Spatiotemporal distribution of strong convective cells over northern Serbia, 2008–2010

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Abstract
Knowledge of the spatial distribution of severe convective cells (SCCs) can determine the areas with the most frequent occurrence of these events, and helps in the protection of the most vulnerable areas. An objective analysis of a three year observation of strong convective cells (CCs) in northern Serbia is presented, based on data collected via meteorological radar. The CC and SCCs are defined by radar reflectivity thresholds of 45 and 55 dBZ, respectively, and are analysed at constant altitude plan position indicator (CAPPI) levels of 4.0 km (CAPPI4) and 5.5 km (CAPPI5). The analysis showed that the dominant occurrence of thunderstorm cells was directed from southwest to northeast. The spatial distribution from year to year was variable; however, the analysis identified areas with frequent thunderstorm cells. The number of grid points where CCs occur is smaller at the CAPPI5 than at the CAPPI4. There is a more frequent occurrence of CCs than SCCs: there were no CCs in only 0.58% of grid points during the entire three year period at the CAPPI4, while for SCCs it was 39.82%. This difference was even greater at the CAPPI5: 1.42% for CCs and 55.47% for SCCs. At most of the grid points (67–79% at the CAPPI4 and 78–88% at the CAPPI5, depending on the year), no SCCs were observed for any given year.

KEYWORDS
frequency of thunderstorm cells, hail, radar reflectivity, severe convective cell

1 | INTRODUCTION

Severe cumulonimbus (Cb) clouds produce hail, lightning, floods and severe winds, all of which are potential hazards for humans and their material goods. Cb clouds are phenomena that usually take place at small temporal and spatial scales, and their forecasting using numerical models is therefore a very demanding task, owing to the coarseness of resolution of the models.

Several European regions suffer severe thunderstorms associated with large hailstones. Owing to this, the frequency and trends of hailstorms have formed the subject of a large number of investigations. Horvath et al. (2008) analysed the distribution of severe thunderstorms in Hungary over a five year period, based on radar measurements. Hermida et al. (2013) researched the spatial, altitudinal and temporal variability of hail precipitation in France, and concluded there was no spatial pattern.
Punge and Kunz (2016) gave an overview of the present state of knowledge on hail frequency across Europe. Burcea et al. (2016) used the radar-derived characteristics of convective storm cells for part of Romania to document their spatial and temporal distributions. Nad and Vujović (2017) found temporal and spatial distribution of hail events in central Serbia, as well as a trend in the number of days with hail. Sanchez et al. (2017) analysed the trends of synoptic fields over France, showing tendencies toward environments more favourable for hail development. Melcón et al. (2017) developed a new forecast tool for predicting hail days and determining the spatial distribution of hailfalls. The results of Jelić et al. (2018) suggested significant year-to-year variations of hail occurrence and a summer dominance of hail for the northeastern Adriatic region. Merino et al. (2019) used an analysis of synoptic fields, like Sanchez et al. (2017), and found that temporal changes in patterns related to hail variability suggest changes in the hail distribution during the warm season.

In Serbia, deep convection is frequent in the warmer part of year (in the Belgrade region, 96.9% of all thunderstorms in a 35 year period between 1975 and 2009 occurred in the warmer part of the year; Todorović and Vujović, 2010). To mitigate any potential damage to material goods and agricultural crops from larger hailstones, cloud seeding with the objective to reduce hail size has been carried out in Serbia between April 15 and October 15 in the 54 years since 1967. Vujović and Protić (2017) give a detailed description of the methodology of the cloud seeding system in Serbia, with accompanying references to many numerical and theoretical studies that have been conducted in order to understand the process better. The system has been continuously developed, and today it comprises 13 meteorological radars and covers a territory of 77,498 km², meaning that Serbia is one of the countries with the densest radar networks. These radar observations were used to carry out an objective analysis of convective cells (CCs).

