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Sounding-derived parameters associated with severe hail events in Romania

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Abstract— The present paper analyzes 549 severe weather events reported to the ESWD (European Severe Weather Database) that caused large hail in the territory of Romania.

Values of atmospheric instability indices have been analyzed for these episodes using data from Bucharest and Budapest sounding stations. For a period of 140 days with episodes of large hail, 24 instability indices were analyzed to describe the atmospheric conditions of the main daily convective activity.

The mean values for most indices characterize an unstable atmospheric environment. Of the indices that measure potential instability, VT (vertical totals index) and TT (totals index) had values that described a conductive atmospheric environment for the development of hailstorms. In addition, the interquartile values of LIV (lifted index using virtual temperature) had values lower than zero. For SWEAT (severe weather threat index) and CAPEV (convective available potential energy index using virtual temperature), only the values in the 75th percentile describe a very unstable environment (according to the literature).

Strong linear correlations were registered between several pairs of indices such as CAPEV-LIV and SWEAT-SI that can be used for the operational forecast of hail.

Key-words: hailstorm, atmospheric instability indices, correlation, hail forecast

1. Introduction

Hailstorms are posing high risk to agriculture, infrastructure, and vehicles (*Hohl et al.* 2002; *Sioutas et al.,* 2009; *Istrate et al.,* 2016), causing major losses estimated in certain cases to tens of millions of Euros (*Kunz* and *Puskeiler,* 2010)

Consequently, hail climate trends have been developed, permitting the identification of hail affected areas, hail frequency, its seasonality and intensity. The spatial distribution of mean hail days per year shows the lowest values in the south-eastern and eastern parts of Romania, while the average number of hail days increases in the other parts of the country as the altitude of the terrain increases (*Clima României*, 2008). The plains of the south, east, and west, and some mountain areas are characterized by average values of 0.5–1.5 hail days, while on the mountain slopes and peaks, the average multiannual hail days range between 2 and 11. The minimum value is 0.3 in the southeast, near the Black Sea, and the maximum value is 11.8, found in the mountains, in the northwestern part of Romania (*Burcea et al.*, 2016). High frequencies (1.02–1.09 hail days) were also found in big urban areas (*Apostol* and *Machidon*, 2011). The national network of weather stations in Romania consists of approximately 160 locations. Based on data collected from these stations, an estimation has been made for the mean hail days per year, and, in our case scenario, this value is around 1.5 days (*Clima României*, 2008). For a 12-year time span, around 2500–3000 hail reports were given from weather stations. The present work, based on the ESDW network, represents an additional source of information, as the ESDW observation points locate in other places than the ones from the weather stations. The European Severe Storms Laboratory (ESSL) developed a preliminary climatology, based on large hail (> 2 cm) reports over Europe, for the period 2000–2007 (*Hand* and *Cappelluti*, 2011).

A good severe instability forecast is a strong requirement for improving nowcasting-type forecasts. The characteristics of other dangerous phenomena caused by severe atmospheric instability are presented in monographic or scientific articles by different authors. Atmospheric lightning could be considered the primary atmospheric phenomenon triggered by high atmospheric instability. Southeast Europe represents one of the regions with the highest annual spatial frequency of atmospheric lightning at continental level (*Anderson* and *Klugmann*, 2014). Some studies have found that the maximum annual CG lightning density occurs in the southwestern and central areas of Romania (*Iliescu*, 1989; *Antonescu* and *Burcea*, 2010).

Therefore, in Romania, the convective phenomena and hailstorms happen quite often during the warm season. Furthermore, the precipitation regime generally displays a continental pattern, especially during the warm semester of the year, with its maximum in July, with a highlighted role of convective precipitation due to periods of enhanced atmospheric instability (*Apostol*, 2008). National annual precipitation amounts generally remained stable (trends without statistical significance), except for certain areas in the northwest/southeast, where statistically significant positive/negative trends were recorded (*Marin et al.*, 2014). Consequently, extreme convective manifestations happen more and more frequently and cause considerable amount of rainfall in the warm season (*Croitoru et al.*, 2015). The intensity and frequency of hailstorms have been studied over the last two decades with the help of weather radar. Studies in this regard focused especially on the western part of the country. For the period 2004–2009, the meteorological radar from Bobohalma recorded numerous hailstones with a diameter of over 7 cm (*Maier et al.*, 2010). Weather-radar-based investigation of long-lived thunderstorms in Hungary in the period of 2004–2012 estimated the number of supercells in a year to be around 67 (*Horváth et al.*, 2015). For the northwestern part of Romania, over the same period, more than 100 highly severe thunderstorms were reported (*Seres* and *Horváth,* 2015).

