# IDÖJÁRÁS 

# Thunderstorm climatology in Hungary using Doppler radar data 

András Tamás Seres ${ }^{1 *}$ and Ákos Horváth ${ }^{2}$<br>${ }^{1}$ Hungarian Defence Forces Geoinformation Service, Szilágyi E. fasor 7-9, H-1024 Budapest, Hungary E-mail: seres.andrastamas@upcmail.hu<br>${ }^{2}$ Hungarian Meteorological Service, Vitorlás u. 17, H-8600 Siófok, Hungary, E-mail: horvath.a@met.hu<br>*Corresponding author

(Manuscript received in final form June 20, 2014)


#### Abstract

This paper presents the results of an objective analysis on thunderstorm climatology in Hungary. The examination was based on composite PPI (plan position indicator) images made by Doppler radars of the Hungarian Meteorological Service between 2004 and 2012. In our research, thunderstorms were represented with so-called thunderstorm ellipses, and their time and spatial distribution were examined. Three types of thunderstorm ellipses and stormy days were defined with radar reflectivity set to 45, 50 , or 55 dBZ . Most stormy days and ellipses happened in late spring and summer of 2007 and 2010. The daily frequency of these objects peaked in the late afternoon period. The detected ellipses had maxima in the north-eastern, north-central, and south-western parts of Hungary. Beyond information and characteristics from the past, these methods and results can be useful for forecasting severe thunderstorms.


Key-words: severe thunderstorm, Doppler radar, climatology, TITAN method, Hungary.

## 1. Introduction

Radar-based thunderstorm climatology has a long history in the United States. The first studies appeared in 1950s (Braham, 1958), followed by many other researches for different parts of the country (for example: Myers, 1964; Henz, 1974; Falconer, 1984; Croft and Shulman, 1989; Mohee and Miller, 2010). In the last two decades, some works have been carried out in this field in Europe (Höller, 1994; Jaeneke, 2001; Rigo and Liasat, 2002; Weckwerth et al., 2010; Rudolph et al., 2011; Davini et al., 2012), South America (Paiva Pereira and

Rutledge, 2003), Canada (Brimelow et al., 2004), and Australia (Steiner and Houze, 1996) as well.

The first Hungarian study on thunderstorm climatology was made by Héjas (1898), followed by Raum (1910). Some studies dealing with different aspects of thunderstorm climatology appeared in the 1960s (Ozorai, 1965; Götz and Pápainé, 1966; 1967). All these works were based on visual observations. Later, radar and satellite data (Boncz et al., 1987; Bodolainé and Tänczer, 1991), then nowcasting methods (Horváth and Geresdi, 2003; Horváth et al., 2007) appeared in the Hungarian studies. However, these works considered thunderstorms from mainly dynamical and synoptical aspects, so our work is the first attempt to examine thunderstorm climatology in Hungary using Doppler radar data. The first results of this research were presented by Horváth et al. (2008) but only for a shorter period.

The aim of this paper is to briefly describe the time and spatial distribution of severe thunderstorms detected by HMS's radars in the period of 2004 to 2012.

## 2. Methodology

### 2.1. Radar measurements

The first weather radar in Hungary was introduced in 1967. In the next decades, other locators were set in the country and the Hungarian Meteorological Service (HMS) built up its radar network system. By 2004, HMS's Soviet-made MRL-5 locators were replaced by modern Doppler radars.

Hungary is covered by three weather radars: (the western, the central, and the eastern locators, and they all operate on C-band (wave length $=5 \mathrm{~cm}$ ) (Geresdi, 2004). During the measurement, the Doppler-wind was applied for noise filtering and the results were upgraded, filtered, and smoothened into composite fields. From each scan column, the highest reflectivity values were taken (Collier, 1996). The resolution of the composite PPI (plan position indicator) images was $2 \mathrm{~km} \times 2 \mathrm{~km}$ in space and 15 minutes in time. To further reduce noises of reflectivity, median-filter method (Tukey, 1977) was also used before beginning the analysis.

### 2.2. Core of the methodology: the TITAN method

The TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting) method was developed by Dixon and Wiener (1993). Using the identification part of this method the irregular-shaped thunderstorms detected by radar could be characterized by regular ellipses. The main point of identification is as follows: the parameters of the ellipses are determined by the covariance matrix of the isolated, irregular-shaped cluster on the image using the condition that the area of the cluster and the ellipse has to be equal. With this method, the focus
points and the equation of the ellipses could easily be determined and the objects were visualized by the Hungarian Advanced WorKstation (HAWK) system developed by HMS (HMS, 2012). These calculated ellipses were called thunderstorm ellipses (Horváth et al., 2008). The detailed background of the identification method is given in the Appendix.

