

Frequency shifts in thunderstorm patterns as key precursors to flash flood events

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Abstract: This study presents the research of thunderstorms in Slovakia using records of thunderstorm days from weather observation stations from 1965 to 2023, as well as radar data, and data from lightning detection systems from 2010 to 2023. An algorithm was developed to identify thunderstorms using radar and lightning data. The temporal distribution of thunderstorms is examined across annual, seasonal, daily, and hourly timescales. Additionally, we focus on the spatial distribution of thunderstorms, where lightning data according to a proposed algorithm were used. The occurrence of thunderstorms is also analyzed in the light of macrosynoptic types, according to a 28-class classification of the Slovak Hydrometeorological Institute. The results show that close thunderstorms (within 3 km of a given location) in Slovakia occur on average on 15 days a year, most frequently in the summer months of June and July, and primarily in the late afternoon between 3 and 5 p.m. Central European Summer Time (CEST). The spatial distribution of thunderstorms in Slovakia is non-homogeneous, with an increased occurrence in Central Slovakia, particularly in the area of Muránska Planina, Stolické, and Volovské Vrchy Mts. Conversely, the fewest thunderstorms occur in the westernmost part of the territory. Severe thunderstorms are most numerous in the Gemer region. The occurrence of thunderstorms is significantly influenced by synoptic types, with the most favorable conditions associated with types B (trough over Central Europe), Bp (traveling trough), C (cyclone over Central Europe), and Cv (upper cyclone). In recent decades, significant decrease in the number of thunderstorm days per year has been observed. This may be due to the observed decreasing trend of cyclonic synoptic situations in Europe, where a substantial number of thunderstorms occur.

Keywords: Thunderstorm; Thunderstorm climatology; Radar, Lightning; Climate change.

1 INTRODUCTION

Thunderstorms are dangerous weather phenomena that produce lightning, strong winds, intense rain, hail, and tornadoes (LaDochy and Witiw, 2023; Mondal et al., 2024; Qie et al., 2020). These hazardous phenomena cause damage to property and pose threats to human health and life (Elsom and Webb, 2017; Hayward et al., 2023; Púčik et al., 2017). Severe thunderstorms often produce heavy rainfall, leading to flash floods that significantly impact both built and natural environments. The effects of flash floods can be devastating, particularly in small rural catchments and urban areas (Hlavčová et al. 2016; Diakakis et al. 2020). This potential for destruction motivates our research on thunderstorms in Slovakia.

Understanding thunderstorm climatology is crucial for weather forecasting, early warning systems, risk assessment, and water management (Dowdy, 2020; Lakshmanan and Kingfield, 2015; Taszarek et al., 2019). Numerous studies address the regional characteristics of thunderstorms, including their temporal and spatial distribution (Burcea et al., 2019; Croft and Shulman, 1989; Dowdy, 2020; Seres and Horvath, 2015; Taszarek et al., 2019). The impact of climate change on the intensity and frequency of thunderstorms is also discussed (Allen, 2018; Haberlie et al., 2022; Púčik et al., 2019; Rädler et al., 2019; Seeley and Roms, 2015). According to the Clausius–Clapeyron relationship, water vapor content increases by 6–7% per degree of warming, which can lead to heavier precipitation and to a greater amount of released latent heat and increased

thunderstorm intensity (Dowdy, 2020). Factors such as high air humidity in the lower levels, atmospheric instability and lifting mechanism are important for the formation of thunderstorms (Doswell et al., 1996). The occurrence of thunderstorms is further influenced by atmospheric circulation and synoptic conditions, with some circulation types having more favorable conditions than others (Piper et al., 2019; Twardosz et al., 2011; Wapler and James 2014).

There are several methods for constructing thunderstorm climatology, based on thunderstorm observation techniques. The first method utilizes human observations at meteorological stations. This method involves monitoring various thunderstorm parameters such as distance from the observation station, duration, intensity, direction of advancement, wind gusts, precipitation, and associated dangerous phenomena (Židek and Lipina, 2003). The disadvantage of these observations are temporal and spatial inhomogeneities, resulting from human errors and lower concentration of stations outside populated areas (Czernecki et al., 2016; Dowdy, 2020).

Automated remote sensing methods, including weather radars, lightning detection systems, and satellite measurements, provide more consistent data. Several algorithms have been developed to identify thunderstorms using radar data, the task of which is to identify clusters of pixels with high reflectivity, indicating the presence of convective cells, and subsequently predict their development (James et al., 2018). For example, the Deutscher Wetterdienst (DWD) has developed the KONRAD algorithm (Deutscher Wetterdienst, 2024), which uses weather

radar data and is based on threshold values of reflectivity of 46 dBZ on an area of 9 km² to identify convective cells. Other algorithm proposed by DWD is CellMOS, which integrates data from radar images, lightning observations, and numerical weather prediction models. The threshold value of reflectivity (area) is 37 dBZ (9 km²), but the presence of at least one lightning strike within a distance of 10 km is also required (Wapler et al., 2012). Similarly, the TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting) algorithm (developed by National Center for Atmospheric Research) uses values of 35 dBZ, and air volume size of 50 km³ (Dixon and Wiener, 1993). Alternatively, the SCIT (Storm Cell Identification and Tracking) algorithm uses up to 7 reflectivity thresholds (30–60 dBZ) (Johnson et al., 1998). Seres and Horvath (2015) investigated the climatology of thunderstorms in Hungary using radar data, where the TITAN algorithm was used to detect severe (above 45 dBZ), highly severe (50 dBZ) and extremely severe (55 dBZ) thunderstorms.

Given that radar measurements are a key data source for detecting thunderstorms and associated hazardous phenomena (Kyznářová and Novák, 2023), considerable attention is devoted to the continuous improvement of radar products (Méri et al., 2021). The most important factors affecting the quality of the back-scattered radar echo are attenuation, ground clutter (reflections from objects on the ground) or beam blockage (Zrníc and Ryzhkov, 1999). Due to beam blockage, estimating precipitation using radar in mountainous areas is particularly challenging. In the highest locations, radar-based precipitation estimates can be underestimated by up to 59% compared to measurements from rain gauge stations (Sleziak et al., 2023).