This evolving process could be caused by recent climate changes. Throughout the entire territory of Romania, the climatic water deficit trends are due to a partial decrease in precipitation (statistically insignificant) and an increase in general evaporation (*Prăvălie et al.*, 2019). For the Extra-Carpathian area, the temperature anomaly variation is characterized by an upward trend, better observed after 1991 (*Barcacianu et al.*, 2015).

That is why we consider that enhancing the medium-term forecasting precision of these disastrous weather phenomena would be beneficial. Multiple forecasting techniques are based on data from sounding stations that forgo the possible hailstorms. The Fawbush–Miller nomogram (*Fawbush* and *Miller*, 1953) made the first step by trying to forecast hail size by measuring temperature, dew point, and wind speed. The nomogram correlates hail size with buoyancy energy between the cloud base and the -5 C° isotherm height.

Recent studies show that in the USA, parameters that combine measures of buoyancy, vertical shear, and low-level moisture reflect the strongest ability to discriminate between supercell classes (*Thompson et al.*, 2003).

Doswell and *Schultz* (2006) developed a framework for the classification of forecast variables, which indicates the limitations of such variables and their suitability for operational diagnosis and forecasting. Analyzing sounding-derived indices from Europe, the highest probability for extreme hail is maximized when the 800–500 hPa temperature lapse rate exceeds 7 $K.km^{-1}$, and when the 0–500 m above ground level mixed layer mixing ratio (MIXR) is around 15 gkg^{-1} (*Taszarek et al.*, 2017). For East Europe, during the summer months, more than 50% of days are characterized by positive buoyancy force (CAPE >0 Jkg-1) (*Siedlecky et al.*, 2009). For the northern area of Northern Greece *Sioutas* and *Flocas* (2003) found that severe thunderstorm development can be anticipated in a percentage ranging from 13.9% of the days (according to TT) and up to 18.8% (according to CAPE).

For the eastern area of Romania (*Sfică et al.*, 2015), it was found that thunderstorms could be better forecasted using CAPE and LI for the mountain region, while KI and CAPE could be used mainly for thunderstorm forecast out of the Carpathian region. For the same area, LI, SWEAT, and TT seemed to be the most powerful forecasting hail indices according to recorded values (*Istrate et al.,* 2015).

The purpose of this study is the enhancement of hail forecasting in Romania, which stands as a support for nowcasting warnings, but also for the proper conduct of operations within the National System of Hail Suppression, which is rapidly expanding (*Istrate et al.*, 2019).

2. Data and methods

The data used in this study comes from two different sources, namely ESWD and sounding stations from Bucharest and Budapest.

Severe weather reports were derived from ESWD for the period of 2006–2017. The main goal of the ESWD database (*Groenemeijer et al.,* 2004, 2005) is to collect and to provide detailed and quality controlled information on severe convective storm events in Europe using a homogeneous data format and web-based, multi-lingual user interfaces where both the collaborating European national meteorological and hydrological services and the public can contribute and retrieve observations (*Dotzek et al.*, 2009).

The European Severe Storms Laboratory (ESSL) rates the credibility of the reports on a 4-level scale: as received (QC0), plausibility check passed (QC0+), report confirmed (QC1), and event fully verified (QC2). In the present study, only the confirmed reports were used (QC1). The development of social media and the increasing number of people interested in severe weather that has taken place in recent years have significantly increased the number of reports (often accompanied by a photograph of the event). This database, which tries to collect all the hailstorms, is not complete, but it is the best existing source for the Romanian territory. The number of reports development over the ten years has been highly influenced by the progress of the ESWD network. The density of large hail reports for the Romanian territory is low (50–70 reports per 10000 km^2) compared to Germany, Austria, or northern Italy, where there are over 200 reports per 10000 km^2 (*Groenemeijer et al*, 2017). In the first year, 2007, a very poor number of events were reported for the territory of Romania. During 2008–2010, between 40 and 50 reports were recorded per year (*Istrate et al.,* 2017). From April 1 to September 30, 2006–2017, there were 549 QC01 credibility rated events reported for the ESWD. Many of these were reported from the neighboring local areas affected by the same hailstorm (*Fig 1*). In addition, we can notice some areas without any reports as the southeastern area or the mountains. In this case, the lack of data can be linked to the sparse population of these territories or the few people interested in meteorological phenomena.