Two types of thresholds: the area limit $\left(\mathrm{N}_{\text {minlimit }}\right)$ and the reflectivity limit ( $\mathrm{R}_{\text {minlimit }}$ ) were defined. The area threshold determined the minimum area of a cluster. In our examination $\mathrm{N}_{\text {minlimit }}$ was set to 5 radar pixels (which equals to $20 \mathrm{~km}^{2}$ ). The reflectivity threshold specified that each pixel of the cluster (in our case 5 pixels) had to reach this limit. $\mathrm{R}_{\text {minlimit }}$ was set to $45 \mathrm{dBZ}, 50 \mathrm{dBZ}$, and 55 dBZ and these objects were named severe, highly severe, and extremely severe thunderstorm ellipses, respectively. Using these high reflectivity values, the detected cells could be considered as severe thunderstorms and the small or weak objects could be eliminated. The original radar image is presented in Fig. la for May 18, 2005 at 16:00 UTC, while ellipses with $\mathrm{N}_{\text {minlimit }}=5$ pixels and $\mathrm{R}_{\text {minlimit }}=45 \mathrm{dBZ}$ are visualized in Fig. 1 lb .


Fig. 1. Composite PPI radar images of thunderstorms observed on May 18, 2005, 16:00 UTC. Left: original image, right: image where thunderstorms were represented by ellipses.

## 3. Results

### 3.1. Time distribution of thunderstorm ellipses and stormy days

A day was called severe, highly severe, or extremely severe stormy day when at least one detected severe, highly severe, or extremely severe thunderstorm ellipse could be found on radar images. Using these data, the number of stormy days could be counted for a given time period.

The highest number of stormy days was counted in 2007 for all categories. The lowest values were detected in 2005 for extremely severe days and in 2012 for the other two types (Table 1). About 80 to $95 \%$ of stormy days and 97 to $98 \%$ of thunderstorm ellipses were detected between April and September, therefore this period was called thunderstorm season. The stormiest month was July followed by June, August, and May. Other months had much lower values (Fig. 2). On average, 118 severe, 82 highly severe, and 20 extremely severe ellipses were detected on a stormy day in the thunderstorm season. Note that these calculated values are not equal to the number of thunderstorms, because a severe thunderstorm may appear on subsequent radar images. Table 2 shows the time distribution of days with at least 50 or 100 objects. The maxima were in 2007 and 2010, while 2004, 2005, and 2012 had the lowest values. The highest number of severe thunderstorm ellipses ( 1,115 objects) were detected on August 20, 2007, while for the other two types, June 14, 2010 had the highest values ( 527 and 139 ellipses). According to ECMWF (European Centre for MediumRange Weather Forecast) analysis, on these days a cold front of a northern cyclone reached the country.

The daily cycle of these ellipses was also investigated (Fig. 3). Only results for the thunderstorm season are shown in this paper. The minima of appearance were detected at 8:30 and 9:15 for severe, 8:30 for highly severe, and 7:00 for extremely severe ellipses. The time distribution of the objects was asymmetric and the maxima were at 16:45 for severe, 16:30 for highly severe, and 16:30 and 17:30 for extremely severe ellipses.

Table 1. Annual distribution of severe, highly severe, and extremely severe stormy days in the period of 2004 to 2012.

| Year | Severe <br> stormy days | Highly severe <br> stormy days | Extremely severe <br> stormy days |
| :---: | :---: | :---: | :---: |
| $\mathbf{2 0 0 4}$ | 189 | 116 | 44 |
| $\mathbf{2 0 0 5}$ | 188 | 101 | 26 |
| $\mathbf{2 0 0 6}$ | 169 | 107 | 38 |
| $\mathbf{2 0 0 7}$ | 190 | 121 | 69 |
| $\mathbf{2 0 0 8}$ | 142 | 94 | 40 |
| $\mathbf{2 0 0 9}$ | 142 | 102 | 45 |
| $\mathbf{2 0 1 0}$ | 141 | 93 | 53 |
| $\mathbf{2 0 1 1}$ | 136 | 99 | 52 |
| $\mathbf{2 0 1 2}$ | 122 | 90 | 43 |
| Average | 158 | 103 | 46 |





Fig. 2. Annual course of a) severe, b) highly severe, and c) extremely severe stormy days in the period of 2004 to 2012.

