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Potential benefit of the ensemble forecasts in case of heavy convective weather situations

Dóra Lázár[1] and **István Ihász**[2*]

[1]Department of Meteorology, Eötvös Loránd University,
P.O. Box 32, H-1518 Budapest, Hungary
E-mail: ldora1989@gmail.com

[2]Hungarian Meteorological Service,
H-1675 Budapest, P.O.Box 39.
E-mail: ihasz.i@met.hu

**Corresponding author*

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Abstract— Nowadays, early warning and alarm for high impact weather situations becomes more and more important. Besides deterministic model forecasts, using ensemble forecasts gets increasing attention, but in case of the convective events, probabilistic forecasts have not been widely used. Due to the fact that convective events are very changeable in space and time, probabilistic approach can have a lot of advantages. Current horizontal resolution of the global ensemble models is around 30 km, so we cannot aim to focus on small scale convective events, but focusing on frontal zones and extended squall lines can be possible. We attempt pioneering steps to develop new methods and tools to support early warning based on ensemble (ENS) forecasts of the European Centre for Medium-Range Weather Forecast (ECMWF). We focus on the forecast probabilities of three main components generating convection.

Key-words: convection, convective available potential energy, ensemble timeline diagram, ensemble vertical profile, probability charts, relative humidity, statistical and case studies, wind shear

1. Introduction

Protection of life and property is one of the most important tasks of weather forecasts. Heavy convective events quite often cause heavy rainfall, hail, or extremely strong wind causing severe damages. The European unified warning system, the so-called Meteoalarm collects the alert information coming from member states of EUMETNET. It provides real time warning on its website: www.meteoalarm.eu. The Hungarian Meteorological Service has been maintaining a warning system for counties and alert system for subregional areas since August 1, 2011. This system provides warnings for up to maximum 48 hours (current day and one day ahead) and alerts for ultra short-range (0.5 – 3 hours). The warning system is mostly based on forecasts coming from different models, for this purpose mainly deterministic models were used in the past. The alert system is mostly based on radar and satellite information besides ultra short-range model forecasts. Even nowadays, usage of the global and regional ensemble models gets increasing attention (*Molteni et al.*, 1996, *Palmer*, 2006; *Persson* and *Riddaway*, 2011, *Barkmeijer et al.,* 2012).

Every five years ECMWF makes a strategic plan covering the forthcoming 10 years. In the current ECMWF's Strategic Plan covering the period 2016–2025, developing methods for early warning up to 4–5 days is among the key elements of the strategy (ECMWF, 2016). During our work, we developed a few new objective methods supporting warnings based on ensemble forecasts.

For the development of heavy convective events, three components are needed: atmospheric vertical instability, adequate moisture, and vertical wind shear (*Horváth* and *Geresdi*, 2001; *Craven* and *Brooks,* 2002).

The atmospheric vertical instability is often characterized by the so-called instability index. One of the most popular and often used indexes is the convective available potential energy (short name is CAPE). CAPE is computed according to the following formula:

$$CAPE = \int_{LFC}^{EL} g \frac{T'_v - T_v}{T_v} dz \,, \tag{1}$$

where *EL* is the equilibrium level (the height at which a rising parcel of air is at the same temperature as its environment), *LFC* is the level of free convection (the height at which the relative humidity of an air parcel will reach 100% when it is cooled by dry adiabatic lifting), g is the gravity, and T_v is the virtual temperature (the temperature at which a theoretical dry air parcel would have a total pressure and density equal to the moist parcel of air).

Vertical wind shear is also a critical factor in the development of the thunderstorms. Vertical wind shear, or the change of winds with height, interacts dynamically with thunderstorms to either enhance or diminish vertical upwelling. So we used the CAPE index, relative humidity, and vertical wind shear (*Horváth*, 2007).

Focusing on these three meteorological parameters, we examined benefits of the usage of ensemble forecasts. To support this, a comprehensive set of tools has been developed.

Our study provides a summary of the newly developed methods based on ECMWF ensemble forecasts (ENS) to assist successful prediction of the convective weather situations. In the first part of the study, key elements of the new approach are presented and illustrated by a few examples. In the second part, result of the statistical investigation is summarized. In the third part, only one selected case study is presented due to some space constraints. Finally, we summarize the benefits of this new system and we have a short outlook too.

2. Statistical studies

Statistical studies of these three parameters were based on a ten-year period of a 51-member ensemble forecasting model for the convective summer season (*Fig. 1*). Relationships between the rate of the convective and total precipitation and the aforementioned three parameters were studied by different statistical methods. On the histogram of CAPE, the values decreased exponentially. On the histograms of the wind shear and relative humidity, the distributions were lognormal.

