SUB-HOURLY PRECIPITATION EXTREMES IN ROMANIA AND THEIR LONG-TERM TEMPORAL TREND

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ABSTRACT

Sub-hourly precipitation extremes represent a critical aspect of climate variability, particularly in regions prone to convective storms. This study analyzes the climatology and trends of extreme short-duration rainfalls in Romania, by using high-resolution precipitation data from 107 weather stations. We computed five sub-hourly precipitation indices (Rx5min, Rx10min, Rx20min, Rx30min, and Rx1hr) and assessed their temporal trends by using the Mann-Kendall test and Theil-Sen's slope estimator. Our results reveal substantial spatial variability in extreme sub-hourly precipitation amounts, with values mounting up to 29.3 mm in 5 minutes and 106.3 mm in one hour. Significant increasing trends are observed in several regions, particularly in areas influenced by Mediterranean cyclones and cut-off low-pressure systems. However, decreasing trends are also present, notably in the Curvature Subcarpathian Hills, where foehn effects may suppress convective activity. These findings highlight the importance of high-resolution precipitation data for understanding extreme rainfall trends, as sub-hourly indices exhibit distinct patterns as compared to daily-scale analyses. Given Romania's vulnerability to flash floods, the observed intensification of short-duration precipitation requires enhanced flood risk management and adaptation strategies.

Keywords: *Sub-hourly precipitation; Heavy rainfall; Pluviograph, Trend analysis.*

1. INTRODUCTION

Heavy precipitation is nowadays the subject of plenty of research papers on climatic changes. Heavy rainfalls and storms frequently cause significant damage and casualties across many regions. Therefore, gaining a deeper understanding of precipitation extremes and their variability is essential for helping communities to better adapt to the challenges posed by a warming climate (Handmer et al., 2012). Recognizing how and why extreme precipitation patterns fluctuate is crucial for disaster preparedness and effective water resource management. This requires both an analysis of historical variations in extreme precipitations and the ability to assess their observed trends and future changes within scenario-based climate projections.

A key statement from the IPCC (Intergovernmental Panel on Climate Change) Sixth Assessment Report highlights the changing nature of extreme precipitations, saying that "*the frequency and intensity of heavy precipitation events have increased since the 1950s over most land area for which observational data are sufficient for trend analysis*" and also that "*it is very likely that heavy precipitation events will intensify and become more frequent in most regions*" (IPCC, 2021). Observations from global datasets based on station data reveal increasing trends in annual sums of daily maximum precipitations (Westra et al., 2013).

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In recent decades, a growing body of research has identified significant positive trends in extreme precipitation events across Europe, at both continental and regional scale studies (Casanueva et al., 2014; Erić et al., 2021; Lakatos et al., 2021; Berényi et al., 2023; Beranová et al, 2025), mostly by analyzing the core indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) (http://etccdi.pacificclimate.org/list_27_indices.shtml).

In Romania, researchers have been studying extreme precipitation since the 20th century. Numerous studies have examined intense rainfall events and their underlying causes across the country (Topor, 1964, 1970; Ion-Bordei, 1988). Several authors have highlighted the significant role of the Mediterranean and retrograde cyclones in driving these extreme weather phenomena (Șorodoc, 1962; Topor & Stoica, 1965; Ion-Bordei, 1983; Apostol, 2008; Garabă & Sfîcă, 2015; Dobri et al., 2017).

Other studies shaped the climatology of (heavy) precipitation in Romania, by analyzing their (long-term) variability and, in some cases, their specific return periods (Ciulache & Ionac, 1993, 2000, 2004; Haidu, 2002; Sorocovschi & Haidu, 2003; Dragotă, 2006; Sandu et al., 2008; Tudose et al., 2013). The maximum (daily) rainfall intensity and several dynamic parameters of convective cells and atmospheric stability indices (for storms that generated torrential rain showers) were also subjects of the climatological research in Romania (Tudose & Haidu, 2012; Haidu & Tudose, 2014).

