Proximity Soundings of Severe and Nonsevere Thunderstorms in Central Europe

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ABSTRACT

The environments of severe and nonsevere thunderstorms were analyzed using 16 421 proximity soundings from December 2007 to December 2013 taken at 32 central European stations. The soundings were assigned severity categories for the following hazards: hail, wind, tornado, and rain. For each of the soundings, parameters were calculated representing the instability, vertical wind profile, and moisture of the environment. The probability of the various hazards as a function of CAPE and 0–6-km bulk shear (DLS) is quite different for each of the hazards. Large hail is most likely for high CAPE and high DLS, a regime that also supports severe wind events. A second severe wind regime exists for low CAPE and very high DLS. These events are mostly cold season events. Storms with significant tornadoes occur with much higher DLS than storms with weak or no tornadoes, but with similar CAPE. The 0–1-km bulk shear (LLS) does not discriminate better than DLS between weak and significant tornadoes. Heavy rain events occur across a wide range of DLS, but with CAPE above the median for nonsevere thunderstorms and are most likely when both absolute humidity in the boundary layer and relative humidity in the low- to midtroposphere are high. LCL height does not discriminate well between the intensity categories of tornadoes, but higher LCL heights were associated with a higher probability of severe hail. Storm relative helicity shows similar results to DLS, but with more overlap among intensity categories.

1. Introduction

Per definition, any thunderstorm produces lightning. Whether thunderstorms produce hazardous convective weather (HCW) such as large hail, severe wind gusts, extreme rainfall, and tornadoes is an important challenge for weather forecasters. Such forecasts require knowledge of the environment of the storms, which can be obtained from radiosonde measurements or numerical weather prediction models.

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This study has three main aims. First, we want to document the environments of severe and nonsevere thunderstorms across central Europe using proximity soundings, radiosonde measurements, taken close to a (severe) thunderstorm, in order to identify potential predictors for the hazardous weather phenomena. The second aim is to compare the environments of all four hazards associated with thunderstorms (large hail, severe wind gusts, tornadoes, and heavy rain). The last aim is to compare our results with the results of proximity sounding studies done in the United States and in different regions and countries in Europe.

Previously, in Europe, a number of such studies have been carried out that considered smaller regions and considered only one or two hazards: Kunz (2007) for hail and storm or flood damage in southwest Germany, Groenemeijer and van Delden (2007) for tornadoes and hail in the Netherlands, Manzato (2012) for hail in northeast Italy, and Taszarek and Kolendowicz (2013) for tornadoes in Poland. In the United States, studies of proximity soundings of severe storms have been more ubiquitous (e.g., Darkow 1968; Brooks et al. 1994; Rasmussen and Blanchard 1998; Rasmussen 2003; Cohen et al. 2007; Jewell and Brimelow 2009). In some relatively recent studies, data from numerical model analyses have been used more and more often in lieu of actual proximity soundings (e.g., Thompson 1998; Thompson et al. 2003; Graf et al. 2011; Grünwald and Brooks 2011; Grams et al. 2012; Allen and Karoly 2014; Johnson and Sugden 2014).

A straightforward way to characterize the environment of thunderstorms is to assess the presence of three ''ingredients'' necessary for the occurrence of deep, moist convection (Johns and Doswell 1992). These are (i) sufficient low-level moisture, (ii) conditionally unstable temperature lapse rates in the midtroposphere, and (iii) sufficient lift to transport a potentially buoyant parcel to its level of free convection. The presence of low-level moisture and midlevel conditional instability ensures that the lifted parcel has sufficient buoyancy to sustain a convective updraft, whereas the lift is required to initiate the storm.

For well-organized storms, such as supercells and squall lines, strong vertical wind shear can be regarded as an additional, fourth, ingredient. This was demonstrated both in numerical studies (e.g., Weisman and Klemp 1982), and in studies of storm environments (Rasmussen and Blanchard 1998; Thompson et al. 2003, 2013). Smith et al. (2012) have shown that such well-organized storms are responsible for the vast majority of significant severe weather in the United States.

Three of the ingredients (i.e., all except lift), can be analyzed using radiosonde data. The combined presence of the ingredients low-level moisture and midlevel conditional instability results in convective available potential energy (CAPE). Previous proximity sounding studies have indeed confirmed that severe weather probability increases with increasing vertical wind shear and with increasing CAPE, both across the United States (Rasmussen and Blanchard 1998; Craven and Brooks 2004; Brooks 2009) and across Europe (Groenemeijer and van Delden 2007; Brooks 2009).

Although all severe storms require these ingredients to some extent, the environmental conditions conducive to a particular hazard differ from one another. For instance, tornadoes are favored by strong vertical wind shear in the lowest kilometer above ground as well as a low lifted condensation level (Brooks and Craven 2002; Thompson et al. 2003; Grünwald and Brooks 2011; Grams et al. 2012). Nontornadic severe winds can be attributed to either long-lived convective windstorms, local downbursts, or a combination of both. Long-lived convective windstorms thrive when CAPE is high and vertical wind shear is strong (e.g., Coniglio et al. 2010), but can form under a wide variety of environments (Evans and Doswell 2001), including environments with very low CAPE (Corfidi et al. 2006; Gatzen 2011). Local downbursts may even form with both small CAPE and weak shear, in case the boundary layer is deep and dry (Wakimoto 1985). This dryness enhances evaporative cooling and promotes negative buoyancy in the downdraft, which can be quantified by downdraft CAPE (DCAPE). In a study for the United States, Kuchera and Parker (2006) found that the product of DCAPE and ground-relative wind in a storm's inflow layer was the most successful predictor of convective severe wind gusts.

Large hail events are often associated with supercells, in particular very large hail (5-cm diameter or more; Smith et al. 2012) and supercells occur with strong deep-layer wind shear. The importance of wind shear for large hail was noted by Berthet et al. (2013) and Johnson and Sugden (2014). In addition, several studies have shown that large hail typically occurs with substantial CAPE (Groenemeijer and van Delden 2007; Kunz 2007; Manzato 2012; Johnson and Sugden 2014). Johnson and Sugden (2014), however, note that the overlap of CAPE distributions between hail size categories is large, in line with the study by Edwards and Thompson (1998) who found that thermodynamic environment parameters (such as CAPE or height of the freezing level) are poor predictors for hail size.

Excessive precipitation events in thunderstorms result from a combination of high rainfall intensity and long rainfall duration (Doswell et al. 1996). Rainfall intensity depends on the upward moisture flux in a storm and on the storm's precipitation efficiency. The upward moisture flux is in part controlled by the updraft speed and also depends on the moisture content of the inflow layer. Precipitation efficiency is controlled, among other factors, by wind shear (e.g., Fankhauser 1988), and tends to be highest when the wind shear is weak.

In what follows, we will present our study, which used 16 421 thunderstorm proximity soundings, a number larger than that of Groenemeijer and van Delden (2007) whose study contained 2045 thunderstorm proximity soundings.

In section 2 of this study, we present the methodology, datasets, and the tested parameters. In section 3, the results are introduced, with subsections dealing with individual parameters or their combinations. Section 4 is dedicated to the discussion of some of the results, while in section 5 we briefly summarize them.

FIG. 1. Terrain map of central Europe. Blue dots represent the locations of the sounding sites.

