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Convective systems and periods with large precipitation in Hungary

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Abstract—This paper presents a study describing the synoptic scale meteorological conditions and the mesoscale structures of phenomena which can cause large amounts of convective precipitation and often flash floods in Hungary. This examination is based on radar observations, 24-hour rain gauge precipitation measurements, model analyses and forecasts in the six-year period of 2003–2010. For the investigated precipitation period, an objective procedure was applied to decide whether convection had determining role in producing of precipitation. The procedure used radar based precipitation measurements and ECMWF precipitation forecasts. ECMWF analyses and forecasts were also applied to determine the representative synoptic scale weather patterns. Based on observed radar image structures and movements of radar echoes, the mesoscale structures were identified. Studies show that most of the cases can be classified into three main clusters: events with (1) convective chains (squall lines) in the warm sector of a cyclone; (2) convective lines with related cold front; and (3) convective lines in occluded cyclones. These most common types are demonstrated by case studies. This study may help to recognize weather conditions and patterns that are responsible for flash flood events in the Carpathian Basin.

Key-words: radar, large precipitation, convection, flash flood, Hungary.

1. Introduction and background

Climate research revealed that a number of extremely rainy days had significantly grown in the last quarter of the 20th century in Hungary (*Bartholy and Pongrácz, 2005*), and the chance of flash floods had increased, too. The aim of this study is to describe the meteorological conditions and the structures of phenomena which can cause flash floods. This examination is based on Hungarian radar observations, rain gauge measurements, and numerical model analyses.

Investigation of flash floods has a long history, especially in the United States. One of the most severe flash floods happened in the Big Thomson Canyon (USA) in 1976, where 143 people were killed (*Caracena et al., 1979*). Intensive research in connecting with these phenomena started after this tragedy. Several examinations investigated flash floods and their hydrological aspects (for example run-off simulations) in the USA and Europe (*Maddox, 1979; Hansen et al., 1982; Browning, 1986; Doswell et al., 1996; Warner et al., 2000; Yates et al., 2000; Davis, 2001; Rigo and Liasat, 2002; Blöschl et al., 2008; Déqué and Somot, 2008*).

Marshall and Palmer (1948) introduced the so-called Z-R relation between radar reflectivity and precipitation intensity, which is still used with little modifications for precipitation estimation.

The main advantage of radars is that the time and spatial resolution of data are much higher than that of the ground observations. However, radar measurements may have many errors and precipitation data are provided indirectly (*Lombardo and Baldini, 2010*). In the last few decades, radar precipitation measurements were used for meteorological and hydrological modeling and forecasts (*Kessler and Wilk, 1968; Wilson and Brandes, 1979; Mimikou and Baltas, 1996; Smith et al., 2007; Rossa et al., 2010*).

In Hungary, the mesometeorological research started at the beginning of the 1960s. Early studies dealt with the structure and dynamics of convective systems and used data obtained by synoptic scale measurements and observations (*Bodolai, 1954; Götz and Bodolainé, 1963a, 1963b, Bodolainé et al., 1967*). From the early 1980s, researches started to use remote sensing (radar, satellite, later lightning) data (*Bodolainé, 1980; Kapovits, 1986; Boncz et al., 1987; Bodolainé and Tanczer, 1991*). The examination of weather situations with heavy precipitation, focusing on extreme floods became more common (*Bodolainé, 1983; Bodolainé and Homokiné, 1984; Bonta and Takács, 1988, 1989, 1990; Takács et al., 2000; Geresdi et al., 2004*). Floods of river Tisza in 1998 and 2001 were described by *Homokiné (1999, 2001)* from a synoptic meteorological point of view. Nowadays, flash floods can be detected by satellite observations (*Kerényi and Putsay, 2005*), and case studies using nowcasting models appeared, too (*Horváth and Geresdi, 2003; Horváth et al., 2007*).

Mesoscale convective complexes (MCCs) are circular mesoscale convective systems which produce large amount of precipitation. These phenomena were firstly described by *Maddox* (1980), and in Hungary by *Bodolainé* and *Tánczer* (2003). MCC-s are very rare in Hungary.

In Hungary, *linear mesoscale convective systems* are more common than circular ones. Convective systems have two main parts: the strongest, mature (thunderstorm) cells which have the highest radar echoes, and the weaker, stratiform zone which consists of dissipating cells with less intense radar echoes. These systems were classified into three main clusters by *Parker* and *Johnson* (2000): the *TS (trailing stratiform)*, the *PS (parallel stratiform)*, and the *LS (leading stratiform)* types. In the TS and LS systems, the heaviest thunderstorms move (almost) perpendicular to the convergence (instability) line, and the weaker, stratiform parts move behind (trailing) or ahead (leading) of the thunderstorm zone. In this paper TS and LS systems are referred to as *convective chains* or *squall lines*. In the PS types (*convective lines*), the strongest cells move (almost) parallel to the convergence line. In this study it was found that the TS and PS systems were common, while LS was very rare in Hungary. All of these systems can produce large precipitation. In Hungary, many squall lines come from southwest, and these phenomena are called *Slovenian instability lines* (*Bodolainé et al.*, 1967).

In this paper, the most significant synoptic patterns and mesoscale precipitation structures responsible for large precipitation are coupled to each other, and large precipitation cases are classified into ascertained types.

2. Methodology

The investigation focused on 24-hour periods (from 06 UTC to 06 UTC next day) from 2003 to 2010. In our work, the following data were applied: daily, 24-hour (from 06 UTC to 06 UTC next day) precipitation amounts provided by the Hungarian rain gauge measurement network, composite radar images (resolution is 2×2 km in space and 15 minutes in time), 24-hour precipitation estimated by radars, and ECMWF (European Centre for Medium-Range Weather Forecast) analysis or 36-hour forecasts (resolution is 30×30 km in space and 3 hours in time). Note that the calculations were based on an area covered by the HMS's (Hungarian Meteorological Service) radar system which is much greater than Hungary ($245\,116$ km² vs. $93\,030$ km²).

