

STEPCLIM: SEVERE THUNDERSTORM EVALUATION AND PREDICTABILITY IN CLIMATE MODELS

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1. INTRODUCTION

While thunderstorms are increasingly recognized as an important hazard to life and property in Europe, still relatively little is known about the effects of climate change on the occurrence of these localized and short-lived hazards. The European Severe Storms Laboratory (ESSL) addresses this issue in the project STEPCLIM (“Severe Thunderstorm Evaluation and Predictability in Climate Models”) that aims to provide a framework to assess the frequency and intensity of severe thunderstorm hazards from climate model data.

2. METHODOLOGY

A set of parameters x_n is defined in order to characterize the local state of the atmosphere at each given point in area and time. These parameters (“proxies”) are of macroscopic nature, i.e. they can be readily computed from reanalysis or forecast fields of standard meteorological variables, like pressure, temperature, humidity and wind. They also have a physical meaning in the dynamics of convective storms and therefore govern the probability of severe weather phenomena. Parameters which are hypothesized to be most important are convective available potential energy (CAPE) as a measure for the thermodynamic state, 0-6 km vertical wind shear (deep-layer shear, DLS) as a measure for the kinematic state, and a not yet closer defined measure for the coverage of thunderstorms.

By comparing reanalysis fields of these proxies with historic severe weather events (or non-events), the sample probability $P(x_1, x_2, \dots, x_n)$ of severe weather for each point in this n -dimensional phase space can be computed. The second essential quantity is the occurrence frequency $f(x_1, x_2, \dots, x_n)$ of finding the atmosphere at this given point in the phase space, which can equally be computed from reanalysis fields. The number of severe weather events N can then be modeled by multiplying P with f and integrating over the whole phase space:

$$N = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} P f dx_n \dots dx_2 dx_1$$

Fig. 1 qualitatively illustrates the distribution of P and f across a 2-dimensional phase space spanned by the square root of CAPE and deep-layer shear. It is worth emphasizing that the two quantities on display show a roughly oppositional behavior: Situations with high CAPE and strong vertical wind shear (i.e., near the upper right corner of the phase space) are characterized by high severe weather probabilities P , but the frequency f of finding the atmosphere in this phase region is low. In contrast, situations with low CAPE and weak vertical wind shear (i.e., near the lower left corner of the phase space) occur more often, but exhibit a low probability of severe weather. It is therefore a priori unclear which region yields a maximum of the product $f \cdot P$ and therefore contributes most to the total number of severe weather events N in a past, present or future European climate.

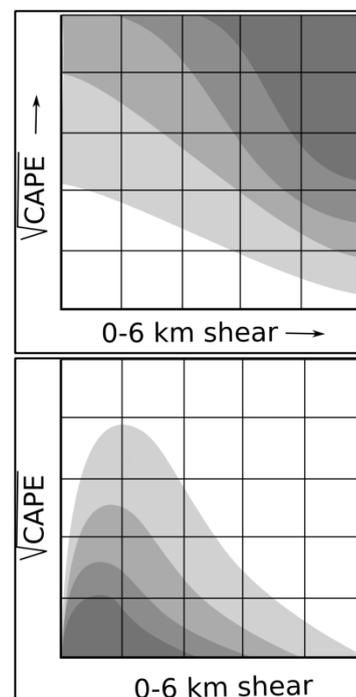


Fig. 1: Qualitative illustration of the severe weather probability P (top) and the occurrence frequency f (bottom) as a function of DLS and the square root of CAPE.

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A crucial assumption is that the proxies' predictive skill shall be invariant towards any change in climate. In other words, the probability P is postulated to remain the same, no matter what the future climate will hold. It is only the probability of occurrence of certain combinations of proxies that is subject to a change in a changing climate, which is fully captured by an according adaptation of the occurrence frequency f . This assumption is justified by the physics-based nature of the underlying proxies: Certain values of e.g. CAPE and deep-layer shear have the same physical meaning, no matter in which climate, environment, time or area they occur.

So far, the relation described here has been investigated for a 2-dimensional phase space with $x_1 = \sqrt{CAPE}$ and $x_2 = DLS$.

