may be wrongly assigned to a nonthunderstorm category. A similar situation occurs in the case of severe weather events. Underreporting issues of ESWD [discussed by Groenemeijer and Kühne (2014)] may result in soundings being erroneously classified as a nonthunderstorm. However, with a relatively large dataset of nonthunderstorm soundings (35 393), erroneous nonsevere thunderstorm and severe weather soundings apply only to a small fraction of this category and should have negligible impact on the results.

Further limitations influencing the results relate to the spatial and temporal unrepresentativeness of the

TABLE 3. Number of nonzero CAPE soundings used in the study, according to year and associated weather phenomena.

	Year							
	2009	2010	2011	2012	2013	2014	2015	Total
Nonthunderstorm	4965	4960	4515	4846	5113	5848	5146	35 393
Thunderstorm nonsevere	1257	1061	1214	1200	954	1743	932	8361
Large hail	99	66	84	116	72	108	93	638
Very large hail	12	17	18	17	22	15	16	117
Severe wind gust	36	53	56	153	150	175	205	828
Extremely severe wind gust	4	4	1	2	2	3	7	23
Waterspout	11	14	4	16	16	20	7	88
Weak tornado	19	38	26	32	25	35	25	200
Significant tornado	5	6	3	3	4	5	3	29
Total	6408	6219	5921	6385	6358	7952	6434	45 677

soundings associated with the mesoscale variability of the atmosphere. Thanks to this, incorrectly assigned soundings may occur in the nonsevere thunderstorm and severe weather categories. It is difficult to estimate the number of such soundings, but it is possible that results obtained within categories of smaller samples (e.g., significant tornadoes, extremely severe wind gusts) may be influenced. Another limitation is also related to the lack of information on the convective initiation and mode (e.g., supercells, squall lines, multicells), which would allow us to better discriminate between environments that vary depending on the mode (e.g., severe wind events).

3. Results

a. Lightning

The occurrence of thunderstorms and thus lightning is mainly a function of CAPE (Fig. 3a). CAPE is determined by two main factors: boundary layer moisture and temperature lapse rates aloft (Figs. 3c and 3d). Thus, the probability for lightning depends heavily on both MIXR and LR85 (Fig. 4a). High lightning probability is associated with a range of environments, with steep lapse rates frequently compensating for poor low-level moisture and vice versa. Thunderstorms are much less likely when MIXR drops to 2–3 g kg^{-1} and LR85 is below 5 K km^{-1}.

The temperature of the equilibrium level (EL) also shows skill in assessing the potential for lightning occurrence (Fig. 3e). Lower EL temperature and high WMAX (maximum vertical velocity derived from parcel theory computed as the square root of 2 times CAPE) have higher lightning probabilities (Fig. 4b). The 75th percentile of EL temperature of nonsevere thunderstorms was below the median of a nonthunderstorm cases at −10°C (Fig. 3e). Almost all severe categories had their 75th percentile values below −10°C with the lowest EL temperatures associated with hail events.

b. Thunderstorm severity in general

The severity of thunderstorm increases with increasing CAPE (Fig. 3a). Large and very large hail events had considerably higher CAPE than nonsevere thunderstorms. In the severe convective wind gust category, CAPE was slightly higher when compared with the nonsevere thunderstorm category, but showed little

TABLE 4. Number of nonzero CAPE soundings used in the study, according to month and associated weather phenomena.

	Month								
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Total
Nonthunderstorm	2419	3333	4569	5092	5463	5887	5094	3536	35 393
Thunderstorm nonsevere	109	553	1242	1576	2279	1660	742	200	8361
Large hail	5	31	166	148	151	112	15	10	638
Very large hail	0	0	18	36	36	22	5	0	117
Severe wind gust	53	27	102	126	268	158	38	56	828
Extremely severe wind gust	7	0	1	2	11	2	0	0	23
Waterspout	0	1	6	6	14	42	18	1	88
Weak tornado	3	7	37	43	36	44	21	9	200
Significant tornado	0	1	5	7	7	8	0	1	29
Total	2596	3953	6146	7036	8265	7935	5933	3813	45 677

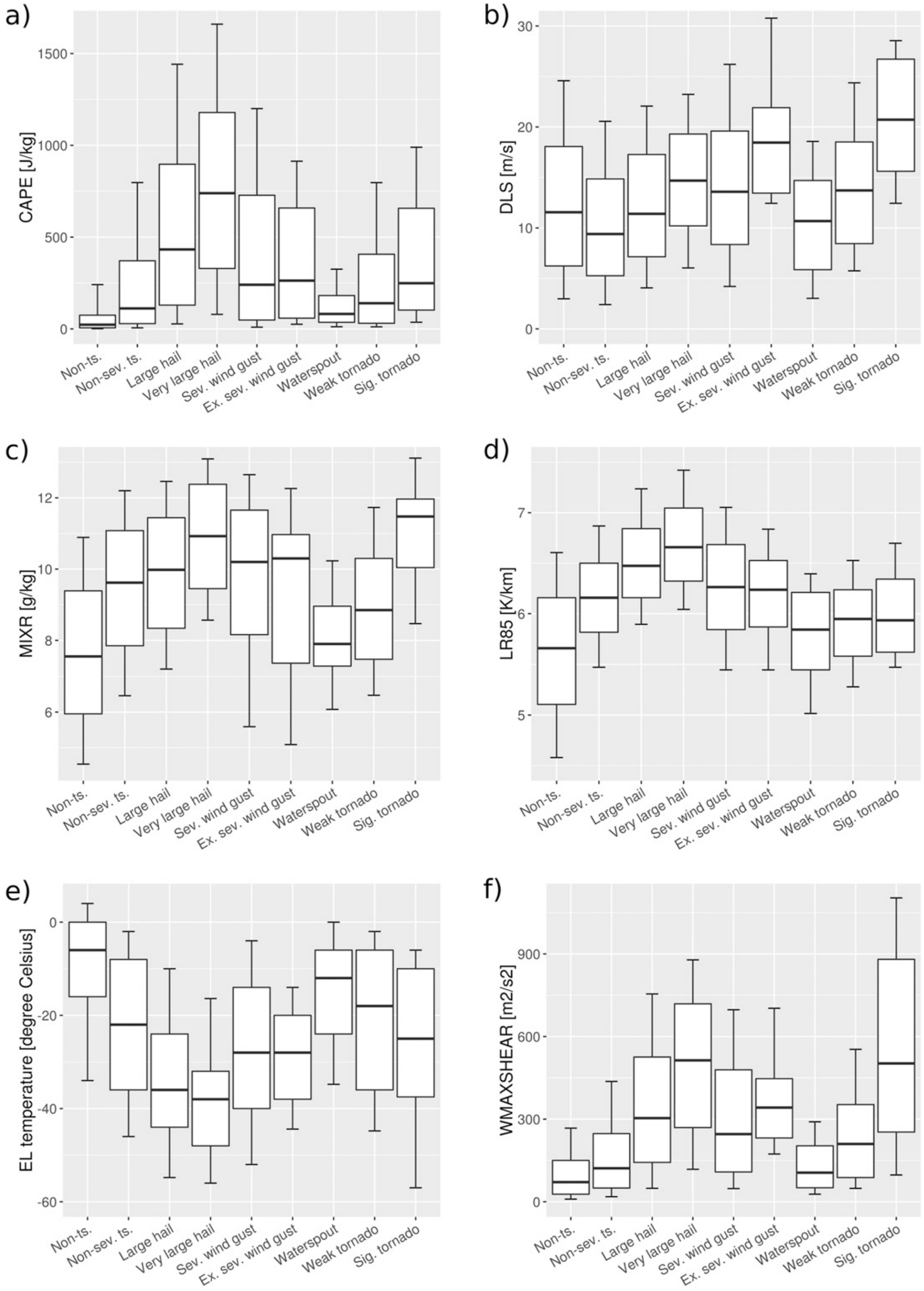

FIG. 3. Box-and-whisker plots of (a) CAPE, (b) DLS, (c) MIXR, (d) LR85, (e) EL temperature, and (f) WMAXSHEAR. The median is represented as a horizontal line inside the box, the edges of the box represent the 25th and 75th percentiles, while whiskers represent the 10th and 90th percentiles.