2. Data and methods

a. Area of study

This study concentrates on central Europe and includes these countries and their sounding measurement sites: Austria, Croatia, the Czech Republic, Germany, Hungary, the Netherlands, Poland, Slovakia, Slovenia, Switzerland, and the northern part of Italy. A map of this area and the sounding sites can be found in Fig. 1.

b. Lightning data

More than six years in total have been investigated, spanning the period between 1 December 2007 and 31 December 2013. To detect the presence of a thunderstorm, we used data from the European Cooperation for Lightning Detection (EUCLID) network. This network consists of more than 140 lightning sensors across Europe and covers the area of study. Schulz et al. (2014) demonstrated that the Austrian section of the network has a flash detection efficiency of 96%, for return stroke peak currents greater than 2 kA, and 100% for peak currents exceeding 10 kA. Lightning data were provided in a gridded format (resolution 0.25°), yielding an hourly number of observed cloud-to-ground strikes for each grid point.

c. Proximity soundings

Sounding data were downloaded from the web server of the University of Wyoming (University of Wyoming 2014). From these data, we computed a number of convection-related parameters. To identify proximity soundings to thunderstorms, we required that at least three lightning strikes were detected within 150 km from the sounding site between the sounding time and 3 hours later. This definition was chosen as a compromise between the representativeness of the sounding measurements and the number of proximity soundings that would result for each hazard type. Similar criteria have been used by other authors; for example, Evans and Doswell (2001) (2 h and 167 km), Craven and Brooks (2004) (3 h and 185 km), and Cohen et al. (2007) (3 h and 200 km). The requirement of a minimum of three lightning discharges was introduced in order to filter out any isolated false lightning detections. Soundings at all available times were used. At some stations, measurements are taken four times per day at 0000, 0600, 1200, and 1800 UTC (e.g., Idar-Oberstein, Germany, Udine, Italy), while most of the stations only measure at 0000 and 1200 UTC. Austrian airport sounding stations (Linz, Graz, and Innsbruck) launch a sounding only at 0300 UTC. The distribution of numbers of proximity soundings across different sites and measurement times can be found in Table 1. For every proximity sounding, we checked whether it contained complete temperature and wind data at least up to 100 hPa and humidity data at least up to 500 hPa. If not, the sounding was discarded. In total, we obtained 16 421 thunderstorm proximity soundings. A list of calculated parameters and their abbreviations can be found in Table 2.

For all CAPE calculations, the virtual temperature correction was applied to the parcel as proposed by Doswell and Rasmussen (1994). DCAPE was calculated by sinking the parcel with the lowest θ_e in the bottom 300 hPa. For storm relative helicity (SRH) calculations, the right-moving storm motion vector from Bunkers et al. (2000) was used. An updated method to estimate storm motion is described by Bunkers et al. (2014). However, we did not use it because some of our soundings involved 0 J kg^{-1} of CAPE whereas this method requires the presence of a buoyant parcel.

d. Severe weather data

For each of the thunderstorm proximity soundings, we checked if severe weather occurred for which we used the same spatial and temporal proximity criterion as for lightning. Severe weather reports were obtained from the European Severe Weather Database (ESWD). More information about the database and its limitations can be found in the publications by Dotzek et al. (2009) and Groenemeijer and Kühne (2014). We considered reports of the hazards ''large hail'' (hereafter hail), ''severe wind gust'' (hereafter wind), ''heavy rain'' (hereafter rain), and ''tornado.''

All reports were divided into three intensity categories: (i) nonsevere, (ii) severe, and (iii) extremely

TABLE 1. Number of proximity soundings associated with particular sounding sites and measurement times. Stations were ordered according to the number of proximity soundings in descending order.

Station ID	Station name	Hour 0	3	6	12	18	Total
16044	Udine	429	0	144	647	77	1297
16080	Milano	411	0	0	555	0	966
11520	Prague	151	0	105	340	296	892
14430	Zadar	382	0	0	500	0	882
10618	Idar–Oberstein	152	0	101	293	297	843
14240	Zagreb	284	0	0	508	0	792
10393	Lindenberg	128	0	91	255	263	737
10238	Bergen	105	0	94	257	233	689
11952	Poprad	197	0	0	461	0	658
11035	Wien	197	0	0	438	0	635
6610	Payerne	214	0	0	390	0	604
10868	Munich	201	0	0	384	0	585
11747	Prostejov	162	0	0	342	0	504
10739	Stuttgart	172	0	0	325	0	497
16144	S Pietro Capofiume	355	0	0	138	0	493
10771	Kuemmersbruck	142	0	0	305	0	447
12843	Budapest	179	0	0	255	0	434
12425	Wroclaw	149	0	0	285	0	434
10548	Meiningen	132	0	0	289	0	421
16113	Cuneo	168	0	0	245	0	413
12374	Legionowo	130	0	0	280	0	410
10410	Essen	115	0	0	264	0	379
10035	Schleswig	143	0	0	219	0	362
6260	De Bilt	156	0	0	202	0	358
12120	Leba	138	0	0	194	0	332
10184	Greifswald	108	0	0	191	0	299
10200	Emden	102	0	0	141	0	243
11240	Graz	0	199	0	0	0	199
12982	Szeged	170	0	0	18	0	188
10113	Norderney	77	0	0	93	0	170
11120	Innsbruck	0	146	0	0	0	146
11010	Linz	0	112	0	0	0	112
Total		5449	457	535	8814	1166	16 421

severe, in accordance with the criteria given in Table 3. In case of heavy rain, we omitted the extremely severe category. The reason for this choice was that most of the rain reports did not include a rainfall measurement and that the severity of a flood also depends on a variety of nonmeteorological factors. We will refer to the non-severe, severe, and extremely severe categories for tornadoes as the ‘‘no tornado,’’ ‘‘weak tornado,’’ and ‘‘significant tornado’’ categories, respectively.

The number of proximity soundings associated with the severe and extremely severe intensities of particular events can be found in Table 4. Out of the 16 421 soundings, 3866 (23.54%) were associated with at least one type of severe weather and 505 (3.08%) of them were associated with at least one type of extremely severe weather. Tornadoes were less frequent compared to the other forms of severe weather as only 3.3% of soundings were associated with tornadoes (both weak and strong), compared to 10.0% associated with severe hail (both severe and extremely severe), 8.0% with severe wind, and 13.7% with severe rain. Situations in which all severe types occurred together were very rare. Just 78 (0.47%) soundings involved all four types of severe weather and only four soundings were associated with extreme intensities of hail, wind, and tornado at the same time.

3. Results

a. CAPE

Based on the results of prior research, one may expect an increase of CAPE for increasing severe weather intensity. Indeed, Fig. 2 shows that for all phenomena MUCAPE is higher for the severe than for the non-severe category, but there is considerable overlap between the distributions. Hail events show the greatest

TABLE 2. Parameters used in the study, including their abbreviations and units.

Parameter description	Abbreviation	Units
Thermodynamic parameters		
50-hPa mixed-layer CAPE	MLCAPE	$J\,kg^{-1}$
Most unstable CAPE of any parcel in the lowest 300 hPa	MUCAPE	$J\,kg^{-1}$
Downdraft CAPE, lowest 300 hPa	DCAPE	$J\,kg^{-1}$
Avg temperature lapse rate in 800 to 600 hPa	LR86	$K\,km^{-1}$
LCL heights		
LCL using 50-hPa mixed-layer parcel	MLLCL	m
LCL using most unstable parcel	MULCL	m
Humidity parameters		
Average dewpoint in the lowest 50 hPa	AVGTD	°C
Average relative humidity surface–600 hPa	AVGRH	%
Wind parameters		
Bulk wind shear 0*–6 km AGL	DLS	$m\,s^{-1}$
Bulk wind shear 0*–3 km AGL	MLS	$m\,s^{-1}$
Bulk wind shear 0*–1 km AGL	LLS	$m\,s^{-1}$
Max wind between 0* and 4 km AGL	WMAX	$m\,s^{-1}$
Storm relative helicity in 0*–3 km AGL	SRH3	$m^2\,s^{-2}$
Storm relative helicity in 0*–1 km AGL	SRH1	$m^2\,s^{-2}$

* The 0 km AGL wind should be understood to mean the wind at 10 m AGL.

increase in MUCAPE for increasing severity. The extremely severe category features a very wide range of MUCAPE values, suggesting that extremely severe hail events are not restricted to the environments of high CAPE.

For wind events, an increase in median MUCAPE is apparent only between the nonsevere and severe category. The median actually slightly decreases when going from the severe to the extremely severe category, because a sizeable fraction of extremely severe wind events are associated with very low CAPE. In total, 56 (25.5%) of the extremely severe wind event soundings had MUCAPE less than $100\,J\,kg^{-1}$. Of these 56 soundings, 27 were taken in the period between October and March.

Tornadoes show very similar results to the wind events as the median CAPE increases only between the no tornado and weak tornado category. Significant tornadoes have a larger variation of CAPE values, with a fatter tail toward high values. Overall, CAPE cannot discriminate between the ''severe'' and ''extremely severe'' categories for wind or tornadoes as the median values of these categories are almost equal. For hail, however, an increase in CAPE with increasing severity can be observed. The CAPE distribution for severe rain events is similar to that of the severe and extremely severe tornado events.

b. 0–6-km bulk shear (DLS)

Several studies found that 0–6-km bulk shear (DLS) discriminates well between supercell and nonsupercell convection (Rasmussen and Blanchard 1998; Thompson et al. 2003). Because supercells are almost always accompanied by severe weather (Duda and Gallus 2010; Smith et al. 2012), we study the changing distribution of DLS with increasing severe weather intensity.