A 24-hour period was considered as a *convective period with large precipitation*, when the following conditions were satisfied:

- (1) Two or more stations of the Hungarian rain gauge measurement network reported at least 50 mm precipitation.

- (2) At least 60% of the forecasted precipitation was convective in the ECMWF model forecast during the period.
- (3) There were one or more pixels (2×2 km areas) with at least 50 mm precipitation measured by radar.
- (4) At least 60% of the radar cells with large precipitation had strong echo (intensity ≥ 40 dBz).

To check the realization of the second condition, the ECMWF convective precipitation and the total precipitation were compared for the whole domain at every grid point for the entire precipitation period.

To test the third and fourth conditions, a radar based precipitation estimation procedure, named TREC, was applied. Using this procedure, it was possible not only to estimate the amount of precipitation in all radar pixels but estimate the rate of intensive convective rainfall, separately. A short description of TREC is given in the Appendix.

In the next step, the most significant mesoscale structures of the precipitation period were examined. The *TITAN-method* (Thunderstorm Identification Tracking Analysis and Nowcasting, *Dixon and Weiner, 1993; Horváth et al., 2008*) was applied to detect the existence of intensive convective echoes in an objective way. It is important to emphasize that the heavy precipitation falls both from the strong cells (intensity > 40 dBz) and from the weaker trailed or associated stratiform zone. Considering the structure based on movement, the convective precipitation systems were divided into three main clusters:

- A. disorganized or weakly organized convective patches (mainly thunderstorms),
- B. convective lines (LS systems, mainly thunderstorm lines), where movements of individual cells along the line are more significant than the replacement of the line, and
- C. convective chains or squall lines (TS systems) where cells move perpendicular to the thunderstorm line.

The appearance of convective precipitation systems was also classified from a synoptic aspect. For this investigation ECMWF analyses were used. The model fields were visualized by the HAWK-2 (Hungarian Advanced Workstation) application. Three main synoptic classes were found:

- (1) cold front (both slow and fast),
- (2) convergence-line of cyclone or cyclone cloud band, and
- (3) sporadic cells in weak pressure depression with featureless distributions of values about the mean-sea-level pressure.

The first type is associated with a cold front, it refers to mostly pre-frontal, frontal, rarely post-frontal synoptic situations. The second cluster contains the precipitation zones which form along the convergence-lines of an (occluded) cyclone. The third type represents those situations, when on the ground there is weak pressure gradient with an upper cold and low trough.

Except for one case, all 24-hour periods were classified into these clusters, and combined categories were created as follows:

- A1: cold front with sporadic thunderstorms;
- A2: sporadic thunderstorms with a convergence line in a cyclone;
- A3: sporadic thunderstorms in a weak depression;
- B1: convective lines related to a cold front;
- B2: convective lines along the convergence zones of a cyclone;
- B3: convective lines in weak depression;
- C1: squall lines related to a cold front;
- C2: squall lines in a cyclone;
- C3: weak squall lines in a depression.

If more than one convective system were detected in a 24-hour period, the most significant was considered.

3. Results

Altogether 56 convective periods with large precipitation were found between 2003 and 2010. As it was expected, most of the convective periods appeared between May and September. Concerning their distribution in time the maximum was in 2010 (*Fig. 1*) and in June (*Fig. 2*). Note that one period was found in March.

In the eight-year period, the most frequent combined types were C1 (squall lines related to a cold front), B2 (convective lines along the convergence zones of a cyclone), and B1 (convective lines related to a cold front). The fourth pattern was A3 (low pressure gradient field with disorganized thunderstorms), followed by C2 (squall lines in cyclone). Frequencies of the other types are only 0 or 1 (*Fig. 3*). Note that periods with squall lines (C1 and C2 types) or situations with cold fronts (A1, B1, C1 patterns) appeared more often than the lines (B1 and B2 patterns) or cyclonic situations (B2, C2 combinations). One situation (May 26, 2003) could not be clustered into this classification. On this day, strong squall lines formed and moved from east to west in the central and western parts of Hungary.

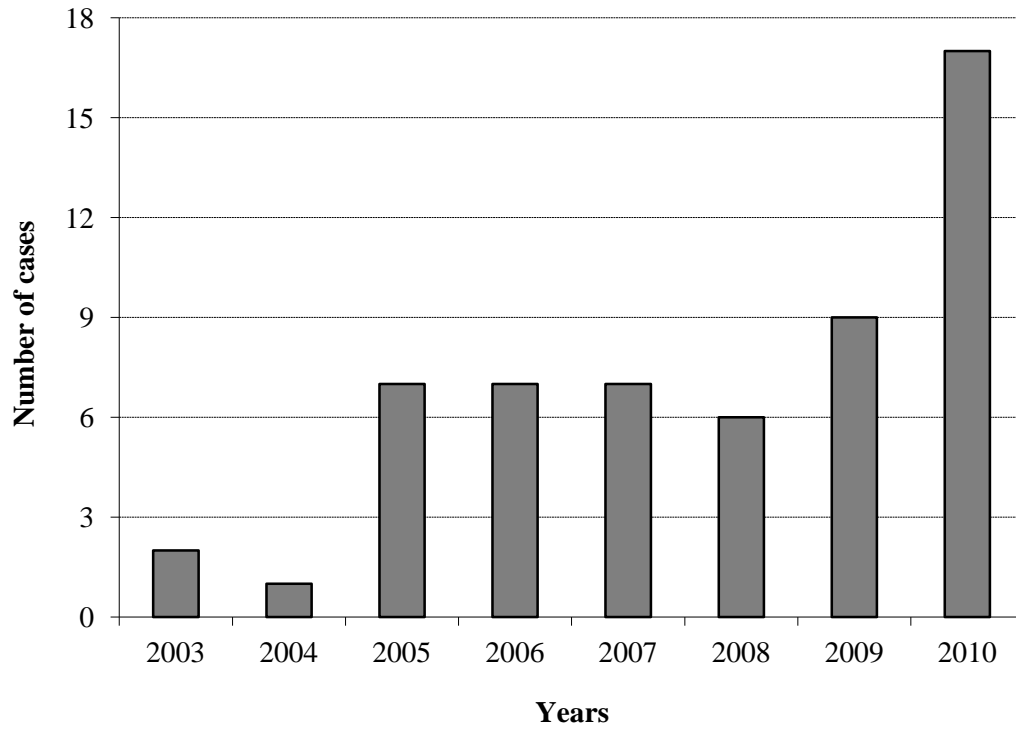


Fig. 1. Frequency distribution of 24-hour periods with large precipitation by year.