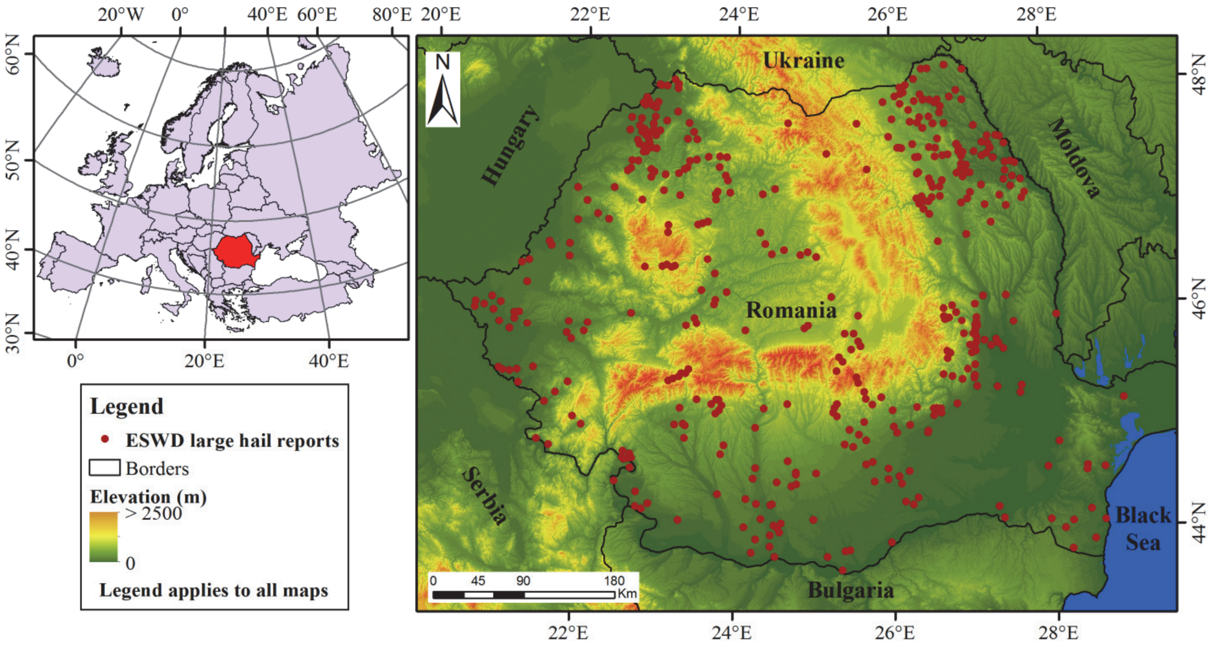

Fig. 1. ESWD large hail reports from April 1 to September 30, 2006–2017, used in this study for analysis.

The rawinsonde measurements were derived from the sounding database of the University of Wyoming. For the period between 2006 and 2017, all the available measurements for 12 UTC were downloaded for the stations from the studied area. Only the data coming from Bucharest and Budapest were used because these two were and still are the most relevant radiosonde stations for the studied territory, from which we were able to access 12 UTC data. In a 24-hour cycle, the maximum of convection phenomena takes place in the afternoon and in the evening. For this reason, the day sounding (12 UTC) better presents the conditions favorable for the development of severe hailstorms. The Carpathian Mountain chain, which causes diurnal air temperature differences that are greater in the east (*Apostol* and *Sfîcă,* 2013), mainly influence the local conditions and extreme rainfall values (*Croitoru et al.,* 2015). For the Extra-Carpathian area, we used data observed at the Bucharest, the Intra-Carpathian, and the Budapest weather stations.

We used isotherm heights such as 0 °C (H0), -10 °C (H-10), and -20 °C (H-20). These can be considered key isotherms used for a medium-term hail forecasting or to detect convective storm cells with hail probability (*Abshaev et al.,* 2010; *Potapov* and *Garaba*, 2016). The altitude of these isotherms was determined by calculating a local, thermal gradient. Furthermore, we established the vertical thermal gradient by using the following formula: $\gamma=\frac{\Delta T}{\Delta z}$, where $\Delta T=T_1-T_2$ and $z=z_1-z_2$ stand for temperature and height increases. Other used variables are the altitude differences between the -10 °C and 0°C (ΔH1), -20 °C and -10 °C (ΔH2) and the -20 °C and 0 °C (ΔH3) isotherms.