Figure 3 shows that DLS increases with increasing severity of hail, wind, and tornadoes, but not of rain. For the hail events, the increase is more pronounced between the severe and extremely severe category than between the nonsevere and severe category. That may be because very large hail is almost exclusively related to supercells (Smith et al. 2012), whereas smaller hail may occur with weakly organized storms.

For wind events, an increase is observed across all intensity categories. There is slightly more overlap between the severe and extremely severe than between the nonsevere and severe category.

TABLE 3. Criteria for nonsevere, severe, and extremely severe events of different hazard type.

Intensity	Event type: Hail (diameter)	Wind (gust speed, or F scale)	Tornado (F scale)	Rain
Nonsevere	<2 cm	$<25\,m\,s^{-1}$	No tornado	No flooding
Severe	2–5 cm	$25–32\,m\,s^{-1}$, or F0	F0 or F1 ''weak tornado''	Flooding
Extremely severe	≥5 cm	$\geq 32\,m\,s^{-1}$, or F1+	F2+ ''significant tornado''	—

TABLE 4. Number of nonsevere, severe, and extremely severe events associated with hail, wind, tornado, and rain. Total severe represents the sum of severe and extremely severe events; percentages are shown in parentheses.

	Event type			
Intensity	Hail	Wind	Tornado	Rain
Nonsevere	14 786 (90.0%)	15 112 (92.0%)	15 885 (96.7%)	14 166 (86.3%)
Severe	1373 (8.4%)	1089 (6.6%)	482 (2.9%)	2255 (13.7%)
Extremely severe	262 (1.6%)	220 (1.3%)	54 (0.3%)	—
Total severe	1635 (10.0%)	1309 (8.0%)	536 (3.3%)	2255 (13.7%)

Tornadoes show almost no increase between the no tornado and weak tornado category. However, the increase is much more pronounced toward the significant tornado category. The 10th percentile of the significant tornado category is higher than the median of weak tornado category. The median is $22\,\mathrm{m\,s^{-1}}$ and the 10th percentile is at $15\,\mathrm{m\,s^{-1}}$. The strongest increase of DLS is between the weak and significant tornado categories. We suppose that this is because the significant tornadoes (F2+), unlike the weak tornadoes, were likely produced mostly by supercells, which require strong DLS. This is also highlighted by the lack of significant tornadoes with low values of DLS. Rain events do not show any dependence on the DLS, with a strong overlap in the median and interquartile range values between the nonsevere and severe categories, both of them largely concentrated in the nonsupercell section of the parameter space (DLS below $20\,\mathrm{m\,s^{-1}}$).

Note that extremely severe hail, wind, and significant tornadoes have a median DLS of around $20\,\mathrm{m\,s^{-1}}$, a value close to those found by Rasmussen and Blanchard (1998) for tornadic and nontornadic supercell convection (18.4 and $19.4\,\mathrm{m\,s^{-1}}$, respectively, for 0–500 m to 6 km AGL bulk shear) or Thompson et al. (2003) (22 and $25\,\mathrm{m\,s^{-1}}$, respectively). This supports the notion that these extremely severe events often occur with well-organized supercell or linear convection. In contrast, the results do not indicate any relation between rain events and the degree of storm organization.

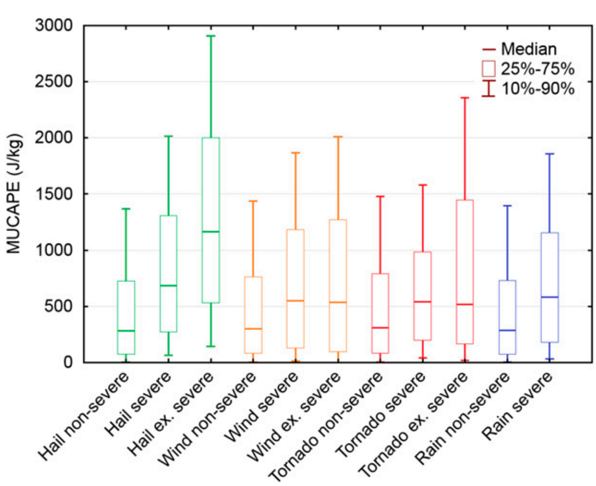

FIG. 2. Box-and-whisker plot of MUCAPE values for each intensity category of hail, wind, tornado, and rain events. The median is represented as a horizontal line, boxes represent the 25th–75th percentile values, and whiskers represent the 10th–90th percentile values.

c. Joint CAPE–shear distribution

The combination of CAPE and DLS has been used as a crude proxy for severe weather environments in climatological studies (e.g., Brooks 2009, 2013; Diffenbaugh et al. 2013). Therefore, we would like to explore the joint distribution of severe events in the two-dimensional CAPE–DLS parameter space. Scatterplots for MUCAPE and DLS confirm that for each of the four event types, nonsevere, severe, and extremely severe events happen over a very wide range of parameter values (Fig. 4). That said, there are clear differences between some of the distributions.

In the case of hail, there is a lack of severe events in low MUCAPE and low DLS environments. The highest concentration of extremely severe events is confined to the space of high MUCAPE and high DLS values. Centroids for severity categories (representing the median values of

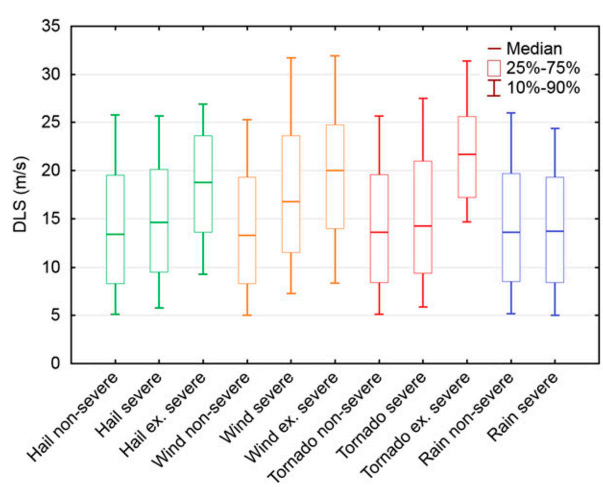

FIG. 3. As in Fig. 2, but for DLS.