3. DATA MATERIAL

Convective indices like CAPE and DLS were computed from the ERA-Interim reanalysis fields (Dee et al., 2011). They cover the period from 1979 to 2011 with a temporal resolution of 6 hours and a spatial resolution of 0.75 degrees. Values of geopotential height, temperature, relative humidity, and the 3-dimensional wind components are provided at 28 vertical levels from 1000 hPa to 70 hPa. The level spacing is 25 hPa across the lower and 50 hPa across most of the upper troposphere. The mixing ratio was calculated from relative humidity, temperature and pressure, then the temperature of a rising parcel was simulated with the Bolton approximation (Bolton, 1980) of an isentropic ascent at a vertical resolution of 1 hPa, starting from the parcel's pressure, temperature and mixing ratio at its level of origin.

We calculated a "near-surface based" CAPE starting from 25 hPa above the local model topography height. This was found to be a computationally efficient way to obtain CAPE values similar to those obtained with a computation using a mixed layer with a thickness of 50 hPa above ground level.

This "near-surface-based" CAPE was supplemented by the computation of elevated CAPE originating from each level of the ERA-Interim reanalysis fields in the lower troposphere, i.e. every 25 hPa. The maximum over these elevated CAPE values and surface-based CAPE provided the "most unstable CAPE", which was henceforth used for this study and which will simply be termed "CAPE" from here on.

Like CAPE, deep-layer shear was computed starting from the local model topography height. The maximum shear value between the wind there and at any level within

the lowest 6 km above it was considered to be the "effective" deep-layer shear. Therefore, the upper bound of the shear-bearing layer was often found at 6 km above ground, but not compulsively so. The resulting shear value will hence be termed "deep-layer shear" (DLS).

Information about the occurrence or non-occurrence of severe weather events was taken from the European Severe Weather Database (ESWD, <http://www.eswd.eu>), operated by ESSL. In the ESWD, severe weather reports from all across Europe are collected, quality-controlled and stored in a uniform and processible format, which turns it into the first adequate tool to conduct pan-European studies on the climatology of localized severe weather events (Dotzek et al., 2009; Groenemeijer et al., 2009). The most important severe weather phenomena in the ESWD are those related to convective storms. Their thresholds were also considered for the present study. Besides, a second definition of "extremely severe" weather was introduced in order to isolate the highest-impact events, following Brooks et al. (2003). The criteria for both severity categories are listed in Table 1.

Phenomenon	Criterion for "severe"	Criterion for "extreme"
Hail	≥ 2 cm	≥ 5 cm
Wind gust	≥ 25 m/s	≥ 33 m/s
Tornado	damage or observation	damage $\geq F2$
Excessive rain	damage	-

Table 1: Definition of "severe" and "extremely severe" weather events.

The proxies computed for a given time were then opposed to the received severe weather reports in the following six hours. Each grid point of ERA-Interim was allocated with a "severe" flag if severe weather occurred, and with an "extremely severe" flag in case of extremely severe weather.

An example of the proxy fields at 12 UTC 23 July 2009, a high-end severe weather day in Central Europe, can be seen in Fig. 2. Ahead of a cyclone and an associated upper-level long-wave trough centered over the British Isles, the air mass exhibits high CAPE values between 1000 and 3000 J/kg over much of Central Europe (Fig. 2 top), and a belt of strong deep-layer shear around 30 m/s stretches from the Iberian Peninsula via France into Germany (Fig. 2 bottom) and partly overlaps with the area of latent instability. Fig. 3 shows the corresponding severe weather reports in the following six hours between 12 and 18 UTC on 23 July 2009. Most striking

feature is the extensive swath of wind reports (yellow squares) in Eastern Germany, the Czech Republic and Poland. Further south, there is also a number of hail (green triangles) and wind reports in Switzerland, Southern Germany and Austria. All of these events occurred in regions with a substantial overlap of CAPE and DLS according to Fig. 2, like it would be expected.