It is common knowledge that the mountainous western and southwestern areas of Serbia are favourable places for Cb formation (Čurić et al., 2003). They are also the areas with the most frequent and intensive hailstorms (Nad and Vujović, 2017). However, northern Serbia is the latest part of the country to be included in the cloud seeding system. This began in the year 2000, when three meteorological radars (Gematronik Meteor 400 SLP13) were installed in consecutive years at the radar centres at Samoš (2000), Bajša (2001) and Fruška Gora (2002). Consequently, less is known about the frequency of Cb clouds and hailstorms in this area; this does not meet the needs of the region, since this part of Serbia is characterized by an abundance of fertile agricultural land, and the primary economic sector is agriculture. As such, it is very sensitive to convective developments and hailstorms. Furthermore, since hailstorms occur at very small temporal and spatial scales and their detection is uncertain, severe convection can be used as an indirect indicator for these. Weather radars are used for forecasting and warning of severe convection. Besides this, they were lately used to study the climatology of thunderstorms. In Europe, some of such studies were conducted by Davini et al. (2012) in Italy, Goudenhoofdt and Delobbe (2013) in Belgium, Seres and Horvath (2015) in Hungary, and Burcea et al. (2018) in Romania. Burcea et al. (2018, p. 11) concluded: “there are intervals within a given month when a great number of storm cells travel on preferential directions.” To the authors’ knowledge, there is no study of this type on Serbia. The goal of the present paper, therefore, is to carry out an objective analysis of the strong CCs over northern Serbia, based on radar reflectivity data. The results obtained can provide statistical support for operational nowcasting activities and improvements to measures to mitigate hail damage in this area.

2 | DATA

The data used are measurements of radar reflectivity carried out using operational weather radar (Gematronik Meteor 400 SLP13) at the radar centre located at the top of Fruška Gora mountain (latitude 45° 09′ 25″ N, longitude 19° 48′ 58″ E, 507 masl) (Figure 1). Table S1 in the additional supporting information gives the technical specifications of the radar equipment, which forms part of the radar network of the Republic Hydrometeorological Service of Serbia (RHMZ). The equipment is dual-polarized Doppler radar, which performs a scan every 5 min. The study used data gathered over three years, from April to October 2008–2010, a period that for the most part coincides with the season of operative hail suppression, which begins on April 15 and finishes on October 15. The best quality data available are for the period chosen here. Table 1 gives the numbers of days with available data during these three years. For technical reasons, the data set is incomplete, that is, the radar was not operational for the entire period owing to some failure or maintenance, and in October 2010, no data at all were gathered. Data from 551 days over the whole period, or 85.83% of the total number of days, were used.

Radiosonde measurements are regularly conducted at the meteorological station at Belgrade-Košutnjak (φ = 44° 46′ N, λ = 20° 25′ E, h = 203 masl), which is representative of northern Serbia. Radiosonde data for a period covering 10 consecutive years from 2001 to 2010 at 1200
UTC were collected from the website of the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html) in order to calculate the average height of isotherms at $-5$ and $-15\,^{\circ}C$. In addition, the RHMZ provided the data on the size of the areas damaged by hail, as well as for the number of days with thunder which is representative for this area.

3 | METHODS

The HASIS3D software package (Rančić et al., 1997, 1999) was used for statistical processing of the data obtained from a series of radar volume scans, each at a progressively higher elevation. One radar volume scan typically consists of 12 preset elevations; for each elevation, there are 360 azimuth angles; and for each angle, there is one data point at each 250 m. The study selected the radar reflectivity as a measure of convective cloudiness, similar to Seres and Horvath (2015), at constant altitude plan position indicator (CAPPI) levels of 4.0 km (CAPPI4) and 5.5 km (CAPPI5), which were created from the interpolation of selected radar information from all elevation angles, and a display representing the weather at a constant altitude was generated. Altitudes of 4.0 and 5.5 km were selected since these were the approximate mean altitudes of the isotherms at $-5$ and $-15\,^{\circ}C$ in the region analysed, respectively (the exact values are 4,081 and 5,677 m, respectively, calculated based on radiosonde measurements for the period 2001–2010). The isotherm at $-5\,^{\circ}C$ was chosen because this temperature represents the secondary maximum for crystal growth due to their hollow columnar shape. The primary maximum is at $-15\,^{\circ}C$, as it represents the largest difference in vapour density between the environment and the crystal surface (Young, 1993).

The analysed region was split into grid points of $1 \times 1\,km^2$, giving a total number of $185 \times 185$ points across the whole region (34,225 in total). These settings allowed the number of occurrences of the defined CCs at each grid point to be found. A CC is defined as a region with a surface of at least $2 \times 2\,km^2$ (i.e. four grid points), with a radar reflectivity $\geq 45\,dBZ$ (similar as Horvath et al., 2008). A severe convective cell (SCC) has a radar reflectivity $\geq 55\,dBZ$, and a surface area of at least $2 \times 2\,km^2$. If the criteria for CCs and SCCs are fulfilled at least once in any term during the day (i.e. the radar reflectivity is $\geq 45$ or $55\,dBZ$) at the CAPPI4 or CAPPI5, this is reported as a day with convective cloudiness. The term is defined here as one volume scan.