In the last two decades, Romanian researchers focused on analyzing the precipitation extremes and their trends by using the ETCCDI indices, both at regional and national scales (Croitoru et al., 2013, 2015, 2018; Micu et al., 2016, 2021; Horvath & Croitoru, 2023). We noticed that some previously analyzed indices have a similar trend pattern with the ones we found for the sub-hourly indices. However, a high temporal resolution dataset was used only in a few studies before (Busuioc et al., 2015, 2017; Lakatos et al., 2021) and the sub-hourly indices being presented in this study were only tested and investigated, by Irașoc et al. (2024), at regional scale (the Dobrudjan Tableland area) in Romania, based on maximum sub-hourly, sub-daily and daily precipitation amounts.

The main objectives of this study were to highlight the climatology of sub-hourly rainfall extremes in Romania and to quantify the changes in sub-hourly precipitation indices over the last half of a century, by using statistical trend tests. This paper is structured as follows: Introduction (including the Characteristics of the Study Area), Data and Methods (with the following sub-chapters: Data Collection; Data Processing and Analysis; Long-term trend estimation), Results (including two sub-chapters: Climatology of the sub-hourly maximum precipitation amounts in Romania; Observed trends in sub-hourly maximum precipitation amounts in Romania), Discussion and Conclusions.

The ensuing findings could provide valuable support for enhancing rainwater management plans and improving the population's response and resilience to (flash) floods. Given Romania's high vulnerability to flooding, as identified both by a government project through national hazard and risk maps (https://inundatii.ro/portal-harti/) and by researchers in academia (Zaharia et al., 2015; Romanescu et al., 2018; Török, 2018; Albano et al., 2020; Arseni et al., 2020; Albulescu et al., 2022), these insights become particularly relevant for mitigating flood-related risks.

2. STUDY AREA

The study area is represented by the entire Romanian territory, located in the South-East of Europe (**Fig. 1**). Romania is bounded to the North by Ukraine and to the East by Republic of Moldova and Ukraine, through the natural borders created by the Prut and Danube rivers. It is bounded to the South-East by the Black Sea and to the South by Bulgaria, mostly through the natural border created by the Danube River. To the South-West, Romania is separated from the Republic of Serbia by both natural (the Danube) and conventional borders. To the West and North-West, it is bounded by Hungary.

Romania's territory extends between the 43°37' to 48°15' North latitude and the 20°15' to 29°41' East longitude. The distance between its northernmost and southernmost points is 525 km, and between its westernmost and easternmost points is 740 km (Badea et al., 1983). Thus, Romania is located halfway between the Equator and the Poles, in the mid-latitude zone.

Fig. 1. Study area (Romania) - location, topography and meteorological network.

The relief elevation in Romania varies between 0 and 2,544 m and its main landforms include: the Alpine mountains (the Carpathians) mostly in the center, the Hercynian mountains (Măcin) in the South-East, plateaus and hilly landforms across all the territory, but mostly inside and on the outer borders of the Carpathians respectively, plains in the South and West, delta landforms (Danube Delta) as well as shoreline landforms, including beaches, cliffs, sandbars and a lagoon system along the shoreline of the Black Sea.

The resident population in Romania is 19,053,815 inhabitants, 52.2% of them living in urban areas (National Institute of Statistics, 2023). During the 2000–2025 period, an average of approximately 17,569 inhabitants were affected by flood events in years with reported impacts (Delforge et al., 2025). Most flood occurrences in Romania are associated with extreme or persistent heavy precipitation, reflecting the dominant hydro-meteorological trigger in the region. Notably, when individual high-impact years are considered, the number of affected persons increases sharply; for example, the 2005 flood events affected more than 120,000 people, illustrating the substantial societal consequences of severe precipitation extremes. In the same year, 78 deaths were reported, representing 32.8% of the flood-related deaths during the 2000-2025 period (Delforge et al., 2025).

According to the Köppen-Geiger classification, as carried out in a recent Romanian study (Cheval et al., 2023), Romania is characterized by six types of climate: **BSk** (cold semi-arid) in the Danube Delta; **Cfa** (warm temperate humid with hot summer) in the Romanian Plain, Western Plain, Dobrogea Plateau and Prut River meadow; **Cfb** (warm temperate humid with warm summer) in most of the hilly and plateau regions and on the peaks of Măcin mountains; **Dfb** (cold humid with warm summer) in some mountainous and sub-mountainous areas; **Dfc** (cold humid with cool summer) in most of the Carpathians and **ET** (alpine tundra) on the peaks of the Carpathians, at elevations above 2,500 m.a.s.l.

