# Sounding-derived parameters and their ability to forecast individual severe weather threats for the region of central Europe.

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## I. INTRODUCTION

Forecasting severe deep, moist convection is of utmost interest to the forecasters, because of the threat to both life and property it poses. In their landmark paper, Johns and Doswell (1992) identified several necessary “ingredients” that are vital for the (severe) thunderstorm occurrence. These are: sufficient low-level moisture, steep lapse rates, initiating factor (that “transports” the air parcel to its level of free convection) and in case of severe DMC, also pronounced vertical wind shear. Three of these factors (except for the initiating factor) might be readily analyzed using the sounding data. These data have been often simplified into the form of so-called indices and parameters (represented by a number, sometimes dimensionless) that would indicate the possibility of (severe) thunderstorms in a given area. Many of these parameters (indices) have been primarily used to evaluate the “instability” of environment (such as CAPE or Lifted Index), while other parameters were developed to forecast the degree of convection organization, relating to the vertical wind shear (such as deep layer shear or storm-relative helicity). It is now widely recognized, based on the studies using both the real sounding (Craven and Brooks, 2004) or re-analysis data (Brooks, 2009), that degree of instability, as well as the vertical wind shear are pertinent to the forecasting of severe thunderstorms.

As we go through the available literature on the topic, we find that most of the studies that somehow assessed the ability of parameters (indices) to recognize severe weather environments was done in United States and were dedicated especially to the prediction of tornadic supercells (e.g. Thompson et al., 2003). Less studies have been done on the topic of severe “straight-line” winds forecasting (Kuchera and Parker, 2006), while very little amount of studies deals with the recognition of severe hail (Groenemeijer and Van Delden, 2007) and excessive rainfall environments.

This study is intended to evaluate the predictability of all 3 basic severe thunderstorm phenomena (large hail, severe wind gusts and excessive rainfall) using some of sounding-derived indices and parameters that are commonly used in the forecasting practice or were evaluated / used in the literature for the prediction of severe thunderstorms.

## II. METHODOLOGY

For the purpose of this study, we decided to concentrate on a region of Central Europe, namely these countries: Germany, Switzerland, Austria, Slovenia, Hungary, Czech Republic, Slovakia and Poland. Naturally, atmospheric phenomena do not recognize national boundaries, so also situation in the immediate surroundings of the region border was put into consideration, e.g. over Northern Italy or Eastern France. Thus, we might name the domain of the study as a "broader" area of Central Europe.

Four years in total have been investigated, spanning the period between 1 January 2008 and 31 December 2011, with the selection of "thunderstorm days" based on the occurrence of at least two lightning discharges in the vicinity of each other within the above-mentioned countries. Lightning data were provided by EUCLID network, comprising approximately 140 lightning sensors across contiguous Europe. Subsequently, we checked European Severe Weather Database (ESWD) for any reports of severe weather that would comply with the thunderstorm activity during the particular thunderstorm day. Reports of these types were put into consideration: "large hail", "severe wind gust", "heavy rain" and "tornado". Besides the general information regarding the report itself, ESWD also includes its plausibility status with different degrees of "quality check" (for more detailed information see Dotzek et al., 2009). We decided to take into consideration reports having at least the status of "plausibility check".

All of the reports were divided into two intensity categories: A/ *severe* and B/ *extremely severe*, in accordance with the criteria given in Table 1. Because of the fact that tornado reports were relatively scarce and also because most of the European NMIs do not consider tornadoes separately in their warning system (Rauhala - Schultz, 2009), we merged the categories "severe wind gust" and "tornado" (reader might find a mention about the tornado environments in the results section). In case of the severe wind gusts and heavy rain, we only took into the account reports that were clearly associated with the convection.

| Type | Intensity | | |
|---|---|---|---|
| | 0 Non-severe | 1 Severe | 2 Ext. severe |
| Hail | $D < 2$ cm | $2 \leq D < 5$ cm | $D \geq 5$ cm |
| | No damage | Minor | Major |
| Gust | $G < 25$ m/s | $25 \leq G < 32$ m/s | $G \geq 32$ m/s |
| | No damage | F0, isolated F1 | F1+ |
| Rain | $RR < 50$mm/3h | $RR \geq 50$ mm/3h | $RR \geq 100$ mm/3h |
| | $RR < 70$mm/6h | $RR \geq 70$ mm/6h | $RR \geq 150$ mm/6h |
| | No flooding | Minor flooding | Major flooding |

Table I. Criteria used in the differentiation of non-severe, severe and extremely severe thunderstorm.