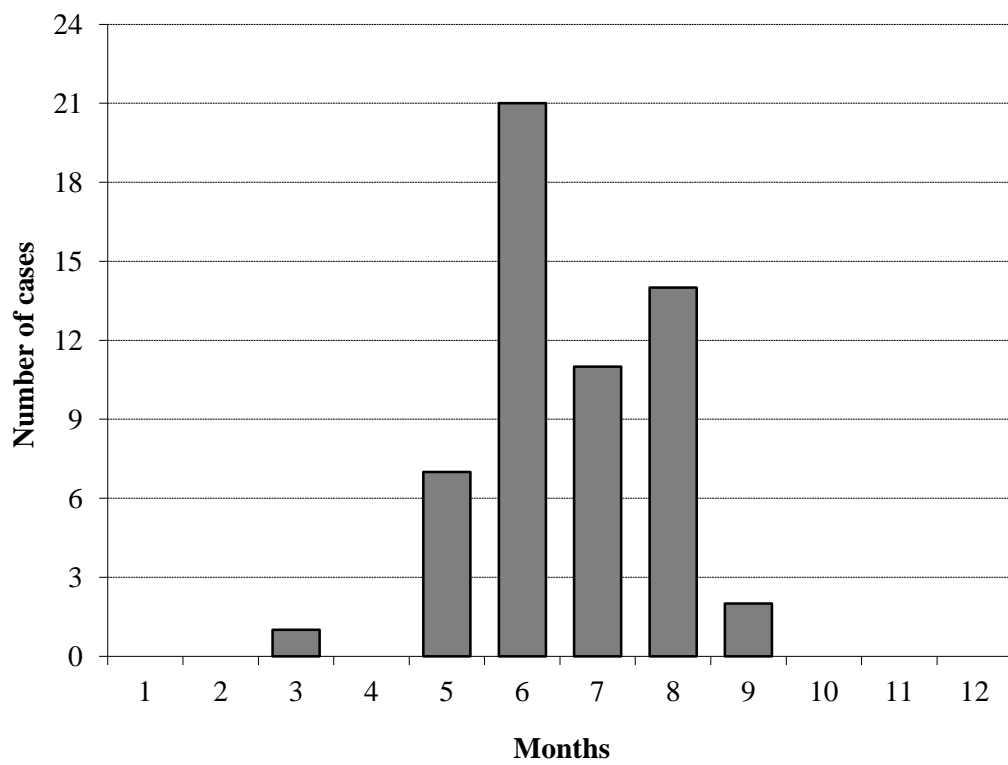


Fig. 2. Frequency distribution of 24-hour periods with large precipitation by month.

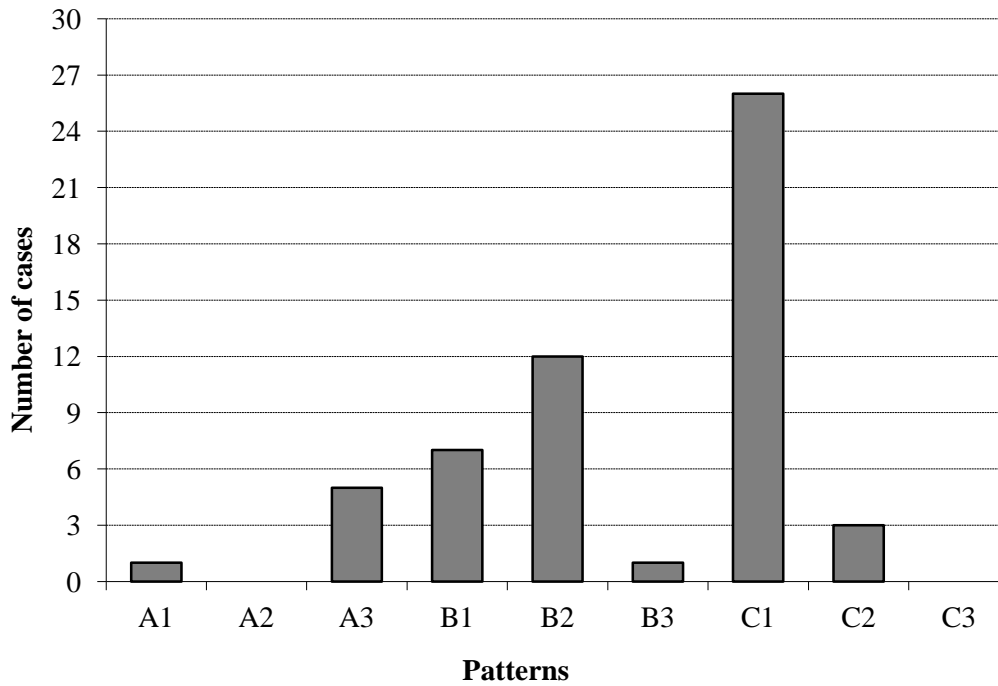


Fig. 3. Frequency distribution of 24-hour periods with large precipitation by combined patterns.