Lightning data are valuable as an addition to radar data for nowcasting thunderstorms and hazardous weather (Novák and Kyznářová, 2011); therefore, several studies focus on lightning climatology (Antonescu and Burcea, 2010; Manzato et al., 2022). An alternative method for identifying thunderstorms involves first identifying thunderstorm environments using data from climate reanalysis or sounding measurements, and then applying parameters closely associated with convection, such as convective available potential energy (CAPE) or wind shear in the 0–6 km layer (Allen et al., 2011; Brooks et al., 2003; Taszarek et al., 2019). Although some studies with in-depth analysis cover regions that include Slovakia (Manzato et al., 2022; Seres and Horváth, 2015; Taszarek et al., 2019), there is still a lack of greater accuracy in the temporal and spatial distribution of thunderstorms, particularly at the local scale within Slovakia. Climatological analyses of thunderstorms in Slovakia (Bochníček et al., 2015; Pecho, 2005; Vido et al., 2023) are generally limited to data from selected observation stations. In these studies, trends in the frequency of thunderstorm days (TDs) were assessed, and a spatial distribution of thunderstorms was created, where the aforementioned inhomogeneities were highlighted. Other studies in Slovakia focus on specific cases of thunderstorms with associated dangerous phenomena (Pekárová et al., 2021; Šinger, 2021a). An analysis of the long-term conditions influencing the formation of supercells and the reasons for their increased frequency in the Gemer region and eastern areas of the territory of Slovakia can be found in Šinger (2021b).

The primary objective of this study is to provide a more comprehensive overview of thunderstorms in Slovakia compared to previous ones. The goal is to classify thunderstorms based on their occurrence across various time scales, specifically annual, seasonal, daily, and hourly. Another objective is to map the spatial distribution of thunderstorms across Slovakia. This analysis is expected to help identify dominant trends in

thunderstorm activity and the extent of variability. Beyond the data from observation stations, data from lightning detection sensors and weather radar will also be incorporated, for a more precise and detailed analysis. Trends in thunderstorm activity obtained from different data sources will be inter-compared. Finally, we will also classify thunderstorms according to macrosynoptic types, and compare their occurrence in the light of individual synoptic types.

2 MATERIAL AND METHODS

2.1 Data from observation stations

The dataset contains recorded thunderstorm days from the network of observation stations of the Slovak Hydrometeorological Institute (SHMI) (Fig. 1). A thunderstorm day (TD) is a day in which at least 1 thunderstorm occurred at the observation station or in its vicinity (Židek and Lipina, 2003). Based on the methodology, thunderstorms are classified by their distance from the observation stations. In this study, we only analyzed the records of TDs with a close thunderstorm at the station (defined as thunderstorm occurring less than 3 km from station point).

The study utilized data from 169 observation stations covering the period from 1965 to 2023. Note that since many stations were not active during the entire period, there are also gaps in the data. Given the inhomogeneities between stations identified in previous studies, we chose to analyze records from all stations simultaneously rather than focusing on individual stations. This approach helps to statistically smoothen the differences among the stations. The number of TDs was always standardized for 1 active station each year. We considered an active station as one from which there is at least 1 record of TD each year. The number of such stations fluctuated around the value of 90 throughout the entire period.

For the purposes of validation, a subset of 12 high-quality stations was created. These stations continuously record measurements, cover the entire period, and the occurrence of TDs was statistically tested for the years 1984–2004 (Vido et al., 2023). We suppose that the dataset of high-quality stations accurately reflects the absolute values, while the dataset of all stations is a useful complement to the previous one if the results based on all stations are interpreted relative to those based on the high-quality dataset. In the analysis, the complete set of 169 observation stations was used.

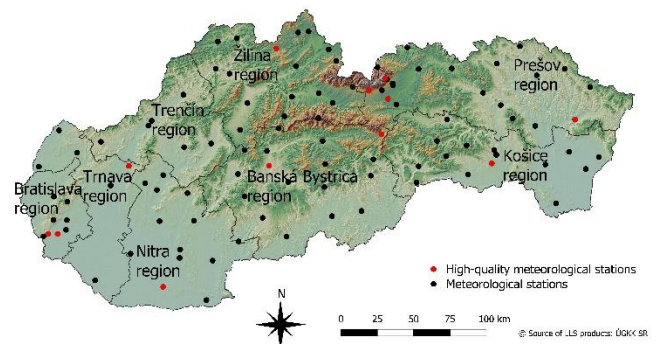


Fig. 1. Locations of observation stations in Slovakia used for recording thunderstorm days from 1965 to 2023. A total of 169 stations were included in the analysis, of which 105 are shown here.

2.2 Radar data

Radar meteorology in Slovakia began in 1972 with the first meteorological radar at Malý Javorník. National radar coverage was achieved with the Automated Radar Measurement System (ARMS) developed by SHMI in the early 1990s. The Slovak radar network has since been modernized, including Doppler capabilities and advancements in data archiving, such as the Tivoli system introduced in 2010 for online archiving. In 2015, the renovation of the Slovak weather radar network started with the replacement of Malý Javorník (Malé Karpaty) and Kojšovská hoľa (Voloenské vrchy) by new dual polarisation SELEX METEOR 735CDP radars. In 2016, two newly built radars were put into operation at Kubínska hoľa (Oravská Magura) and Španíľ (near Veľký Krtíš). The radars operate at a wavelength of 5 cm (C-band frequency), with a working range of 240 km, 1° azimuthal and 250 m radial resolution. The radars perform volume scans every 5 minutes at 12 different antenna elevations (SHMI, 2024). In this study, radar data were used in the period October 2010 – September 2023 (13 years), that is, the dataset is a combination of older and newer data. The area of interest, i.e., the territory of Slovakia and its immediate vicinity (47.3°–49.9° N, 16°–23° E) was chosen considering the effective range of the radars. The Maximum product was at our disposal – a two-dimensional composite map of the maximum radar reflectivity in a vertical column with a spatial resolution (pixel size) of approximately 330 meters, compared to 660 meters with the older radars. This product is suitable for tracking thunderstorm clouds, which have significant vertical extent (SHMI, 2024). The data were available every 5 minutes throughout the observation period, with only a very small amount of missing data (less than 1%), e.g., during radar outages.