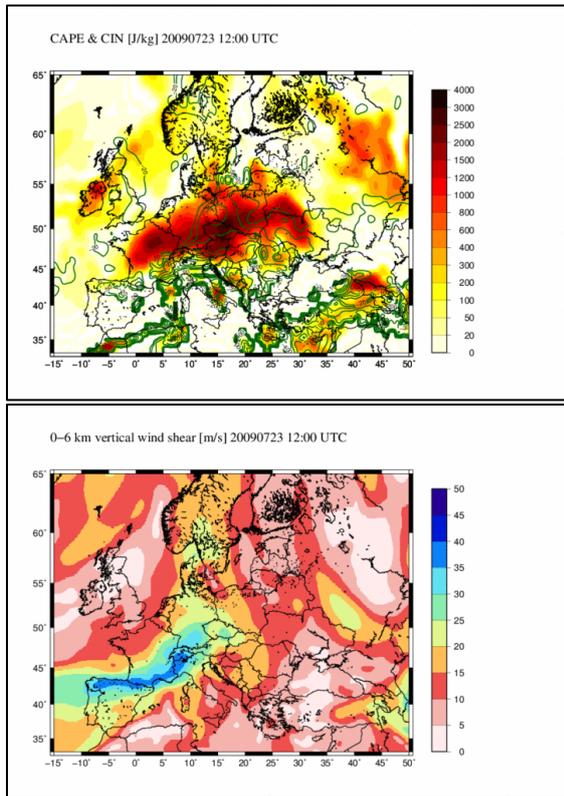


Fig. 2: Example of proxies derived from ERA-Interim reanalysis fields at 12 UTC 23 July 2009. Top: CAPE (color shades) and CIN (green contour lines à 50 J/kg); bottom: Deep-layer shear.

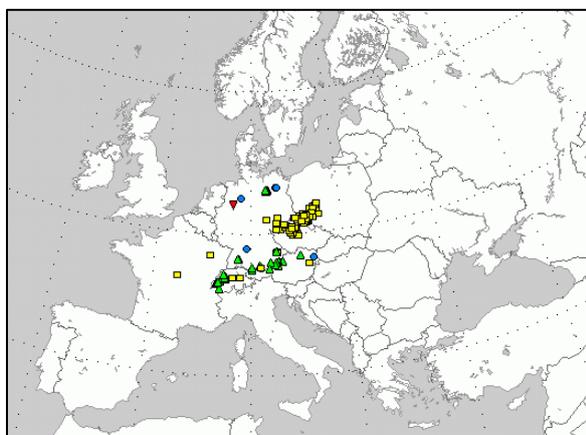


Fig. 3: Severe weather reports in ESWD between 12 and 18 UTC on 23 July 2009; green triangles ... large hail, yellow squares ... severe wind gusts, red triangles ... tornadoes, blue circles ... excessive rainfall.

4. PRELIMINARY RESULTS

To start with an impression of the ESWD sample size, Table 2 summarizes the number of events in each of the “severe” and “extremely severe” categories defined in the previous section. It needs to be mentioned that a roughly equal bin occupancy does not necessarily mean that these phenomena are indeed equally likely. In particular, past research in Europe focused more on tornadoes than on straight-line wind events or large hail, which is why a relatively higher number of historic tornado events were filed in literature and could therefore be incorporated into ESWD upon its implementation. In reality, however, it is much more likely for any given location in Europe to experience large hail or severe straight-line winds than a tornado. Due to the absence of a quantitative criterion for excessive rainfall, a comparison of its occurrence is pointless from a climatological point of view.

Likewise, the occurrence of *extremely* severe events of any of these phenomena is certainly overrepresented with respect to the total sample size, because the reporting efficiency rises with the extremity and associated impact of an event. Underreporting of weaker events certainly needs to be accounted for in Europe in one way or another (Brooks, 2008), although it is luckily not an issue as big as in sparsely populated Australia (Allen et al., 2011).

Phenomenon	severe	extreme
Hail	6659	491
Wind gust	6257	1225
Tornado	4854	1555
Excessive rain	6733	-
All	24503	3371

Table 2: Number of severe and extremely severe weather events in Europe from 1979 to 2011 according to ESWD entries (extracted on 02 Oct. 2012).