For each of the thunderstorm occurrence, we attempted to find a so-called "proximity sounding". Because of a rather poor temporal and spatial resolution of the sounding data it was necessary to choose a definition of the "proximity sounding" which would on one hand not limit the database too much and on the other hand would ensure that measurements really represent the environment in which the storms formed. Such definition has been handled variously by different authors while study by Potvin et al. (2010) offered an interesting discussion about this issue. For our purposes, we decided to use a spatial constraint of proximity sounding being located within 200 km radius from the lightning / severe weather report and within 3 hours of the event occurrence. Moreover, we took the advection by horizontal winds into consideration (whether the airmass sampled by a sounding would be in the 200 km radius at the time of the lightning / report) and subjectively evaluated whether the sounding was e.g. contaminated by convection, taken after the frontal passage or displaying false data. For the given 4 years, we managed to acquire 1962 proximity soundings.

Afterwards, all of the soundings were processed into 35 different parameters (indices) that can be divided into these categories:

**1. Parameters related to the vertical displacement of an air parcel**

- *Mixed layer CAPE (CIN)*, J/kg, with the mean value of mixing ratio and potential temperature in the lowest 50 hPa layer
- *Most unstable CAPE (CIN)*, J/kg, from the highest $\theta_e$ layer in the lowest 300 hPa. For both ML and MUCAPE, we also calculated the portion of CAPE in the warm part of the cloud (from the lifted condensation level up to -10°C) and in the so-called hail-growth zone (-10 to -30°C).
- *Lifted indices (°K)*
  We calculated standard lifted index (for the level of 500 hPa) using mixed-layer method. Moreover, we calculated the "*best lifted index*", which is a minimum value attained between the condensation level and equilibrium level for both mixed-layer and most-unstable parcel choices and a *temperature*, at which is this minimum achieved.
- *Average lapse rates* (°Kkm$^{-1}$) in the surface to 850 and 800 to 600 hPa layer
- *Lifted condensation level*, (LCL hereafter) using both mixed-layer and most-unstable methods.
- *Warm cloud layer depth*, defined as the depth of the cloud between the LCL and -10°C.
- *DCAPE*, calculated from the lowest $\theta_e$ in the bottom 300 hPa
- $\Delta\ \theta_e$, calculated between the surface and lowest $\theta_e$ in the bottom 300 hPa

**2. Moisture / humidity characteristics**

- *Average dew point,* calculated for the lowest 50 hPa
- *Average relative humidity*, calculated for the layer between the surface and 600 hPa

**3. Characteristics associated with the vertical wind profile**

- *Bulk wind shear* (ms$^{-1}$)- in the layers from the surface to 1, 3 and 6 km and a maximum value between the surface and a level between the LCL and EL
- *Storm relative helicity* - for the layers of 0-1 and 0-3 km, with storm motion vector considered for a right-moving supercell according to Bunkers et al. (2000).
- *Corfidi vectors* - for both up and downwind propagating MCS according to Corfidi (2003)

**4. "Composite" parameters**

- *SWEAT index*, as postulated by Miller (1972).
- *Energy-Helicity index, EHI,* as defined by Hart and Korotky (1991).
- *Severe index, SVRI* (m$^2$s$^{-2}$) which has been modified from the study by Craven and Brooks (2004) and theirs "significant severe" parameter. Our index was calculated using both ML and MUCAPE as:

$$SVRI = \frac{\sqrt{2 * CAPE}}{2} * DLS$$

Ability of the parameters to discriminate between the severity levels of different thunderstorm phenomena were determined by non-parametric statistical tests. We used Kruskall-Wallis test to consider all 3 severity levels and Mann-Whitney U-test to evaluate the discriminatory power between pairs of levels (e.g. between non-severe and severe).

## III. RESULTS AND CONCLUSIONS

For the purpose of a better clarity, we decided to divide the result section into a “bullet-form”, so that reader can address different points separately. A table of the 6 parameters attaining the best test-scores for discriminating intensities of individual severe weather threats can be found below.

| Hail | | | Wind gusts | | | Excessive precipitation | | |
|---|---|---|---|---|---|---|---|---|
| Index | Category | | Index | Category | | Index | Category | |
| | 1 | 2 | | 1 | 2 | | 1 | 2 |
| MUSVRI | 239 | 515 | MUSVRI | 238 | 428 | MLDPTH | 372 | 432 |
| MLSVRI | 139 | 357 | MLSVRI | 142 | 270 | AVG TD | 12,8 | 15,2 |
| MUCAPEGR | 353 | 564 | SWEAT | 140 | 182 | MUDPTH | 391 | 457 |
| MLCAPEGR | 167 | 368 | DLS | 12,8 | 19,9 | MLCAPERA | 41 | 111 |
| ML LI | -1,2 | -3,1 | MLS | 8,8 | 13,7 | MUCAPERA | 139 | 209 |
| MU LIM | -4,2 | -6 | EHI | 0,1 | 0,2 | ML LI | -0,8 | -2,2 |