The threshold of 45 dBZ was selected due to the operational practice of cloud seeding by the RHMZ. The isosurface of 45 dBZ borders the zone with an enhanced radar echo, and when the height of this zone is greater

![FIGURE 1](image) Northern Serbia above which the frequency of cumulonimbus was analysed. RC marks the position of the radar centre Fruška Gora

| Year | April | May | June | July | August | September | October |
|------|-------|-----|------|------|--------|-----------|--------|
| 2008 | 30    | 31  | 29   | 30   | 24     | 22        | 19     |
| 2009 | 27    | 30  | 28   | 29   | 31     | 22        | 31     |
| 2010 | 30    | 31  | 30   | 31   | 31     | 16        | No data |
than the height of the isotherm at $-14^\circ C$, cloud seeding commences (Vujović and Protić, 2017) in hail-suppression activities. A radar reflectivity $\geq 55$ dBZ was related to the existence of hail (Wapler, 2017), a threshold first suggested by Mason (1971) and used in analyses of hail damage to crops (Hohl et al., 2002). Voormansik et al. (2017, p. 523) also distinguished storm areas using radar reflectivity thresholds. They stated that “higher threshold values are better for detecting individual convective cores, while lower thresholds allow larger scale storm systems, which can include multiple convective cores, to be identified.” This method could have some limitations. Namely, using the constant altitudes for the CAPPI4 and CAPPI5 allow the omission of some CCs that could occurred out of these levels. Nevertheless, these methods count all strong and long-lived cells.

When the observers reported hail, two commissions determined the size and extent of the damaged area: the municipal and the commission of the RHMZ. The damage only concerns that to agriculture (damaged crops from the individual and municipal fields). During the estimation of damage, even the damage caused by the loss of crop quality in the areas partially damaged by hail was taken into consideration (Mitić et al., 2009). The damage is expressed as a percentage of the plant’s damage and the percentage of the damaged area. A thunder day refers to a day with detected thunderstorms in the area of interest reported by professional meteorological observers at climatological stations.

4 | RESULTS

The region of interest includes a territory of approximately 100 km around the radar centre at Fruska Gora. Northern Serbia is intersected by three large rivers, the Danube, Sava and Tisa, which naturally divide the territory into three parts: Banat in the east, Bačka in the northwest and Srem in the southwest (Figure 1). The terrain is mainly flat, except at Srem, which contains Fruska Gora mountain (539 masl), and the southeast part of Banat, which contains Vrsački Breg mountain (641 masl). It is fertile arable land with rich agricultural production, and is therefore very sensitive to hailstorms.

Table 2 shows the total and daily average operational hours of the radar for each year, that is, the hours during which radar observations were available. The daily average working hours for each month are calculated by dividing the total working hours by the total number of working days from Table 1. As can be seen in Table 2, 2010 was the year best covered by data (up to 100% of operational hours), with the exception of October when the radar was not operational. In order to ensure that these missing data would not affect the analysis of the frequency of CCs and SCCs, the data were also examined for operational cloud seeding, which were provided by the RHMZ. It was found that on days when there were no radar observations at radar centre Fruska Gora, there was also no cloud seeding, according to the information from the other two radar centres that also cover the territory of the research. This does not mean that there was no convection at all, but that there was no severe convection to initiate cloud seeding (radar reflectivity of CCs should be $> 45$ dBZ, and its height should be higher than the defined threshold; Vujović and Protić, 2017). Therefore, this lack of the data could affect the obtained results to some extent. The only dates for which this could not be checked were April 9, 2009, and the period October 16–30, 2010, as these dates fell outside the season of operational hail suppression (which runs from April 15 to October 15 each year). However, these dates constitute only 2.49% of all days in the three year period analysed.