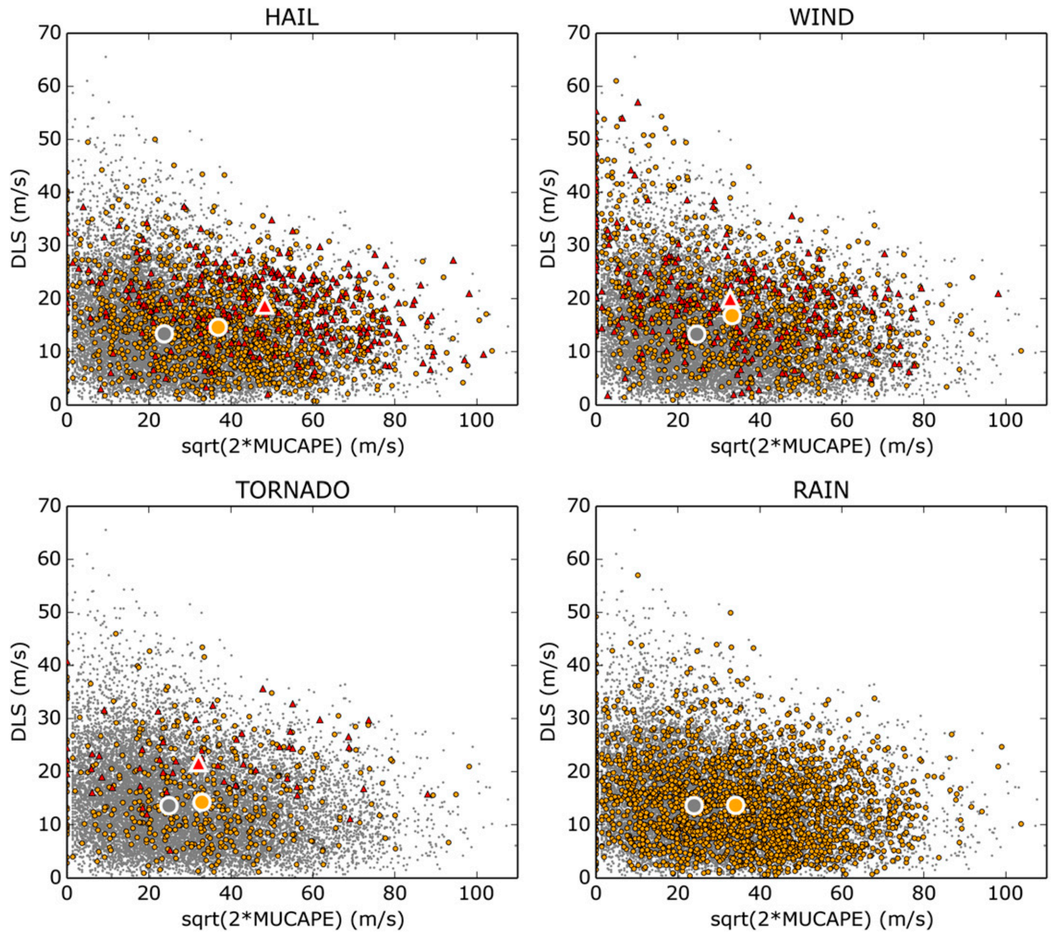

FIG. 4. Scatterplot of nonsevere (gray dots), severe (yellow dots), and extremely severe events (red triangles) with respect to the distribution of $(2 \times \mathrm{MUCAPE})^{1/2}$ and DLS for hail, wind, tornado, and wind categories. The large gray dot, yellow dot, and red triangle represent the median values of $(2 \times \mathrm{MUCAPE})^{1/2}$ and DLS of nonsevere, severe, and extremely severe events, respectively.

MUCAPE and DLS for the given category) shift primarily to increasing MUCAPE with increasing severity. Shift toward both increasing MUCAPE and DLS occurs between the severe and extremely severe category.

In the case of wind, the centroid shifts toward both higher MUCAPE and DLS between the nonsevere and severe category. Shift in the centroid between severe and extremely severe category is only toward the higher DLS. Furthermore, they are in close proximity to each other meaning that the combination of MUCAPE and DLS does not discriminate well between severe and extremely severe wind gusts. The scatterplot also shows numerous severe and extremely severe events in environments of very low CAPE and very high DLS (values above $30\,\mathrm{m\,s^{-1}}$), which are likely the winter type, strongly forced situations we discussed above.

The centroid of tornadoes first shifts to higher MUCAPE when going from the no tornado to the weak tornado category and then shifts to higher DLS for the significant tornado category. It appears that tornadoes require some amount of CAPE, and typically occur with somewhat more CAPE than an average thunderstorm, but their intensity depends mainly on the degree of vertical wind shear.

Severe rain events only show dependence on MUCAPE, which is demonstrated by the shift of the centroid toward the higher MUCAPE but not toward DLS. It is also apparent that severe rain occurs almost across the entire MUCAPE–DLS space. Rain events are only rare for low CAPE and strong DLS.

Although the scatterplot of Fig. 4 gives an indication of the distribution of the data points, it is very hard if at all possible to estimate the ratios of the density of the intensity categories at any one location in parameter space. The small differences in centroids of the distributions may give the impression that these ratios will not

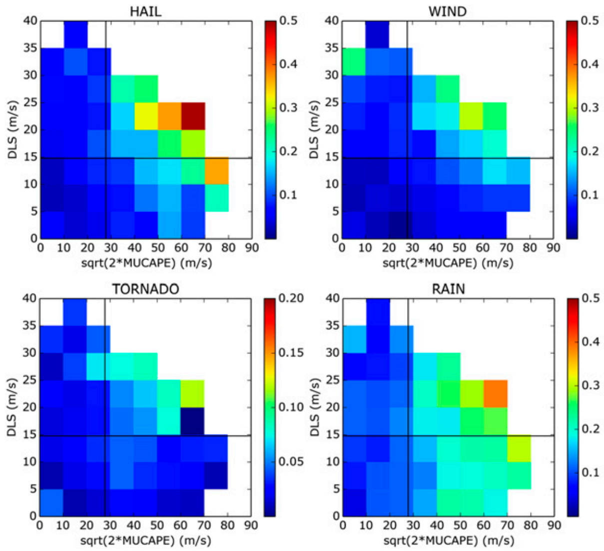

FIG. 5. Probability of severe (including extremely severe) as a function of $(2 \times \mathrm{MUCAPE})^{1/2}$ and DLS. Note that the color scale maximum is 0.2 for tornadoes and 0.5 for the other event types. All boxes containing fewer than 50 soundings were masked. Black horizontal line represents the mean value of DLS and vertical line represents the mean value of $(2 \times \mathrm{MUCAPE})^{1/2}$ of all thunderstorm soundings.

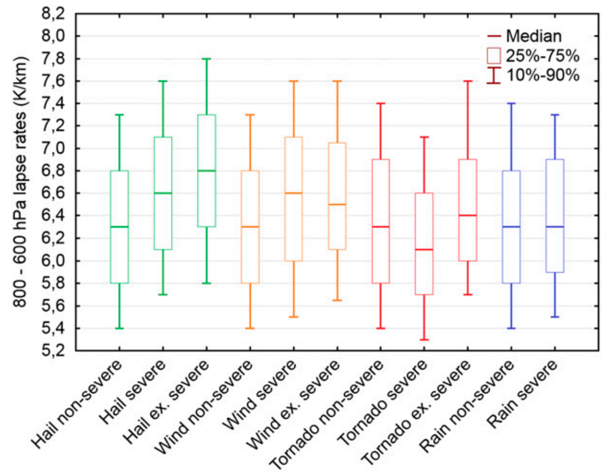

FIG. 6. As in Fig. 2, but for LR86.

differ much across the parameter space, but Fig. 5 illustrates that they do.

Figure 5 shows the relative frequency of the severe and extremely severe categories combined. This is an estimate of the true probability of severe or extremely severe weather given that a thunderstorm occurs. Hereafter, the term probability instead of relative frequency will be used. Boxes that contained less than 50 cases were masked in order to reduce the noise in the results.

The probability for all four types of events is highest where MUCAPE is high and DLS is high. The probability of hail strongly increases toward the higher MUCAPE and higher DLS, even reaching 0.5 in one of the boxes, the highest value of all events. Below 30 m s^{-1} of $(2 \times \mathrm{MUCAPE})^{1/2}$, the probability is less than 0.15 in all boxes.

Wind also shows an increase in the probability toward higher MUCAPE and DLS. In contrast to hail, this increase is not as pronounced with a maximum probability of 0.30. The probability of the wind events is small if DLS is below 10 m s^{-1} and if $(2 \times \mathrm{MUCAPE})^{1/2}$ is below 30 m s^{-1}. The only exception to this is a secondary maximum found in the zone of very low CAPE and very high DLS (>30 m s^{-1}). This maximum likely represents the environment of cold season convective systems we mentioned above.

The probability of tornadoes is generally lower than for other events, its maximum value not exceeding 0.15. As for the other phenomena, it generally increases with increasing CAPE and DLS. With DLS values below 15 m s^{-1}, the probability does not exceed 0.05 regardless of the amount of CAPE. The probability is also very low when $(2 \times \mathrm{MUCAPE})^{1/2}$ is below 20 m s^{-1}.

The probability of rain events generally increases for increasing CAPE, both for low and high DLS. There is also an increase for increasing DLS when $(2 \times \mathrm{MUCAPE})^{1/2} > 30$, even though the value distribution of DLS does not differ much between the nonsevere and severe categories (recall Figs. 3 or 4).

d. The 800–600-hPa lapse rate (LR86)

Jointly with low-level moisture, the lapse rate is an important contributor to CAPE. Therefore, it is not surprising that it shows a similar pattern as MUCAPE for hail and wind events (Fig. 6). Only for hail events does the median of LR86 increase with increasing severity (i.e., from 6.3 to 6.8 K km^{-1} between the nonsevere to the extremely severe category), however, with a significant overlap of the interquartile range values.