Table II. List of the 6 best indices (in descending order from top to bottom) for each severe weather type with the values of 25th percentile indicated for severe (category 1) and extremely severe (category 2) intensities. ML (MUSVRI) denote Severe index using ML(MUCAPE) values, CAPE GR/RA amount of CAPE in the hail growth zone and in the warm cloud layer respectively. ML LI stands for Lifted index using mixed-layer method, MU LIM is "the best lifted index" using most-unstable method. DLS and MLS are values of bulk wind shear in 0-6 and 0-3 km layer, (ML) MUDPTH warm cloud layer depth using either mixed layer or most unstable parcel method.

***General implications:***

***1.*** We have found out that none of the tested parameters was equally suitable for all three types of severe weather.

***2.*** All of the parameters exhibited at least marginal overlap between the parameter values of individual severe weather intensities.

***3.*** Using tested parameters, we found that it is perhaps the easiest to predict the hail intensity, while it was most difficult to discriminate among the rainfall intensities.

***4.*** Premise that the highest probability of severe weather is found in the environments with good overlap of CAPE and vertical wind shear relationship proved true for both (extremely) large hail and severe wind gust environments (see figure 1), but not for excessive rainfall. It also seems that shear and instability compensate for each other.

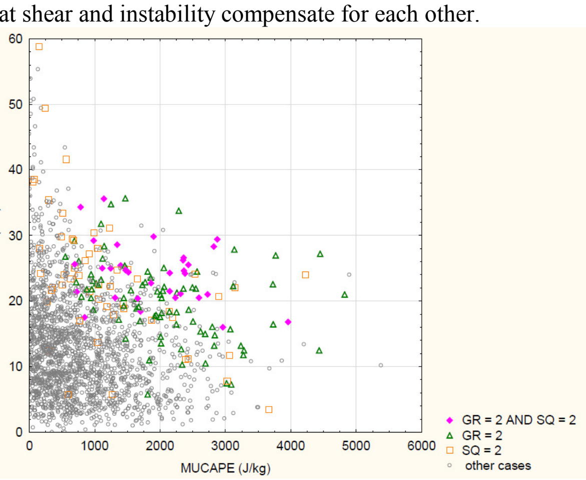


Figure 1: Scatter plot of the extremely severe hail (GR), wind gust (SQ) events and their combination (GR AND SQ) in relation to the distribution of DLS - bulk wind shear 0-6 km (ms$^{-1}$) and MUCAPE (Jkg$^{-1}$).

***5.*** No "threshold" values should be used for forecasting, probability of (extremely) severe phenomena often increases very gradually as the values of parameter change.
***6.*** Many indices (especially instability related) strongly correlated with each other, so it might be redundant to utilize all kinds of their variations when forecasting.
***7.*** Deep layer shear was in almost all cases superior predictor to all other wind-shear related indices.
***8.*** CAPE values seem to better correspond with the low-level dew points than the mid-tropospheric lapse rates (see figure 2 below).
***9.*** Severe thunderstorm events typically involved more than one type of severe weather, e.g. over 60% of severe wind gust reports coincided with large hail report. However, simultaneous occurrence of two extremely severe weather types was much less common.

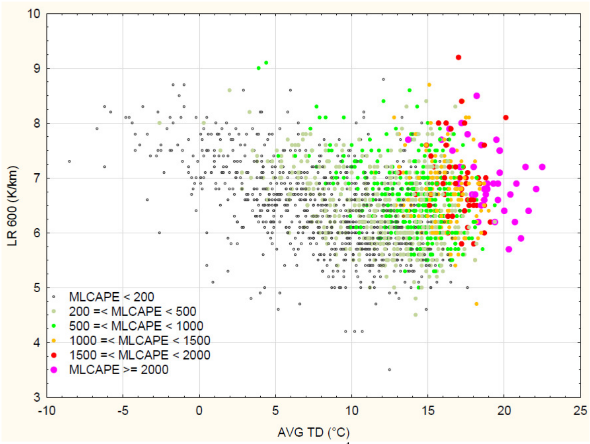


Figure 2: Scatter plot of MLCAPE (Jkg$^{-1}$) values with respect to the distribution of the average dewpoint in the lowest 50 hPa AVGTD (°C) and mid-level lapse rates LR600 (Kkm$^{-1}$).