Despite these limitations (and always keeping them in mind), the sample size is large enough to allow first quantitative conclusions on the European severe weather climatology. Fig. 4 shows a scatterplot of all known severe weather events from 1979 to 2011 as a function of CAPE and deep-layer shear, and Table 3 extracts the median values of CAPE and DLS for each of the phenomena. It is noteworthy that:

- The median tornado environment closely corresponds to the median environment of all severe weather events (i.e., without further specifying into certain phenomenon types);

- The median environments of hail and excessive rain are shifted towards higher CAPE (especially hail) and somewhat lower DLS; and
- The median severe wind environment is shifted towards lower CAPE and higher DLS.

These findings are in qualitative line with the physics favoring each of these respective phenomena, namely the role of stronger updraft speeds (partly realizable by higher CAPE) for large hail, and the role of vertical momentum transport (realizable by stronger deep layer shear) for severe wind gusts. The statistical significance level of each of these findings is rather low, though, showing how noisy the dataset is due to the wide range of possible environmental conditions for severe weather and due to the aforementioned underreporting problem.

Comparing the environments of severe weather with those of extremely severe weather, a plausible increase of median CAPE and DLS can be found for all types except for straight-line winds, where the median DLS is even marginally lower for extremely severe events. No airtight explanation for this surprising finding can be provided yet. It can only be speculated that the contribution of vertical momentum transport to severe wind gusts might approach a natural saturation limit, and it is the other two contributions – namely the downdraft enhancement due to evaporative cooling and hydrometeor load (Yeung et al., 2008) – which discriminate better between cases of severe and extremely severe wind gusts. More examinations are needed to confirm this hypothesis, though.

The logarithmization of both axes in Fig. 4 is intended to account for the occurrence frequency f , which is skewed towards low values of CAPE and DLS. It can sufficiently de-skew the $(CAPE, DLS)$ space to allow the qualitative conclusion that the number of severe weather events in Europe is maximized for moderate (10^2 - 10^3 J/kg) CAPE and moderate (~ 10 m/s) DLS. This is also quantitatively confirmed by the median values in Table 3. However, it is important to note that this finding only considers the *actual number* of severe weather events (termed N in section 2), without taking the overwhelming number of non-events under similar conditions into account. Therefore it is not possible to derive the *probability* of severe weather (termed P in section 2) from Fig. 4. Since P is assumed to be the invariable and therefore relevant quantity to address any questions related to climate change, the logical next step is to take into account the non-events as well.

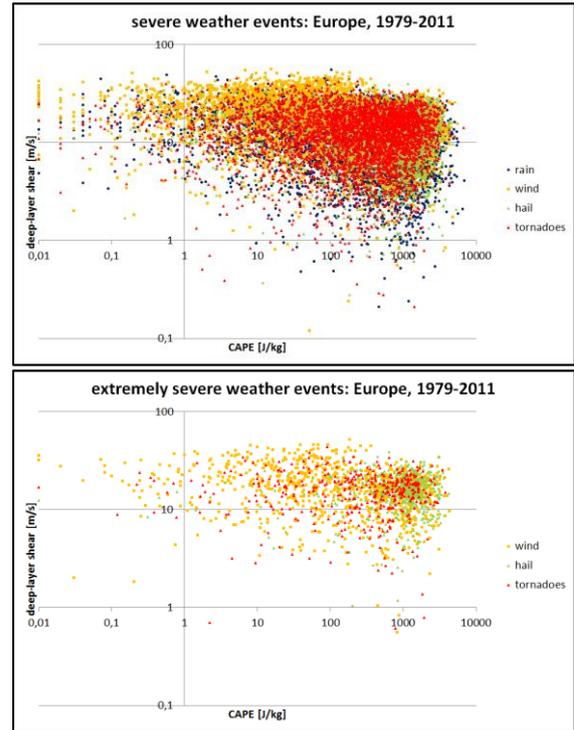


Fig. 4: Scatterplot of severe (top) and extremely severe weather events (bottom) in Europe from 1979 to 2011 as a function of CAPE and DLS.

Phenomenon	CAPE [J/kg]		DLS [m/s]	
	sev.	ext.	sev.	ext.
Hail	713	1052	12.6	15.5
Wind gust	84	94	17.7	17.3
Tornado	212	308	13.2	15.8
Excessive rain	352	-	12.0	-
All	296	310	13.7	16.2

Table 3: Median values of CAPE [J/kg] and DLS [m/s] for various types of severe and extremely severe weather.