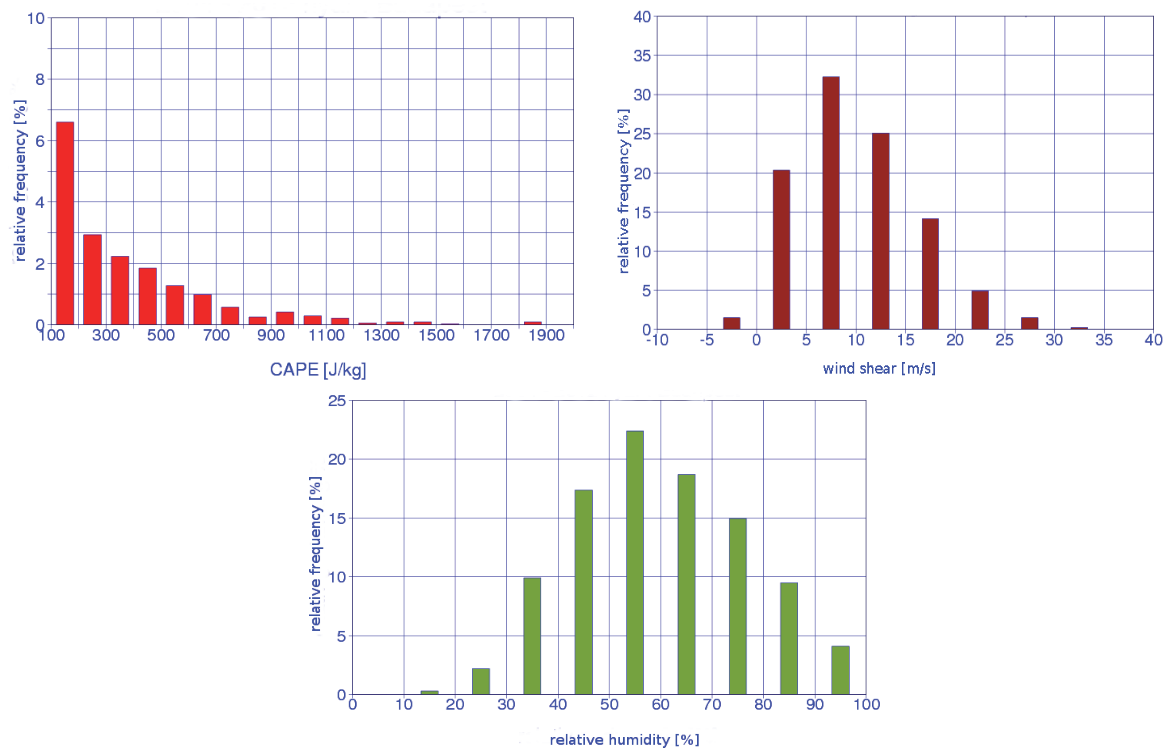

Fig. 1. Histograms of CAPE (J/kg), wind shear (m/s), and relative humidity (%) in summer seasons for Budapest between 2004 and 2013.

We studied whether high rate of convective precipitation was associated with high CAPE values in convective weather situations. Convective/total precipitation rate was calculated and the relationship of these two parameters was studied with crossdiagrams (*Fig. 2*). The thresholds of the CAPE were 0, 500, 1000, 1500, 2000, and 2500 J/kg, and the comparison of the convective/total precipitation rate and CAPE was made for selected thresholds of total precipitation (0, 1, 5, 10, 15, 20, and 25 mm). In the most typical situation, low convective/total precipitation rate was connected with low CAPE values. In case of the extreme values, this relationship was not so strong, thus strong convection was connected not only with CAPE, some other meteorological variables could be quite important too.