Table. 2. Annual distribution of days with 50 or 100 severe, highly severe, or extremely severe ellipses in the period of April to September between 2004 and 2012.

|  | Days with at least 50 |  |  | Days with at least 100 |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Year | severe | highly <br> severe | extremely <br> severe | severe | highly <br> severe | extremely <br> severe |  |  |  |  |  |  |
|  | ellipses |  |  |  |  |  |  |  |  | ellipses |  |  |
| $\mathbf{2 0 0 4}$ | 57 | 12 | 1 | 34 | 6 | 0 |  |  |  |  |  |  |
| $\mathbf{2 0 0 5}$ | 45 | 10 | 0 | 30 | 2 | 0 |  |  |  |  |  |  |
| $\mathbf{2 0 0 6}$ | 61 | 18 | 1 | 39 | 13 | 0 |  |  |  |  |  |  |
| $\mathbf{2 0 0 7}$ | 75 | 40 | 1 | 59 | 19 | 0 |  |  |  |  |  |  |
| $\mathbf{2 0 0 8}$ | 65 | 20 | 2 | 42 | 12 | 0 |  |  |  |  |  |  |
| $\mathbf{2 0 0 9}$ | 62 | 15 | 1 | 42 | 4 | 0 |  |  |  |  |  |  |
| $\mathbf{2 0 1 0}$ | 67 | 35 | 2 | 54 | 20 | 1 |  |  |  |  |  |  |
| $\mathbf{2 0 1 1}$ | 72 | 32 | 3 | 53 | 16 | 0 |  |  |  |  |  |  |
| $\mathbf{2 0 1 2}$ | 54 | 23 | 0 | 36 | 8 | 0 |  |  |  |  |  |  |
| Average | 62 | 23 | 1 | 43 | 11 | 0 |  |  |  |  |  |  |



Fig. 3. Daily cycle of the detected severe ( 45 dBZ ), highly severe ( 50 dBZ ), and extremely severe ( 55 dBZ ) thunderstorm ellipses in the period of April to September between 2004 and 2012. The time resolution is 15 minutes. Times are given in Hungarian Local Time (HLT = UTC +2 hours).

### 3.2. Spatial distribution of thunderstorm ellipses

The spatial distribution of thunderstorm ellipses was analyzed by constructing thunderstorm statistic maps. The area resolution was set to $18 \mathrm{~km} \times 18 \mathrm{~km}$.

Thunderstorm statistic maps were created for the entire year in the period of 2004 to 2012, but only results for the thunderstorm season are represented in this paper. Between October and March, there was only a few objects detected, while the measurement noises were high, especially in the early years. During the nine-year period, the maxima of severe, highly severe, and extremely severe thunderstorm ellipses were detected mostly in the north-eastern, north-central, and south-western parts of Hungary. Fewer objects appeared in the northwestern and south-eastern parts of the country. Note that minima were mostly far from radars; these lower values could be originated to detecting problems (Fig. 4).

## 4. Summary and conclusions

This paper presents the results of an objective, radar-based analysis on thunderstorm climatology in Hungary for the nine-year period of 2004 to 2012. Most stormy days and ellipses were detected in late spring, summer and in 2007, 2010. The daily frequency of these objects peaked in the late afternoon period. The detected ellipses had maxima in the north-eastern, north-central, and southwestern parts of Hungary. Beyond information and characteristics from the past, these methods and results can be useful for forecasting severe thunderstorms. The cell-detection algorithm should be more integrated into automatic warning systems or can be used in researches on supercells. In the future, this objective examination can be carried out for previous years but better noise-filtering methods should be developed. Furthermore, satellite and lightning data can be combined with these results as well.


Fig. 4. Spatial distribution of a) severe, b) highly severe, and c) extremely severe thunderstorm ellipses in the period of April to September between 2004 and 2012. The area resolution is $18 \mathrm{~km} \times 18 \mathrm{~km}$. These images were visualized by the Hungarian Advanced WorKstation (HAWK) system developed by the Hungarian Meteorological Service.