***Large hail prediction:***
***1.*** While we found out that especially extremely severe hail is best predicted using CAPE-bulk wind shear combination (Severe index) - see figure 3, it seems that hail intensity is more sensitive to CAPE than the bulk wind shear. Wind shear was important especially in discriminating between severe and extremely severe events. Some of the severe events did occur in quite inconspicuous conditions.

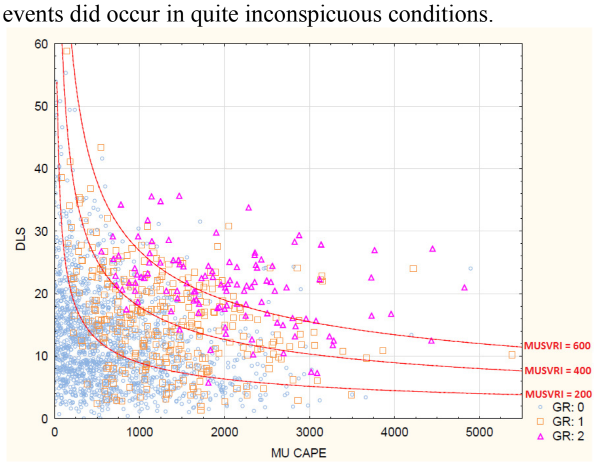


Figure 3: Scatter-plot of the hail events (GR) and their intensity (0 - non severe or no hail, 1 - severe, 2 - extremely severe) in relation to the distribution of DLS (ms$^{-1}$) and MUCAPE (Jkg$^{-1}$). Isolines of Severe index using MUCAPE, MUSVRI, (values of 200, 400 and 600 m$^2$s$^2$) are plotted as well.

***2.*** MUCAPE in the hail growth layer proved as the best index related to the instability measures.
***3.*** Hail intensity also seemed to be somehow linked to the increasing LCLs, decreasing average relative humidity, increasing mid-tropospheric lapse rates and decreasing temperature at which "maximum buoyancy" was observed.

***Severe wind gust prediction:***
***1.*** Wind gust intensities were also best discriminated using the Severe index, while in contrast to hail, severe wind gusts were more sensitive to the wind shear measures, especially the bulk shear 0-6 km (figure 4).
***2.*** Average 50 hPa dew point proved to be a slightly better predictor than CAPE-related measures.
***3.*** Measures of downdraft intensity (such as DCAPE) proved inferior to CAPE and especially wind shear related measures.
***4.*** (Significant) tornadic events were better determined from the non-tornadic events using 0-3 km bulk shear, rather than 0-1 km bulk shear (figure 5). Interestingly, even in the favourable range of conditions (given by strong wind shear in the lowest 3 km and low LCLs), non-tornadic cases were dominant.

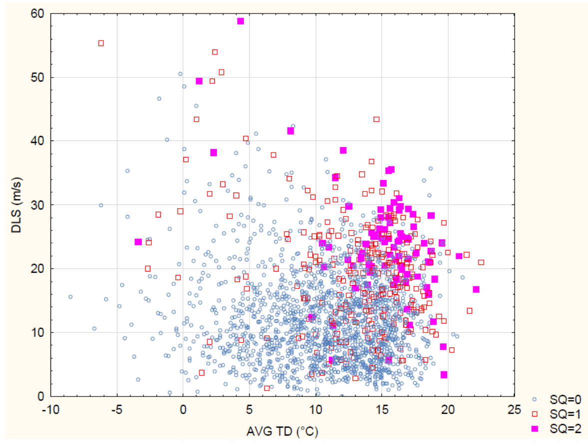


Figure 4: Scatter plot of the wind gust events (SQ) and their intensities (0 - non severe, 1 - severe, 2 - extremely severe) in relation to the distribution of AVGTD (°C) and DLS (ms$^{-1}$).

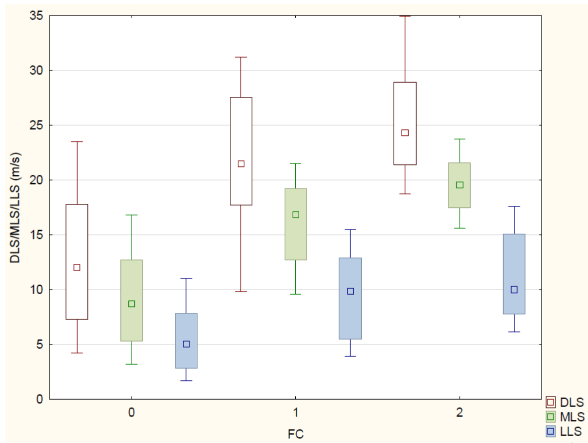


Figure 5: Box plot of bulk wind shear in 0-6 km layer - DLS (ms$^{-1}$), 0-3 km layer - MLS (ms$^{-1}$) and 0-1 km layer - LLS (ms$^{-1}$) values for non-tornadic cases (0), weakly tornadic, F0 to F1, cases (1) and significantly tornadic, F2+, cases (2). Small squares represent median value, boxes 25 to 75th percentile value and whiskers 10th to 90th percentile value range.