Considering all case studies, it was found that in average, the amount of radar estimated precipitation was larger than 50 mm only on 0.23% of the entire area (that means 564 km² of 245 116 km²). In the large precipitation areas, 18% of the precipitation arose from echoes with reflectivity ≥ 40 dBz (this was the so-called *convective part*). Meanwhile, nearly at about 50% of all cases, the rate of convective precipitation was higher than 60% in large precipitation areas. It was also found that there was at least one strong echo (intensity ≥ 40 dBz) in about 92% of areas with large precipitation. Average characteristics of the most frequent five types as well as the average values for all the seven types are shown in *Table 1*.

3.1. C1 type (*Squall line related to cold front*)

On August 20, 2007, a cold front reached Hungary from north-west (*Fig. 4*). Thunderstorms developed in front of the cold front, and formed an extended squall line. Behind the intensive cells, a massive stratiform zone was forming. In advance of the squall line, in the prefrontal zone (in the Great Plain), isolated convective systems developed. In the western part of Hungary (Transdanubia), large amounts of precipitation fell both from the intensive cells and from the trailed stratiform regions of the squall line, while in south-east the precipitation fell mainly from the most intensive parts. There was strong contrast in temperature at 850 hPa level, while at 700 hPa wet airmasses were advected. In the mid-troposphere region (at 500 hPa), Hungary was situated in front of a cold low. There was strong, southerly wind, and the cold advection was just

beginning from south-west in the afternoon. This case can be considered as a type of large precipitation with intensive, fast moving thunderstorms.

Table 1. Average characteristics of the most frequent patterns and for all cases. Rows mean: Note: the last column shows the average values for all (seven) cases.

	A3	B1	B2	C1	C2	All
1	0.04	0.20	0.14	0.30	0.37	0.23
2	6.57	26.21	7.45	26.75	26.32	17.92
3	45.34	52.50	43.02	57.08	54.03	50.34
4	90.87	91.88	85.66	97.40	95.59	91.94

1 Ratio of areas with large precipitation (where the calculated 24-hour amount is above 50 mm). Total area: 245116 km².

2 Rate (in percentage) of convective (calculated only from echoes above 40 dBz) and total precipitation in areas with large precipitation.

3 On areas with large precipitation ratio of pixels where the convective part reached at least 60 % of the total amount.

4 On areas with large precipitation percentage of pixels where at least one strong echo (intensity \leq 40 dBz) appeared.

Case studies also show that for types C1 or C2, greater amount of the large precipitation originated from strong echoes, and the convective activity was heavier having more cells with large precipitation as compared to other types.

Short case studies of the three most frequent combinations are described below.

3.2. B2 combination (Convective lines along the convergence zones of cyclone)

On August 11–12, 2007, a shallow, occluded cyclone could be analyzed on surface weather maps (*Fig. 5*). In the upper levels, the synoptic scale vorticity was more significant, especially at 500 hPa, where a cut-off low zone could be detected. The relative humidity analyses on the 700 hPa level marked the wet convergence lines (so-called cyclone arms). One of these convective lines is shown in the radar image. The higher reflectivity echoes, surrounded by less intensive but still convective-derived areas, move almost in parallel to the curved convective line. This is a typical PS system (convective line). The maxima of the 24-hour precipitation are organized almost in lines in Transdanubia. This situation is a good example of a decaying, occluded cyclone, which can stay in the region of the Carpathian Basin for several days. In the upper levels, the cold, cut-off low and the stronger (but not jet-stream) winds guarantee the convective instability. The convergence lines ('arms') of the cyclone collect the humidity, and developing thunderstorms propagate slowly along these lines, producing large amounts of precipitation. This case can be considered as a type of large precipitation with less intensive thunderstorms.

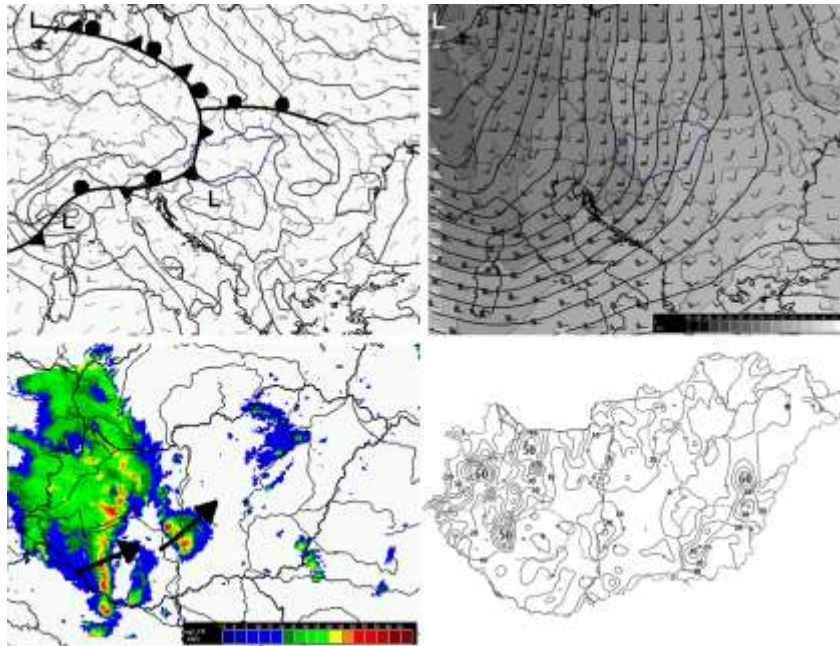


Fig. 4. Top: ECMWF analyses for August 20, 2007, 12:00 UTC. Top left: MSL pressure (isobars by 2 hPa) wind field at the 925 hPa level and fronts. Top right: geopotential heights (lines by 20 gpm), temperature (monochrome shades by 2 °C) and wind field at 500 hPa level. Bottom left: composite radar image on August 20, 2007, 14:45 UTC. The arrows show the motion of the most intensive cells. Bottom right: Spatial distribution of 24-hour precipitation from August 20, 2007, 06:00 UTC to August 21, 2007, 06:00 UTC.