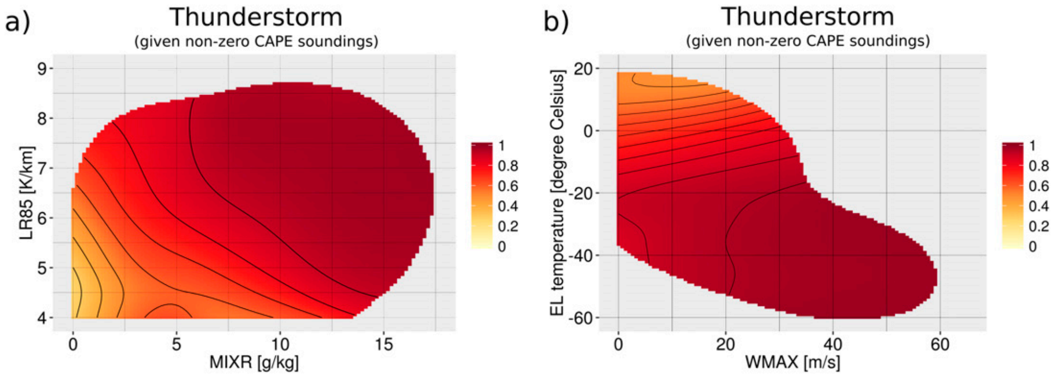

FIG. 4. Probability for thunderstorm given nonzero CAPE sounding as a function of (a) LR85 and MIXR, and (b) EL temperature and WMAX. Contour fields are limited to values of kernel density estimation of nonzero CAPE sounding higher than 10^{-3}. Contour lines denote constant values.

discrimination between different wind magnitudes. In tornado events, CAPE increased with increasing severity, but the overall values overlapped with nonsevere thunderstorms. Waterspouts demonstrated a lower CAPE than most nonsevere thunderstorms indicating that only a little CAPE is necessary to their formation.

In contrast to CAPE, DLS shows discrimination between the severity of convective wind gusts. The median value for extremely severe wind gusts was approximately at the level of the 75th percentile of severe wind gusts (Fig. 3b). DLS turned out to be an excellent discriminator between weak and significant tornadic environments. Although DLS for weak tornadoes was similar to nonthunderstorm and nonsevere thunderstorm datasets, significant tornadoes had considerably higher DLS than all other categories. Increases in DLS were also associated with an increase in hail severity, although less significant than in tornadoes. The lowest average DLS values were associated with waterspouts, suggesting that these are associated mainly with weakly sheared environments.

Since both CAPE and DLS appear to show discrimination in forecasting severe thunderstorms, we created two-dimensional probability plots using the KDE technique applying these two parameters. Instead of CAPE we used the WMAX to have the same units ($\mathrm{m\,s^{-1}}$) as a shear term. The most common combination of WMAX and DLS is in relatively low shear and low WMAX (both less than $20\,\mathrm{m\,s^{-1}}$) (Fig. 5a), that are unlikely to produce severe thunderstorms (Brooks 2013; Púčik et al. 2015). The distribution for nonsevere thunderstorms indicates that the occurrence of thunderstorm is almost entirely a function of an available WMAX (Fig. 5b). For severe thunderstorms, however, the probability increases with both the increasing DLS and WMAX (Fig. 5c). In the case of extremely severe, the presence of WMAX was important, but the increase in probability was mainly a function of increasing DLS (Fig. 5d). Thus, it can be concluded that WMAX is mainly responsible for the occurrence of thunderstorms, but the severity is strongly dependent on the amount of vertical wind shear.

The product of WMAX and DLS (hereafter WMAXSHEAR) proved to be the most effective among all analyzed parameters in discriminating between nonsevere and severe categories, and also between the intensity of each phenomena (Fig. 3f). The median of the nonsevere thunderstorm category was at the 25th percentile of severe weather events while the 75th percentile was at the 25th percentile of extremely severe cases, thus showing a great potential in forecasting severe thunderstorms.

c. *Large hail*

Hail occurrence is greater with higher WMAX (Fig. 6a). However, when we look at the largest hail category (equal or greater than 5-cm diameter), the probability is more dependent on DLS for moderate to high WMAX environments rather than on WMAX itself (Fig. 6b). The probability is maximized with DLS between 20 and $30\,\mathrm{m\,s^{-1}}$, which has been previously found to be conducive for the occurrence of supercell thunderstorms (Doswell and Evans 2003).

When considering LR85 and MIXR, +2-cm hail is mainly a function of LR85 rather than MIXR (Fig. 6c). However, it was unlikely to see large hail in environments with MIXR lower than $5\,\mathrm{g\,kg^{-1}}$. The analysis of +5-cm cases indicated that except for the presence of steep lapse rates, boundary layer moisture is equally important in producing very large hail (Fig. 6d). The highest probability for extreme hail is maximized when LR85 exceeds $7\,\mathrm{K\,km^{-1}}$ and MIXR is around $15\,\mathrm{g\,kg^{-1}}$. The analysis of both parameters in box plot charts also revealed that hail severity increases with increasing values of MIXR and LR85 (Figs. 3c and 3d).

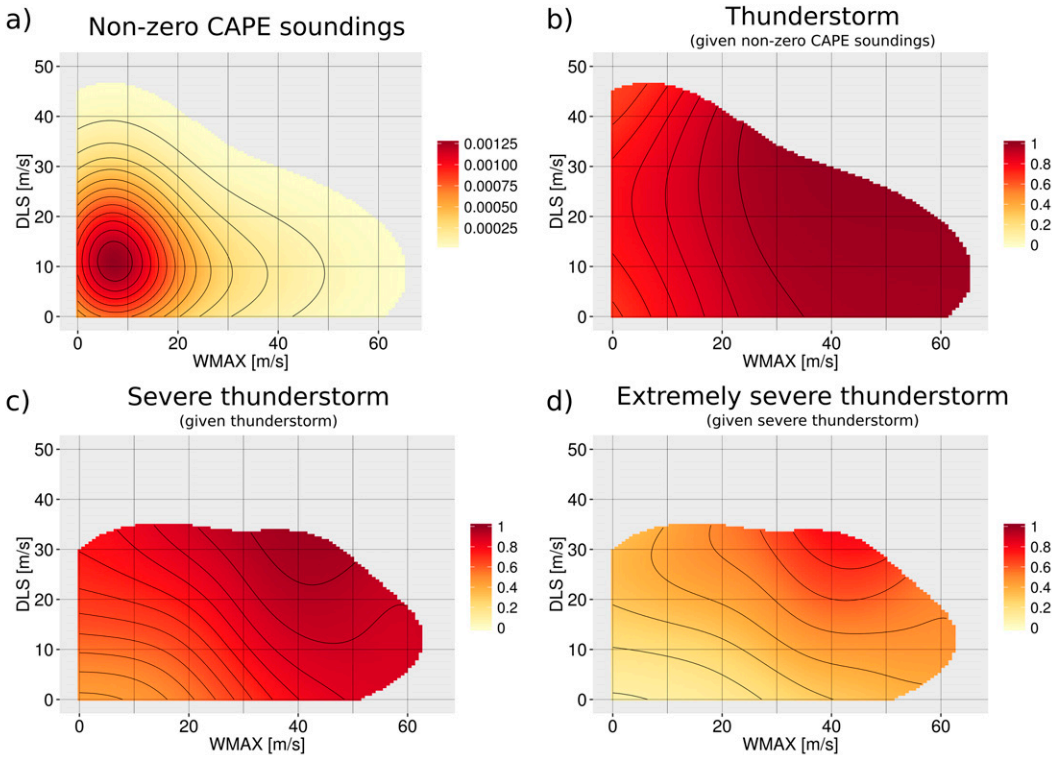

FIG. 5. (a) Kernel density estimation of nonzero CAPE soundings, and probability for (b) thunderstorm given nonzero CAPE sounding, (c) severe thunderstorm given thunderstorm, and (d) extremely severe thunderstorm given severe thunderstorm as a function of DLS and WMAX. Contour fields are limited to values of kernel density estimation of a particular category higher than 10^{-4}. Contour lines denote constant values.