For wind events, a similar median increase between nonsevere and severe categories is found, but from the severe to extremely severe categories, the median slightly decreases. For tornadoes, the behavior is perhaps unexpected with a decrease going from the nonsevere to the severe category and an increase going from the severe to the extremely severe category. We can only speculate that nonmesocyclonic weak tornadoes perhaps depend more on the lower-tropospheric than midtropospheric lapse rates. In case of rain events, there is no change in the lapse rates between the nonsevere

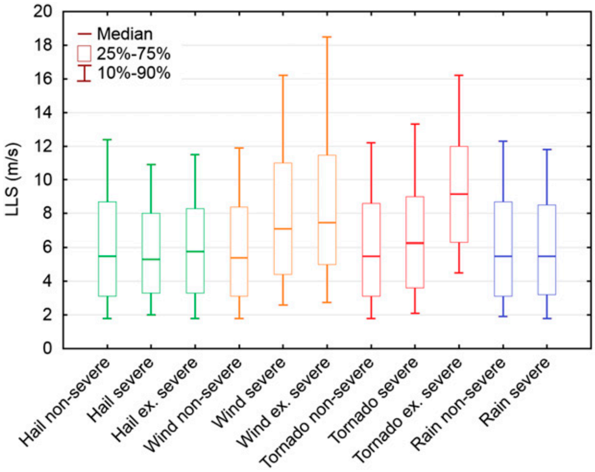

FIG. 7. As in Fig. 2, but for LLS.

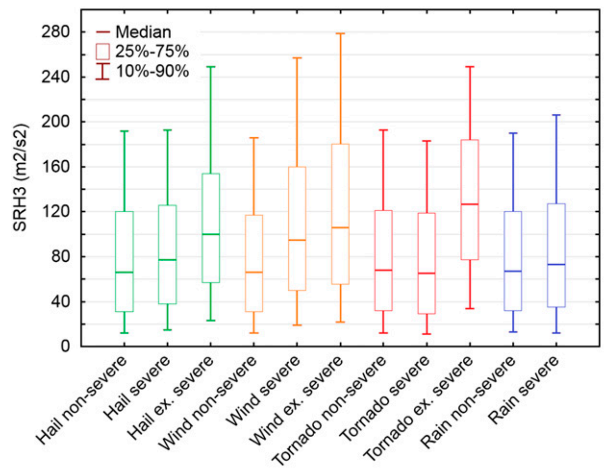

FIG. 8. As in Fig. 2, but for SRH3.

and the severe category, which contrasts with the increase in MUCAPE (Fig. 2). Thus, it is likely that low-level moisture plays an important role in rain events and this ingredient will be discussed more in relation to the rain events in section 3i.

e. Low-level shear (LLS)

The distributions of LLS (Fig. 7) for the event intensities overlap more than was the case for DLS (Fig. 3) for hail and wind as well as tornadoes. For hail events, LLS does not change notably with increasing intensity at all, which contrasts with the substantial increase of DLS between the severe and extremely severe hail categories. For wind events, there is some increase, which, like DLS, is primarily between the nonsevere and severe categories. For tornadoes, however, the increase is mostly between the weak and significant tornado categories. This is the largest difference between any two intensity categories of any hazard. For rain events, LLS is similar for the nonsevere and severe categories.

f. Storm relative helicity

SRH is a parameter commonly used for forecasting supercells and tornadoes. Rasmussen and Blanchard (1998) and Thompson et al. (2003) found that tornadic supercells typically occurred with higher SRH than nontornadic supercells, which in turn occurred with higher SRH than nonsupercells. Therefore, SRH might be a useful predictor for severe weather occurring with organized convection, such as supercells. Indeed, for hail and wind events, we find that SRH3 increases with increasing severity (Fig. 8). For tornadoes, we find an increase as well, but it occurs only between the weak and significant tornado categories. This increase is the greatest among the all other categories, which was also true for DLS and LLS. As we argued for DLS and LLS, we attribute this to the fact that significant tornadoes occur with supercells that thrive in high SRH environments and we assert that weaker tornadoes are mostly nonsupercellular. However, it is impossible to prove this assertion without the radar data. For rain events, SRH3 does not discriminate between the nonsevere and severe categories as interquartile ranges have almost the same values. This can be expected since severe rainfall is not restricted to supercell convection.

Compared to SRH3, DLS is better discriminator between the weak and significant tornadoes, severe and extremely severe hail, or nonsevere and severe wind events, with less overlap between the interquartile range values (refer back to Fig. 3). One possible reason for this is the high spatial and temporal variability of SRH3 (Markowski et al. 1998). Hence, SRH3 values could differ more than DLS between the sounding and event location. We also studied SRH1, with results being similar to SRH3. However, there was more value overlap between the intensity categories of all events (not shown). We believe that this could be attributed to even higher variability of SRH1 compared to SRH3.

g. Lifted condensation level

Mean lifted lifting condensation level (MLLCL) is used for tornado forecasting (e.g., Thompson et al. 2003), with lower values implying a higher tornado probability. Figure 9 shows that for all event types, there are large overlaps between the intensity categories. The median MLLCL changes with increasing severity are the greatest for the hail categories. The increase is primarily between the nonsevere and severe categories. For the wind events, a slight increase of median across all intensity categories is observed. For the tornado events

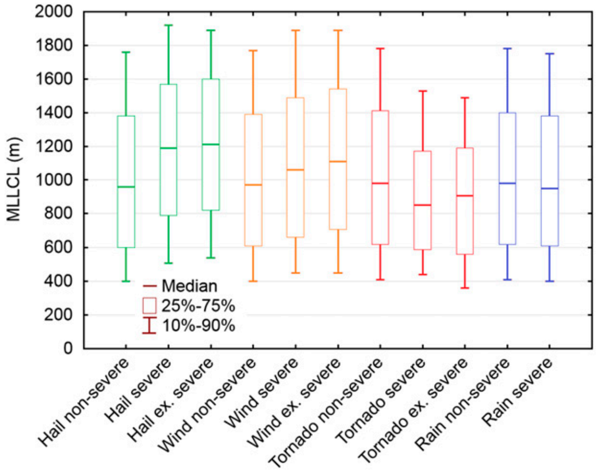

FIG. 9. As in Fig. 2, but for MLLCL.

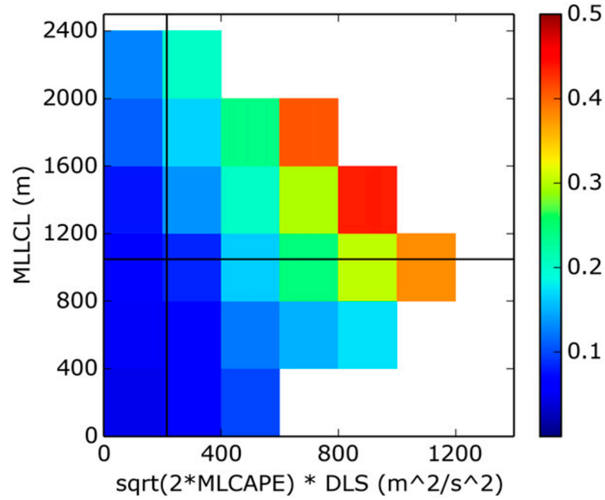

FIG. 10. As in Fig. 5, but for the gridded space of $(2 \times \text{MUCAPE})^{1/2} \times$ DLS vs MLLCL and only for the hail events.

the MLLCL is lower for weak tornado than for the no tornado category. The MLLCL for significant tornado events is not lower than for the weak tornado events. The value distribution of MLLCL (e.g., the interquartile ranges) for rain events shows almost no change between the nonsevere and severe category. We can conclude that MLLCL alone is a poor discriminator among the intensities of all four event types, due to the high overlap of interquartile ranges between the intensity categories. However, in combination with other predictors, parameters may still be useful.

We find that for hail, MLLCL contains additional information about the probability of severe hail besides MLCAPE and DLS. We constructed a predictor for hail by multiplying the square root of MLCAPE with DLS, which per Fig. 5 should be a good predictor. Displaying this parameter against MLLCL shows that the probability of severe hail increases as a function of either predictor (Fig. 10). In other words, given any product of CAPE and shear, a high MLLCL seems to further increase the probability of large hail.

h. *Predictors for wind gusts*

We calculated several parameters specifically for the purpose of severe wind event discrimination. These parameters are DCAPE, bulk wind shear across three different layers, and ground-relative wind speed. The ground-relative wind speed was included because Kuchera and Parker (2006) identified it to be a superior predictor of severe wind gusts compared to bulk wind shear. Ground-relative wind may indeed better represent the momentum to be transported downward by downdrafts than bulk wind shear. We evaluate the maximum ground relative wind speed up to a height of 4 km (WMAX) above ground level.