**Table 2**  Number of working hours for the radar during the period 2008–2010

|        | April      | May        | June       | July       | August     | September  | October    |
|--------|------------|------------|------------|------------|------------|------------|------------|
| 2008   | Total (hr) | 385:47:00  | 467:57:00  | 412:07:00  | 481:01:00  | 301:06:00  | 274:50:00  | 242:46:00  |
|        | Daily (hr) | 12:51:34   | 15:05:43   | 14:12:39   | 16:02:02   | 12:32:45   | 12:29:33   | 12:46:38   |
|        | %          | 53.58%     | 62.90%     | 59.21%     | 66.81%     | 52.27%     | 52.05%     | 53.24%     |
| 2009   | Total (hr) | 479:43:00  | 456:40:00  | 399:53:00  | 510:27:00  | 744:00:00  | 474:27:00  | 718:13:00  |
|        | Daily (hr) | 17:46:02   | 15:13:20   | 14:16:54   | 17:36:06   | 24:00:00   | 21:33:57   | 23:10:06   |
|        | %          | 74.03%     | 63.43%     | 59.51%     | 73.34%     | 100%       | 100%       | 89.86%     | 96.53%     |
| 2010   | Total (hr) | 744:00:00  | 744:00:00  | 744:00:00  | 744:00:00  | 744:00:00  | 301:28:00  | No data    |            |
|        | Daily (hr) | 24:00:00   | 24:00:00   | 24:00:00   | 24:00:00   | 24:00:00   | 18:50:30   |            |
|        | %          | 100%       | 100%       | 100%       | 100%       | 100%       | 78.51%     | 0%         |

Note: Shown are the total and daily average working (operational) hours of the radar; percentages show the percentage of working hours for the radar in the month.
4.1 Spatial distribution of the number of days with convection and severe convection

For each point in the grid, the number of days with convective cloudiness for the three year period 2008–2010 was counted (Figure 2). The white circle in Figure 2 marks the position of the radar centre at Fruška Gora. In the entire region of interest, there are almost no grid points at which there were no CCs (only 0.58% of grid points at the CAPPI4 in Figure 2a; and 1.42% at the CAPPI5 in Figure 2b). However, a large number of grid points did not experience a single day with SCCs over the three year period at the CAPPI4 and CAPPI5: 39.82% and 55.47%, respectively (Figure 2c, d). The northwest part of Bačka, central and northern Banat, northern Mačva, and eastern and southeastern Srem had the highest number of days with CCs and SCCs, at both altitudes. These areas match the data for the size of the agricultural area damaged by hail in the same period: in Sečanj (central Banat) in 2008 and 2009 the damage was the highest in the whole research area and amounted to 10.44% and 11.834% of the total agricultural area in this municipality, respectively. In 2010, the largest damage was in eastern Bačka (Ada municipality) and eastern Srem (Indija municipality) with 14.9% and 13.26% of the total agricultural area in those municipalities, respectively. Sremski Karlovci (eastern Srem) suffered large hail damage on 7.79% of its total agricultural area in 2010. There is not always hail on the radar reflectivity of 55 dBZ, but this is a generally accepted threshold used to discriminate hail cells from non-hail cells proposed by Mason (1971). Another threshold is also used: when the maximum height of 45 dBZ extends to 1.4 km above the daily 0°C isotherm, the presence of the hail is very likely (Waldvogel et al., 1979). The reflectivity of hail depends on its size, but also on the state of its surface, whether it is wet or dry. Wet hailstone produces a larger reflectivity than dry hailstone of the same size. Figure 2 shows the areas with the dominant occurrence of CCs that spread
out from southwest to northeast, which is particularly noticeable for SCCs at the CAPPI5 (Figure 2d). It reflects fact from a practice that the dominant direction of movement of CCs in this area is from southwest to northeast, which is noticeable from radar observations. Burcea et al. (2018) obtained a similar result. Pocakal et al. (2009) found that > 66% of Cb clouds enter Croatia (the western neighbour of Serbia) from westerly directions (west, northwest and southwest) and continue to move in the same direction. Furthermore, Vujovic et al. (2016, p. 108) conducted a wind sector analysis of two-dimensional backward trajectories calculated at 925 hPa for eastern Serbia and found that “precipitation arrives from three dominant, almost equally important, sectors: the west sector (15.3% of all trajectories), the southwest (SW) sector (13.9%), and the northwest (NW) sector (15.1%). These three sectors give in sum almost half of all precipitation days.”

Table 3 gives descriptive statistics of the number of days and terms when CCs were observed. The largest average number of days with CCs is observed in 2010, followed by 2009 and 2008. By comparing the two CAPPI levels, it is shown that there is a larger difference in the number of days with criteria fulfilled for CCs than for SCCs. This probably means that SCCs mostly reached the higher level (the approximate level of the −15°C isotherm), while CCs (the less intense cells) generally had less vertical development or lasted for less time and could not be observed at the CAPPI5. Davini et al. (2012, p. 55) found that “a cell showing a maximum reflectivity not exceeding 45 dBZ in the first 20 min of its life will decay in the following 10 min with a probability of about 90%.” The highest number of days with CCs at one grid point was 26 at the CAPPI4 and 17 at the CAPPI5, while the highest number of days with SCCs at one grid point was six at the CAPPI4 and five at the CAPPI5.