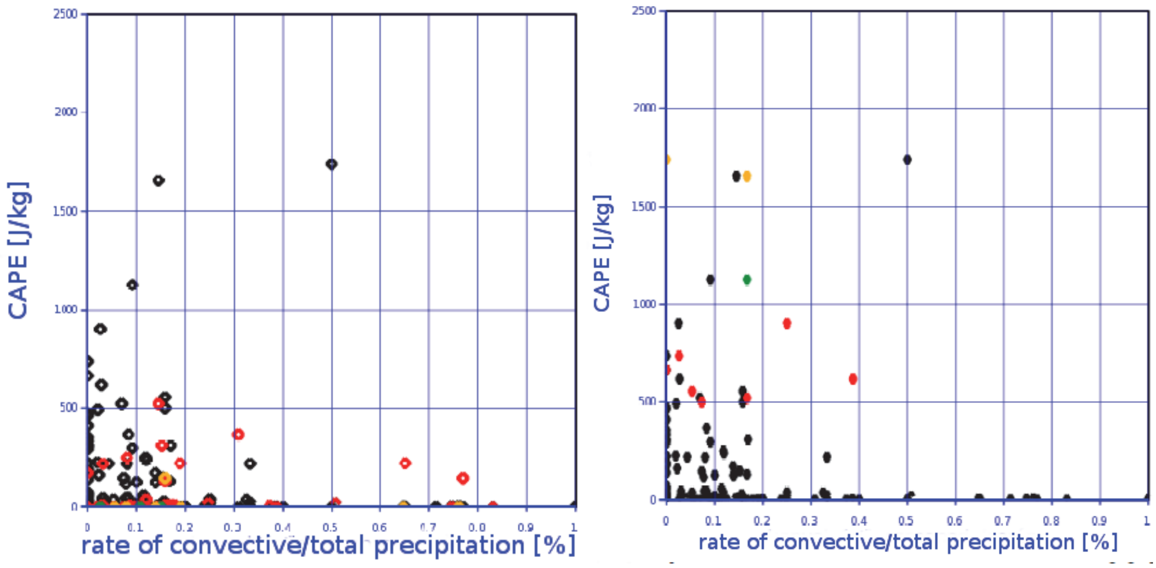

Fig. 2. Crossdiagrams of CP/TP precipitation rate and CAPE values: (left) threshold of CAPE: 0 J/kg, thresholds of precipitation (with quantity): black dot: 0 – 5 mm (125 cases), red dot: 5 – 15 mm (38 cases), orange dot: 15 – 20 mm (3 cases), green dot: above 20 mm (2 cases) for Budapest, (right) threshold of precipitation: 0 mm, thresholds of CAPE (with quantity): black dot: 0 – 500 J/kg (163 cases), red dot: 500 – 1000 J/kg (7 cases), orange dot: 1000 – 1500 J/kg (1 cases), green dot: above 1500 J/kg (1 case) for Budapest

We studied the characteristics of the convective/total precipitation rate forecasts based on different model runs. As the most intensive convective activity typically occurs in the early afternoon, it seemed to be useful to study the similarities and differences of the 00 and 12 UTC model runs. On the histogram *(Fig. 3)*, the total 24-hour sum of the precipitation can be seen, 00 and 12 UTC ENS and control models associated with different thresholds (1, 5, 10, 15, 20, and 25 mm) were plotted. Generally, the 12 UTC model runs produced less number of heavy convective cases than the 00 UTC model runs, but with increasing CP/TP ratio to the proportion of the former grows. At the thresholds of 1 and 5 mm, the relative frequency of the CP/TP ratio extends from 10 to a maximum of 15%. At 15 mm, another column of 75–85% appeared (not shown). At 20 and 25 mm, due to the low number of cases, comparing distributions was not possible.