LCL, known as one of the good tornado forecasting ingredient (Rasmussen and Blanchard 1998; Thompson et al. 2003; Craven and Brooks 2004; Groenemeijer and van Delden 2007; Kaltenböck et al. 2009; Taszarek and Kolendowicz 2013; Púčik et al. 2015), turned out to be also useful in defining large hail environments. Large and very large hail occur in higher cloud bases than the nonsevere thunderstorm category (Fig. 7b). Since the combination of WMAX and DLS (WMAXSHEAR) turned out to be a good tool in distinguishing between hail environments (Fig. 3f), we combined WMAXSHEAR with LCL. The results indicate that the probability for large hail increases along with increasing WMAXSHEAR and LCL values (Fig. 6e). However, considering only very large hail cases with WMAXSHEAR values higher than 300 $\mathrm{m^2\,s^{-2}}$, it is almost entirely a function of the WMAXSHEAR (Fig. 6f). This may be explained by the fact that very large hailstones occur almost exclusively within supercell thunderstorms and these are favored by high WMAXSHEAR values. In LCL below 1000 m AGL and WMAXSHEAR below 300 $\mathrm{m^2\,s^{-2}}$ probability for large hail significantly drops. In addition, large hail is more likely to occur in environments with high and cold EL (Figs. 3e and 7c) and high values of LR03 (Fig. 7a).

d. Tornadoes

Tornadoes occur in high DLS environments and their intensity increases with increasing vertical wind shear (Fig. 3b). As shown in Fig. 8, LLS, MLS, 0–1-km SRH, and 0–3-km CAPE show utility in predicting tornadic thunderstorms. Among all shear parameters, MLS turns out to be the best in distinguishing between weak and significant tornadic environments (the 75th percentile for weak tornadoes is approximately the 25th percentile for significant tornadoes).

An analysis of WMAX and DLS shows that peak probability for tornadoes occur in a high DLS and moderate WMAX environment, especially when DLS exceeded 20 $\mathrm{m\,s^{-1}}$ (Fig. 9a). In the case of significant tornadoes, it was noted that the increase in thermodynamic instability in a highly sheared environment increases the chances that the tornado will become significant if it forms (Fig. 9b).

The median values of 0–3-km CAPE in weak and significant tornado cases were higher compared to

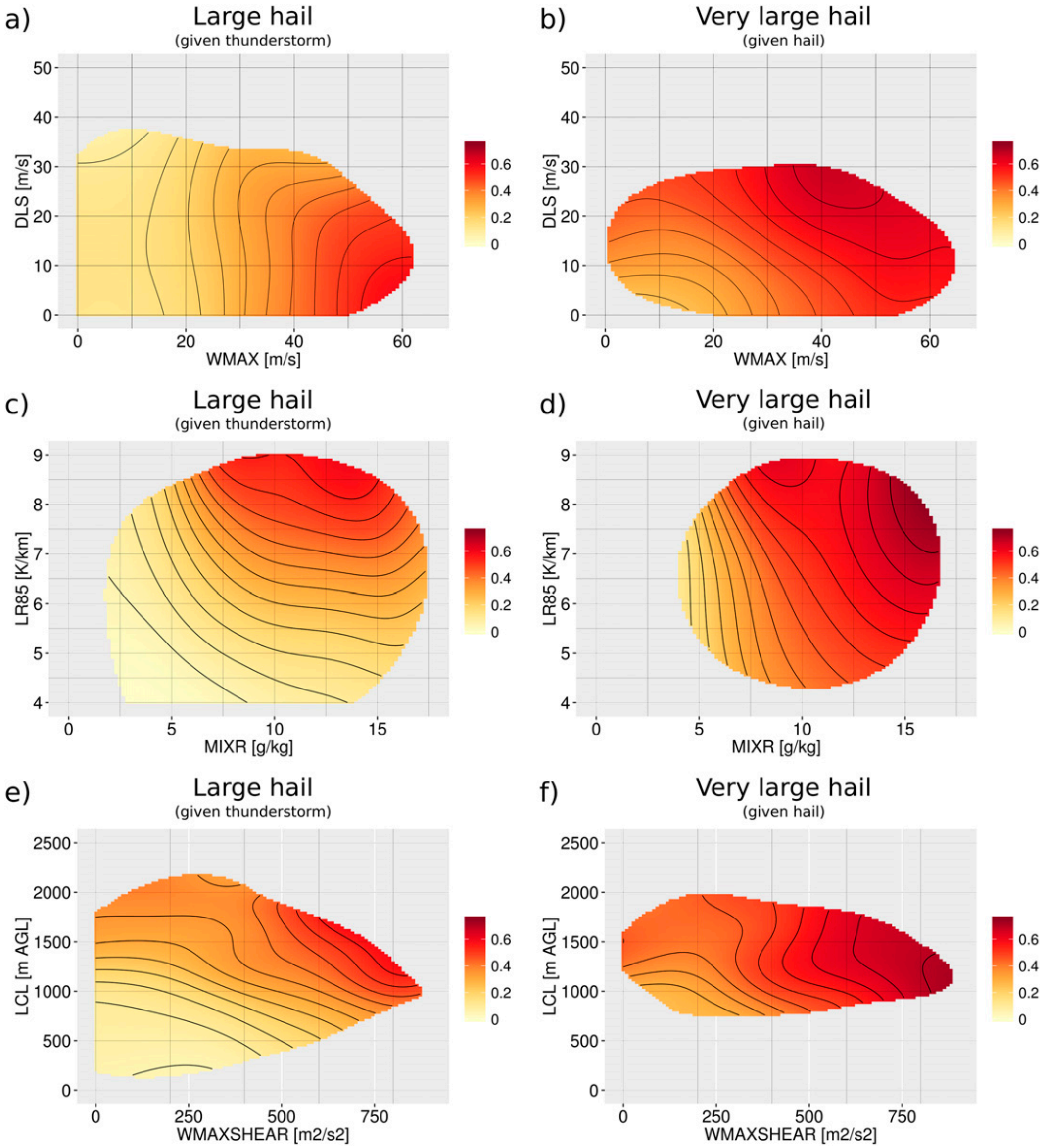

FIG. 6. Probability for large hail given thunderstorm and very large hail given hail as a function of (a),(b) DLS and WMAX; (c),(d) LR85 and MIXR; and (e),(f) LCL and WMAXSHEAR. Contour fields are limited to values of kernel density estimation of a particular category higher than 10^{-4}. Contour lines denote constant values.

nonsevere thunderstorm category, thus showing a skill as a predictor (Fig. 8d). A combination of this parameter with 0–1-km SRH indicated that although +F0 tornado probability maximizes when 0–3-km CAPE falls between 100 and 150 J kg^{-1} and 0–1-km SRH exceeds 100 m^2 s^{-2} (Fig. 9c), the occurrence of significant tornadoes is almost entirely a function of increasing 0–1-km SRH (Fig. 9d).