Thunderstorms are more likely to form when the boundary layer's mixing ratios are higher than 8 $\mathrm{gkg^{-1}}$. Deep convection is also more likely to occur when the vertical temperature lapse rates (between the 800 and 500 hPa air pressure layers) exceed $6°\mathrm{C.km^{-1}}$ (*Kolendowicz et al.,* 2017). The values of the thermal gradients for the analyzed scenarios exceeded 0.6 °C/100 m, reaching 0.9 °C/100 m in some cases, recording a temperature lapse rate of at least 6 °C $\mathrm{km^{-1}}$ between the 800 and 500 hPa air pressure layers.

24 indices were analyzed, derived from the sounding data over a period of 140 days in which large hail was reported. Besides the main height of isotherm indices, meteorological variables from the Showalter sounding-derived indices of atmospheric instability were used (*Showalter*, 1953; *Hart* and *Korotky*, 1991), such as total totals (TT), vertical totals (VT), cross totals (CT) (*Miller*, 1975), K index (KI) (*George,* 1960), lifted index (LI) (*Galway*, 1956; *Johns* and *Doswell III*, 1992), CAPE and CAPEV (*Glickman*, 2000), and other sounding-derived parameters (*Table 1*).

We statistically analyzed these indices to find possible correlations between them. Using the XLSTAT software, we discretized the variables, analyzed some variables using the box plot diagrams and the correlation matrix.

3. Results and discussion

3.1. Characterization of sounding-derived indices

The H0, H-10 and H-20 monthly mean values are showing an increasing trend from May to August (*Fig. 1*). This case scenario is typical in the climate zone in which Romania is situated. The western oceanic influences dispense thermic inertia, which is a common thing happening in the high lands, with peak values in August (*Clima României*, 2008). For April, when only two events were recorded, the high values can be considered as exceptions.

For values between 3000 and 4000 m for the 0°C isotherm, 5000 and 6000 m for the -10 °C isotherm, and 6500–7500 m for the -20 °C isotherm, most storms were accompanied by hail.

Table 1. The 24 sounding-derived indices investigated in this study. Units are shown in the second column in parentheses

Acronym	**Index name**	**References**	**Minimum**	**Maximum**	**Mean**	**Std. deviation**
H0	Height of the 0°C isotherm (m)	-	1642	5524	3445	679.7
H-10	Height of the -10°C isotherm (m)	-	2941	7383	5051	675.4
H-20	Height of the -20°C isotherm (m)	-	4311	8518	6538	678.5
ΔH1	Altitudinal difference between the -10°C and 0°C isotherms (m)	-	806	2523	1605	234.2
ΔH2	Altitudinal difference between the -20°C and -10°C isotherms (m)	-	1010	2955	1487	194.9
ΔH3	Altitudinal difference between the -20°C and 0°C isotherms (m)	-	2478	4981	3093	283.4
SI	Showalter index	*Showalter* (1947)	-5.15	10.15	0.98	2.57
LIV	Lifted index using virtual temperature	*Galway* (1956)	-9.41	12.11	-1.36	3.1
SWEAT	SWEAT index	*Miller* (1972)	24.68	364.56	158.5	69.06
KI	K index	*George* (1960)	-11.7	37.4	26.98	7.54
CTI	Cross totals index	*Miller* (1975)	7.1	29.9	21.3	3.4
VT	Vertical totals index	*Miller* (1975)	17.7	47.8	27.87	2.94
TT	Total totals index	*Miller* (1975)	34.3	731.45	53.79	57.41
CAPEV	CAPE computed by using the virtual temperature (J/kg)	*Glickman* (2000)	0	3052.4	542.49	607.14
CIN	Convective inhibition (J/kg)	*Colby* (1984)	-412.08	0	-66.19	82
EL	Equilibrium level (hPa)	*Glickman* (2000)	0	748.42	357.25	151.01
LFC	Level of free convection (m)	-	454.81	947.99	756.03	82.62
BRNV	Bulk Richardson number using CAPV	*Weisman* and *Klemp* (1982)	0	3320.43	104.94	412.78
LCLT	Temperature (°C) at the lifted condensation level	-	-3.15	18.52	8.31	22.63
LCLP	Pressure [hPa] of the lifted condensation level	-	287.18	956.14	839.33	70.773
MLPT	Mean mixed layer potential temperature	-	8.46	855.25	301.65	47.051
MLMR	Mean mixed layer mixing ratio(g/kg)		4.01	300.32	11.67	24.48
1000-500 hPa Thick	1000 hPa to 500 hPa thickness (meters)	-	11.99	5809	5588.641	478.63
TPW	Precipitable water (mm) for the entire sounding.	-	13.4	5651	67.47	471.91