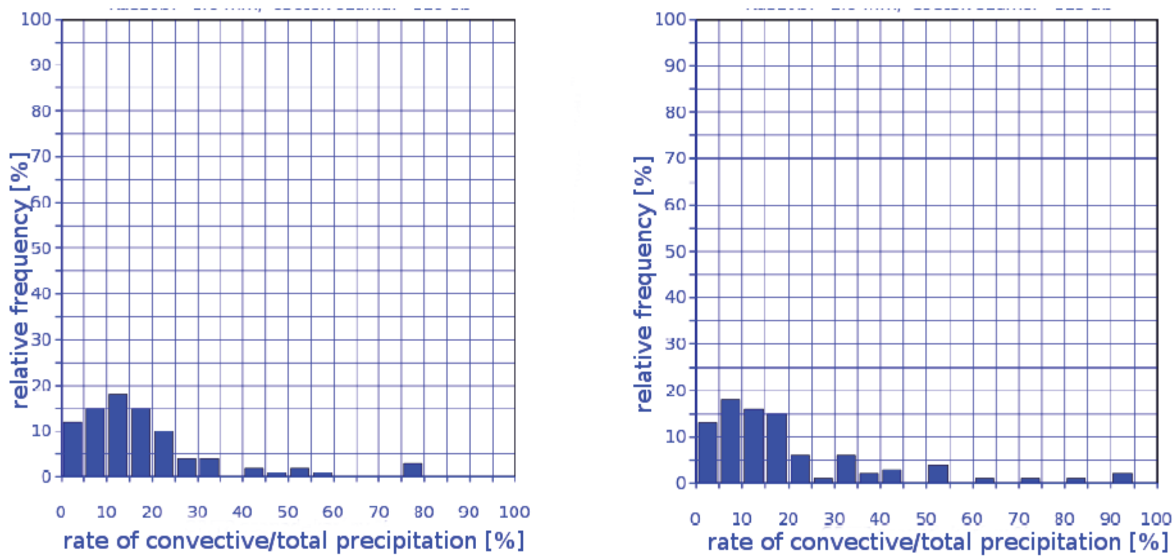

Fig. 3. Histograms for rate of the convective and total precipitation with 1 mm threshold for Budapest: (left) 00 UTC (116 cases), (right) 12 UTC (115 cases)

We also examined the similarity of the distribution curves with the help of the two-sample Kolmogorov-Smirnov test. We checked the condition whether the distribution functions of random examined variable corresponds to a specific distribution function. Consider the (ξ, η) as a random variable pair and ξ, η, n_1 and n_2 as thereof derived independent element patterns. Mark the distribution function of ξ as $F(x)$, the empirical distribution function calculated from the sample as $F_{n1}(x)$, and using the same method for the random variable η, mark its distribution function and empirical distribution function as $G(x)$ and $G_{n2}(x)$. Chosen probe attached to the probe test statistic:

$$D_{1,2} = \sqrt{\frac{n_1 - n_2}{n_1 + n_2}} \left(\sup \left| F_{n_1}(x) - G_{n_2}(x) \right| \right), \tag{2}$$

whereof (*Kolmogorov*, 1933, *Smirnov*, 1936):

$$P\left(D_{1,2} < x\right) = K(x), \tag{3}$$

where $K(x)$ is the limit distribution function. To define the range of acceptance, it is necessary to assign x_α values for the most important levels of significance (*Table 1*).

Table 1. x_α values for the most important levels of significance

A	0.1	0.05	0.001
x_α	1.23	1.36	1.63

We take the x_α values from the table of $K(x)$ distribution function, $K(x_\alpha) = 1–\alpha$. Our acceptance range of $(0, x_\alpha)$ interval is on the level of α significance. Thus, the null hypothesis is kept $0 \leq D_n < x_\alpha$. The null hypothesis is rejected when $D_n \geq x_\alpha$ (*Dévényi* and *Gulyás,* 1988).

As our value was about 2.1, it was found that in a 95% hypothesis test the distribution of the convective/total precipitation rates for 24 hours based on 00 and 12 UTC model runs are different. In both cases of the visual and statistical methods, the same conclusion was made.

In this chapter, three parameters (CAPE, wind shear, relative humidity) were examined with statistical methods which revealed their physical features. Long-period investigations showed the most frequent values and revealed the attributes of the above-mentioned parameters. Using these data in the case studies, the threshold values can be easily chosen. We studied the relationship between the CAPE values and the convective/total precipitation rate, therefore, the convective/total precipitation rate parameter was added to the examination. Thereafter, features of the convective/total precipitation rate were examined with various time and threshold values on histograms and with the Kolmogorov-Smirnov test too.

3. New comprehensive probabilistic approach to forecast convective events

As it has been mentioned, CAPE index, relative humidity, and vertical wind shear were investigated. Focusing on these three meteorological parameters, we studied potential opportunities of the ensemble forecasts with four newly developed graphical tools.

Two of the four visualization methods, the ensemble meteogram and the ensemble vertical profiles (*Ihász* and *Tajti*, 2011) were available at the beginning of our work. These two point forecast products have been operationally available at the Unit of Methodology Development of Hungarian Meteorological Service since 2011. Both methods show probability distributions of the meteorological parameters for the selected location.

On the ensemble meteogram you can see the probability of the CAPE index, the wind shear between 10 m and the 500 hPa level, and the average relative humidity between 850 and 500 hPa levels. The ensemble vertical profile is based on temperature, dew point, wind direction and speed at 91 ensemble model levels.

Additionally, we developed two new methods for studying convective events. The first method provides probability map of the event exceeding predefined thresholds. Probability of CAPE, wind shear, and relative humidity with other parameters are studied. Other parameters are the 500 hPa geopotential height, 300 hPa potential vorticity, and convective precipitation. Applying this approach we can study weather situations in more details. Intensity of the dangerous weather conditions can be well estimated. Intensive convective periods are clearly marked during the forecasting period. Another new visualization tool shows time evolution of predefined multiple thresholds in graphical form for any selected location. In our case studies, CAPE and wind shear with different thresholds were examined.