***Excessive rainfall prediction:***
***1.*** In contrast to other two severe weather types, CAPE-shear

overlap does not seem as a good discriminator among the intensity levels.

***2.*** From the instability-related measures, CAPE in the warm part of the cloud (below -10°C) attained the best results.

***3.*** The best discriminatory results were achieved by the average 50 hPa dew points and a warm cloud depth using the mixed layer parcel method

***4.*** Higher intensities were confined to the environments with lower LCLs, higher RHs and with maximum buoyancy confined to the warmer temperatures.

***5.*** Vertical wind shear was a very poor predictor, as well as the Corfidi´s upwind MCS propagation vector method (see also figure 6).

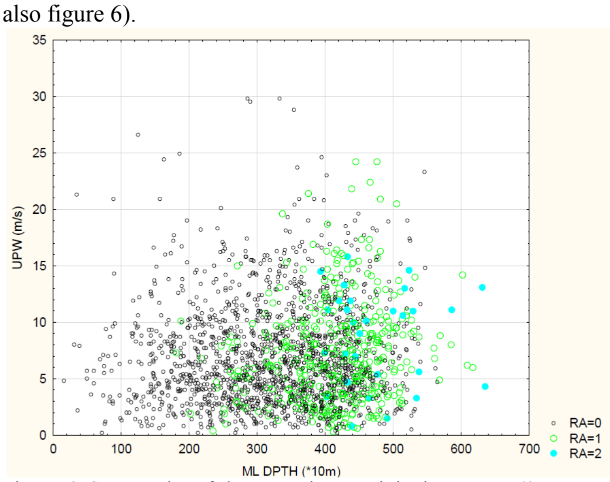


Figure 6: Scatter plot of the excessive precipitation events (0 - non severe, 1 - severe, 2 - extremely severe) in relation to the distribution of warm cloud layer depth using mixed-layer parcel method - MLDPTH (10m) and magnitude of Corfidi´s upwind propagating MCS vector($ms^{-1}$).

## IV. DISCUSSION AND CONCLUSION

While sounding-derived parameters and indices clearly offer a potential in forecasting severe thunderstorm phenomena in the region of Central Europe, it seems that especially for excessive precipitation forecasting, much more is needed to correctly anticipate the threat. This is likely because sounding data do not offer any information of real 3-D structure of atmosphere, e.g. regarding flow orientation with respect to the initiating boundary or to the existing thunderstorm complex, which might be extremely important for either excessive precipitation or severe wind gust threats. A very interesting result from our study was the poor performance of Corfidi´s upwind vector technique to identify quasi-stationary or backbuilding MCS environments. Perhaps in the terrain-rich Central Europe, interaction of low-level flow with the local orography plays a very important role. In case of severe wind gusts, another issue stands out – they can be the result of different phenomena, either induced by the circulations of a well-organised convective system, local downburst or a tornado. Our results would suggest that most of the severe wind gust cases in Europe belong to the group including the generation of a well-organised MCS (or supercells) in the environment of rich boundary-layer moisture and strong vertical wind shear.

Moreover, we need to remember that our rather broad definition of "proximity sounding" likely did not allow to sample local variations in environmental conditions, which could have, at least in some of the cases played a determining role in the ensuing convective scenario. Again, local terrain might play a crucial role here, especially in enhancing the conditions important for severe weather occurrence (e.g. famous pre-alpine hailstorms).

In conclusion, we would like to say that even though sounding-derived parameters are very useful for forecasting severe thunderstorm phenomena, they should be used and chosen carefully, particularly because they perform differently for individual severe weather threats. For example, while both (extremely) severe hail and wind gusts phenomena favour environments with sufficient overlap of instability and vertical wind shear, situation is very different for excessive precipitation. Furthermore, parameters (indices) will often not convey the full complexity of the atmosphere and thus it could be more beneficial to spend time on careful analysis rather than looking for the exceedance of the "threshold" values. With this in mind, reader is advised to consult a paper by Doswell and Schultz (2006), who cover the topic of parameter use in greater detail.

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