The median value for LCL was below 1000 m AGL in all tornadic categories, lower than in other severe and nonsevere categories (Fig. 7b). LCL height turned out to influence the chances for any tornado, rather than distinguishing its intensity. Since MLS turned out to be the best parameter in distinguishing between tornado intensity (Fig. 8a), we combined it with LCL. The highest chances for any tornado occurred in LCL of around 500 m AGL and MLS of 15 m s^{-1} (Fig. 9e). When considering only significant tornado cases, the importance of LCL decreased and the probability was mostly a function of MLS (Fig. 9f), confirming that LCL is a poor parameter in distinguishing tornado intensity. In addition, significant tornadoes were also more likely to form in a high MIXR environment (Fig. 3c) distinguishing them well from weak tornadic environments.

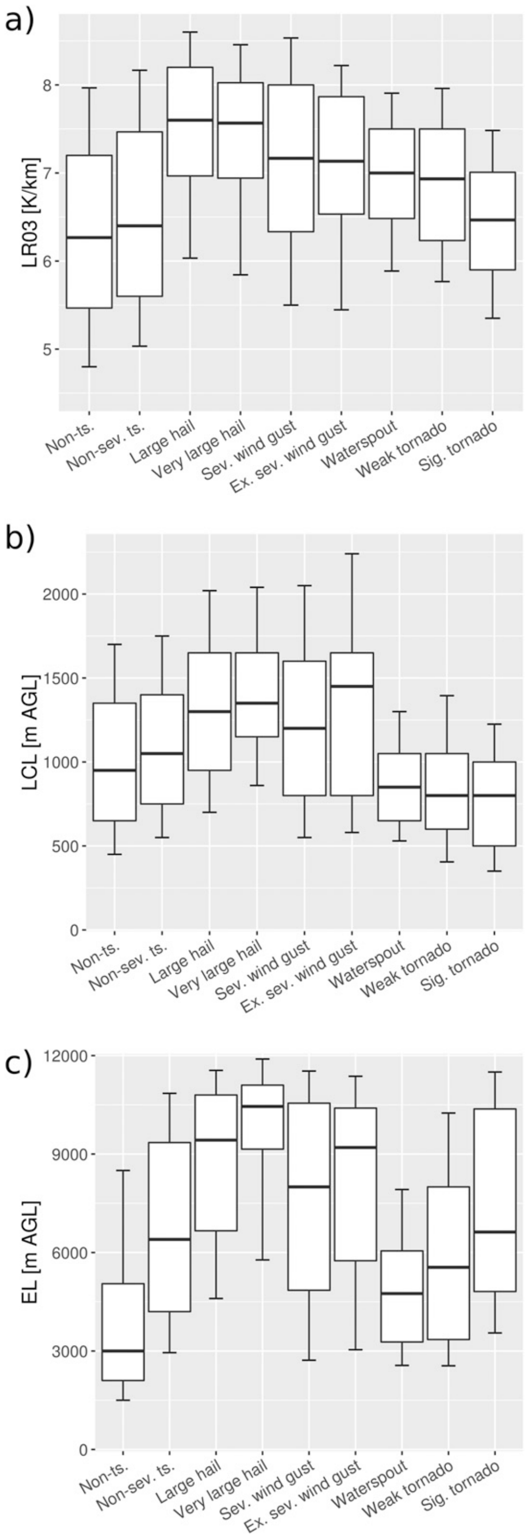

FIG. 7. As in Fig. 3, but for (a) LR03, (b) LCL, and (c) EL.

e. *Severe wind gusts*

The peak probability for wind gusts of at least 25 m s^{-1} falls on a low WMAX, high DLS environment (Fig. 10a). However, a signal of increased probability also exists in a moderate to high WMAX and moderate DLS. Considering only extremely severe wind gusts with wind speeds equal or exceeding 33 m s^{-1}, peak probability is located in the same area. However, considerable probability is also distributed in a higher WMAX environments and it seems to be mainly a function of an available vertical wind shear rather than thermodynamic instability (Fig. 10b). This is also seen when the vertical wind shear is considered as a single variable (Figs. 3b and 8a,b).

Low-level lapse rates, 0–1-km SRH, and LCL were also found to be higher in severe wind gusts cases compared to nonsevere thunderstorm and nonthunderstorm categories (Figs. 7a,b and 8c). MLS, DLS, and a parameter of WMAXSHEAR turned out to be the most useful in distinguishing between intensity of the wind gusts (Figs. 3b,f and 8a).

f. *Waterspouts*

The probability that a waterspout will occur given a thunderstorm maximizes when the vertical wind shear is very low (Figs. 3b, 8a,b, and 11a). Waterspouts usually form in a weakly unstable environment (Fig. 3a) with a shallow free convective layer (Fig. 7c). Most of the CAPE in such days is located in low levels (Fig. 8d) and is associated with steep low-level lapse rates (Fig. 7a) and relatively low LCL (Fig. 7b). Waterspouts were most likely in the environments with around 500 m AGL LCL and LR03 exceeding 8 K km^{-1} (Fig. 11b).

4. Conclusions and discussion

In this study we investigated more than 45 000 proximity soundings from central and western Europe including 169 associated with extremely severe thunderstorms, 1754 with severe thunderstorms, 8361 with nonsevere thunderstorms, and 35 393 with nonthunderstorm nonzero CAPE for years 2009–15. An analysis helped us to define which thermodynamic and kinematic parameters show value in distinguishing between severe and nonsevere environments, and between intensity of large hail, severe wind gusts, and tornadoes. In addition, we also determined predictors for lightning and waterspouts. Below, the most important conclusions and their relationship to previous studies are highlighted.

a. *Lightning*

The occurrence of lightning is mainly a function of CAPE that consists of low-level moisture and