First of all, our aim was to study the probability maps, so we could identify the time and spatial location of the convective weather situation. Then we used multiple thresholds timeline diagrams in selected points, so we could see when the most extreme values of these parameters were predicted and how they changed in time. In the third part of our study we investigated the evolution of the vertical properties of the atmosphere in time. In the end, we studied the relationships among these three parameters with ensemble meteograms. We studied the day-to-day consistency of the forecasts too, so the analyzed period was between day –4 and day –1 before the event.

Horizontal resolution of the numerical models are regularly increased (*Horányi et al.,* 2011, *Szintai et al.,* 2015). In spring 2016, ECMWF increased the horizontal resolution of the high resolution (deterministic) model from 16 km to 9 km. At the same time, the horizontal resolution of the ensemble model changed from 32 km to 18 km. After 2020 running of global non-hydrostatic models would be necessary (*Wedi* and *Malardel*, 2010). These developments will likely cause increasing reliability of the forecasts in heavy convective situations too.

In this chapter, new applied visualization tools were presented. We intended to explore their applicability in forecast situations, therefore case studies were investigated. A selected case study is presented in the next chapter.

4. Case study of heavy convective events

During our former studies (*Lázár,* 2013), comprehensive case studies were done. Weather situations representing different type of convective events were selected in summer 2012. In this paper, weather situation of July 29, 2013 is presented, this event followed the hottest period of summer 2013. On July 29, 2013 lots of thunderstorms were observed in Hungary (*Horváth* and *Kolhmann*, 2013).

It was a really hot weather situation when new record maximum temperatures were registered before a thunderstorm line reached Hungary. In front of the cold front, the temperature had been increasing and 23 °C appeared at the 850 hPa level. In Western Europe, intense thunderstorms connected to the cold front were erupted. Around 20 UTC, the upper air cold front with stormy winds (60–80 km/h) reached the Transdanubian Region from southwest direction. In the early hours of July 29, the northwestern cold front arrived in the lowest levels.

During our study, first the probability maps were examined, forecasts of day –4 to day –1 were used (*Fig. 4*). The investigated time was July 29, 2013, 21 UTC, so the studied forecasts were made on the following three consecutive days: July 26, 27, 28, 2013, 00 UTC. High probability of high CAPE values could be seen in the northwestern part of the country. The local maximum of the potential vorticity was located northwest to this area. A pair of ridge and trough was connected to this region too, the latest forecast showed stronger contrast between the ridge and trough.