3. DATA AND METHODS

3.1. Data collection

For this research we used sub-hourly precipitation data from 107 weather stations (WSs) of Romania's national network. These data were provided by the National Meteorological Administration of Romania (NMAR). The dataset has a temporal resolution up to 1 minute and was recorded by two automatic instruments: the pluviographs, which were in use until 2007-2008 (at most of the stations) and the automatic rain gauges (with tipping bucket and weighing system) from this time period onward. The recordings from pluviographs were only available for the convective season (April to October), due to technical requirements (as this instrument can only measure liquid water). Thus, the current study is representative only for the rainfall events related to the convective season, the cold interval from November to March not being included in the present analysis due to missing data. The time range of the dataset varies at each weather station (WS), with the first recordings starting in 1898 at București-Filaret WS. The WSs are located at elevations between 1.4 and 1,897.0 m.a.s.l.

3.2. Data Processing and Analysis

The statistical processing of the rainfall data and the precipitation maps were based on several scripts we developed in the R programming language (R Core Team, 2024).

The maximum precipitation amounts at different time spans were calculated by means of the running sums (moving sums) method rather than by using a fixed time interval, simply because the results of some previous studies demonstrated that the first method can yield better estimates of the intensity and duration of extreme rainfall events, even if spanning over two or more days on end (Boughton & Jakob, 2017; Morbidelli et al., 2017, 2018; Weder et al., 2017; Irașoc et al., 2024).

Next, the quantitative analysis on sub-hourly maximum precipitation in Romania was based on the annual values of five ETCCDI indices (as shown in **Table 1**), which were adapted to a finer temporal resolution (e.g., Rx1day), similar to other scientists' approach (Barbero et al., 2019; Lakatos et al., 2021; Buda et al., 2024).

Table 1.

List of indices used in this study.

No	Short name	Definition	Unit
1	Rx5min	Maximum value of total precipitation that falls in 5 consecutive minutes	mm
2	Rx10min	Maximum value of total precipitation that falls in 10 consecutive minutes	mm
3	Rx20min	Maximum value of total precipitation that falls in 20 consecutive minutes	mm
4	Rx30min	Maximum value of total precipitation that falls in 30 consecutive minutes	mm
5	Rx1hr	Maximum value of total precipitation that falls in one hour	mm

3.3. Long-term trend estimation

For the trend analysis, we used two statistical tests, the Mann-Kendall trend test and the Theil-Sen's slope estimator, respectively.

The Mann-Kendall (MK) test is a robust non-parametric method widely used to assess long-term trends in climatological and hydrological studies. The first version of the MK test was used by Mann (1945) to investigate trends in rainfall and temperature time series and it was further studied by Kendall (1975).

The MK test provides the following statistical outputs: the Kendall (Tau) value, the p-value (at 95% confidence) and z-statistics. The z-score, a positive or negative value, suggests an increasing or decreasing trend, respectively, in the time series. The MK test can be expressed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \quad (1)$$

where n represents the number of data points, xi and xj are the data values in the time series i and j, respectively, and sign(x_j-x_i) is the sign function:

$$sign(x_j - x_i) = \begin{cases} +1 & x_j - x_i > 0 \\ 0 & x_j - x_i = 0 \\ -1 & x_j - x_i < 0 \end{cases} \quad (2)$$

The variance can be expressed as:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{p} t_i(t_i-1)(2t_i+5)}{18} \quad (3)$$

where p represents the number of tied groups and t_i is the number of values in the p^{th} tied group.

The Sen's slope (SS) is a non-parametric test used to estimate the linear trend slopes, expressing the magnitude (rate) of observed changes in the time series. For each set of data values (k = 1, 2, ..., n), the slope is calculated as follows:

$$SS_k = \frac{x_j - x_i}{j - i} \quad (4)$$

where x_j and x_i are the data values of rank j and i (j > i), respectively.