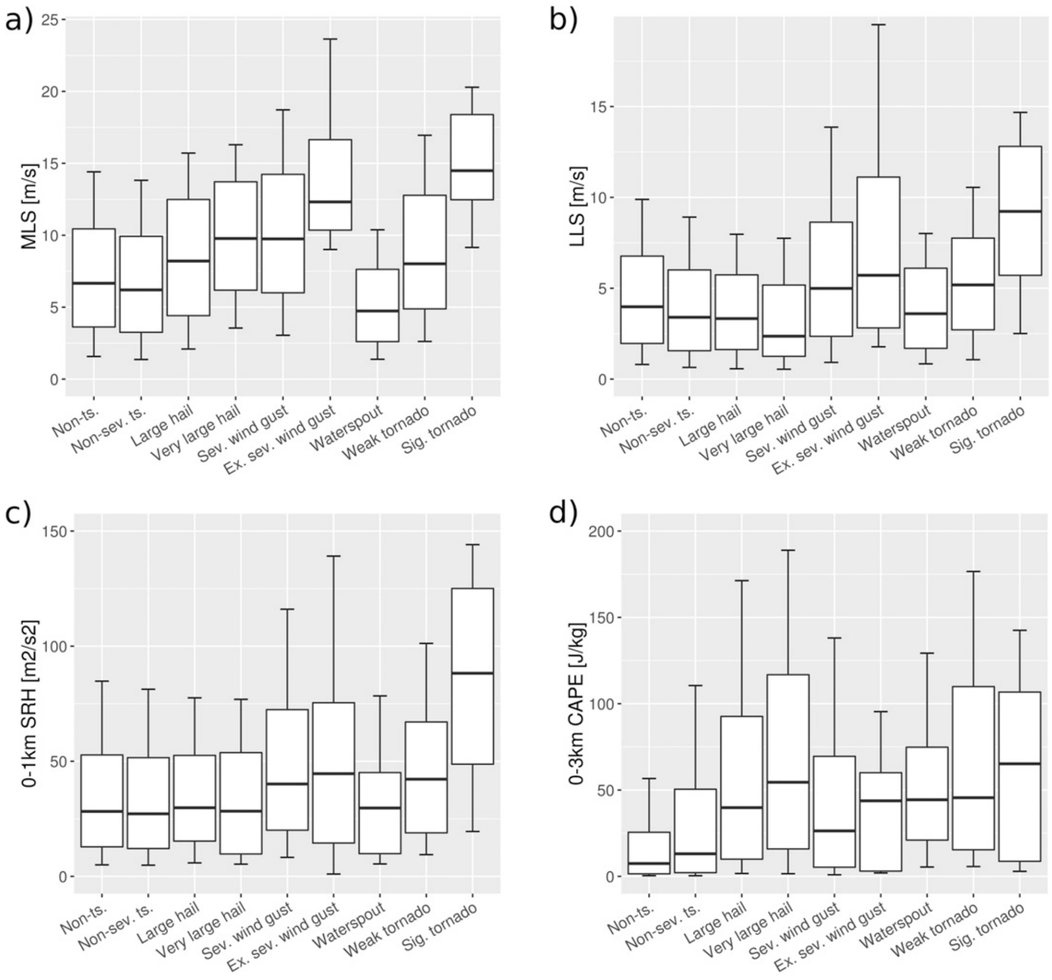

FIG. 8. As in Fig. 3, but for (a) MLS, (b) LLS, (c) 0–1-km SRH, and (d) 0–3-km CAPE.

midtropospheric lapse rates. This agrees with Craven and Brooks (2004) on discriminating between thunderstorm and nonthunderstorm environments. Our distribution of CAPE values in the thunderstorm category is also similar to that obtained by Kaltenböck et al. (2009) within the use of ECMWF reanalysis soundings. High lightning probability is associated with environments with poor lapse rates and high low-level moisture, and steep lapse rates with poor low-level moisture. Thunderstorms are unlikely when MIXR is less than 3 g kg^{-1} and LR85 is less than 5 K km^{-1}. Occurrence of lightning is more likely when the temperature of EL drops below -10°C. Similiar finding was also denoted in the study of Petersen et al. (1996).

b. Thunderstorm severity in general

While the presence of nonsevere thunderstorms is almost entirely a function of CAPE, a presence of severe thunderstorms is dependent on both CAPE and DLS. The occurrence of extremely severe thunderstorms is entirely dependent on available DLS for small to moderate CAPE environments. Among all analyzed parameters, WMAXSHEAR, combining both instability and shear turned out to be the best not only in discriminating between nonsevere and severe environments, but also in assessing the severity of convective phenomena. A similar parameter presented as a "significant severe parameter" in the study of Craven and Brooks (2004) and Brooks (2009), also showed skill in distinguishing between severe and nonsevere environments. In addition to WMAXSHEAR, MLS also discriminated well between severe and extremely severe thunderstorms producing tornadoes and severe wind gusts.

c. Large hail

The probability for large hail maximizes with high boundary layer moisture, steep mid- and low-level lapse rates (thus high CAPE), and a high LCL height.

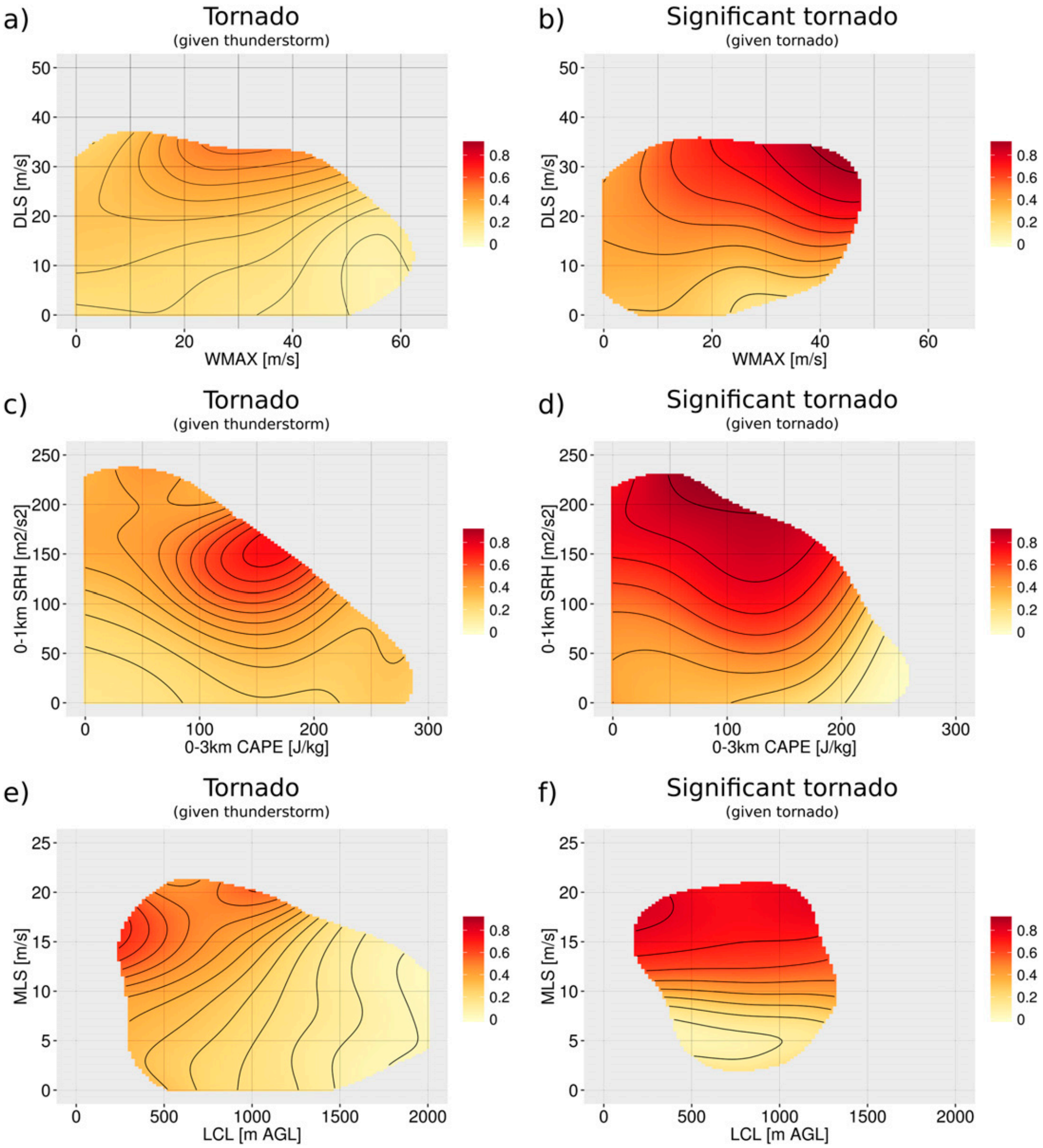

FIG. 9. Probability for tornado given thunderstorm and significant tornado given tornado as a function of (a),(b) DLS and WMAX; (c),(d) 0–1-km SRH and 0–3-km CAPE; and (e),(f) MLS and LCL. Contour fields are limited to values of kernel density estimation of a particular category higher than 10^{-4}. Contour lines denote constant values.