2.3 Lightning data

Data from the VLF/LF (very low frequency/low frequency) Lightning Detection Network LINET system (Betz et al., 2009) were used in the same period as the radar data (Oct. 2010 – Sep. 2023). The LINET system detects cloud-to-ground (CG), cloud-to-cloud (CC), and intra-cloud (IC) lightning by measuring the electromagnetic radiation emitted by lightning strikes. The position and time of the strike is determined by the triangulation method by comparing the duration of the signal from several sensors; there are 12 of them in Slovakia (Fig. 2). The accuracy of determining the position of a strike is within 100–200 m, with the position being determined at the point of the highest emitted current. The system can also record the strength (maximum current) and polarity of the lightning strike, as well as the altitude of CC lightning. However, these data will not be used, and we will not differentiate between types of lightning. The first part of the data up to 2015 consists of data from the European system, from 2016 we utilize data from Slovak sensors network. Only lightning data from the same area as with the radars (about 150,000 km²) were analyzed. In total, nearly 15 million strikes were recorded in the monitored period. When counting TDs, the territory was divided into a grid of 5 km x 5 km squares (such an area roughly corresponds to the observed territory at the stations), and a TD was counted if at least 1 lightning struck in the given square per day. When evaluating the daily cycle of lightning frequency, all lightning flashes over the entire period and domain area were counted within each 5-minute time window (e.g., 00:00 to 00:05, 00:05 to 00:10, etc.), providing a measure of lightning frequency at different times of day.

2.4 Algorithm for thunderstorm identification

For simplicity reasons and available computing capacity, the following algorithm was developed to identify thunderstorms using radar and lightning data (Fig. 2). We based our approach on existing algorithms, such as KONRAD, CellMOS, and TITAN (see Introduction for details), selecting threshold values for reflectivity and size of thunderstorm, and also required the presence of lightning within the cells.



Fig. 2. Positions of LINET lightning detection sensors in Slovakia since 2016.

In order to better determine the reflectivity threshold, an empirical probability distribution of relative frequencies of pixel values in dBZ in the vicinity of individual lightning flashes was created (Fig. 3): On each radar image, all lightning flashes during the given 5-minute interval were first displayed. Pixels within a radius of 3 km around each lightning flash (distance corresponding to that of a close thunderstorm at the station) were selected and the frequencies of individual pixel values in dBZ were counted. Each pixel has one reflectivity value in dBZ in the range 0–95.5, with a resolution of 0.5 dBZ, corresponding to the precipitation intensity. This approach provided us with a probabilistic distribution for the entire period. Fig. 3 also displays the distribution for dBZ values within radius 10 km around lightning strikes, where we can observe that (1) the peak is shifted to lower values, (2) a significant portion of the territory is now outside the thunderstorm cells (reflectivity close to 0), and (3) the portion of high dBZ values did not increase, indicating that no additional cores were identified.

The first parameter for the threshold reflectivity, based on the frequency analysis of the reflectivity intensity, was chosen to be 30 dBZ (thereby capturing most of the thunderstorm cores - Fig. 3) for ordinary thunderstorms and 50 dBZ for severe thunderstorms. The threshold reflectivity values are consistent with thresholds commonly used in similar studies. For example, Houston et al. (2015) used minimum reflectivity value 30 dBZ. Although some other studies used a threshold of 40 dBZ to better differentiate the convective precipitation (Hocker and Basara, 2008; Goudenhoofd and Delobbe, 2013), the lower threshold used here is justified because lightning is included.

For severe thunderstorms, Seres and Horvath (2015) used threshold values 45–55 dBZ. Another parameter is the size of the storm. The National Weather Service (2016) reports a typical thunderstorm diameter of 24 km, Wei et al. (2023) found an average thunderstorm area of 392 km² (which corresponds to a diameter of ~22 km). By visually assessing radar images, we inferred that the typical size of thunderstorms (maximum diameter) is around 20 km, as our algorithm effectively captured the cores of most thunderstorms, while higher values would

increase the likelihood of including stratiform precipitation, which we aim to exclude.

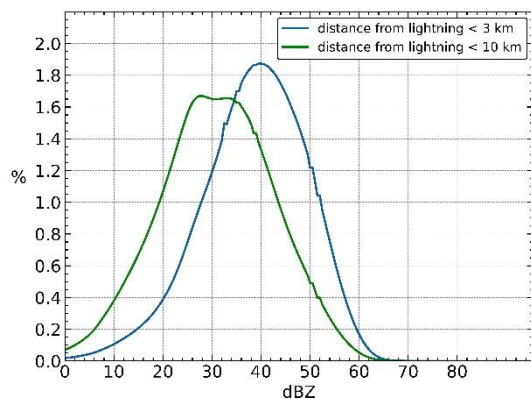


Fig. 3. Empirical probability distribution of radar reflectivity values in dBZ near lightning within 3 km and 10 km. Period: 2010/10–2023/09.

The way the above-described algorithm works is illustrated in Fig. 4. On the radar image, we display all lightning strikes recorded during the given time window (5 minutes). We create a circle with a radius of 10 km around each flash and mark all pixels exceeding the reflectivity threshold value within the circle. A radius of 10 kilometers around each lightning event was considered (i.e., a diameter of 20 km), aligning with the typical size of a thunderstorm. We will say that a thunderstorm occurred on these marked pixels, with a duration of 5 minutes (because the time resolution of one frame is also 5 minutes). Note that it is important to understand the thunderstorm duration, especially in the context of flooding, which is often caused by prolonged and intense thunderstorms (Doswell et al., 1996). The algorithm was used to create the spatial distribution of thunderstorms (their duration). The duration of storms was calculated at each point within the target territory (2270 x 1560 pixels), averaged over 1 year.

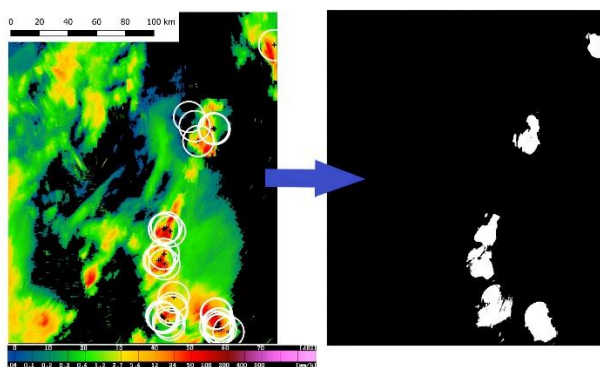


Fig. 4. Schematic diagram of the simple custom algorithm for thunderstorm identification using radar and lightning data. Left – part of the original radar image showing maximum reflectivity (20230923 19:30 UTC) with flashes shown (black '+' signs) and with a circle of 10 km radius around the flashes. Right – filtered thunderstorm cells.