All four investigated parameters (LLS, MLS, DLS, and WMAX) increase with increasing severity of wind gusts (Fig. 11). Considerable overlap between the interquartile ranges of categories exists in particular for LLS. Each of the parameters shows less interquartile range overlap between nonsevere and severe than between severe and extremely severe. MLS and WMAX show more overlap than LLS and DLS between nonsevere and severe. DLS, on the other hand, has the least interquartile range value overlap between severe and extremely severe.

Figure 12 shows that DCAPE has an additional predictive value over MLS, as the probability of severe wind gusts increases with increasing DCAPE, with the only notable exception being environments of very strong MLS (above 25 m s^{-1}). We believe that this is a reflection of strongly forced convection in winter.

Because convection often forms in different conditions in winter than in summer, we look at the differences between the cold (October–March) and warm season (April–September) severe wind gust events. Table 5 shows that cold season thunderstorm wind events are less frequent than warm season events. One of the differences is that cold season severe wind gusts occurred in much stronger vertical wind shear: the median DLS for cold season events is around 33.2 m s^{-1}, while for warm season events it is only 16.1 m s^{-1}. Vertical wind shear in winter is more confined to the lower levels. Ratio of LLS to DLS is 0.55 for cold season events while it is 0.41 for warm season events. On the other hand, warm season events formed in more moist and unstable environments. The median CAPE for cold season events is only 14 J kg^{-1}. Apparently, cold season

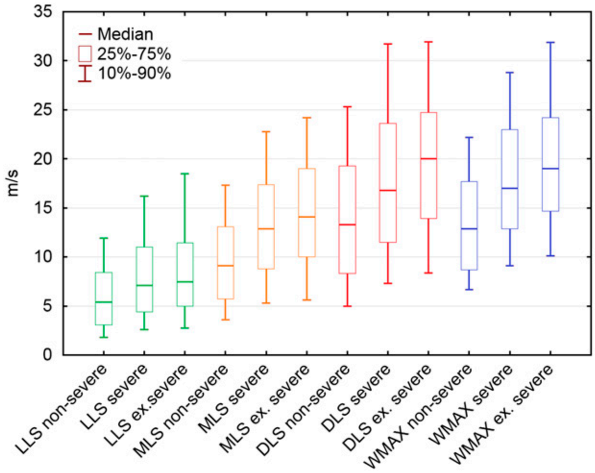

FIG. 11. As in Fig. 2, but for LLS, MLS, DLS, and WMAX, considering only the nonsevere, severe, and extremely severe wind events.

convective storms form in very low CAPE environments. In addition, wintertime proximity soundings may be less representative than in summer, because of the fast movement of convective systems in winter, thereby failing to capture the narrow bands of CAPE ahead of such systems (Gatzen et al. 2011).

i. Rain-related parameters

For the purpose of severe rain events discrimination, we consider parameters related to absolute humidity, the low-level dewpoint temperature (AVGTD), and the relative humidity in the low- to midtroposphere (AVGRH). AVGTD is a measure of the moisture provided to the storm's updraft, while AVGRH reflects the potential for hydrometeor evaporation. The probability of severe rain increases with increasing AVGTD (Fig. 13). A relation with AVGRH can be seen as well: the probability is much lower for AVGRH below 60% than for higher values. Above 60% of AVGRH, the probability seems not to depend on AVGRH. In summary, both plentiful low-level moisture and sufficient relative humidity in the lower troposphere strongly enhance the probability of severe rainfall.

TABLE 5. Number of events and median values of various parameters (MUCAPE, DCAPE, AVGTD, DLS, and LLS) associated with cold and warm season severe wind gust events.

	Cold season	Warm season
No. of events	174	1135
MUCAPE ($\mathrm{J\,kg^{-1}}$)	14	695
DCAPE ($\mathrm{J\,kg^{-1}}$)	79	588
AVGTD (°C)	2.1	14.1
DLS ($\mathrm{m\,s^{-1}}$)	33.2	16.1
LLS ($\mathrm{m\,s^{-1}}$)	18.1	6.6

4. Discussion

a. Comparison with prior results from Europe

Since our study is the first study of proximity soundings of severe thunderstorms in Europe of this magnitude, it is of interest to compare the results with prior studies. Unfortunately, it is difficult to make such a comparison with some of the European studies. The primary reason is the fact that the authors of prior studies used different criteria for severe weather than

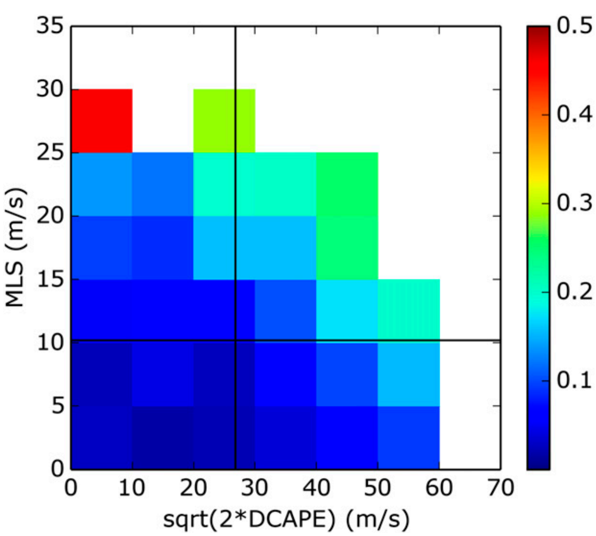

FIG. 12. As in Fig. 5, but for the gridded space of $(2 \times \mathrm{DCAPE})^{1/2}$ vs MLS and only for the wind events.

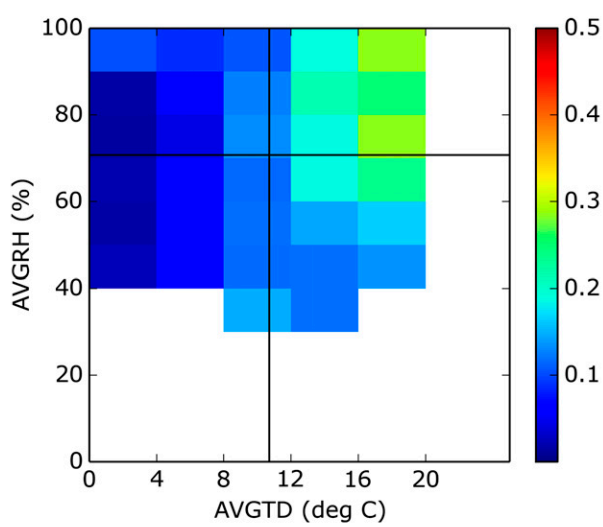

FIG. 13. As in Fig. 5, but for the gridded space of AVGTD vs AVGRH and for the rain events only.

the *Storm Data* or ESWD definitions. For example, studies of Kunz (2007), Manzato (2012), and Berthet et al. (2013) all deal with hail, but none of them use a hail diameter to define the hail severity.

However, similar definitions and approaches to ours were used by Kaltenböck et al. (2009) who investigated severe weather environments in central and western Europe during the warm seasons of 2006 and 2007, but instead of radiosonde measurements used ECMWF forecast data. In total, they used 3406 severe weather events from ESWD, which they divided into severe hail, severe wind gust, weak tornado (F0–F1), significant tornado (F2+), and severe precipitation categories. Groenemeijer and van Delden (2007) performed a very similar study using radiosondes, considering thunderstorm, large hail (categories of hail < 3 cm and hail > 3 cm), and tornado events (categories of F0 and F1+ category) in the Netherlands in the period between December 1975 and August 2003, using severe weather reports from amateur observers. They used sounding data from six stations in and nearby the Netherlands. Taszarek and Kolendowicz (2013) investigated environments of 97 tornado events in Poland (from the ESWD) using the proximity sounding data from 10 sounding stations in and near Poland. They categorized tornadoes into unrated, weak (F0–F1), and significant (F2–F3) and compared their environments against nontornadic thunderstorm environments.

A comparison with Kaltenböck et al. (2009) reveals that many of their results are qualitatively similar to ours, but there are important differences in the absolute values of parameter values. For example, their LCL heights are much lower for all categories, with 320 m as the median for thunderstorms, compared to our 1000 m for nonsevere thunderstorms, the 789 m that was found by Groenemeijer and van Delden (2007), and the 1125 m found by Taszarek and Kolendowicz (2013). The small differences with Groenemeijer and van Delden (2007) and Taszarek and Kolendowicz (2013) may result from the higher (lower) relative humidity that may be expected in the marine Netherlands (continental Poland) compared to our area of study. Like Taszarek and Kolendowicz (2013) and Grünwald and Brooks (2011) we did not find a decrease of LCL when going from weak to significant tornado events, which contrasts with Kaltenböck et al. (2009). Our study confirms the result of Kaltenböck et al. (2009) and Groenemeijer and van Delden (2007) that severe hail events are associated with higher LCL heights than thunderstorms in general.