In the situation of having a strong updraft, the ice pellets can grow to impressive sizes if their course runs more into the cold area of the cloud. Therefore, in more than 70% of the reports, the ΔH3 value was between 3000 and 4000 meters (*Fig. 2*).

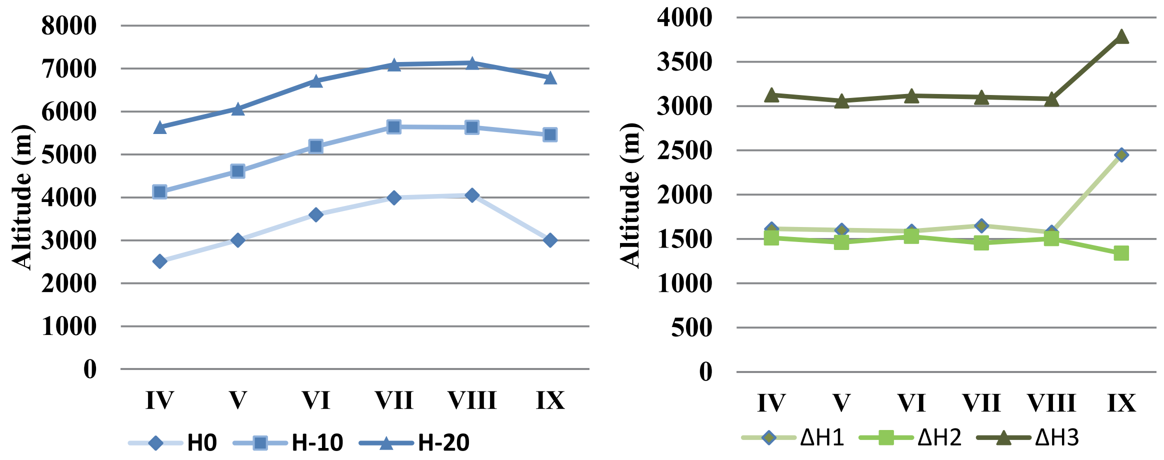

Fig. 2. The evolution of the monthly mean indices, H-10, H-20, ΔH1, ΔH2, ΔH3 for 140 days with large hail reported.

Looking at ΔH1, and ΔH2, one can observe the backwards correlation between them. In the months in which the ΔH1 value increases, ΔH2 decreases, and vice versa. The figures of these two indices also indicate how the vertical temperature gradients evolve in the days in which hail occurs. In the first part, with negative temperatures between H0 and H-10, the gradients are larger compared to the area between H-10 and H-20 in all of the warm season months.

The SI, KI, LIV, CTI, VT, and TT sounding-derived indices group, that measures the potential instability of the atmosphere, only includes indices calculated by using information from two levels. Out of the two-level instability, indices VT and TT have mean values, which describe an atmosphere that would develop extreme convections. The interquartile values of LIV are negative, and SI shows values which stand for extreme instability in the atmosphere (*Fig. 3*).

Another group of indices is the one that measures the potential instability above the level of free convective. The box-plots for two of these kind of indices – sweat index and CAPV – only show the highest values as being close to the ones that would describe an extremely unstable atmosphere. However, in all of the days, when their values were analyzed, hailstorms were reported. The explanation for this would be the climate conditions and the relief in Romania that are different from those in the US, where these indices were built in the first place. Also, the box-plot for the CAPE index values that came out in this study is nearly identical to most of the ones in Europe in days with large hail (*Taszarek et al.,* 2017).