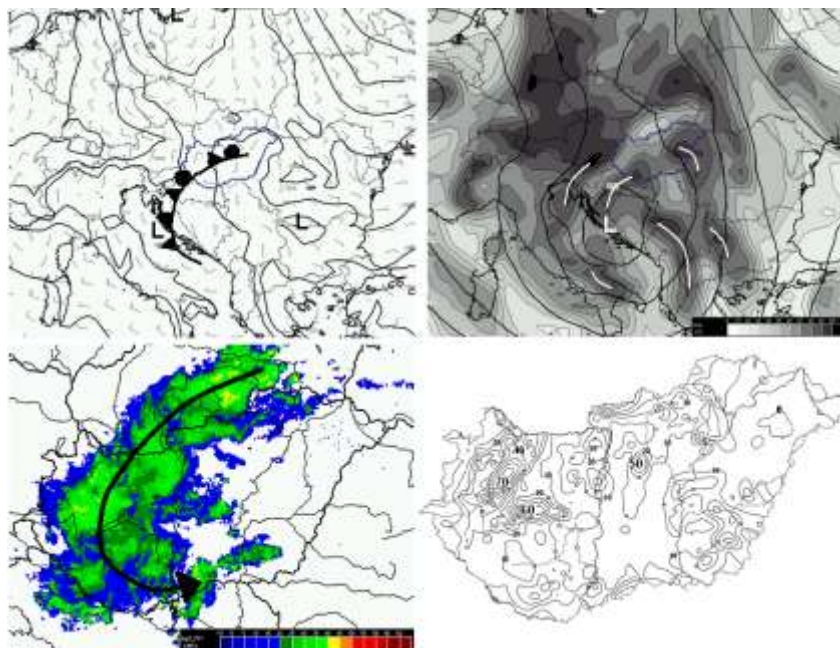


Fig. 5. Top: ECMWF analyses for August 11, 2007, 12:00 UTC. Top left: MSL pressure (isobars by 2 hPa) at the 925 hPa level wind field and fronts. Top right: geopotential heights (lines by 20 gpm), 700 hPa humidity (monochrome shades) and wind. Convergence lines are drawn by white, curved lines. Bottom left: mosaic radar image on August 12, 2007, 03:30 UTC. The arrow marks the convective line. Bottom right: spatial distribution of 24-hour precipitation from August 11, 2007, 06:00 UTC to August 12, 2007, 06:00 UTC.

3.3. B1 type (Convective lines with cold front)

On July 14, 2008, a cold front was located over Hungary (Fig. 6). The front came from north-west and was moving slowly to south-east. Heavy thunderstorms developed ahead of it; some of them were long-living supercells. The most intensive storms were moving along lines from south-west to north-east, almost parallel to the front-line (Csonka and Kolláth, 2008). At the 500 hPa level, on the prefrontal side of the cold low (situated west of Hungary), cold advection could be observed, while on lower levels, the colder air reached only the north-western parts of Hungary. Strong upper winds generated significant shear, while at 700 hPa, from south-west humid airmasses were approaching. The maxima of 24-hour precipitation marked the path of the strongest cells. This case can be considered as the type of relative slow moving, sometimes extremely strong severe thunderstorms with supercells.

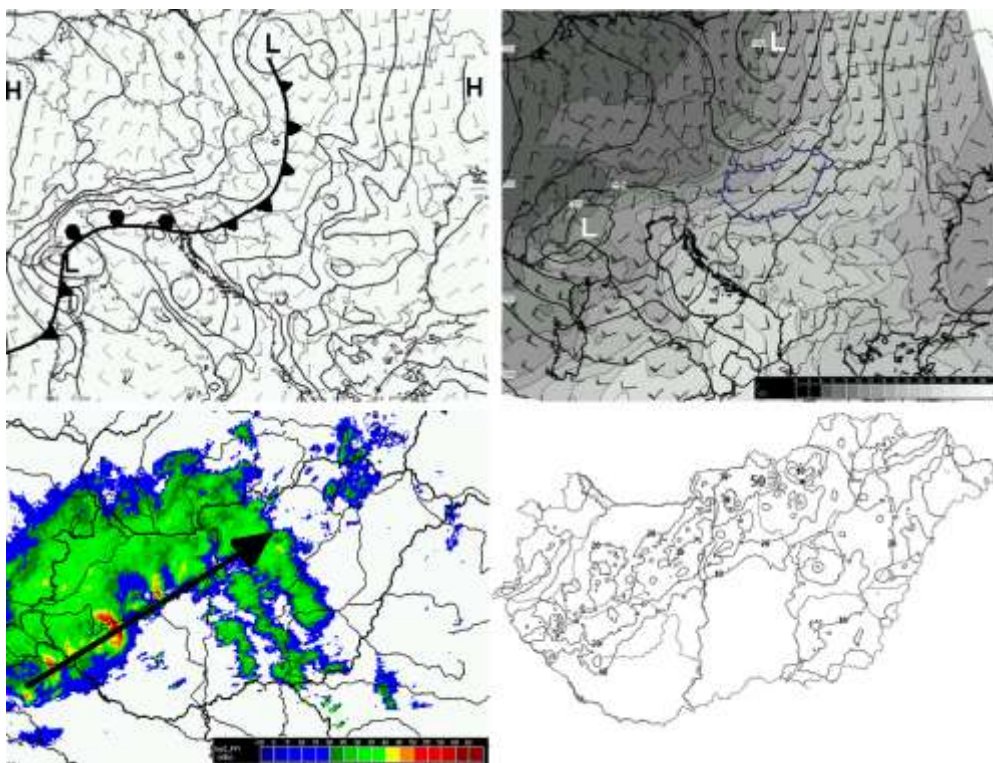


Fig. 6. Top : ECMWF analyses for July 14, 2008, 00:00 UTC

Top left: MSL pressure (isobars by 2 hPa) and the wind fields at the 925 hPa level and the front lines. *Top right:* geopotential heights (lines by 20 m), temperature (monochrome shades by 2 °C) and wind field of the 850 hPa level. *Bottom left:* composite radar images on July 14, 2008, 06:00 UTC. The arrow indicates the tracks of the most intensive storms. *Bottom right:* spatial distribution of 24-hour precipitation from July 14, 2008, 06:00 UTC to July 15, 2008, 06:00 UTC.