2.5 Synoptic types

The synoptic type for each day of the investigated period (1965–2023) was obtained from the Slovak Hydrometeorological Institute (SHMI, 2023). The classification is based on the catalog of Hess and Brezowsky (1952) and Brádka (1968). It contains 28 types (Tab. 1), characterized by the distribution of pressure systems and circulation patterns over

Europe. It is expected that this distribution will have a significant impact on the occurrence of thunderstorms. Although typification is currently less used, mostly due to replacement by numerical methods, it is still suitable for monitoring long-term trends and changes in atmospheric circulation (Bissolli and Dittmann, 2001).

Thunderstorm days recorded from observation stations were used for classification according to synoptic types, due to the extensive available time series data (1965–2023). We evaluated the number of TDs in the entire territory of Slovakia. A TD in the entire Slovakia was counted if a TD was recorded at least at 1 station within the entire territory (only a close thunderstorm at the station was considered). For each synoptic type, the probability of the occurrence of a TD was determined as:

P = average number of TDs per year for the given synoptic type / average number of days of occurrence of the given synoptic type per year.

We also applied the classification by synoptic types to the spatial distributions of thunderstorms obtained using the algorithm described above. We divided the period during which the algorithm was used into periods when individual synoptic types occurred and determined the average duration of thunderstorms for each type. For the sake of data completeness, the period 2011–2022 was used since data for the year 2023 were not yet available for synoptic classification. Since some synoptic types occurred more frequently than others during the examined period, we further normalized the duration of thunderstorms to the occurrence of 1 TD for a given synoptic type. For this purpose, we used the data of the average number of TDs per year for a given synoptic type (in the period 2011–2022, as described in the method above). Normalization allows us to compare synoptic types with each other, enabling us to determine not only the spatial distribution but also the average duration of thunderstorms on a day when a given synoptic type occurs.

3 RESULTS AND DISCUSSION

3.1 Temporal distribution of thunderstorms

The average number of TDs at the observation station is around 15 per year (Fig. 5). Given that thunderstorms at the stations are recorded only within a 3 km radius, the significance of the result implies that, on average, any location in Slovakia experiences 15 TDs per year. However, over a larger area or the entire region, the number of thunderstorms will be higher. For instance, Taszarek et al. (2019) utilized multiple data sources to analyze the spatial distribution of thunderstorms across Europe, reported 15–30 thunderstorm days per year within grid cells of approximately 50 km x 50 km resolution in regions of Slovakia. There is an average of 99 TDs per year in the entire territory of Slovakia – when we count a TD in the entire territory if it occurred at least at one observation station. In Fig. 5, a significant decrease in the number of TDs can be discerned, especially in the recent decades. The interannual variability in thunderstorm days is generally modest, with year-to-year changes typically being small. However, this variability can sometimes be significant; for example, in the years 2005 and 2007, the number of thunderstorm days in one year was up to twice as high as in the other.

When comparing the thunderstorm dataset containing all stations with the dataset from high-quality stations, we observe that more TDs were recorded at the high-quality stations (approximately 1.3 times more). This observed difference may be attributed to the fact that some stations had incomplete or intermittent data, which could lead to an underestimation of thunderstorm days. Although we cannot precisely quantify the missing data, it is likely that the presence of more complete data at

the high-quality stations contributed to the higher number of recorded TDs. Furthermore, we can observe that this ratio remains mostly constant across individual years throughout the period. In other words, if a higher number of thunderstorm days was recorded at the high-quality stations in a given year, a higher number was also recorded across all stations (or conversely, a lower number). We have thus confirmed a high correlation between the datasets, making it reasonable to continue using the dataset from all stations.

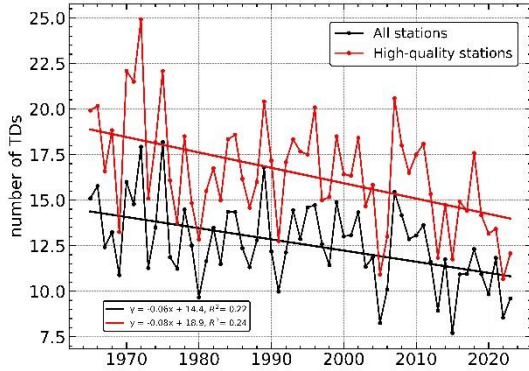


Fig. 5. Evolution of the average number of thunderstorm days at observation stations over the period 1965–2023.

Thunderstorm occurrence peaks during the summer months (Figs. 6 and 7). This is primarily due to higher convective instability, which leads to stronger upward movements, as well as increased available moisture (Doswell et al., 1996). In this paper, the seasons are defined as follows: Spring (March–May), Summer (June–August), Fall (September–November), and Winter (December–February). Figure 6 shows the most significant decline in summer thunderstorms in the analyzed period, whereas the decrease in fall and winter thunderstorms is only minor. The difference between the decreasing trends in spring and autumn thunderstorms may also be attributed to a shift in the thunderstorm season in recent decades (Fig. 7a). In the period 1965–1984, the peak was reached in the months of May, June, July, in 1985–2004 it was June, July, and in 2005–2023, most thunderstorms occurred in July and August. The number of TDs is approximately 3 per month during the summer months, but it should be noted that in Fig. 6 and 7a, all stations were used, therefore the actual number may be slightly higher (about 1.3 times - according to the observed differences between the high-quality and all-station datasets, as mentioned above). Lightning activity throughout the year across the entire territory (Fig. 7b) aligns well with the number of thunderstorm days in Fig. 7a.

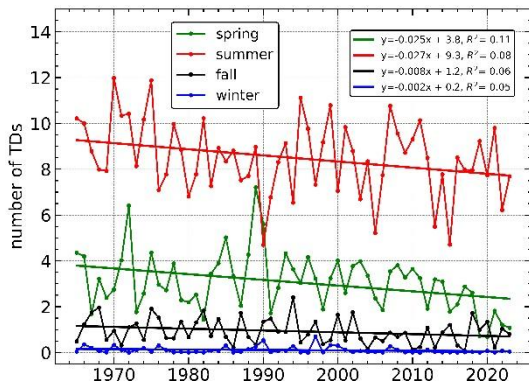


Fig. 6. Evolution of the average number of thunderstorm days at all observation stations by season over the period 1965–2023.