The median CAPE values of severe events found by Kaltenböck et al. (2009) are very similar to us, but their median CAPE value for nonsevere thunderstorms was close to $0\,\mathrm{J\,kg^{-1}}$, much lower than our value of $280\,\mathrm{J\,kg^{-1}}$. Our results confirm the findings of Kaltenböck et al. (2009) and Groenemeijer and van Delden (2007) that severe hail events show the highest CAPE values of all considered severe phenomena.

Kaltenböck et al. (2009) defined DLS differently than we did, so that a comparison of absolute values is not possible: their bulk shear was computed between the lowest model level and the 500-hPa level, whereas we have computed it from 10 m AGL to 6 km AGL. Our study shows that DLS discriminates rather well between weak and significant tornado events, which is in line with Groenemeijer and van Delden (2007) and Taszarek and Kolendowicz (2013), but was not reproduced by Kaltenböck et al. (2009). For the Netherlands, Groenemeijer and van Delden (2007) show a decrease in DLS between hail < 3 cm and hail > 3 cm. This is in contrast with our increase in DLS with increasing hail severity. Their explanation is that bigger hail sizes occurred exclusively in the warm season, when DLS values are usually not very high.

With respect to LLS, our results are in line with Groenemeijer and van Delden (2007) in showing similar distributions for thunderstorms with and without (severe) hail, but elevated LLS for significant tornadoes compared to weak and no tornadoes. SRH3 values of Kaltenböck et al. (2009) are less than half of our values for each category, which we cannot explain.

b. *Comparison with results from other regions*

Our results indicate a number of differences with those obtained in prior studies in the United States. One difference is that in Europe, severe wind events occur with less buoyancy than in the United States. Median MUCAPE of severe wind gust events in the United States is $1903\,\mathrm{J\,kg^{-1}}$ (Kuchera and Parker 2006) while we found $549\,\mathrm{J\,kg^{-1}}$ in central Europe. One of the reasons for the lower MUCAPE in Europe could be the abundance of convective wind gusts in the cold season, some of which are associated with severe, long-track bow echoes. For example, a derecho on 1 March 2008 with a 1500-km pathlength (Gatzen et al. 2011) had no proximity sounding with MUCAPE above $50\,\mathrm{J\,kg^{-1}}$. In the United States, cold season bow echoes occur as well, but with much higher CAPE than in Europe. Burke and Schultz (2004) found that the mean CAPE for cold season bow echoes is $1366\,\mathrm{J\,kg^{-1}}$. This is much higher than the median CAPE for cold season severe wind gusts ($14\,\mathrm{J\,kg^{-1}}$) in central Europe, and even higher than the median CAPE of all severe wind gusts, regardless of the season ($549\,\mathrm{J\,kg^{-1}}$)! If we take only warm season wind events into consideration, median MUCAPE is still not very high (approximately $700\,\mathrm{J\,kg^{-1}}$). Thus, it is likely that in the United States, higher CAPE environments are much more common.

Difference in DLS is not so pronounced than in case of CAPE, with median value of 16 m s^{-1} according to Kuchera and Parker (2006) and 17.3 m s^{-1} in our case.

With respect to tornadoes, we found a good correspondence with U.S. studies regarding LLS. Median LLS for extremely severe tornadoes in central Europe is 9.2 m s^{-1}, which is very similar to the value of 9.8 m s^{-1} found by Thompson et al. (2003). LLS is typically used as a predictor for (significant) tornadoes and better discriminates between weak and significant tornadoes in comparison to DLS (Thompson et al. 2003). For central Europe, DLS discriminates slightly better than LLS between weak and significant tornadoes, which may be surprising. However, the weak tornadoes in our study were not restricted to supercells, unlike in the Thompson et al. (2003) study. Thus, it may well be that, given a European supercell, LLS would be a better discriminator than DLS. To address these, and other, questions it is necessary that studies be done in Europe that characterize convective modes using radar data.

LCL height is usually discussed in the context of tornado forecasting. It has been found that LCL is usually lower for significant tornadoes than for weak tornadoes in the United States (Thompson et al. 2003, 2012). For Europe, however, Grünwald and Brooks (2011) or Taszarek and Kolendowicz (2013) found that LCL is actually higher for significant tornadoes, which our study confirms. Therefore, LCL does not seem to be a useable predictor for significant tornadoes in Europe. A possible reason for the difference between the United States and Europe could be that LCL heights are generally lower than in the United States and thus are less likely to become a negative factor in tornadogenesis. Indeed, the median LCL heights of nontornadic storms found by Thompson et al. (2003) are 1339 and 1768 m for nontornadic supercells and nonsupercell thunderstorms, whereas we found 970 m for the nontornadic category. Craven and Brooks (2004) also found generally higher LCL heights for nontornadic storms (1300–1800 m). Our median LCL height for significant tornado events (905 m) is, however, similar to the corresponding value from these studies: 1004, 900, and 875 m for Thompson et al. (2003), Craven and Brooks (2004), and Thompson et al. (2012), respectively.

We find that LCL is actually more useful in identifying severe hail environments. Even though not specifically discussed by these authors, the studies of Rasmussen and Blanchard (1998) or Grams et al. (2012) also suggest that severe hail events occur with higher LCL heights than in case of nonhail events. Numerical simulations performed by McCaul and Cohen (2002) showed that the updraft intensity and storm diameter generally increased as LCL was increased.

c. *Occupancy of parameter space*

We have shown that each of the severe weather types has a different distribution across the multidimensional space of forecast parameters, a fact stressed before by Brooks (2013). To illustrate this Fig. 14 shows, in CAPE–DLS space, the fraction of severe events of a particular type to all severe events.

This is important as many climatological studies (Diffenbaugh et al. 2013; Gensini and Mote 2015) use a function of CAPE and DLS as a crude proxy for any convective severe weather, whereas it is quite possible to distinguish between the various hazards. As Brooks (2013) suggests, climate scenarios in which one event type becomes more frequent and another less frequent are quite thinkable. Figure 14 shows that with high CAPE and high shear, large hail is involved in up to 80% of severe weather cases. However, severe convective winds are most prevalent in a high shear, low CAPE environment. This contrasts with Brooks (2013), who found that in the United States, severe convective winds are most prevalent in a high CAPE, low shear regime. For rain events the highest fraction is found in the low shear regime. Tornado events take up only a small fraction compared to other phenomena anywhere.

If climatic changes occur in the frequency with which areas in CAPE–shear space are visited, then this may impact the relative frequency of different types of severe weather very differently. All other things staying equal, a climate scenario in which CAPE increases will benefit large hail the most. If low CAPE, high shear situations become more frequent, then the relative frequency of wind events (to all severe events) can be expected to increase, based on our proximity sounding sample for central Europe.

d. *Different depictions of the same data*

Using box and probability plots yields different perspectives on the same data. While box plots provide a good overview of the parameter value distributions, they are easy to mislead a user, because the number of events in each severity category is not the same. The severe categories are populated less by a factor of 10–33 (see Table 4) compared to the nonsevere categories. The extremely severe categories are populated by yet another factor of 5–10 less, which means for any parameter value one cannot determine which category is the most likely to occur. Indeed, some signals relevant for forecasters stand out clearer in direct plots of probability.