Rasmussen and Blanchard (1998), Groenemeijer and van Delden (2007), Kaltenböck et al. (2009), Grams et al. (2012), and Púčik et al. (2015) also noted that LCL during hail days was higher compared with nonsevere thunderstorms. Although the occurrence of +2-cm hail depends mostly on the available thermodynamic instability, +5-cm hailstones depend mainly on the available DLS in the presence of moderate to high CAPE and moist low levels. Good discriminators between large hail and nonsevere thunderstorms consider also temperature and height of EL, and a parameter of WMAXSHEAR. The combination of DLS and CAPE as a good large hail forecasting tool was also indicated by Craven and Brooks (2004) and Púčik et al. (2015).

d. Tornadoes

The highest chances for tornadoes exist when both vertical wind shear and CAPE are high. This agrees with Rasmussen and Wilhelmson (1983), Brooks et al. (2003), and Thompson et al. (2003). We find MLS as one of the most skillful parameters in distinguishing between thunderstorms producing significant tornadoes and nonsevere thunderstorms. This contrasts with Púčik et al. (2015) who found DLS as a better discriminator.

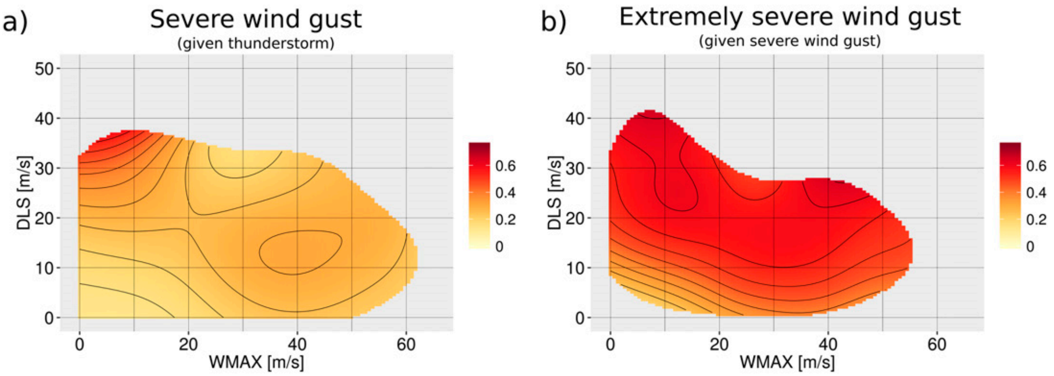

FIG. 10. Probability for (a) severe wind gust given thunderstorm and (b) extremely severe wind gust given severe wind gust as a function of DLS and WMAX. Contour fields are limited to values of kernel density estimation of particular category higher than 10^{-4}. Contour lines denote constant values.

Chances for significant tornadoes increase also along with increasing values of MIXR, DLS, LLS, and 0–1-km SRH. Parameters of 0–3-km CAPE and LCL discriminate between tornadic cases and the nonsevere thunderstorm category. The median value for LCL is below 1000 m AGL in all tornadic categories, lower than in other categories. Similar results were obtained by Craven and Brooks (2004), Groenemeijer and van Delden (2007), and Kaltenböck et al. (2009). Unlike some previous work (Grünwald and Brooks 2011; Taszarek and Kolendowicz 2013; Púčik et al. 2015) we did not find an increase of LCL when going from weak to significant tornado events in Europe. In the United States, Thompson et al. (2003, 2012) found that significant tornadoes tend to form in lower LCL than weak tornadoes, similar to our results.

e. Severe wind gusts

Severe convective wind gusts occur in a variety of meteorological conditions, making it difficult to define straightforward parameters useful in their forecasting (e.g., Corfidi et al. 2006; Evans and Doswell 2001; Púčik et al. 2015). At least three different environments responsible for their occurrence can be found. One relates to widespread events associated with strong large-scale horizontal pressure gradient and a marginal thermodynamic instability. Such setups are associated with deep synoptic lows and very strong airflow. Gusts in this mode are produced mainly within bowing segments of convective lines that originate in areas with strong synoptic-scale lift (Gatzen 2011). A second mechanism with large CAPE, low shear conditions can be related to local downbursts in deep and dry boundary layers (Wakimoto 1985; Holmes and Oliver 2000). The third mechanism refers to a high CAPE, high shear environment in which organized long-lived squall lines including derechos with widespread damaging wind gusts can occur (Doswell and Evans 2003; Celiński-Mysław and Matuszko 2014).

In our study, severe wind events were the most common in a high shear, marginal CAPE conditions, in contrast to Brooks (2013), who found that severe wind

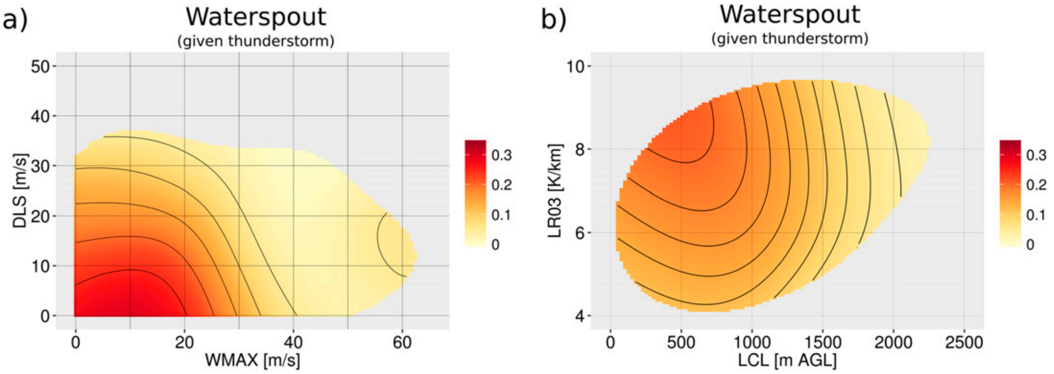

FIG. 11. Probability for waterspout given thunderstorm as a function of (a) DLS and WMAX, and (b) LR03 and LCL. Contour fields are limited to values of kernel density estimation of a particular category higher than 10^{-4}. Contour lines denote constant values.

events in the United States are most frequent in high CAPE, low shear conditions. Similar to our results, Sherburn and Parker (2014) found that LR03 and MLS are valuable in differentiating the threat for severe convective winds and tornadoes. Except for low CAPE, high shear setups, our study is similar to Púčik et al. (2015) who denote a secondary signal of increased probability for severe wind in a moderate to high CAPE and moderate DLS environment. In addition, as Kaltenböck et al. (2009) noted, severe wind events occur in Europe with increased 0–1-km SRH and the same thing was observed also in our dataset. As with tornadoes, MLS turned out to be the best parameter in distinguishing between severe and extremely severe wind events.

f. Waterspouts

The probability for waterspouts is maximized in a weak vertical wind shear, shallow free convective layer (low EL), and small thermodynamic instability. This is in accordance with Szilagyi (2009), Keul et al. (2009), and Sioutas et al. (2013). Low LCL and increased 0–3-km CAPE with steep low-level lapse rates are also conducive to waterspout occurrence. Our study agrees with Renko et al. (2013) that thermodynamic instability indexes alone (e.g., CAPE) are usually insufficient in forecasting waterspout activity due to their strong similarity with the nonsevere thunderstorm category.

g. Severe thunderstorms and climate change

As Brooks (2013) denoted, as climate changes, the magnitude of CAPE and shear is also changing. Given that different combinations of CAPE and shear favor the occurrence of different convective phenomena, this may provide insight into expected future changes in the distribution and nature of convective hazards. For example, if in the future days both CAPE and shear increase, tornadoes and hailstorms will likely become more common. If low CAPE, high shear days will be more frequent, the number of severe convective wind gust events may increase. Bearing in mind these issues, we recommend that future studies address the question of how the distribution of severe thunderstorm ingredients will change, particularly in the context of the complex European topography. Preliminary results from climate projections for Europe indicate that an increase in CAPE and a slight increase in shear are expected in the next 100 years (Púčik 2016). Because of this, the number of unstable, strongly sheared environments is projected to increase as well. As a result, thunderstorms capable of producing severe and extremely severe phenomena may become more frequent.