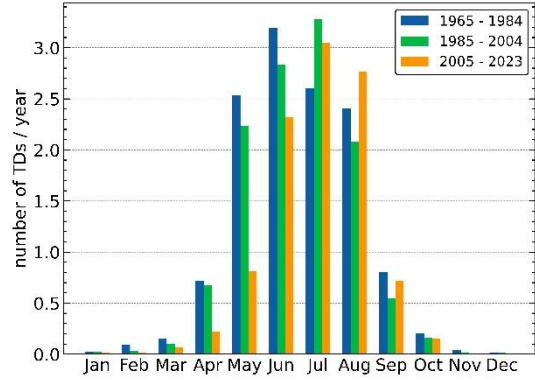


Fig. 7. (a) Average number of thunderstorm days at observation stations in individual months in selected periods.

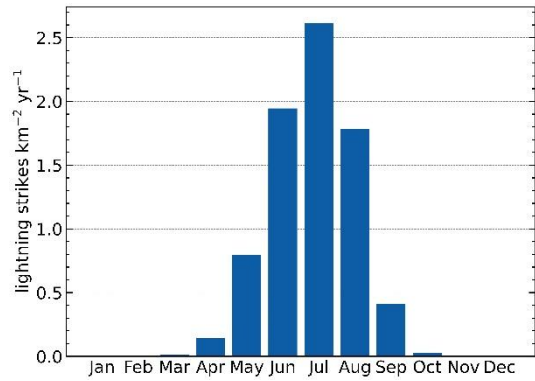


Fig. 7. (b) Average number of lightning strikes per month in the period 2010/10–2023/09.

The diurnal cycle of thunderstorms corresponds with expectations based on physical principles. In the morning, the lower atmosphere is typically cooler, leading to greater atmospheric stability. As the day progresses, the lower layer warms up, resulting in destabilization of the atmosphere, which promotes vertical movements – an important condition for thunderstorm formation. Later in the evening and at night, the stability in the lower layer increases, and convection conditions deteriorate (Markowski and Richardson, 2010). Such daily behavior can also be observed in the case of lightning, averaged over the entire domain area and time period (Fig. 8). The fewest lightning strikes occur in the morning around 10 a.m., with the peak activity between 3 p.m. and 5 p.m. CEST. This diurnal pattern (Fig. 8) closely matches results from the previous studies, such as those on lightning in Romania (Antonescu and Burcea, 2010) and radar-detected thunderstorms in Hungary (Seres and Horvath, 2015). Therefore, we can infer that the distribution of thunderstorms throughout the day is likely to exhibit a similar pattern to the lightning distribution shown in Fig. 8.

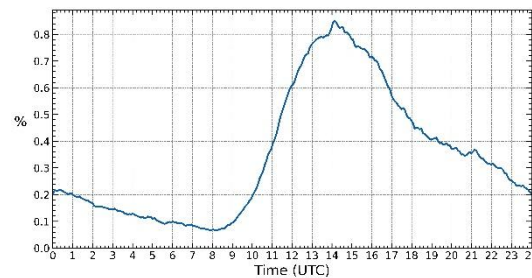


Fig. 8. Diurnal distribution of lightning strikes in Slovakia (the entire domain area), in the period 2010/10–2023/09, with a time resolution of 5 minutes. The percentage of the total number of flashes (15 million) for each time window is displayed on y-axis.

Note: A radius of 10 km overestimates the size of an individual thunderstorm because multiple lightning strikes can occur within one storm (as observed in Fig. 4), thus increasing the total size of the storm beyond the mentioned values. We also tested other radius values, yielding very similar results. The algorithm also does not enable differentiation of thunderstorms based on their formation mechanisms, such as frontal or air mass thunderstorms.

3.2 Spatial distribution of thunderstorms

The spatial distribution of thunderstorms, determined based on lightning activity and radar data, is inhomogeneous in Slovakia, with the highest frequency observed in the southern half of Central Slovakia (Fig. 9a, b and 10a). The highest lightning activity is in the Banská Bystrica region and in the western part of the Košice region (Fig. 9b), and thunderstorms also last the longest here (Fig. 10a); therefore, we can expect the highest thunderstorm activity in these areas. The number of thunderstorm days (Fig. 9a) is also the highest in the mentioned territories, but the regional differences are much less significant. This results from the methodology of determining TDs, when the intensity and frequency of thunderstorms on a given day is no longer considered. The absolute values of TDs determined by lightning data (Fig. 9a) range from about 12 in the westernmost part of Slovakia to about 20 in areas with the highest thunderstorm activity. The average value is around 15, which we also found in Fig. 5 using data from observation stations.

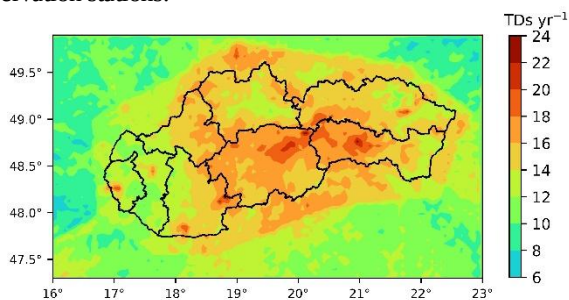


Fig. 9. (a) Spatial distribution of thunderstorm days in Slovakia determined by lightning in a 5 km x 5 km grid, in the period 2010/10–2023/09.

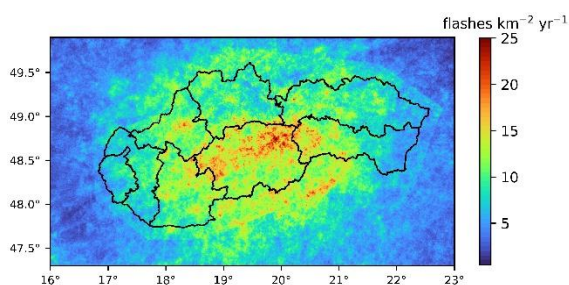


Fig. 9. (b) Map of absolute lightning frequency in Slovakia in a 1 km x 1 km grid (b), showing the number of flashes per square kilometer per year, for the period 2010/10–2023/09.

The average number of lightning strikes (Fig. 9b) in one year per km² ranges from 5 in the westernmost and easternmost parts of the territory, and the basins of northern Slovakia (Oravská kotlina, Liptovská kotlina) to 15 to 20 in the Banská Bystrica region. It is also worth to mention places where the absolute maximum number of lightning strikes occurs, particularly on the peaks of Kráľova Hoľa (Low Tatras) and Skalka (Kremnické vrchy Mts.), where the number of lightning strikes per km² per year exceeds 200 due to the presence of transmission towers (these data were due to this reason omitted in Fig. 9b). An increased occurrence of CG (Cloud-to-Ground) lightning around

transmission towers was also observed in Novák and Kyznarová (2011). The average number of lightning strikes in the entire territory of Slovakia is around 10 lightning strikes per km² and per year. The number of CG lightning per km² in 1 year ranges up to 4 in Austria (Schulz et al., 2005) and around 3 in the Czech Republic (Novák and Kyznarová, 2011) and in Romania (Antonescu and Burcea, 2010). The higher number we found is likely due to the inclusion of all types of lightning flashes, not just CG strikes. Lightning in thunderstorms is primarily composed of IC flashes, which typically account for 70–80% of all lightning occurrences (Medici et al., 2017).