Further, SS is calculated as the median from all SS_k slopes, involving different formulas based on whether n is odd or even:

$$SS_{med} = \begin{cases} SS_{[\frac{n+1}{2}]} & \dots (if\ n\ is\ odd) \\ \frac{SS_{[\frac{n}{2}]} + SS_{[\frac{n+2}{2}]}}{2} & \dots (if\ n\ is\ even) \end{cases} \quad (5)$$

In this study, the trend analysis was performed by using the *trend* R package (Pohlert, 2015), on a common time range for all WSs (1970-2021). Thus, we computed the trends for 88 WSs which have less than 33% missing data during this time window and we used a statistical significance threshold of 95% (p-level < 0.05).

4. RESULTS

In order to assess the maximum values of the aforementioned indices and to provide a more accurate representation of (short-duration) extreme rainfall events occurring in Romania, we used all the data that were available at the start of this research work, despite their variations in the time range across the WSs. Notably, the national records for these indices were set up during periods when comprehensive data were available for most stations, especially that, for the trend analysis, we had to use a consistent time span across all WSs.

4.1. Climatology of the sub-hourly maximum precipitation amounts in Romania

The values of the maximum **Rx5min** index in Romania (**Fig. 2**) vary between 10 mm (at Voineasa and Gura Portiței WSs, located in the Southern Carpathians and Danube Delta, respectively) and 29.3 mm (Făgăraș WS, in the Transylvanian Depression). The highest amount (29.3 mm), with a rainfall intensity of 5.86 mm/min, occurred at Făgăraș on July 16^{th}, 1991. This precipitation event was associated to the advection of a humid air mass from the North-West of Europe which, most likely, upon contact with the northern slopes of the Făgăraș Mountains, was subject to orographic convection. Over 25 mm were also recorded at Caracal (2005) and Sibiu (1970).

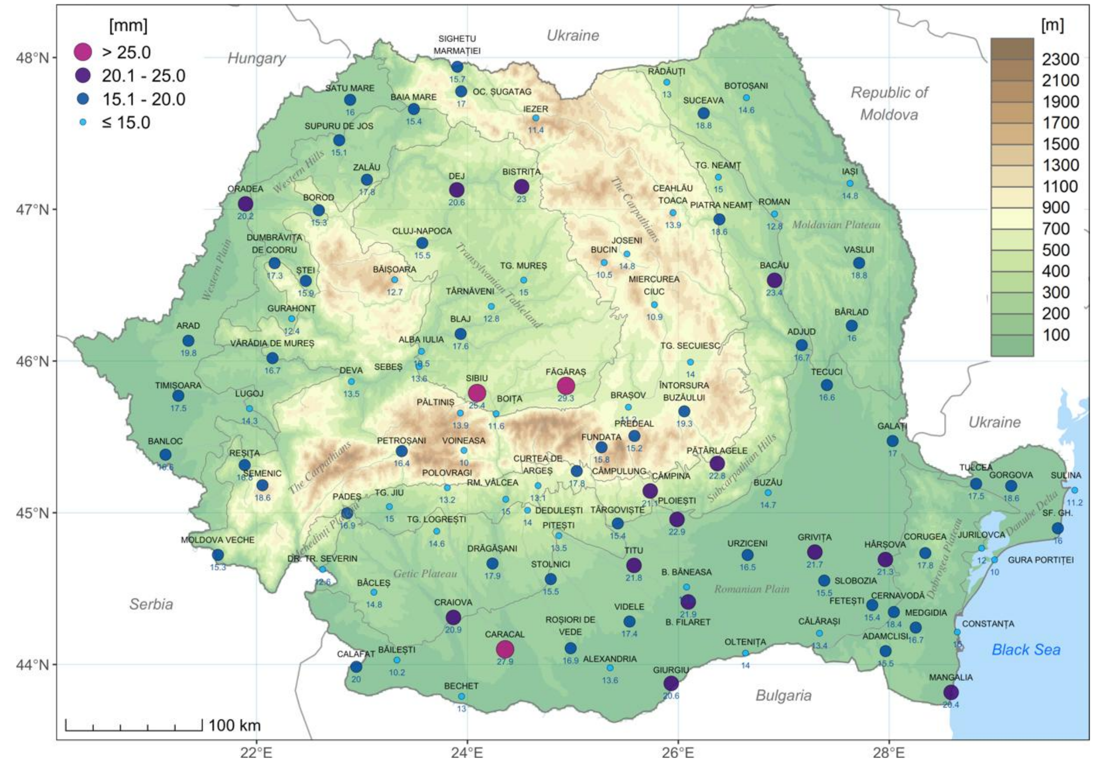

Fig. 2. Spatial distribution of the maximum precipitation amount during 5 minutes (*Rx5min)* in Romania.