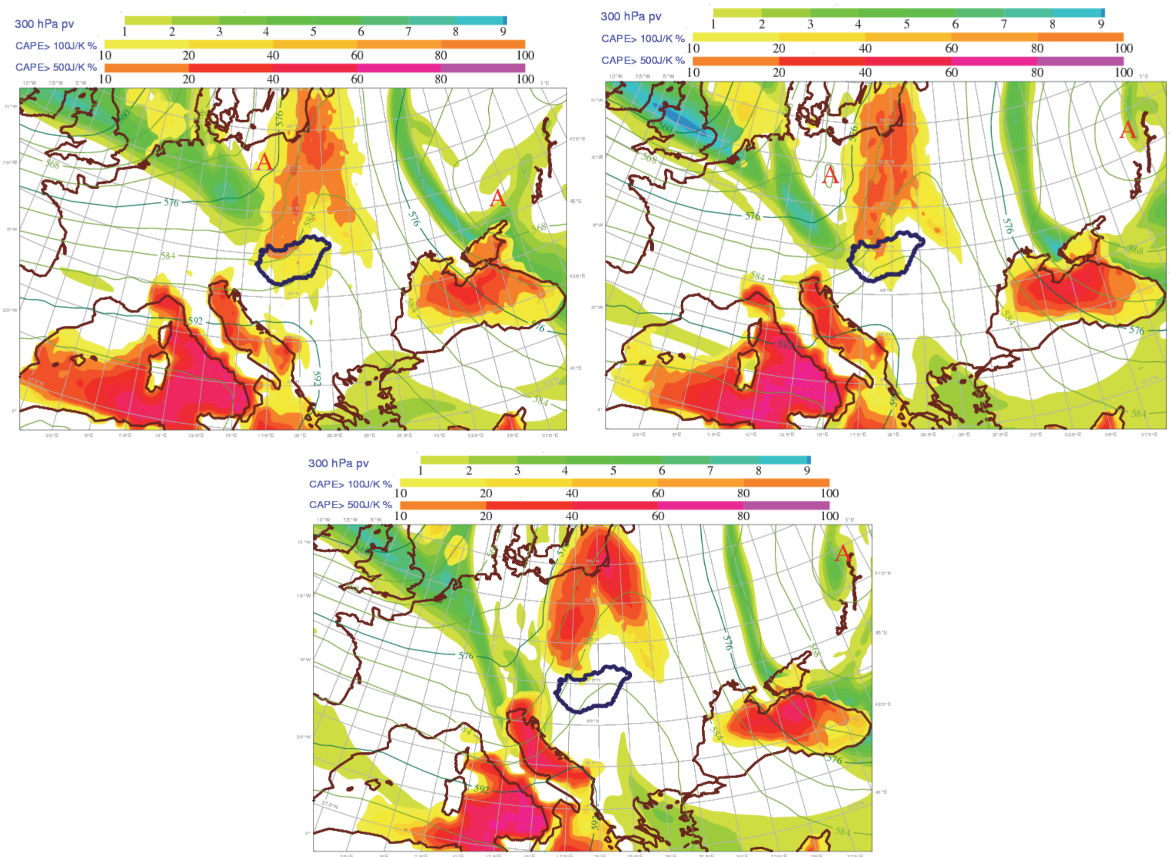

Fig. 4. Forecast of the CAPE probability (shaded yellow to pink), potential vorticity values (shaded green to blue), and 500 hPa height fields (green lines) at July 29, 2013, 21 UTC (by forecast of July 26, 2013, 00 UTC + 93 hours, July 27, 2013, 00 UTC +69 hours, and July 28, 2013, 00 UTC +45 hours)

At the second step, particular locations, like Szombathely were selected, where the time evolution of the predefined multiple thresholds of CAPE values was studied. The most dangerous time period, early late afternoon was predicted in every model run. Intensity of the probabilities was changed from model run to model run (*Fig. 5*).