The mountain regions in Germany serve as the first significant obstacle to the westerly winds, creating favorable conditions for orographically triggered thunderstorms (Wapler, 2013). Since the increased occurrence of thunderstorms in the Alpine regions has been proven (Taszarek et al., 2019), we expected a higher number of thunderstorms in the mountains in Slovakia as well. The maximum, however, is not reached in the Tatras, as is the case with precipitation (Bochníček et al., 2015), but in the lower mountains of Central Slovakia (Figs. 9b, 10a), such as the Muránska planina, the eastern part of the Low Tatras, Stolické and Volovské vrchy Mts. In addition, we see some correlation with altitude, e.g., in the northern half of Central Slovakia, there is a decrease in thunderstorm activity in wide basins (Turčianska kotlina, Liptovská kotlina, Oravská kotlina) and an increase in the surrounding mountains (Figs. 9b, 10a). It should also be noted that the duration of thunderstorms (in Figs. 10a, b) in the highest elevated locations may actually be slightly longer, as the radar tends to record lower reflectivity of precipitation in mountainous areas than what is observed in reality (Sleziak et al., 2023), and this could have been a problem around the reflectivity threshold values when using the algorithm.

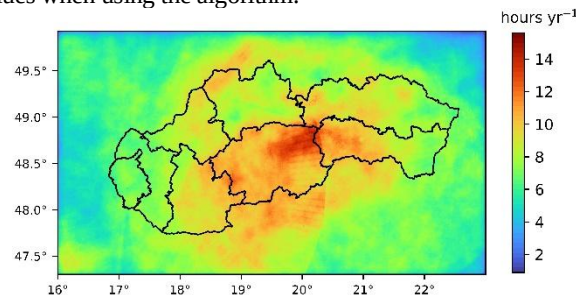


Fig. 10. (a) Spatial distribution of thunderstorm duration in Slovakia. All storms with reflectivity above 30 dBZ. Data obtained using the methodology described for the period 2010/10–2023/09. The total average storm duration in hours per year is shown for each 330 m x 330 m pixel.

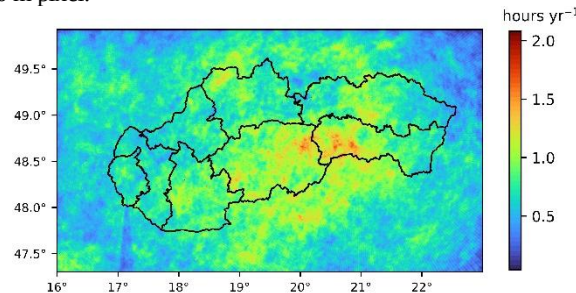


Fig. 10. (b) Spatial distribution of thunderstorm duration in Slovakia. Severe thunderstorms with reflectivity above 50 dBZ. Data obtained using the methodology described for the period 2010/10–2023/09. The total average storm duration in hours per year is shown for each 330 m x 330 m pixel.

The increased occurrence of thunderstorms in the southern part of Central and Eastern Slovakia (Fig. 10a) and severe thunderstorms in the Gemer region and in the western part of the

Košice region (Fig. 10b) is probably caused by specific local orography in the given regions. When analyzing supercell environments (Šinger, 2021b), suitable conditions for deep convection were found in these areas. It has been demonstrated that with prevailing westerly and northwesterly winds in the lower troposphere, colder and drier air is forced to flow around the Carpathians, reaching the Gemer region and its surroundings to a lesser extent. This allows warmer, more humid, and more unstable air masses to persist longer in that area. Additionally, there is increased vertical wind shear and the formation of convergence lines. With warm southerly to easterly winds, anabatic flow on the windward sides of the mountains becomes significant, leading to an increase in CAPE (Convective Available Potential Energy).

3.3 Classification of thunderstorms according to synoptic types

The macrosynoptic types have a significant impact on the occurrence of precipitation and thunderstorms (Markovič et al., 2021; Twardosz et al., 2011). In Poland, two times more precipitation falls during summer thunderstorms in cyclonic weather types compared to anticyclonic ones (Twardosz et al., 2011). Similarly, over the territory of Slovakia, most TDs occur in cyclonic types (Fig. 11). On average, there are 99 TDs per year in the entire territory. Figure 11 breaks down this number for each synoptic type (blue parts of the columns), based on the average number of thunderstorm days per year recorded for each class.

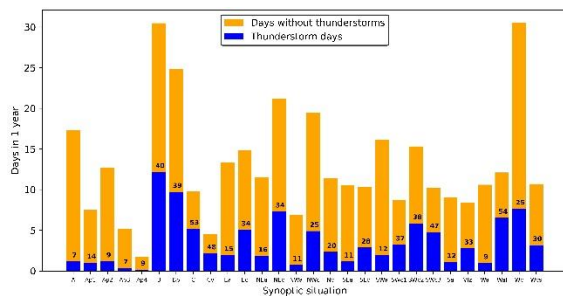


Fig. 11. Average number of thunderstorm days (TDs) for synoptic types compared to the total number of days of occurrence of each synoptic type during the year, for the period 1965–2023. All column values add up to 365. Shown is also a value in percentages that expresses the probability of a thunderstorm day. Obtained from TDs at the stations across the entire territory of Slovakia.

For individual classes, anticyclonic conditions typically result in about 1 to 3 TDs per year, while cyclonic conditions can lead to more than 10 TDs (in the cases of B and Bp). Regarding the probability of a thunderstorm day occurrence (according to the methodology), the lowest probability is, of course, during anticyclonic weather types (around 10%), as the conditions are the least favorable to thunderstorm formation. Under cyclonic conditions, the probability can be as high as 40 to more than 50%. The Wal type is particularly interesting; although it is classified as anticyclonic one, the occurrence and probability of thunderstorm days resemble those of cyclonic synoptic types.