Fig. 5 shows the probabilities of the various types of severe and extremely severe weather as a function of the square root of CAPE and DLS. Taking the square root of CAPE instead of CAPE itself was a convenient way not only to match the physical unit of both proxies, but also to assimilate the range of occurring values.

Two measures were taken in order to reduce the noise: First, the data were discretized into bins of 2 m/s each, and second, these bins were only plotted when they contained at least $N = 5$ events. The authors are aware that applying the second action only to the number of *events* (instead of the sum of events and non-events) will lead to over-estimation of the displayed probability in regions where little data is available. However, this operation does not affect the raw data, which are used for the subsequent calculations outlined in section 5.

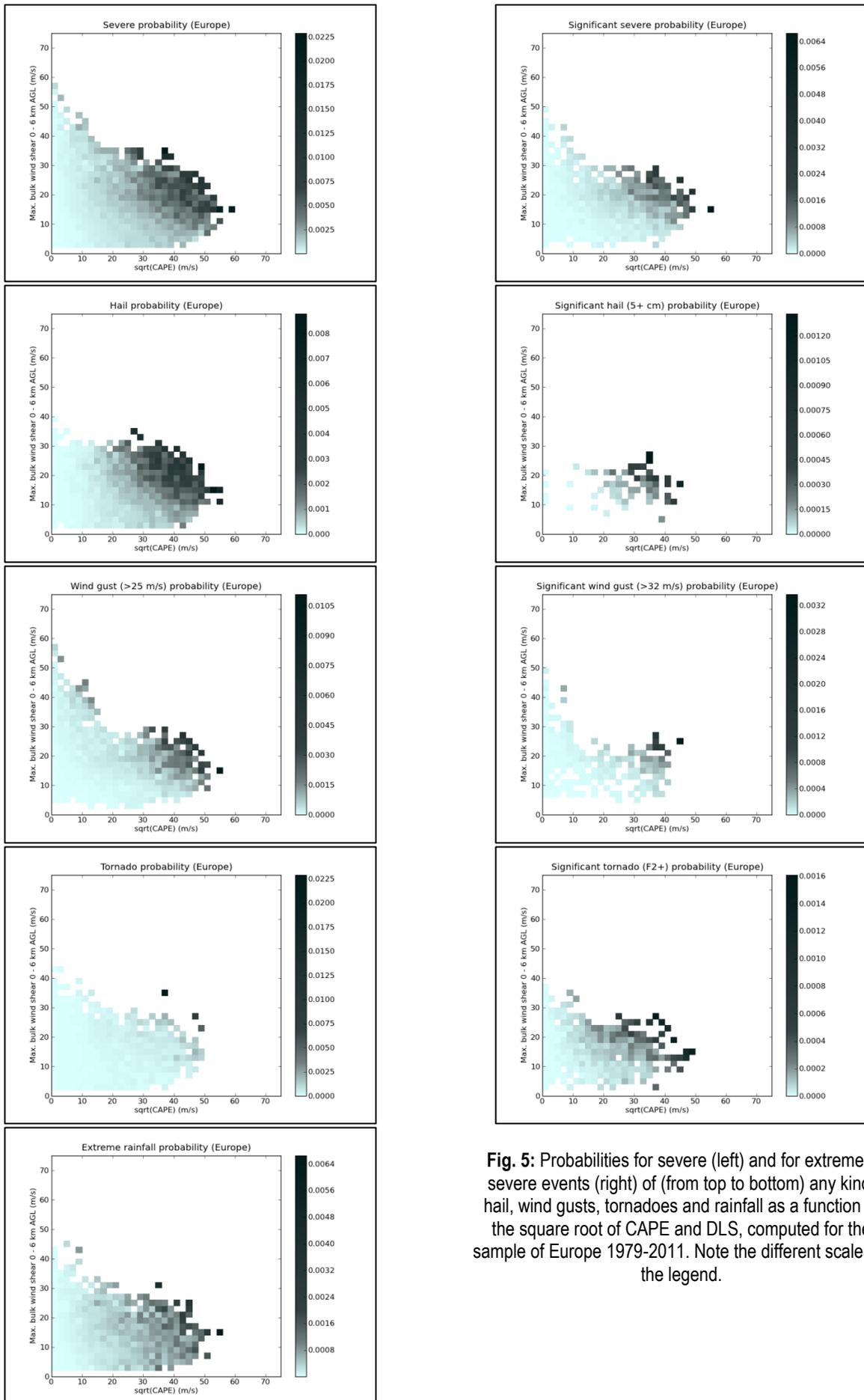


Fig. 5: Probabilities for severe (left) and for extremely severe events (right) of (from top to bottom) any kind, hail, wind gusts, tornadoes and rainfall as a function of the square root of CAPE and DLS, computed for the sample of Europe 1979-2011. Note the different scales of the legend.