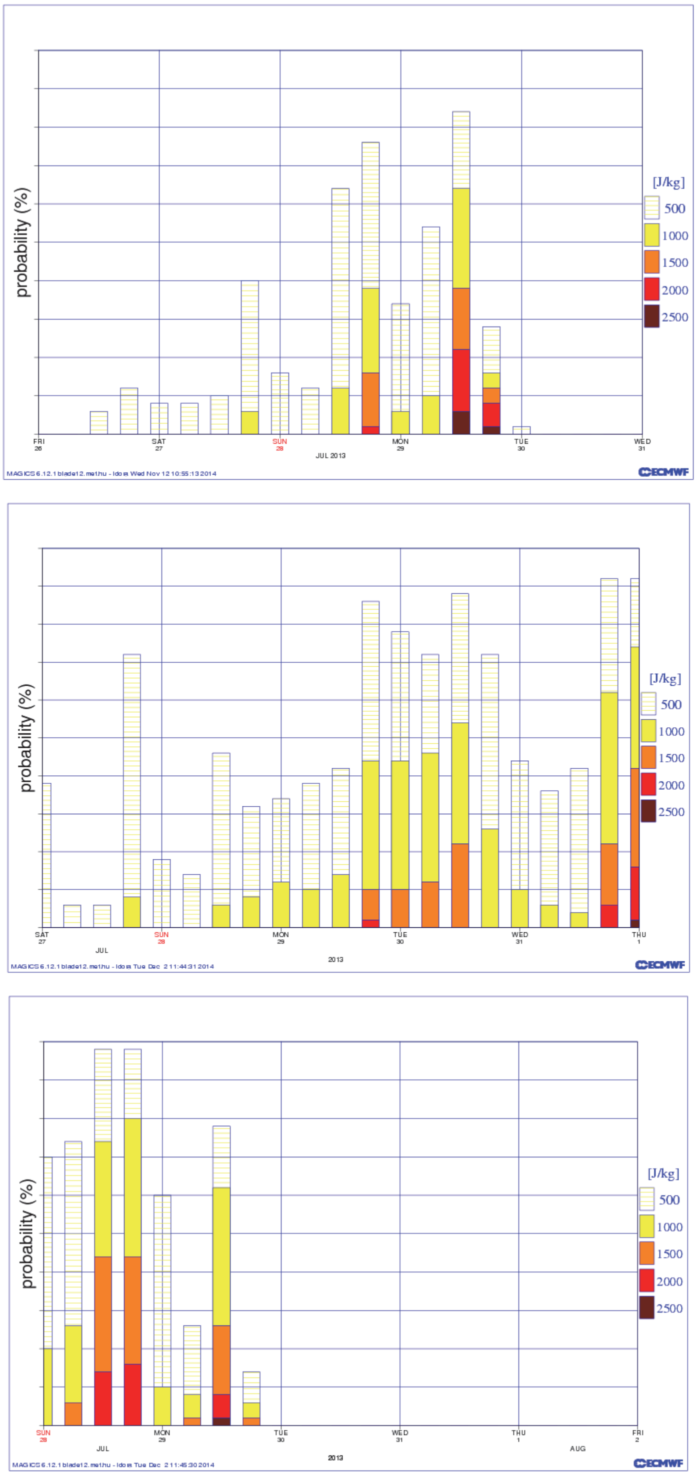

Fig.5. Time evolution of predefined multiple thresholds of CAPE values (the thresholds: 500 (yellow dot), 1000 (yellow), 1500 (orange), 2000 (red) and 2500 (brown) J/kg) based on modeled values of July 26, 27, 28, 2013 for Szombathely.

The third studied diagram was the ensemble vertical profile for the selected location (*Fig. 6*). It can be clearly seen, that the lower troposphere was relatively dry, and between 700 and 300 hPa an extended wet layer could be found which supported the possibility of severe convective events.