Acknowledgments. We appreciate the valuable comments of the reviewers, which helped to improve this study. This research was supported by the grant of Polish National Science Centre (Project 2014/13/N/ST10/01708). The leading author obtained the funds for the preparation of his doctoral dissertation within doctoral scholarship at the National Science Centre (Project 2015/16/T/ST10/00373). The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect the views of NOAA or the Department of Commerce.

REFERENCES

Anderson, G., and D. Klugmann, 2014: A European lightning density analysis using 5 years of ATDnet data. *Nat. Hazards Earth Syst. Sci.*, **14**, 815–829, doi:10.5194/nhess-14-815-2014.

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

Beebe, R. G., 1955: Types of airmasses in which tornadoes occur. *Bull. Amer. Meteor. Soc.*, **36**, 349–350.

——, 1958: Tornado proximity soundings. *Bull. Amer. Meteor. Soc.*, **39**, 195–201.

Berthet, C., E. Wesolek, J. Dessens, and J. L. Sanchez, 2013: Extreme hail day climatology in Southwestern France. *Atmos. Res.*, **123**, 139–150, doi:10.1016/j.atmosres.2012.10.007.

Brooks, H. E., 2009: Proximity soundings for severe convection for Europe and the United States from reanalysis data. *Atmos. Res.*, **93**, 546–553, doi:10.1016/j.atmosres.2008.10.005.

——, 2013: Severe thunderstorms and climate change. *Atmos. Res.*, **123**, 129–138, doi:10.1016/j.atmosres.2012.04.002.

——, and R. B. Wilhelmson, 1993: Hodograph curvature and updraft intensity in numerically modeled supercells. *J. Atmos. Sci.*, **50**, 1824–1833, doi:10.1175/1520-0469(1993)050<1824:HCAUII>2.0.CO;2.

——, C. A. Doswell III, and J. Cooper, 1994: On the environments of tornadic and nontornadic mesocyclones. *Wea. Forecasting*, **9**, 606–618, doi:10.1175/1520-0434(1994)009<0606:OTEOTA>2.0.CO;2.

——, J. W. Lee, and J. P. Craven, 2003: The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmos. Res.*, **67–68**, 73–94, doi:10.1016/S0169-8095(03)00045-0.

Bunkers, M. J., B. A. Klimowski, J. W. Zeitler, R. L. Thompson, and M. L. Weisman, 2000: Predicting supercell motion using a new hodograph technique. *Wea. Forecasting*, **15**, 61–79, doi:10.1175/1520-0434(2000)015<0061:PSMUAN>2.0.CO;2.

——, ——, and ——, 2002: The importance of parcel choice and the measure of vertical wind shear in evaluating the convective environment. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 379–382.

Celiński-Mysław, D., and D. Matuszko, 2014: An analysis of selected cases of derecho in Poland. *Atmos. Res.*, **149**, 263–281, doi:10.1016/j.atmosres.2014.06.016.

Clark, M. R., 2009: The southern England tornadoes of 30 December 2006: Case study of a tornadic storm in a low

CAPE, high shear environment. *Atmos. Res.*, **93**, 50–65, doi:10.1016/j.atmosres.2008.10.008.

Coniglio, M. C., D. J. Stensrud, and M. B. Richman, 2004: An observational study of derecho-producing convective systems. *Wea. Forecasting*, **19**, 320–337, doi:10.1175/1520-0434(2004)019<0320:AOSODC>2.0.CO;2.

Corfidi, S. F., S. J. Corfidi, D. A. Imy, and A. L. Logan, 2006: A preliminary study of severe wind-producing MCSs in environments of limited moisture. *Wea. Forecasting*, **21**, 715–734, doi:10.1175/WAF947.1.

Craven, J. P., and H. E. Brooks, 2004: Baseline climatology of sounding derived parameters associated with deep moist convection. *Natl. Wea. Dig.*, **28**, 13–24. [Available online at http://www.nssl.noaa.gov/users/brooks/public_html/papers/cravenbrooksnwa.pdf.]

——, R. E. Jewell, and H. E. Brooks, 2002: Comparison between observed convective cloud-base heights and lifting condensation level for two different lifted parcels. *Wea. Forecasting*, **17**, 885–890, doi:10.1175/1520-0434(2002)017<0885:CBOCCB>2.0.CO;2.

Czernecki, B., M. Taszarek, L. Kolendowicz, and J. Konarski, 2016: Relationship between human observations of thunderstorms and the PERUN lightning detection network in Poland. *Atmos. Res.*, **167**, 118–128, doi:10.1016/j.atmosres.2015.08.003.

Darkow, G. L., 1969: An analysis of over sixty tornado proximity soundings. Preprints, *Sixth Conf. on Severe Local Storms*, Chicago, IL, Amer. Meteor. Soc., 218–221.

Davies, J. M., and R. H. Johns, 1993: Some wind and instability parameters associated with strong and violent tornadoes: 1. Wind shear and helicity. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards*, *Geophys. Monogr.*, Vol. 79, Amer. Geophys. Union, 573–582, doi:10.1029/GM079.

Doswell, C. A., III, and E. N. Rasmussen, 1994: The effect of neglecting the virtual temperature correction on CAPE calculations. *Wea. Forecasting*, **9**, 625–629, doi:10.1175/1520-0434(1994)009<0625:TEONTV>2.0.CO;2.

——, and J. S. Evans, 2003: Proximity sounding analysis for derechos and supercells: An assessment of similarities and differences. *Atmos. Res.*, **67–68**, 117–133, doi:10.1016/S0169-8095(03)00047-4.

Dotzek, N., P. Groenemeijer, B. Feuerstein, and A. M. Holzer, 2009: Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD. *Atmos. Res.*, **93**, 575–586, doi:10.1016/j.atmosres.2008.10.020.

Edwards, R., and R. L. Thompson, 1998: Nationwide comparisons of hail size with WSR-88D vertically integrated liquid water and derived thermodynamic sounding data. *Wea. Forecasting*, **13**, 277–285, doi:10.1175/1520-0434(1998)013<0277:NCOHSW>2.0.CO;2.

Evans, J. S., and C. A. Doswell III, 2001: Examination of derecho environments using proximity soundings. *Wea. Forecasting*, **16**, 329–342, doi:10.1175/1520-0434(2001)016<0329:EODEUP>2.0.CO;2.

Evans, M., 2010: An examination of low CAPE/high shear severe convective events in the Binghamton, New York county warning area. *Natl. Wea. Dig.*, **34**, 129–144.

Fawbush, E. J., and R. C. Miller, 1952: A mean sounding representative of the tornadic airmass environment. *Bull. Amer. Meteor. Soc.*, **35**, 303–307.

——, and ——, 1954: The types of air masses in which North American tornadoes form. *Bull. Amer. Meteor. Soc.*, **35**, 154–165.

Fujita, T. T., 1971: Proposed characterization of tornadoes and hurricanes by area and intensity. SMRP Research Paper 91, University of Chicago, 42 pp.