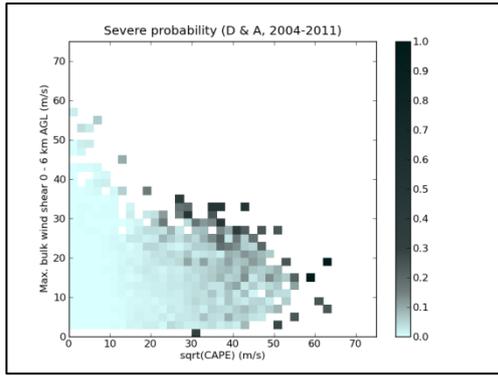


Fig. 6: Probabilities for severe weather computed for the subsample of Germany and Austria 2004-2011. Compare with the upper left plot in Fig. 5 and note the different scale of the legend again.

Some of the previous findings from Fig. 4 and Table 3 are confirmed by the probability plots in Fig. 5. For example, the comparably stronger dependence of hail and (in particular) excessive rainfall on CAPE, as well as the comparably stronger dependence of wind gusts on DLS, can be qualitatively seen: The downward slope of imaginary contour lines of equal probabilities would be steeper for hail and excessive rain than for wind gusts, although a statistical post-processing like a linear discriminant analysis (Wilks, 1995) is necessary for a quantitative confirmation. On the other hand, the previous finding for severe wind gusts is somewhat put into perspective: Whereas Fig. 4 hinted at a rather high number of severe wind events in environments with low CAPE and strong DLS (i.e., the upper left corner of the plots), Fig. 5 reveals that the probabilities are only slightly enhanced in this region of the phase space. In other words: Even though there is an augmented number of severe wind events with low CAPE and strong DLS, it is still dwarfed by a much higher number of non-events, as this setup corresponds to a rather typical situation at high geographical latitudes and hence occurs very frequently.

5. FUTURE WORK

One of the next planned steps is to fit analytical functions for the probabilities P of each severe weather phenomenon via a logistic regression (Wilks, 1995) with the constraint of minimizing the standard error between observations (i.e., events or non-events) and analytically “forecasted” severe weather probabilities. This approach would also allow the inclusion of an arbitrarily high number of further proxies x_n and a quantitative test whether or not each of them provides additional skill by further reducing the standard

error. A particular aim is to find a separate proxy for the coverage of thunderstorms and/or the probability of convective initiation.

Another big topic that needs to be dealt with is the underreporting of severe weather events, which causes the ESWD sample to be spatially and temporally inhomogeneous. A possible solution is to compute the severe weather probabilities P only with a subset of data where the reporting rate of events can be considered sufficiently high, for example in Germany and Austria since 2004, when amateur storm spotters organized themselves in national Skywarn networks that have since collaborated in collecting data for the ESWD. Re-computing the severe weather probabilities for this subset indeed yields values which are by at least an order of magnitude higher than for the whole European domain (Fig. 6), indicating that the reporting rate is probably as low as 10% or less across much of Europe. It is therefore alluring to fit the analytical function for P only with this “reliable” subset of data and at the same time to get an estimate of the magnitude of underreporting in other European countries, although care is needed in order to avoid overfitting.

On a longer term, it is planned to apply the derived analytical functions for the severe weather probabilities to reanalysis fields of the parent project MiKlip (“mittelfristige Klimaprognosen”, “medium-range climate forecasts”) with the aim to address the benefit of a finer model resolution. The ultimate goal is an application of the refined algorithm to the MiKlip forecast data in order to accomplish projections of the future decadal severe thunderstorm risk in Europe.

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