Figure 3 shows the number of CCs at the two CAPPI levels by year, indicating the annual variability in the convection. The variability from year to year is more noticeable at a higher level (CAPPI5), where the differences in the distribution of regions with a smaller and a larger numbers of days with convection become apparent. The years 2009 and 2010 had more days with CCs

| Year | Reflectivity | Number of volume scans | Number of days |
|------|--------------|------------------------|----------------|
|      | Height       | CC (45 dBZ)             | SCC (55 dBZ)   | CC (45 dBZ) | SCC (55 dBZ) |
|      |              | 4,000 masl 5,500 masl  | 4,000 masl 5,500 masl | 4,000 masl 5,500 masl |
| 2008 | Median       | 4 2 0 0             | 3 1 0 0       |           |           |
|      | Average      | 5.40 2.86 0.32 0.19  | 2.81 1.41 0.23 0.12 |        |           |
|      | SD           | 4.46 3.63 0.90 0.76  | 1.58 1.17 0.46 0.35 |        |           |
|      | Maximum      | 43 41 16 16         | 10 9 4 3     |           |           |
|      | Minimum      | 0 0 0 0             | 0 0 0 0      |           |           |
| 2009 | Median       | 7 3 0 0             | 4 2 0 0      |           |           |
|      | Average      | 7.21 3.72 0.47 0.29 | 3.77 2.05 0.39 0.24 |        |           |
|      | SD           | 4.33 2.91 0.79 0.61 | 1.81 1.35 0.61 0.47 |        |           |
|      | Maximum      | 30 20 7 5           | 11 9 5 4    |           |           |
|      | Minimum      | 0 0 0 0             | 0 0 0 0      |           |           |
| 2010 | Median       | 7 4 0 0             | 4 2 0 0      |           |           |
|      | Average      | 8.25 4.73 0.36 0.27 | 4.30 2.54 0.30 0.22 |        |           |
|      | SD           | 5.04 3.58 0.72 0.63 | 1.93 1.49 0.53 0.45 |        |           |
|      | Maximum      | 40 28 11 10         | 14 11 4 3   |           |           |
|      | Minimum      | 0 0 0 0             | 0 0 0 0      |           |           |
| 2008–2010 | Median   | 20 10 1 0 1 0 11 6 1 0 |           |           |
|      | Average      | 20.86 11.30 1.15 0.75 10.88 6.00 0.92 0.58 |        |           |
|      | SD           | 8.97 6.41 1.42 1.17 3.36 2.50 0.95 0.75 |        |           |
|      | Maximum      | 67 52 16 16 26 17 6 5 |           |           |
|      | Minimum      | 0 0 0 0             | 0 0 0 0      |           |           |
FIGURE 3 Number of days with convective cells (CCs) at levels CAPPI4 (left) and CAPPI5 (right) for 2008 (a, b), 2009 (c, d) and 2010 (e, f). The CAPPI4 and CAPPI5 are constant altitude plan position indicator radar product at altitudes of 4.0 and 5.5 km, respectively.

During 2008, compared with 2009 and 2010, there were 21% and 11% fewer thunder days, respectively.

In addition, the relative distributions of the numbers of grid points for a specified number of days with fulfilled criteria for CCs for the CAPPI4 (Figure 4a) and CAPPI5...
(Figure 4b) was calculated for each of the three years, and over the three year period. Figure 4a shows that, in 2008, 24% of grid points had CCs on two or three days at the CAPPI4, and these were the most frequent cases. In 2009, the criterion for CCs at the CAPPI4 was fulfilled most frequently over three or four days; while in 2010, CCs were observed above most grid points for four days (21%). Based on this, it seems that, in 2010, although CCs passed over the same regions and the frequency of CCs decreased, the number of days showing this convection increased. Over the three year period, since different parts of the observed territory were affected differently by CCs from one year to the next, the number of grid points without the criterion fulfilled was considerably lower, and at most grid points, the conditions were fulfilled on 10 and 11 days. A similar effect was found for CCs at the CAPPI5, although the number of days with the greatest frequency of CCs was smaller, and the frequency was greater than in the previous case (Figure 4b).