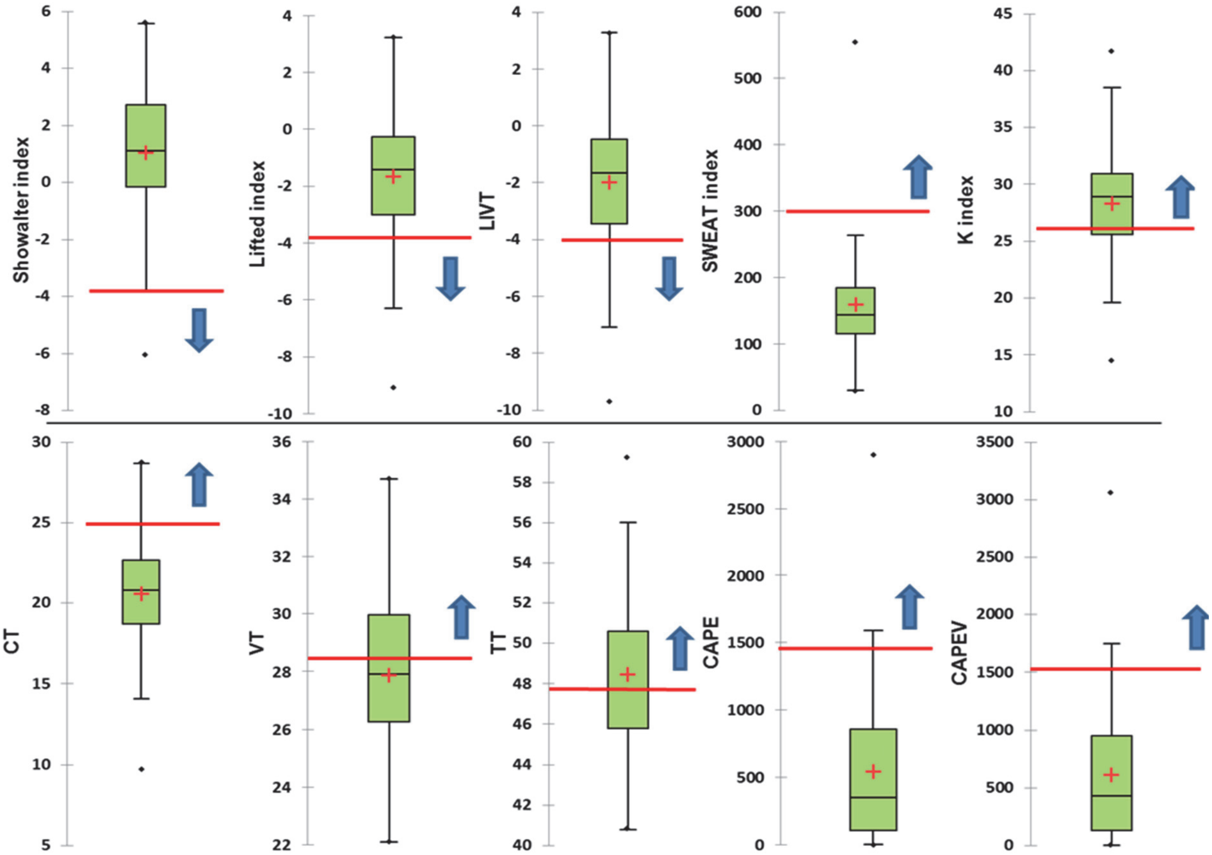

Fig. 3. Box-and-whisker plot of 10 selected indices. The median is represented as a horizontal line inside the box, edges of the box represent the 25th and 75th percentiles, while whiskers represent the 10th and 90th percentiles. The red line represents the limit from which the parameter value describes a very unstable environment (according to the literature), and the blue arrow indicates the direction in which the evolution of its value would lead to extreme convective manifestations.

In the northwestern part of Spain, the mean values of CAPE index with hail observations are 360 Jkg^{-1}, while thunderstorm occurrence shows a mean CAPE index of about 260 Jkg^{-1} (*López et al.,* 2001). Over northern Italy, tornado events are observed when KI index exceeds 30. CAPE values are 700–2,500 Jkg^{-1} and SWEAT index is 250–300 (*Costa et al.,* 2001). Over Cyprus, 10% of the strongest thunderstorms are observed when KI index exceeds 30. Over Greece (*Dalezios* and *Papamanolis,* 1991), there is a high probability of hail occurrence when KI index is above 25 and TTI index exceeds 44. In Switzerland, weak, isolated thunderstorms give average CAPE values of 210 Jkg^{-1} at 00 UTC radio soundings and 400 Jkg^{-1} at 12 UTC radio soundings, over the Czech Republic, during severe weather, 80 percent of CAPE is around 322 Jkg^{-1} (*Pešice et al.,* 2003). This means that for both this index and other indices, another scale of values should be fixed, adjusted to the topographic and climatic conditions, which could show different convective instability rates. Therefore, for most of the days when hail was reported, CAPEV index values were between 100 and 800 Jkg^{-1}, SWEAT between 120 and 200, Showalter index between -0.5 and 2, and LIV between 0 and -3.