To better understand the impact of climate change on thunderstorm formation, we also examined the trends of all cyclonic and anticyclonic weather types since 1965, shown in Fig. 12. Generally, changes in the number of days with cyclonic and anticyclonic types over a longer period can indicate overall shifts in air mass circulation patterns in Europe. As shown in Fig. 12, the number of cyclonic weather types has decreased in recent decades, while anticyclonic ones have become more frequent and/or longer lasting. This may explain the observed decrease in the number of

thunderstorm days shown in Figs. 5 and 6, as most thunderstorms occur during cyclonic weather types. In the context of climate change and global warming, it is important to consider that increasing average air temperatures and absolute humidity do not automatically lead to more frequent thunderstorms. One should also account for global changes in air mass circulation, as indicated in Bluestein (2013).

Among the different synoptic types, we found that thunderstorms most frequently occur during the classes labelled as B and Bp (Fig. 11). Nevertheless, the average duration of thunderstorms per day is shorter for these types compared to some other classes, such as C, Cv, and Ap3 (Fig. 13).

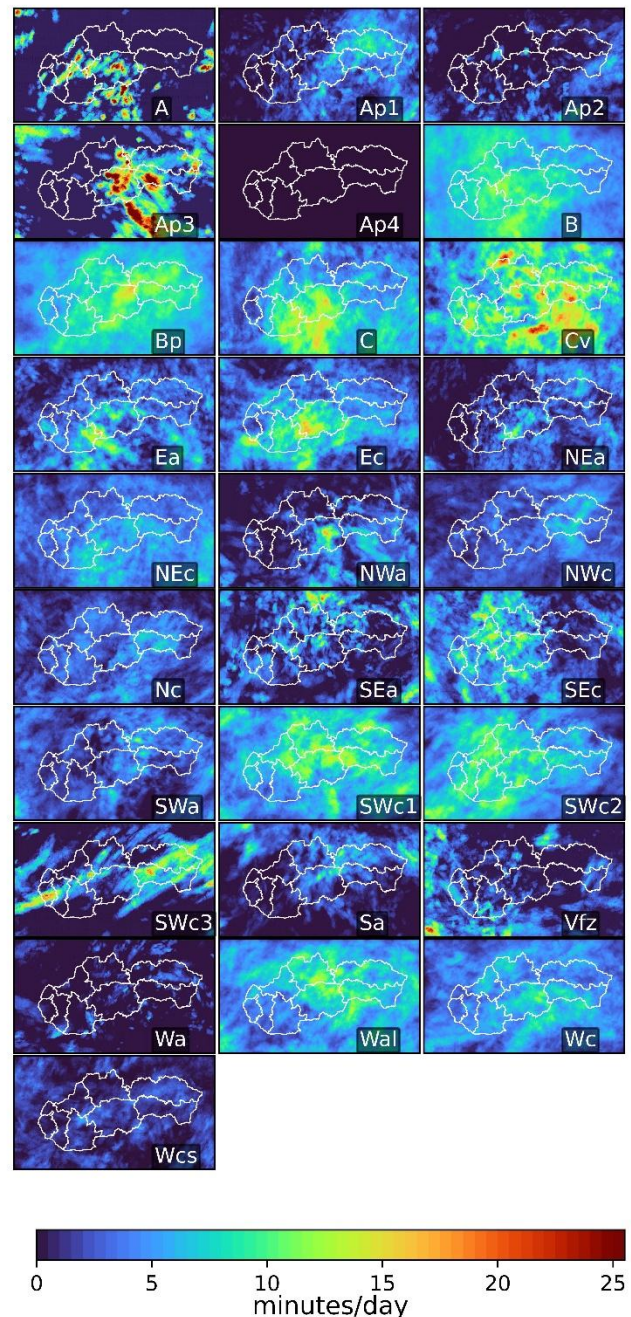


Fig. 13. Spatial distribution of thunderstorms (their duration) in Slovakia for individual synoptic types in the period 2011–2022. The time scale represents the average duration of thunderstorms in minutes per 1 day at a given location. Obtained similarly as in Fig. 10a, further normalized for individual situations according to the data from Fig. 11 (but for a different period).

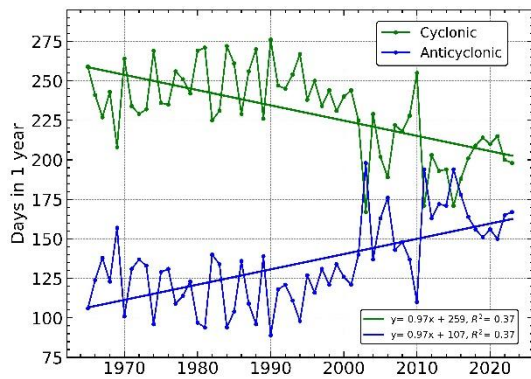


Fig. 12. Evolution of the number of days with cyclonic and anticyclonic synoptic types in the period 1965–2023.

This indicates that the most thunderstorms (or the longest-lasting ones) occur during these weather types. For anticyclonic types, the reliability of the results shown in Fig. 13 is naturally lower, as thunderstorm days are less frequent (as seen in Fig. 11). Therefore, after normalizing the duration of thunderstorms to one thunderstorm day according to the blue columns in Fig. 11, we obtained high values for classes A and Ap3 (Fig. 13). Note that the absolute values of thunderstorm duration in the spatial distribution do not hold significant meaning, as they are averaged over a longer period and cannot accurately predict the duration of a single storm. These values are primarily useful for comparative purposes between different regions, allowing us to identify areas with relatively longer or shorter thunderstorm activity. Regarding spatial distribution, some types show a prevalence of thunderstorms in specific areas. For instance, class Ap1 in the northeast, B and C in the south, SEc and SWc2 in the western parts, and Cv in the eastern parts of the country. In many other cases, thunderstorms occur more or less uniformly across the entire territory, indicating that their occurrence is random. In the upcoming subsections, we describe some interesting cases in more detail, where thunderstorms are significantly influenced by the synoptic conditions.

Synoptic type C – Cyclone over Central Europe

The main feature of this synoptic type is a stationary cyclone (Fig. 14a), expressed mainly at height, which lies in the western part of the Central Europe. Around this cyclone, fronts from the Mediterranean Sea pass through the eastern part of Central Europe, where they turn to the northwest. The pressure high over Eastern and Northern Europe is connected with the Azores pressure high with a trough over the British Isles. We found that the most thunderstorms and thus the most suitable conditions for their formation were in the observed period in the Nitra and Banská Bystrica regions (Fig. 14b). When thunderstorms occurred, their duration in these areas was on average about 15 minutes per day. This synoptic type occurs most often in the summer months (May to August).