The spatial distribution of days with SCCs for each year suggests that at most of the grid points (67–79% at the CAPPI4 and 78–88% at the CAPPI5, depending on the year) there were no SCCs at the selected heights. In < 5% of the grid points, SCCs were observed for two days in one year at the CAPPI4, and in < 2% of the grid points at the CAPPI5. Over the analysed period, the highest number of SCCs were observed in 2009. Over the three year period, there were severe convection at 60% and 45% of the grid points at the CAPPI4 and CAPPI5, respectively. This also highlights the great diversity in the spatial distribution of severe convective cloudiness from one year to the next. However, in two of the three years analysed (2008 and 2009), the severe convective areas in the eastern part of Central Banat coincided. This is supported by the data on the large area of damage from hail registered in the municipality of Sečanj in eastern Banat in 2008 (10–70% of damage to crops over 10.44% of the total agricultural area) and 2009 (10–70% of damage over 11.834% of the total agricultural area). Figure S1 in the additional supporting information shows the parts of the total municipalities’ agricultural area damaged by hail and their coincidence with the frequency of SCCs at 4,000 m for 2008. The spatial distribution of SCCs shows a greater area covered by SCCs in 2009 and 2010 than in 2008. This is in agreement with the data on the hail-damaged areas, as well as with the number of days with thunder. In 2010, the area of hail damage was 415.6 km² (26 days of observed CCs); in 2009, it was 223.4 km² (22 days with SCCs); and in 2008, it was 199.3 km² (19 days with SCCs).

4.2 Spatial distribution of the number of terms with CCs and SCCs

The figures showing the number of terms over the whole period (2008–2010) in which the conditions for CCs or SCCs are fulfilled (Figure 5) are more clearly distinguished by the path of severe thunderstorms than when displaying the number of days. This is clearly visible in the case of SCC in Figure 5c, d, where the southwest–northeast path is noticeable. The areas with a greater number of terms with the occurrence of CCs and SCCs coincide closely with the areas with a greater number of days with CCs and SCCs (Figure 2). The maximum number of terms with CCs at one grid point over the whole period 2008–2010 was 67 at the CAPPI4, and 52 at the CAPPI5 (Table 3). There was a lower average number of terms with SCCs compared with CCs at both the CAPPI levels (Table 3).

Figure 6 shows the annual variability in SCCs, displaying the number of terms with the occurrence of SCCs year on year. It is significant that 2008 contributed in large part to the trajectory of SCCs in eastern Banat.
The maximum number of terms with SCCs was 16 at both heights in this year (Figures 5c, d). In the following year, 2009, this path was still visible, but in 2010, it was not. Mainly two outstanding storms in central Banat occurring at two consecutive years 2008 and 2009 left on almost the same trajectory. The paper will now briefly describe each storm.

4.2.1 Storm of May 19, 2008

A cyclonal circulation with the centre over Italy characterized the synoptic situation for this date (Figure 7a). The upper level air current was from the southwest. The analysis of aerological data shows, according to Vujović et al. (2015), that there were favourable conditions for the development of thunderstorm clouds and hail precipitation. Strong convection appeared in western, northern and northeastern Serbia. The CCs moved from southwest to northeast very slowly at < 5 kmh⁻¹. The meteorological conditions enhanced the initiation of convection in central and southern Banat, with large number of CCs originating at high levels. Therefore, most frequently the first radar echoes were observed at altitudes > 6 km and quickly reached intensities > 55 dBZ. Seven strong CCs formed here between 1545 and 2000 local time (UTC + 2) and crossed Sečanj municipality, giving large hail. Radar reflectivity in the horizontal plane and its vertical projections of one of these cells is shown at Figure 7c, showing the height of the top at > 10 km and maximum reflectivity of about 70 dBZ. Crops were damaged (10–70%) over 11.83% of the total agricultural area.