4. Conclusions

This paper presents the results of a study of large amount precipitation events in Hungary for the eight-year period of 2003–2010. The aim of this study was to describe these phenomena (which may cause flash flood) and to cluster them from synoptic and mesoscale points of view. Following this objective, 24-hour precipitation data, composite radar images, radar precipitation measurements, and ECMWF analyses and forecasts were applied. Nine combined patterns were created by considering mesometeorological, phenomenological, and synoptic points of view. The most frequent three types were demonstrated with case studies.

The main results of the research are as follows:

- 56 convective periods with large precipitation were found, and 55 were classified into 7 combined clusters.
- Most of the periods appeared in summer, the maxima were in June and in 2010.
- The most frequent combined types were squall lines with cold front (C1), convective lines along the convergence zones of a cyclone (B2), and convective lines with cold front (B1).
- Periods of convective squall lines with cold fronts appeared more often than convective lines in cyclonic situations.
- In each period, pixels with large precipitation (the calculated 24-hour amount is above 50 mm) appeared in about 0.23% of the total area (which is 564 km²) on the average.
- Considering the large precipitation areas, the average ratio of convective precipitation (calculated only from strong echoes with reflectivity higher than 40 dBz) was approximately 18% in each period, but in about 50% of these cases the convective part was at least 60%.
- Periods with squall lines have higher convective activities and more cells with large precipitation than periods with lines or disorganized/weakly organized convective patches, because greater part of the large precipitation was produced by strong echoes.

In the future, this examination will be extended by focusing on regions endangered by flash floods involving more hydrological aspects.

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Appendix

Calculation of motion vectors and accumulated precipitation using time series of radar reflectivity

HMS radar network collects data in 15-minute cycles, which can result in significant under-sampling in both space and time. A typical 12-hour accumulation precipitation field based on HMS radar network observation is shown in *Fig. 7*. The under-sampling strongly depends on the velocity of the radar cells, and can result in serious underestimation of the surface accumulated precipitation in the case of the fast moving squall lines.

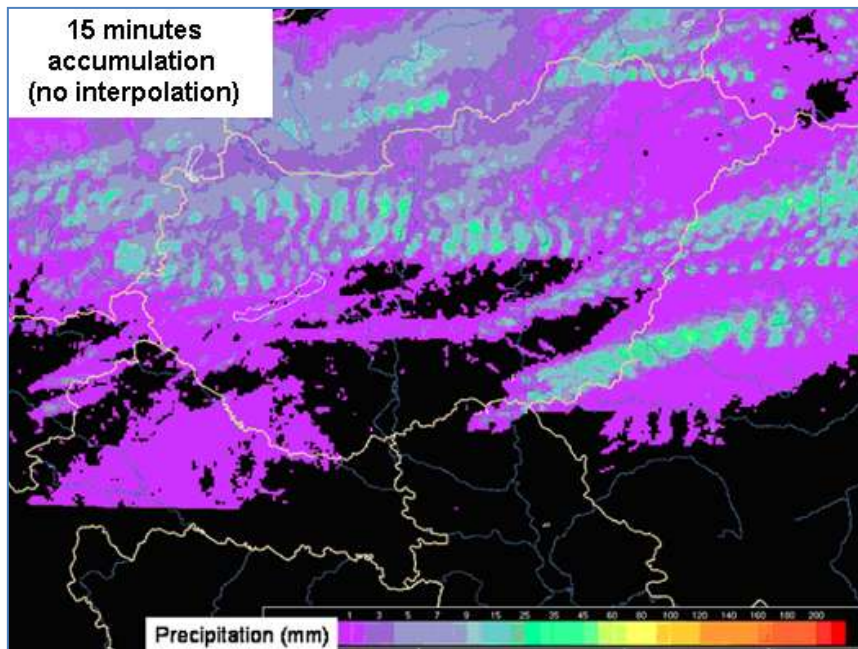


Fig. 7. 12-hour accumulated precipitation calculated by radar images with 15-minute time resolution.

The error caused by the under-sampling was reduced by using correlation tracking method (TREC, Tracking Radar Echoes by Correlation). During the TREC procedure, the radar grid was divided into so-called macro grids, and the calculation of motion vectors was based on maximum correlations for the macro grids. After quality control to filter out noisy vectors on macro grids, fine resolution motion vectors were interpolated for all grid points of the original radar grid. Once a motion vector field belonging to radar images at times T_2 and T_1 is available, interpolation of the radar reflectivity can be done at any time between T_1 and T_2 . Echoes from T_1 are moved forward and echoes from T_2 moved backward by motion vectors, and the reflectivity of a given pixel is

interpolated between the forward and backward moving reflectivity values as shown in *Fig. 8*.