Synoptic type SWc3 – South-west cyclonic type (3rd type)

This class is characterized by a frontal zone, running through southern France and Central Europe to the northeast (Fig. 15a). A cold cyclone, often just a wake of low pressure, lies at higher levels over the North Sea and British Isles. Above the ocean, there is a massive ridge of high pressure, often reaching as far as Iceland. A cold anticyclone in the area of Iceland brings cold air to the south, which meets a very warm and relatively moist southwesterly flow, creating a sharp boundary between these two air masses with

different temperatures and humidity, both at the ground and at height.

It would seem that the thunderstorms in this synoptic type were formed along this boundary (Fig. 15b). From Fig. 15b we can deduce, on the basis of the duration of the storms, an agreement with the description of the given synoptic type. The distribution of thunderstorms has a northeast-southwest orientation, which indicates the presence of a colder air mass advancing from the northwest and a warmer one lying on the southeast side of the boundary. The models of the synoptic types (at Figs. 14a, 15a) and their definitions were taken from SHMI (2023).



Fig. 14. (a) A model of the synoptic type C.

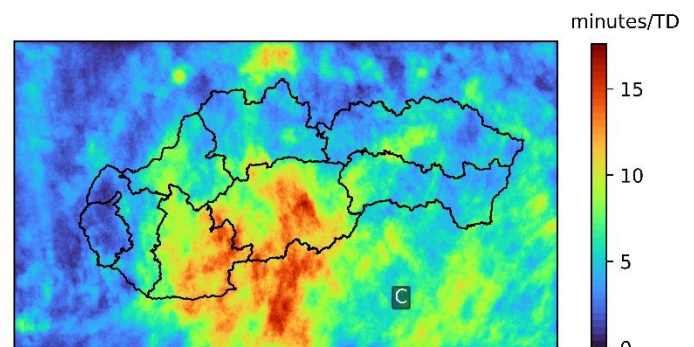


Fig. 14. (b) Spatial distribution of thunderstorms in this synoptic type - same as in Fig. 13.

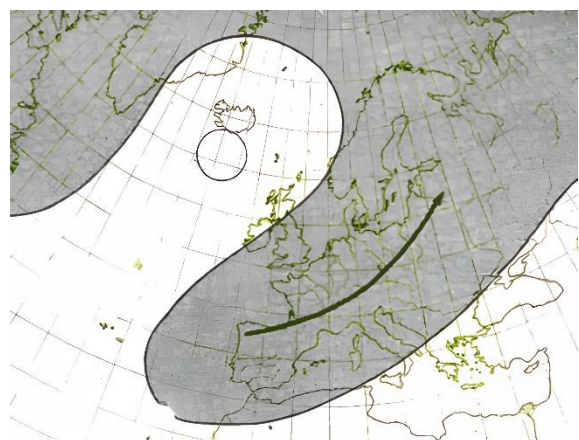


Fig. 15. (a) A model of the synoptic type SWc3.

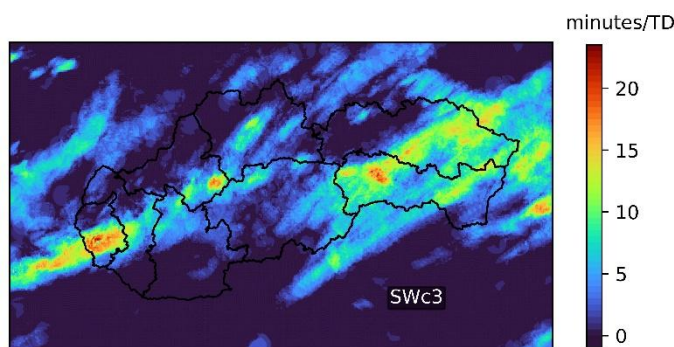


Fig. 15. (b) Spatial distribution of thunderstorms in this synoptic type - same as in Fig. 13.

4 SUMMARY AND CONCLUSIONS

In this study, we assessed the thunderstorms in Slovakia using a comprehensive approach that integrated data from various sources, including station observations, radar, and lightning measurements. We examined key trends in thunderstorm activity across both temporal and spatial scales and analyzed thunderstorm occurrences within different synoptic weather types. It allows us to better understand the events associated with flash floods, which pose a significant danger in this region. The main conclusions of this study are:

- By analyzing data from observation stations alongside lightning measurements, we found that thunderstorms occurring within a 3 km radius of a given location in Slovakia occur on average on 15 days per year. Overall, Slovakia experiences approximately 99 thunderstorm days annually. Most thunderstorms occur in the summer months of June and July, although recent decades have shown a shift, with peaks now occurring in July and August. Daily thunderstorm activity is lowest in the morning around 10 a.m. CEST, with the highest frequency observed in the afternoon between 3 and 5 p.m. CEST. These trends align well with the physical principles governing thunderstorm formation and agree with findings from previous studies.
- The spatial distribution of thunderstorms, as revealed by radar and lightning data, indicates that thunderstorm activity is highest in the Banská Bystrica region and the western part of the Košice region, with peaks observed in the Muránska Planina, Stolické Vrchy, and Volovské Vrchy mountains. The fewest thunderstorm activity was found in the westernmost part of Slovakia. Severe thunderstorms are most frequent in the Gemer region, likely influenced by local orographic features. This observation is consistent with findings from previous research.
- When classifying thunderstorms according to synoptic types, we found that they are significantly influenced by the specific character of the individual synoptic types. Thunderstorms are most common in cyclonic types B, Bp, NEc, and Wc, with a probability of a thunderstorm day occurrence around

40% in these cyclonic classes compared to just 10% in anticyclonic ones. The longest average duration of storms is in synoptic types C, Cv.

- Long-term trends in the number of thunderstorm days reveal a significant decrease in the average number of TDs per year over recent decades. Contrary to many studies in different countries suggesting an increase in thunderstorm activity, our findings do not confirm this trend. The observed reduction could be linked to a decreasing trend of cyclonic weather types, which are associated with higher thunderstorm activity. Such a decline may reflect broader changes in the circulation of air masses on a synoptic scale across Europe.

In conclusion, while the global trend is increasing extreme weather, the last result of our study is slightly surprising. However, the extreme may manifest more significantly in the intensity of thunderstorms rather than an increase in their frequency (number of TD). This hypothesis will be further investigated in our subsequent research.

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