3.2. *Correlations among indices*

To establish which indices are the most suited to be used for hail forecasting, we chose a bivariate primary analysis of all these 24 indices. In order to be relevant in forecasting, these sounding-derived indices should be able to describe the pre-convective atmospheric details with decent precision. For 52 indices, *Manzato* (2012) made a bivariate analysis between each index, and the hit hail pads in 6 h were done as a preliminary attempt to evaluate the utility of these indices for forecasting hail. It is found that some measures of instability (like updraft, hail diameter, and LI) seem to have more skill than the other indices when classifying the hail-event occurrence. When estimating the number of hit hail pads, the best correlation is obtained by the indices belonging to the "lifted index family". The correlation matrix of these 24 variables indicates a Pearson coefficient value of over 0.7 only to several pairs of indices (*Fig. 4*).

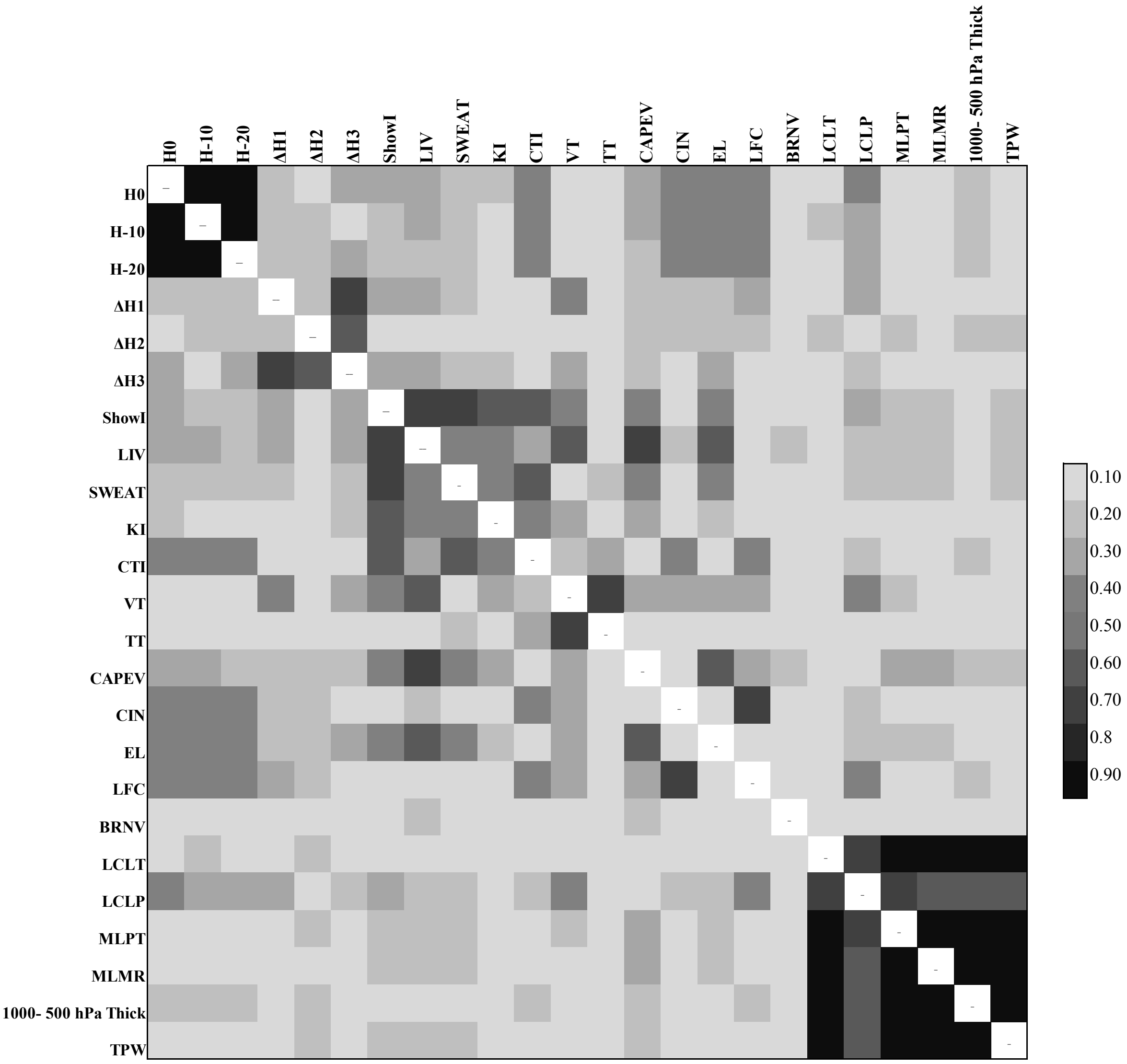

Fig. 4. The absolute value of the correlation matrix among the 24 sounding-derived indices listed in *Table 1*. The absolute values of the Pearson's ǁRǁ are shown in grayscale: high ǁRǁ is dark and ǁRǁ = 0 is white.

In most of the cases, the highest coefficient values reveal autocorrelations between indices that use the same parameters. These autocorrelations are not suggestive, and they cannot add any contribution for hail forecasting. One of the autocorrelations that can help to forecast hail is the one between SI and SWEAT indices. SI indicates the increase of convective potential when a cold air mass of less than 850 mb approaches. SWEAT index takes into account many essential parameters, including low-level moisture, instability, and vertical wind shear. Therefore, under the circumstance of a cold front, the accretion of ice pellets is faster when the updraft contains a large amount of water. This large amount of water caused by the tremendous relative humidity values from the lower troposphere. Another relevant and robust correlation is the one between CAPV and LIV indices. The negative value of LIV indicates that the planetary boundary level is unstable, compared to the middle troposphere, and the CAPV's high values reflect a significant amount of latent heat released following the condensation of water vapor. Thus, almost every day of the 140 days in which hail occurred, the atmosphere was characterized by pronounced instability, fluctuating energy, positive buoyancy, and a large amount of humidity.