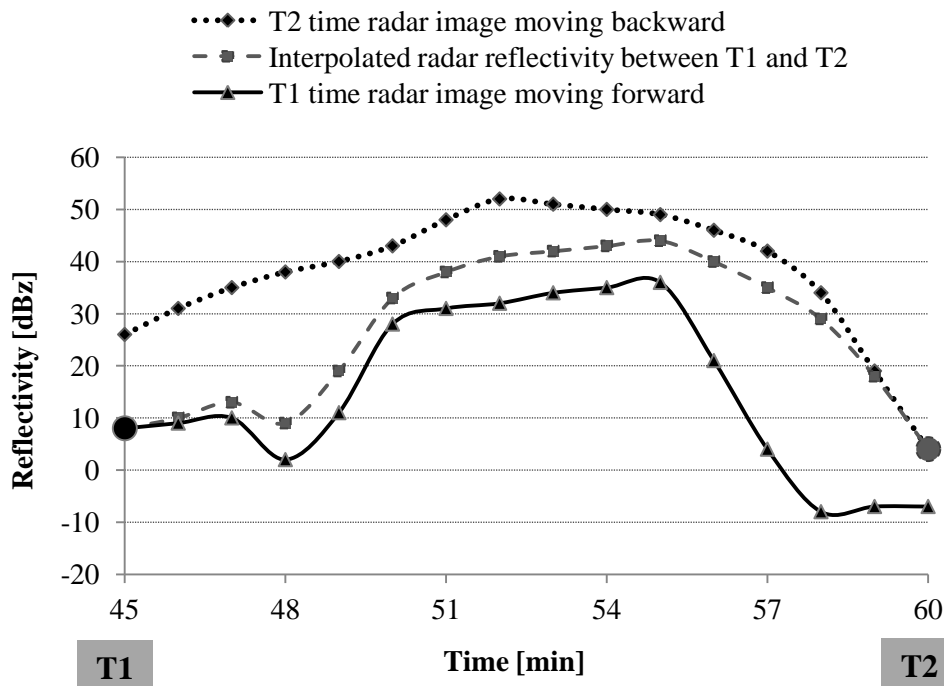


Fig. 8. Interpolation of radar reflectivity using motion vectors.

The application of the TREC method offers a more realistic accumulated precipitation field (*Fig. 9*). The 12-hour precipitation field in *Fig. 9* is calculated from 15-minute sampling cycle data. The optimal interpolation time step for precipitation calculation was found to be 1 minute.

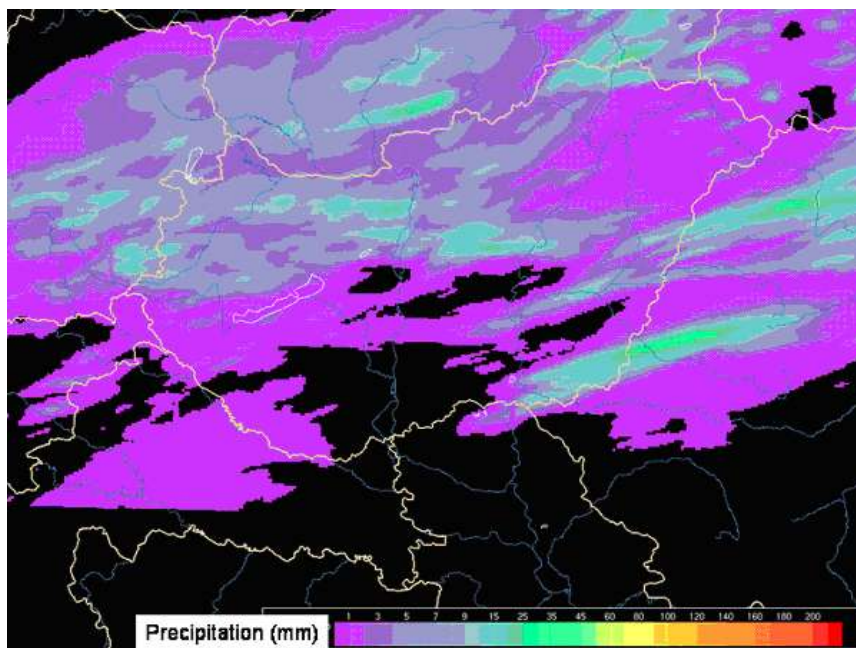


Fig. 9. 12-hour accumulated precipitation calculated by 1 minute interpolated radar images.

References

- Bartholy, J. and Pongrácz, R., 2005: Tendencies of extreme climate indices based on daily precipitation in the Carpathian Basin for the 20th century. *Időjárás* 109, 1–20.
- Blöschl, G., Reszler, C. and Komma, J., 2008: A spatially distributed flash flood forecasting model. *Environ. Modell. Softw.* 23, 464–478.
- Bodolai, I., 1954: *Aerological and synoptical conditions of forming convective thunderstorms* (in Hungarian). Az OMI Kisebb Kiadványai 27, OMSZ, Budapest, 80 pp.
- Bodolainé, J.E., 1980: *Using of radar measurements in short-range forecasting of precipitation* (in Hungarian) Az OMSZ Kisebb Kiadványai 48, OMSZ, Budapest, 79 pp.
- Bodolainé, J.E., 1983: *Synoptical conditions of flood waves in the catchment of the Danube and Tisza* (in Hungarian). Az OMSZ Hivatalos Kiadványai 56, OMSZ, Budapest, 126 pp.
- Bodolainé, J.E., Bodolai, I. and Böjti, B., 1967: Macrosynoptical conditions for the formation of Slovenian squall lines and some properties of cold fronts with thunderstorm. *Időjárás* 67, 129–143.
- Bodolainé, J.E. and Homokiné, U.K., 1984: *Quantitative precipitation forecasts using the orographic precipitation enhancement* (in Hungarian). Az OMSZ Kisebb Kiadványai 57, OMSZ, Budapest, 45 pp.
- Bodolainé, J.E. and TAnczer, T., 1991: Instability line in a regional cyclone (in Hungarian). *Időjárás* 95, 178–195.
- Bodolainé, J.E. and TAnczer, T., 2003: *Mesoscale convective complexes producing flash floodwaves* (in Hungarian). Budapest, OMSZ, 184 pp.
- Boncz, J., Kapovits, A., Pintér, F. and TAnczer, T., 1987: A method for the complex analysis of synoptic weather radar and satellite data. *Időjárás* 91, 11–22.
- Bonta, I. and Takács, Á., 1988: *Construct of warning system for heavy rainfall in Hungary* (in Hungarian). Az OMSZ Kisebb Kiadványai 63, OMSZ, Budapest, 31 pp.
- Browning, K.A., 1986: Conceptual Models of Precipitation Systems. *Weather Forecast.* 1, 23–41.
- Caracena, F., Maddox, A.R., Hoxit, R.L., and Chappell, C.F., 1979: Mesoanalysis of the Big Thompson Storm. *Mon. Weather Rev.* 107, 1–17.
- Csonka, T. and Kolláth, K., 2008: ‘Transpannon monster’, long-lived supercells on July 14, 2008 (in Hungarian). Published on the Internet: <http://owww.met.hu/pages/bogacs20080714.php>
- Davis, R.S., 2001: Flash Flood Forecast and Detection Methods. In *Meteorological Monographs* 28, (ed: Doswell, C.A.), AMS, 481–525.
- Déqué, M. and Somot, S., 2008: Analysis of heavy precipitation for France using high resolution ALADIN RCM simulation. *Időjárás* 112, 179–190.
- Dixon, M. and Wiener, G., 1993. TITAN: Thunderstorm Identification, Tracking, Analysis and Nowcasting – A radar-based methodology. *J. Atmos. Ocean. Tech.* 10, 785–797.
- Doswell, C.A. III, Brooks, H.E. and Maddox, R.A., 1996: Flash flood forecasting: An ingredients-based methodology. *Weather Forecast.* 11, 560–581.
- Geresdi, I., Horváth, Á., and Mátyus, Á., 2004: Nowcasting of the precipitation type, Part II.: Forecast of thunderstorms and hailstone size. *Időjárás* 108, 33–50.
- Götz, G. and Bodolainé, J.E., 1963a: About mesosynoptical forms (in Hungarian). *Időjárás* 67, 46–53.
- Götz, G. and Bodolainé, J.E., 1963b: Structures and analyses of instability lines (in Hungarian). Az OMI Kisebb Kiadványai 33, OMSZ, Budapest, 79 pp.
- Hansen, E.M., Schreiner, L.C. and Miller, J.F., 1982: *Application of probable maximum precipitation estimates – United States East of the 105th meridian*. Hydrometeorological Report 52, National Weather Service, NOAA, US Department of Commerce, Washington, DC., 168 pp.
- Homokiné, U.K., 1999: Flood of River Tisza at autumn (in Hungarian). *Légekör* 64(1), 2–6.
- Homokiné, U. K., 2001: Flood in March in Transcarpathia (in Hungarian). *Légekör* 66(2), 2–5.
- Horváth, Á., Ács, F. and Seres, A.T., 2008: Thunderstorm climatology analyses in Hungary using radar observations. *Időjárás* 112, 1–13.
- Horváth, Á. and Geresdi, I. 2003: Severe Storms and Nowcasting in the Carpathian Basin. *Atmos. Res.* 67–68, 319–332.