——, 1990: Downbursts: Meteorological features and wind field characteristics. *J. Wind Eng. Ind. Aerodyn.*, **36**, 75–86, doi:10.1016/0167-6105(90)90294-M.

Gatzen, C., 2011: A 10-year climatology of cold-season narrow cold-frontal rainbands in Germany. *Atmos. Res.*, **100**, 366–370, doi:10.1016/j.atmosres.2010.09.018.

——, T. Púčik, and D. Ryva, 2011: Two cold-season derechoes in Europe. *Atmos. Res.*, **100**, 740–748, doi:10.1016/j.atmosres.2010.11.015.

Grams, J. S., R. L. Thompson, D. V. Snively, J. A. Prentice, G. M. Hodges, and L. J. Reames, 2012: A climatology and comparison of parameters for significant tornado events in the United States. *Wea. Forecasting*, **27**, 106–123, doi:10.1175/WAF-D-11-00008.1.

Groenemeijer, P. H., and A. van Delden, 2007: Sounding-derived parameters associated with large hail and tornadoes in the Netherlands. *Atmos. Res.*, **83**, 473–487, doi:10.1016/j.atmosres.2005.08.006.

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

Grünwald, S., and H. E. Brooks, 2011: Relationship between sounding derived parameters and the strength of tornadoes in Europe and the USA from reanalysis data. *Atmos. Res.*, **100**, 479–488, doi:10.1016/j.atmosres.2010.11.011.

Holmes, J. D., and S. E. Oliver, 2000: An empirical model of a downburst. *Eng. Struct.*, **22**, 1167–1172, doi:10.1016/S0141-0296(99)00058-9.

Johns, R. H., and C. A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7**, 588–612, doi:10.1175/1520-0434(1992)007<0588:SLSF>2.0.CO;2.

Kaltenböck, R., G. Diendorfer, and N. Dotzek, 2009: Evaluation of thunderstorm indices from ECMWF analyses, lightning data and severe storm reports. *Atmos. Res.*, **93**, 381–396, doi:10.1016/j.atmosres.2008.11.005.

Keul, A. G., M. V. Sioutas, and W. Szilagyi, 2009: Prognosis of central-eastern Mediterranean waterspouts. *Atmos. Res.*, **93**, 426–436, doi:10.1016/j.atmosres.2008.10.028.

Markowski, P. M., and Y. P. Richardson, 2009: Tornadogenesis: Our current understanding, forecasting considerations, and questions to guide future research. *Atmos. Res.*, **93**, 3–10, doi:10.1016/j.atmosres.2008.09.015.

Petersen, W. A., S. A. Rutledge, and R. E. Orville, 1996: Cloud-to-ground lightning observations from TOGA COARE: Selected results and lightning location algorithms. *Mon. Wea. Rev.*, **124**, 602–620, doi:10.1175/1520-0493(1996)124<0602:CTGLOF>2.0.CO;2.

Przybylinski, R. W., 1995: The bow echo: Observations, numerical simulations, and severe weather detection methods. *Wea. Forecasting*, **10**, 203–218, doi:10.1175/1520-0434(1995)010<0203:TBEONS>2.0.CO;2.

Púčik, T., 2016: Future changes in severe thunderstorm environments over Europe. *28th Conf. on Severe Local Storms*, Portland, OR, Amer. Meteor. Soc., 2.2. [Available online at https://ams.confex.com/ams/28SLS/webprogram/Paper300871.html.]

——, P. Groenemeijer, D. Rýva, and M. Kolář, 2015: Proximity soundings of severe and nonsevere thunderstorms in central Europe. *Mon. Wea. Rev.*, **143**, 4805–4821, doi:10.1175/MWR-D-15-0104.1.

Rasmussen, E. N., and R. B. Wilhelmson, 1983: Relationships between storm characteristics and 1200 GMT hodographs, low-level shear, and stability. Preprints, *13th Conf. on Severe Local Storms*, Tulsa, OK, Amer. Meteor. Soc., J5–J8.

——, and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Wea. Forecasting*, **13**, 1148–1164, doi:10.1175/1520-0434(1998)013<1148:ABCOSD>2.0.CO;2.

Renko, T., T. Kozarić, and M. Tudor, 2013: An assessment of waterspout occurrence in the Eastern Adriatic basin in 2010: Synoptic and mesoscale environment and forecasting method. *Atmos. Res.*, **123**, 71–81, doi:10.1016/j.atmosres.2012.06.018.

——, J. Kuzmić, V. Šoljan, and N. S. Mahović, 2016: Waterspouts in the Eastern Adriatic from 2001 to 2013. *Nat. Hazards*, **82**, 441–470, doi:10.1007/s11069-016-2192-5.

Sherburn, K. D., and M. D. Parker, 2014: Climatology and ingredients of significant severe convection in high-shear, low-CAPE environments. *Wea. Forecasting*, **29**, 854–877, doi:10.1175/WAF-D-13-00041.1.

Silverman, B. W., 1986: *Density Estimation for Statistics and Data Analysis. Monogr. on Statistics and Applied Probability*, Vol. 26, Chapman and Hall/CRC Press, 176 pp.

Sioutas, M., W. Szilagyi, and A. Keul, 2013: Waterspout outbreaks over areas of Europe and North America: Environment and predictability. *Atmos. Res.*, **123**, 167–179, doi:10.1016/j.atmosres.2012.09.013.

Smith, B. T., R. L. Thompson, J. S. Grams, C. Broyles, and H. E. Brooks, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part I: Storm classification and climatology. *Wea. Forecasting*, **27**, 1114–1135, doi:10.1175/WAF-D-11-00115.1.

Szilagyi, W., 2009: A waterspout forecasting technique. Preprints, *Fifth European Conf. on Severe Storms*, Landshut, Germany, ECSS/European Meteorological Society, 12–16.

Taszarek, M., and L. Kolendowicz, 2013: Sounding-derived parameters associated with tornado occurrence in Poland and Universal Tornadic Index. *Atmos. Res.*, **134**, 186–197, doi:10.1016/j.atmosres.2013.07.016.

——, B. Czernecki, and A. Kozioł, 2015: A cloud-to-ground lightning climatology for Poland. *Mon. Wea. Rev.*, **143**, 4285–4304, doi:10.1175/MWR-D-15-0206.1.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting*, **18**, 1243–1261, doi:10.1175/1520-0434(2003)018<1243:CPSWSE>2.0.CO;2.

——, B. T. Smith, J. S. Grams, A. R. Dean, and C. Broyles, 2012: Convective modes for significant severe thunderstorms in the contiguous United States. Part II: Supercell and QLCS tornado environments. *Wea. Forecasting*, **27**, 1136–1154, doi:10.1175/WAF-D-11-00116.1.

——, ——, A. R. Dean, and P. T. Marsh, 2013: Spatial distributions of tornadic near-storm environments by convective mode. *Electron. J. Severe Storms Meteor.*, **8** (5). [Available online at http://ejssm.org/ojs/index.php/ejssm/article/viewArticle/125.]

Wakimoto, R. M., 1985: Forecasting dry microburst activity over the high plains. *Mon. Wea. Rev.*, **113**, 1131–1143, doi:10.1175/1520-0493(1985)113<1131:FDMAOT>2.0.CO;2.

Wapler, K., 2013: High-resolution climatology of lightning characteristics within Central Europe. *Meteor. Atmos. Phys.*, **122**, 175–184, doi:10.1007/s00703-013-0285-1.

Weisman, M. L., and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.*, **110**, 504–520, doi:10.1175/1520-0493(1982)110<0504:TDONSC>2.0.CO;2.