4.2.2 Storm of June 10, 2009

The frontal system crossed the territory of northern Serbia in the late afternoon and evening (Figure 7b), causing severe convection with thunderstorms, showers and hail. The multicell cloud system was moving from
southwest to northeast at about 50 km·hr⁻¹ and had reached Mačva, Bačka, Srem and Banat. The strongest cloud cells arose after 2000 local time (UTC + 2) in Banat, where peaks of individual CCs > 14 km and radar reflectivity intensities were > 60 dBZ (Figure 7d). The CC that gave hailfalls with extensive damage had an intensity of > 60 dBZ for > 80 min, with a maximum of 72 dBZ at the time of the hailfalls around 2130 local time (UTC + 2). Hail sizes were from hazelnut to walnut size. The crops in the municipality Sečanj, which was most affected, suffered extensive damage: 10.44% of the total agricultural area had 10–70% crop damage.
5 | CONCLUSIONS

The study used radar reflectivity data measured at the radar centre at Fruška Gora. The sample selected for analysis included data for the period 2008–2010, from April to October. An analysis of the obtained results shows the following characteristics for convective cells (CCs) above northern Serbia:

- The areas with the maximum number of days with observed CCs and severe convective cells (SCCs) matched at two selected heights, and can be observed in northwestern Bačka, middle Banat, Mačva and southeastern Srem. The difference in the two constant altitude plan position indicator (CAPPI) levels is much less than those with CCs and SCCs (over the three year period from 2008 to 2010).
- A yearly variation of the convective activity was observed.
- The spatial distribution of the number of days with a SCC indicates that at most grid points (67–79% at the CAPPI4 and 78–88% at the CAPPI5, depending on the year, where CAPPI4 and CAPPI5 are constant altitude plan position indicator radar product at altitudes of 4.0 and 5.5 km, respectively) there were no severe convective storms.
- The dominant trace of CC and SCC occurrence was southwest–northeast.
- The spatial distribution of the CCs and SCCs agrees well with the reports on damage from hail and the data for the number of days with thunder.

The analysis could be used in the better organization of the hail-suppression system. If there are obvious tracks

**FIGURE 7** Synoptic charts and radar images for two selected storm days of May 19, 2008 (a, c), and June 10, 2009 (b, d), at 1800 UTC. Radar images present radar reflectivity in the horizontal plane and its vertical projections. Synoptic charts were downloaded from www.wetter3.de/Archiv/archiv_dwd.html. The Republic Hydrometeorological Service of Serbia provided the radar images
of strong convective cells (e.g. southwest–northeast in Banat, as observed here), more rocket launchers should be installed in this area. Another possibility is that anti-hail nets could be installed in a region with frequent strong convective cells.

To obtain even better and more representative results, this research needs to be continued. One option would be the analysis of the product of maximum reflectivity, meaning that the layer in which the maximum reflectivity is required is limited. For example, searching would not take place below the average height of the zero isotherm. The current research could also be repeated with a stricter criterion regarding the definition of the dimensions of CCs. In addition, a larger sample of data should be used for analysis, that is, over more years, since this will show the characteristics of convective cloudiness more clearly. However, the radar at radar centre Fruška Gora has experienced several technical difficulties in recent years, and the best-quality data available are for the period chosen herein.

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REFERENCES

Burcea, S., Cica, R. and Bojariu, R. (2016) Hail climatology and trends in Romania: 1961–2014. Monthly Weather Review, 144, 4289–4299.

Burcea, S., Cica, R., and Bojariu, R. (2018) Radar-derived convective storms climatology for Prut River Basin: 2003–2017, Natural Hazards and Earth System Sciences. Discussion. https://doi.org/10.5194/nhess-2018-354.

Čurić, M., Janc, D., Vujović, D. and Vučković, V. (2003) The 3-D model characteristics of a Cb cloud which moves along a valley. Meteorology and Atmospheric Physics, 84(3–4), 171–184.

Davini, P., Bechini, R., Cremonini, R. and Cassardo, C. (2012) Radar-based analysis of convective storms in Northwestern Italy. Atmosphere, 3, 33–58.

Goudenhoofdt, E. and Delobbe, L. (2013) Statistical characteristics of convective storms in Belgium derived from volumetric weather radar observations. Journal of Applied Meteorology and Climatology, 52, 918–934.

Hermida, L., Sánchez, J.L., López, L., Berthet, C., Dessens, J., García-Ortega, E. and Merino, A. (2013) Climatic trends in hail precipitation in France: spatial, altitudinal, and temporal variability. Scientific World Journal, 2013, 1–10. https://doi.org/10.1155/2013/494971.

Hohl, R.R., Schiesser, H.H. and Aller, D.D. (2002) Hail fall: the relationship between radar-derived hail kinetic energy and hail damage to buildings. Atmospheric Research, 63(3–4), 177–207.

Horváth, A., Acs, F. and Seres, A.T. (2008) Thunderstorm climatology analyses in Hungary using radar observations. Idojarás, 112(1), 1–13.