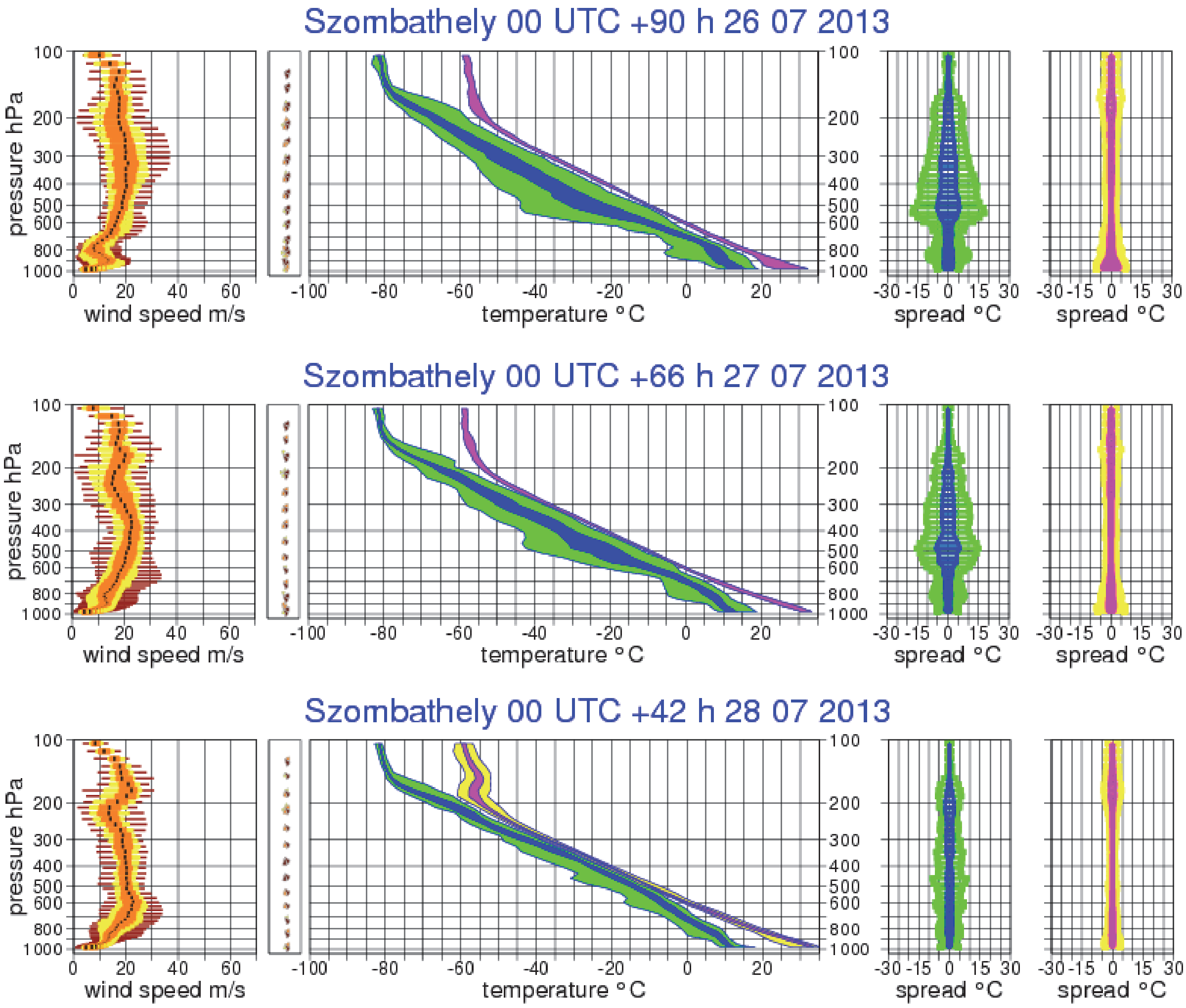

Fig. 6. Ensemble vertical profiles based on model runs of 00 UTC July 26, 27, 28, 2013 for Szombathely

Finally, we studied the ensemble meteograms of these three parameters (*Fig. 7*). In the forecast of July 27, 00 UTC, it could be seen that the probabilities of the CAPE and wind shear were increasing gradually until the evening of July 29. Probabilities of the relative humidity were decreasing gradually until the evening of July 29. After July 30, the CAPE values were near to zero, the intensity of the wind shear decreased, and the relative humidity increased. This statement could be seen in the forecast of July 28, 00 UTC, but it was not so much strong as in the forecast of July 27, 00 UTC.

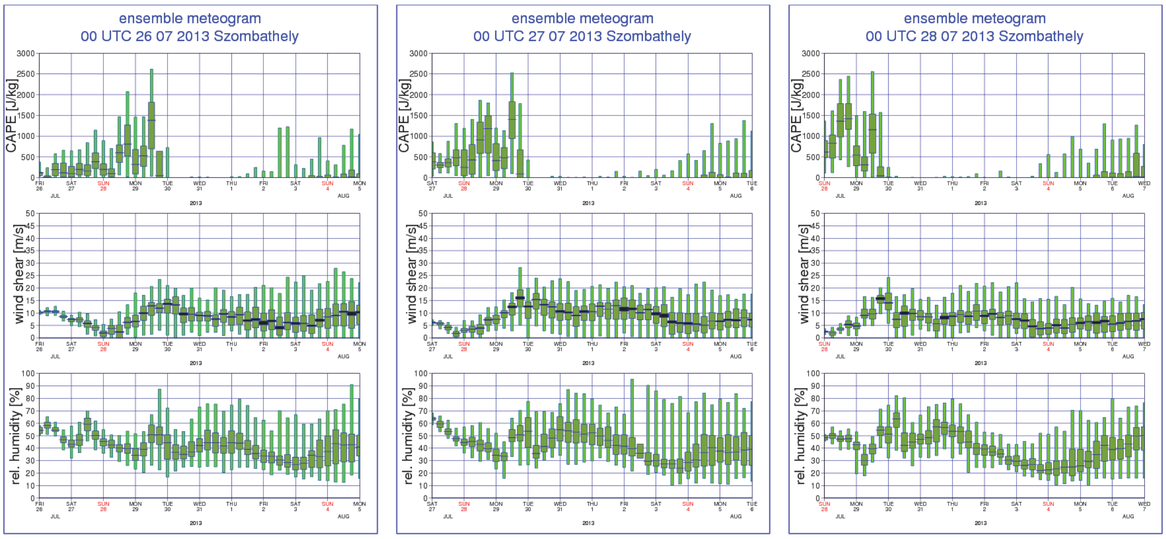

Fig. 7. Ensemble meteograms of CAPE (top), wind shear (middle), relative humidity (bottom) of July 26, 27, 28, 2013 for Szombathely.

5. Summary and conclusions

In this paper, it was shown how important it is to forecast the probability of the dangerous weather situations as precisely as possible. We attempted to provide a combination of new probabilistic tools for supporting successful forecasts of dangerous weather situations. Four graphical probabilistic methods were applied for three meteorological parameters, which are CAPE, wind shear, and relative humidity. It can be stated that wind shear is the most predictable parameter. Relative humidity has more uncertainty, but mostly it can be characterized as a respectable parameter. The medium-term forecast of CAPE index is not always successful, but with other fields it can provide useful extra information in the operational forecast. In the future, this new complex approach can be used for high resolution hydrostatic and nonhydrostatic ensemble models, as ALADIN and AROME.

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