## Appendix

## Mathematical background of the identification

The method of calculating ellipses is as follows (Dixon and Wiener, 1993):
Suppose there is an irregular cluster on a radar image which has $n$ detected pixels. The center of a cluster is defined by

$$
\begin{equation*}
\bar{x}=\frac{1}{n} \sum_{i=1}^{n} x_{i}, \quad \bar{y}=\frac{1}{n} \sum_{i=1}^{n} y_{i} \tag{1}
\end{equation*}
$$

where $x$ and $y$ indicate the longitude and latitude of pixels which have reflectivity higher than a given threshold value. The covariance matrix of this cluster is

$$
A=\operatorname{cov}_{x y}=\left[\begin{array}{ll}
d & e  \tag{2}\\
e & f
\end{array}\right]
$$

where $d$ is the deviation from the center by the $x$ coordinate

$$
\begin{equation*}
d=\frac{1}{n-1} \sum_{i=1}^{n}\left(x_{i}-\bar{x}\right)^{2}, \tag{3}
\end{equation*}
$$

$f$ is deviation from the center by the $y$ coordinate

$$
\begin{equation*}
f=\frac{1}{n-1} \sum_{i=1}^{n}\left(y_{i}-\bar{y}\right)^{2} \tag{4}
\end{equation*}
$$

and $e$ is

$$
\begin{equation*}
e=\frac{1}{n-1} \sum_{i=1}^{n}\left(x_{i}-\bar{x}\right)\left(y_{i}-\bar{y}\right) \tag{5}
\end{equation*}
$$

The eigenvalues of the covariance matrix are given by

$$
\begin{equation*}
\lambda_{1}, \lambda_{2}=\frac{(d+f) \pm\left[(d+f)^{2}-4\left(d f-e^{2}\right)\right]^{1 / 2}}{2} \tag{6}
\end{equation*}
$$

The normalized eigenvectors of this matrix are

$$
\begin{equation*}
v=\left[\frac{1}{(1+g)^{2}}\right]^{1 / 2}, \quad \mu=-g v \tag{7}
\end{equation*}
$$

where

$$
\begin{equation*}
g=\frac{f+e-\lambda_{1}}{d+e-\lambda_{2}} \tag{8}
\end{equation*}
$$

Then the rotation of the ellipse major axis relative to the $x$ axis is given by these vectors

$$
\begin{equation*}
\theta=\tan ^{-1}\left(\frac{v}{\mu}\right) \tag{9}
\end{equation*}
$$

The eigenvalues of the covariance matrix ( $\lambda_{1}$ és $\lambda_{2}$ ) represent the variances of the data (pixels)

$$
\begin{equation*}
\sigma_{\text {major }}=\lambda_{1}^{1 / 2}, \quad \sigma_{\min o r}=\lambda_{2}^{1 / 2} . \tag{10}
\end{equation*}
$$

The area of the detected cluster is

$$
\begin{equation*}
A=n d x d y \tag{11}
\end{equation*}
$$

where $d x$ and $d y$ are the grid spacing on the radar image.
The area of an ellipse is given by

$$
\begin{equation*}
T=\pi a b \tag{12}
\end{equation*}
$$

where $a$ and $b$ represents the major and minor axes of the ellipses.
The main idea is that the area of the irregular cluster and the area of the ellipse have to be equal, therefore

$$
\begin{equation*}
A=T . \tag{13}
\end{equation*}
$$

So the major and minor axes of the ellipses can be calculated by

$$
\begin{equation*}
a=\sigma_{\text {major }}\left(\frac{A}{\pi \sigma_{\min o r} \sigma_{\text {major }}}\right)^{1 / 2}, \quad b=\sigma_{\min o r}\left(\frac{A}{\pi \sigma_{\min o r} \sigma_{\text {major }}}\right)^{1 / 2} . \tag{14}
\end{equation*}
$$

With these parameters $(\bar{x}, \bar{y}, a, b, \theta)$, the focus points and the equation of the ellipse can be determined.