Jelić, D., Megyeri, O.A., Belušić, A., and Telišman Prtenjak, M. (2018) Hail climatology and lightning jump climatology along north-eastern Adriatic region with accompanying weather types, EMS Annual Meeting Abstracts, Vol. 15, EMS2018-195, Budapest, 2–7 September 2018.

Mason, B.B. (1971) The physics of clouds. In: Oxford Monographs on Meteorology, 2nd edition. Oxford: Clarendon Press.

Melcón, P., Merino, A., Sánchez, J.L., López, L. and García-Ortega, E. (2017) Spatial patterns of thermodynamic conditions of hailstorms in southwestern France. Atmospheric Research, 189, 111–126. https://doi.org/10.1016/j.atmosres.2017.01.011.

Merino, A., Sanchez, J.L., Fernandez-Gonzalez, S., Garcia-Ortega, E., Marcos, J.L., Berthet, C. and Dessens, J. (2019) Hailfalls in southwest Europe: EOF analysis for identifying synoptic pattern and their trends. Atmospheric Research, 215, 42–56.

Mišić, M., Vučinić, Z., and Babić, Z. (2009) Cost-benefit analysis of the Hail Suppression Project in Serbia. 5th European Conference of Severe Storms, 12–16 October 2009 Landshut, Germany.

Nad, J. and Vujović, D. (2017) Trend of hail occurrence in Serbia in the period 1981–2012, 2nd European Hail Workshop, University of Bern, Bern, Switzerland, April 19–21.

Počakal, D., Večenaj, Ž. and Stalec, J. (2009) Hail characteristics of different regions in continental part of Croatia based on influence of orography. Atmospheric Research, 93, 516–525.

Punge, H.J. and Kunz, M. (2016) Hail observations and hailstorm characteristics in Europe: a review. Atmospheric Research, 176–177, 159–184. https://doi.org/10.1016/j.atmosres.2016.02.012.

Rančić, D., Smiljanić, M., Đorđević-Kajan, S., Kostić, A., Eferica, P., Vuković, P. and Vučinić, Z. (1997) Radar Data Processing for Cloud Seeding in Hail Suppression Information System, RADME 98, Rome, June 9–10. pp. 137–149.

Rančić, D., Smiljanić, M., Đorđević-Kajan, S., Eferica, P., Vuković, P., and Kostić, A. (1999) Meteorological radar data processing software. 19th EARSel Symposium on Remote Sensing in the 21, Valladolid, Spain, pp. 149–156.

Sanchez, J.L., Merinoa, A., Melcóna, P., García-Ortega, E., Fernández-González, S., Berthet, C. and Dessens, J. (2017) Are atmospheric conditions favoring hail precipitation change in southern Europe? Analysis of the period 1948–2015. Atmospheric Research, 198, 1–10. https://doi.org/10.1016/j.atmosres.2017.08.003.

Seres, A.T. and Horváth, Á. (2015) Thunderstorm climatology in Hungary using Doppler radar data. Idojarás, 119(2), 185–196.

Todorović, N. and Vujović, D. (2010) Analysis of frequency of thunder and lightning in the Belgrade area in Serbia in the
period 1975–2009. 8th European Conference on Applied Climatology (ECAC), Zurich, Switzerland, pp. 13–17 (September 2010).

Voormansik, T., Rossi, P.J., Moisseev, D., Tanilosoa, T. and Posta, P. (2017) Thunderstorm hail and lightning detection parameters based on dual-polarised Doppler weather radar data. Meteorological Applications, 24(3), 521–530.

Vujović, D. and Milić-Petrović, B. (2016) Analysis of bulk precipitation chemistry in Serbia for the period from 1982 to 2010. Journal of Atmospheric Chemistry, 73(1), 101–118. https://doi.org/10.1007/s10874-015-9318-0.

Vujović, D. and Protić, M. (2017) The behaviour of the radar parameters of cumulonimbus clouds during cloud seeding with AgI. Atmospheric Research, 189, 33–46. https://doi.org/10.1016/j.atmosres.2017.01.014.

Vujović, D., Paskota, M., Todorović, N. and Vučković, V. (2015) Evaluation of the stability indices for the thunderstorm forecasting in the region of Belgrade, Serbia. Atmospheric Research, 161–162, 143–152. https://doi.org/10.1016/j.atmosres.2015.04.005.

Waldvogel, A., Federer, B. and Grimm, P. (1979) Criteria for the detection of hail cells. Journal of Applied Meteorology, 18, 1521–1525.

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