- Horváth, Á., Geresdi, I., Németh, P. and Dombai, F., 2007: The Constitution Day storm in Budapest: Case study of the August 20, 2006 severe storm. *Időjárás* 111, 41–63.
- Kapovits, A., 1986: Hydrological aspect of using radar precipitation measurements (in Hungarian). *Vízügyi Közlemények* 68., 486–499.
- Kerényi, J. and Putsay, M., 2005: Extreme flood monitoring in Romania and Hungary using Earth Observation Data, *Időjárás* 109, 205–216.
- Kessler, E. and K.E. Wilk, 1968: Radar measurements of precipitation for hydrological purposes. Report 5, International Hydro. Decade. WMO, Geneva
- Lombardo, F. and Baldini, L.: 2010: *Study on the rainfall dependence structure using radar and rain gauge data*. International Workshop Advances in Statistical hydrology, May 23–25 2010, Taormina, Italy
- Maddox, R.A., 1979: A methodology for forecasting heavy convective precipitation and flash flooding. *National Weather Digest: Flood* 4(4), 30–42.
- Maddox, R.A., 1980: Mesoscale convective complexes. *B. Am. Meteorol. Soc.* 61, 1374–1387.
- Marshall, J.S. and Palmer, W.M., 1948: The distribution of raindrops with size. *J. Meteorol.* 5, 165–166.
- Mimikou, M.A. and Baltas, E.A., 1996: Flood Forecasting Based on Radar Rainfall Measurements. *J. Water Res. Plan. Manage.* 122, 151–156.
- Parker, M.D. and Johnson, R. H., 2000: Organizational Modes of Midlatitude Mesoscale Convective Systems. *Month. Wea. Rev.* 128, 3413–3436.
- Parker, M.D. and Johnson, R.H., 2004: Structures and Dynamics of Quasi-2D Mesoscale Convective Systems. *J. Atmos. Sci.* 61, 545–567.
- Rigo, T. and Liasat, M.C., 2002: Analysis of convective structures that produce heavy rainfall events in Catalonia (NE of Spain), using meteorological radar. *Proc. ERAD*, 45–48.
- Rossa, A.M., Cenzon, G., and Monai, M., 2010: Quantitative comparison of radar QPE to rain gauges for the 26 September 2007 Venice Mestre flood. *Nat. Hazards Earth Syst. Sci.* 10, 371–378.
- Smith, J.A., Baeck, M.L., Meierdiercks, K.L., Miller, A.J., and Krajewski, W.F., 2007: Radar rainfall estimation for flash flood forecasting in small urban watersheds. *Adv. Water Res.* 30, 2087–2097.
- Takács, Á., Girz, C., Tollerud, E., and Kertész, S., 2000: New methods for severe precipitation warning for Hungary. *Időjárás* 104, 1–67.
- Warner, T.T., Brandes, E.A, Sun, J., Yates, D.N., and Mueller, C.K., 2000: Prediction of a flash flood in complex terrain. Part I: A comparison of rainfall estimates from radar, and very short range rainfall simulations from a dynamic model and an automated algorithmic system. *J. Appl. Meteorol.* 39, 797–814.
- Wilson, J.W., and Brandes, E.A, 1979: Radar measurement of rainfall – a summary. *B. Am. Meteorol. Soc.* 60, 1048–1058.
- Yates, D.N., Warner, T.T., and Leavesley, G.H., 2000: Prediction of a flash flood in complex terrain. Part II: A comparison of flood discharge simulations using rainfall input from radar, a dynamic model, and an automated algorithmic system. *J. Appl. Meteor.* 39, 815–825.