## References

Bodolainé, J. E. és Tänczer, T., 1991: Instabilitási vonal regionális ciklonban. Idöjárás 95, 178-195.
Bodolainé, J.E. és Tänczer T., 2007: Mezoskálájú konvektív komplexumok (szerk.: Horváth, Á.) A légköri konvekció, Országos Meteorológiai Szolgálat, Budapest, 35-45.
Boncz, J., Kapovits, A., Pintér, F. and Tänczer, T., 1987: A method for the complex analysis of synoptic weather radar and satellite data. Időjárás 91, 11-22.
Braham, R.R., 1958: Cumulus cloud precipitation as revealed by radar- Arizona 1955. J. Meteor. 15, 75-83.
Brimelow, J.C., Reuter, W.G., Bellon, A. and Hudak, D., 2004: A Radar-Based Methodology for Preparing a Severe Thunderstorm Climatology in Central Alberta. Atmosphere-Ocean 42, 13-22.
Collier, C.G., 1996: Application of weather radar system: A Guide to uses of radar in meteorology and hydrology. John Wiley \& Sons,
Croft, P.J. and Shulman, M.D., 1989: A five-year radar climatology of convective precipitation for New Jersey. Int. J. Climatol. 9, 581-600.
Davini, P., Bechini, R., Cremonini R. and Cassardo, C., 2012: Radar-Based Analysis of Convective Storms over Northwestern Italy. Atmosphere 3, 33-58.
Dixon M. and Wiener, G., 1993: TITAN: Thunderstorm Identification, Tracking, Analysis and Nowcasting - A radar-based methodology. J. Atmos. Ocean. Tech. 10, 785-797.
Falconer, P.D., 1984: A Radar-Based Climatology of Thunderstorm Days across New York State. J. Appl. Meteorol. 23, 1115-1120.
Geresdi, I., 2004: Felhőfizika. Dialog Campus, Budapest, 153-170.
Götz, G. és Pápainé, Sz. G., 1966: Zivatartevékenység a nyári félévben Magyarországon. Időjárás 70, 106-116.
Götz, G. és Pápainé, Sz. G., 1967: Zivatartevékenység a téli félévben Magyarországon. Időjárás 71, 302-309.
Henz, J., 1974: Colorado High Plains thunderstorm systems - a radar synoptic climatology. Colorado St. Univ., M.S. thesis.
Héjas, E., 1898: Zivatarok Magyarországon az 1871-től 1895-ig terjedő megfigyelések alapján. Királyi Magyar Természet Tudományi Társulat, Budapest, 174 pp.
Höller, H., 1994: Mesoscale organization and hailfall characteristics of deep convection in Southern Germany. Beitr. Phys. Atmosph. 67, 219-234.
Horváth, Á. and Geresdi, I., 2003: Severe storms and nowcasting in the Carpathian Basin. Atmos. Res. 67-68, 319-332.
Horváth, Á., Ács, F. and Seres, A. T., 2008: Thunderstorm climatology analyses in Hungary using radar observations. Időjárás 112, 1-13.
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. Idöjárás 111, 41-65.
Hungarian Meteorological Service, 2012: HAWK-3 visualization system. http://www.met.hu/en/omsz/tevekenysegek/hawk/

Jaeneke, M., 2001: Radar Based Climatological Studies of the Influence of Orography of Thunderstorms Activity in Central Europe. In: Proceedings of the 30th International Conference on Radar Meteorology, Session 12A, Munich, Germany, 19-24 July 2001; p. 12A5.
Mohee, F.M. and Miller, C., 2010: Climatology of Thunderstorms for North Dakota, 2002-06. J. Appl. Meteorol. Climatol. 49, 1881-1890.
Myers, J., 1964: Preliminary radar climatology of central Pennsylvania. J. Appl. Meteor. 3, 421-429.
Paiva Pereira, L.G. and Rutledge, S.A., 2003: Convective Characteristics over the East Pacific and Southwest Amazon Regions: A Radar Perspective. EPIC 2001 Workshop, Boulder, CO, 15-16 September 2003.
Ozorai, Z., 1965: A zivatarok gyakorisága Budapest-Ferihegy repülőtéren. Időjárás 69, 375-377.
Raum, $O$., 1910: A Magyarországon észlelt 15 évi zivatarok megfigyelések eredményei az 1896-1910 időszakban. Királyi Magyar Természettudományi Társulat Évkönyve 40, 2.
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.
Rudolph, J.V., Friedrich, K. and Germann, U., 2011: Relationship between Radar-Estimated Precipitation and Synoptic Weather Patterns in the European Alps. J. Appl. Meteor. Climatol. 50, 944-957.
Steiner, M. and Houze, R., 1996: Sensitivity of the Estimated Monthly Convective Rain Fraction to the Choice of Z-R Relation. J. Appl. Meteorol. 36, 452-462.
Tukey, J.W., 1977: Exploratory Data Analysis. Addison-Wesley, Reading.
Weckwerth, T.M., Wilson, J.W., Hagen, M., Emerson, T.J., Pinto, J.O., Rife, D.L. and Grebe, L., 2010: Radar climatology of the COPS region. Q. J. Roy. Meteorol. Soc. 137, 31-41.