For example, the box or scatterplots of MUCAPE and DLS (Figs. 2–4) show that many of the intensity categories overlap significantly. However, Fig. 5 shows that the probability actually increases quite strongly with an

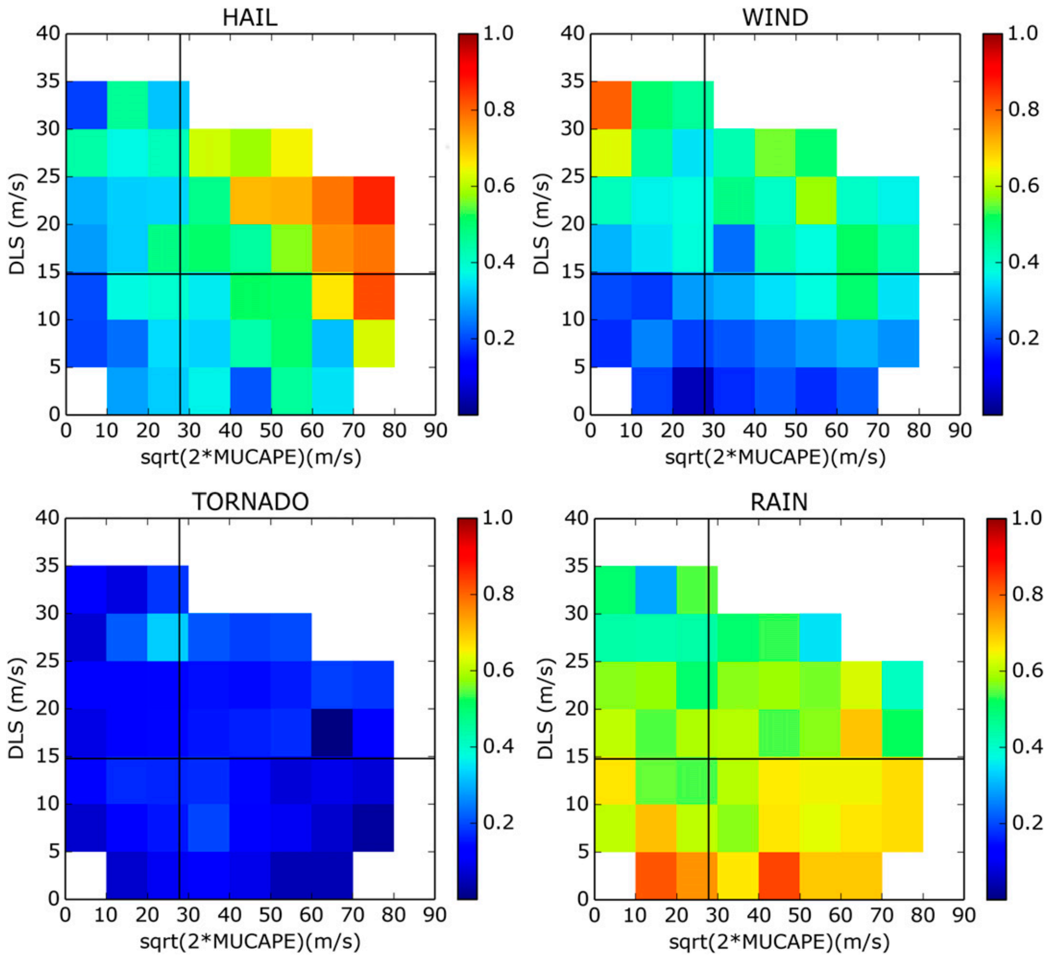

FIG. 14. Fraction of hail, wind, tornado, or rain events to all severe events as a function of $(2 \times \mathrm{MUCAPE})^{1/2}$ and DLS. Boxes with less than 20 events were masked. The black horizontal line represents the mean value of DLS and the vertical line represents the mean value of $(2 \times \mathrm{MUCAPE})^{1/2}$ of all thunderstorm soundings.

increase in either CAPE or DLS. For rain events, the two approaches at first glance appear to be in contradiction. The box and scatterplots (Figs. 3 and 4) do not show any difference in DLS between the distributions of the nonsevere and severe category, but the probability plot (Fig. 5) shows that the highest probability of rain occurs for high DLS. This can occur only because there is a discrepancy between the typical parameter value observed when a severe event occurs and that for which it is most likely to occur. This is something forecasters must keep in mind when using either of the visualizations.

e. Limitations of the approach

There are a number of limitations to our approach. The first concerns the potential underreporting in the ESWD, so that some of the soundings could incorrectly have been considered to be nonsevere. It is impossible to quantify how many soundings were incorrectly categorized. To reduce this error to minimum, we decided only to concentrate on central Europe, which has more uniform and reliable reporting than the rest of Europe (Groenemeijer and Kühne 2014). Many of the countries in central Europe (e.g., Germany, Austria, Czech Republic, Slovakia, and Poland) involve organizations, either national meteorological institutes or voluntary observer networks, which have established cooperation with European Severe Storms Laboratory (ESSL) and are reliably reporting severe weather to the ESWD.

A second limitation is the potential unrepresentativeness of the sounding. Sounding stations are located hundreds of kilometers apart (Fig. 2) and are taken only every 6 or 12 h, so that a relaxed criterion for proximity measurement was chosen in order to gather a sufficient number of soundings. Measurement representativeness can be different for the various parameters that we investigated. As discussed above, SRH3 is one of the more sensitive parameters, as it strongly depends on the boundary layer flow, which can be highly variable. This variability could be especially pronounced in the regions with rich topography, where conditions can differ and low-level flow is channeled along the valleys (Peyraud 2013). Potvin et al. (2010) analyzed the impact of different proximity sounding criteria on the climatology of significant tornado environments and concluded that soundings too far away may be more representative of large-scale environment than the storm itself.

A third limitation concerns the use of gridded lightning data. Gridded data could have caused some erroneous classifications of the proximity soundings, because the real location of the lightning could have been different from the location of the grid point. However, because average grid size in our location is approximately 28-km latitude and 17-km longitude, which is much smaller than our 150-km proximity definition, the error that is thus introduced cannot have any major impacts on the results.

The final limitation concerns using only one-dimensional profile of temperature, moisture, and wind to characterize severe weather environments. Numerous authors discuss the importance of the convective mode and of the orientation of the prevailing flow to the thunderstorm system. For example, Smith et al. (2013) found that quasi-linear convective systems produced many more severe wind gusts than isolated supercells, which, in turn, produced large hail more often. According to Gatzen (2013), 58% of the severe wind reports in Germany in summer were associated with bow echoes. Corfidi (2003) discussed how the same environmental conditions may result in both quasi-stationary convection and a rapidly moving convective system, depending on the orientation of the prevailing flow to the gust front. Doswell and Evans (2003) stressed that proximity soundings to bow echoes and to supercells are almost identical. We believe that the convective mode and the orientation of the convective system with respect to the flow both play a very important role, while they cannot be assessed in a study using sounding derived parameters. Radar data covering a large portion of Europe will be needed to identify convective mode. Recently, the Operational Programme for the Exchange of weather Radar information (OPERA) program has started to distribute pan-European radar composites on an operational basis (Huuskonen et al. 2014), making such studies possible.

5. Conclusions

In this study, we investigated the environments of thunderstorms accompanied by various convective hazards. In accordance with the expectation that strong updrafts are required for hail formation, we found that (very) large hail typically occurs with high CAPE and that its probability increases when conditions become more favorable for supercells (i.e., when CAPE and DLS increase). In addition to high CAPE and DLS, hail events are also associated with slightly greater LCL height, which may be because high cloud bases tend to enhance updraft speed (McCaul and Cohen 2002). We also found that the lapse rate between 800 and 600 hPa becomes higher for increasing hail size.

Significant tornadoes were found to occur typically with higher DLS than any other hazard type, and with notably higher DLS than weak tornadoes. Surprisingly, we found that LLS does not discriminate better than DLS between weak and significant tornadoes. This is not in contradiction with previous findings that indicated LLS was the best discriminator, since these studies were limited to supercell environments. LCL height does not discriminate well between the intensity categories of tornadoes, unlike what studies in the United States have shown. This is likely caused by the lack of high LCL heights in Europe compared to the United States.

We found that wind events typically occur with high DLS, but that two regimes can be distinguished in which they are likely, namely moderate to high CAPE/high DLS events and low CAPE/very high shear events, the latter of which are mostly cold season events. The severe and extremely severe events have very similar distributions of CAPE and of DLS. It thus appears that other factors, such as the convective mode, play an important role. In the comparison with studies from the United States, we found that high wind events occur with much lower CAPE ($549\,\mathrm{J\,kg^{-1}}$) in Europe than in the United States ($1903\,\mathrm{J\,kg^{-1}}$), but with similar DLS (17.3 vs $16\,\mathrm{m\,s^{-1}}$).

Heavy rain events occur across a wide range of DLS, but with CAPE above the median for nonsevere thunderstorms. They require an environment in which both absolute humidity in the boundary layer and relative humidity in the low- to midtroposphere are high.

An important limitation to this study is that we have not distinguished convective modes (e.g., single cells, multicells, supercells, and squall lines) using radar data. We recommend that follow-up research address this and study the probability of the convective mode as a function of environmental parameters and the probability of a convective hazard as a function of convective mode.

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