Strong correlations were also found in the indices group that describe the convective air from a temperature point of view (*Table 2*). One can observe the correlation between H0 and H-10, respectively H-20 or between H-10 and H-20. Strong bonds can also be seen between ΔH_2 and ΔH_3. These correlations can be explained by the existence of positive vertical gradients and, consequently, the absence of temperature inversion between H0 and H-20. Also, the in-tandem increase of ΔH_2 and ΔH_3 describes a larger area of growing ice particles. Therefore, under the circumstance of the convective energy described by other indices, the growing size trend has led to impressive ice stone diameters which did not have enough time to melt in the troposphere's layer with positive temperatures when falling onto the ground.

Table 2. Groups of sounding-derived indices that have a linear correlation coefficient $\|R\| \geq 0.7$

Indices	**Couples**	**R**
SI	SI-SWEAT index	-0.75
CAPV	LIV – CAPV	-0.80
LIV	LIV – EL	0.80
H0	H0 – H-10	0.86
H-10	H0 – H-20	0.88
H-20	H-10 – H-20	0.93
ΔH_2	$\Delta H_2 - \Delta H_3$	0.73

4. Conclusion

This paper has analyzed a number of sounding-derived parameters associated with ESWD hail reports in Romania. Out of the 549 ESWD database reports between 2007 and 2017, with QC1 credibility rate, many of these were recorded from the same hailstorm that affected the neighboring local areas. We found 140 days in which hail was reported for which we characterized the atmospheric conditions of the main daily convective activity using 24 sounding-derived indices coming from Bucharest and Budapest stations.

Out of the two-level instability indices, VT and TT had the mean values, which describe an atmosphere that would develop extreme convections. The interquartile values, between 75th and 25th percentiles for CAPEV, were between 100 and 800 Jkg^{-1}, 120 and 200 for SWEAT, -0.5 and 2 for ShowI and for LIV, between 0 and -3. In 50% of the days when hail occurred, the atmosphere characterized by pronounced instability, flotation energy, positive buoyancy, and large amounts of humidity.

The primary analysis of the 24 indices used in this study revealed several strong linear correlations. The strongest correlations were found between the following indices: LIV – CAPV, SI – SWEAT, LIV – EL, H0 – H-10, H0 – H-20, and H-10 – H-20. The main drawback of this study is that hail reports occurred far from the sounding sites. In the future, we intend to use convection-related parameters and synoptic-scale fronts from ERA5 reanalysis to improve these results.

The present study was done as a preliminary attempt to evaluate the utility of these indices for forecasting hail in Romania.

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