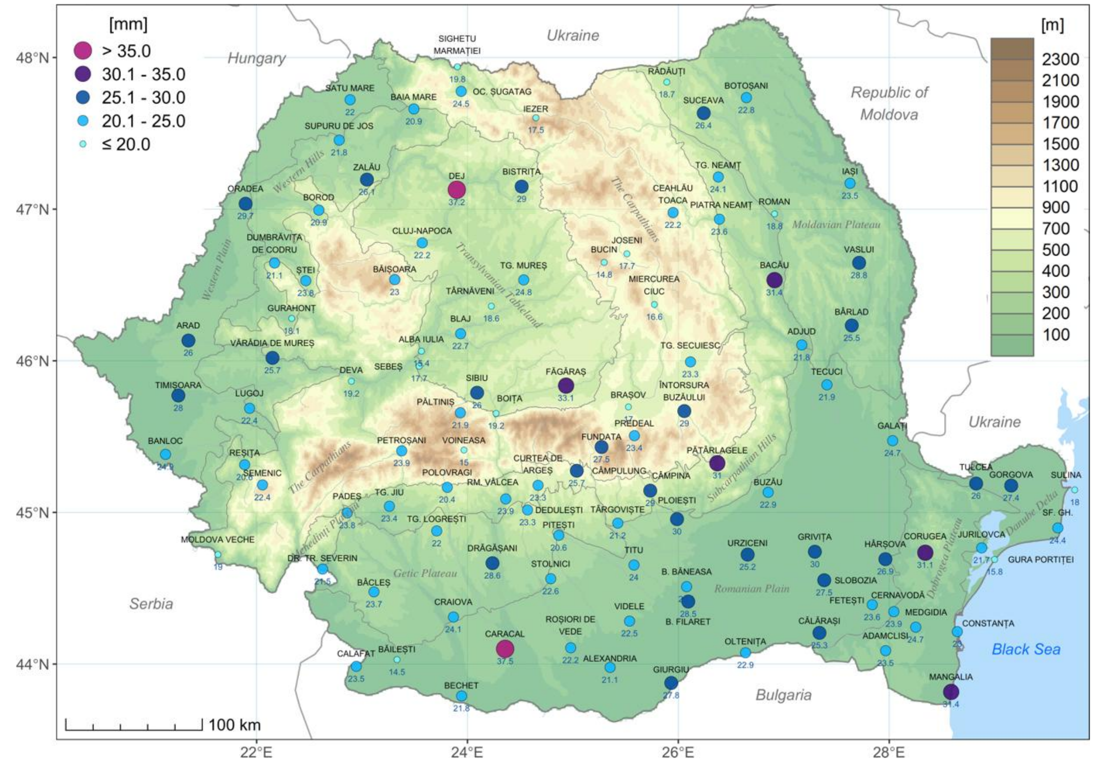

Fig. 3. Spatial distribution of the maximum precipitation amount during 10 minutes (*Rx10min)* in Romania.

The maximum values of the **Rx10min** index in Romania (**Fig. 3**) ranged from 14.5 mm (Băilești, in the Great Romanian Plain) to 37.5 (Caracal, in the Romanian Plain as well). A maximum amount, exceeding 37 mm, occurred at Dej WS, in the Transylvanian Depression, on July 16th, 1975. The maximum value recorded at Dej WS resulted from the interaction between the western atmospheric circulation and the Carpathian Mts., as the largely-opened topography of north-western Romania facilitated the rapid advection of humid air into the Transylvanian Tableland. Furthermore, on July 16th, 1975, the northern parts of the Transylvanian Tableland were quite under the contact line between a low-pressure system located in northern Europe and an anticyclone to the South.

Actually, the values of these two indices exhibit an extremely uneven spatial distribution, so, in order to identify any distinct clusters, the highest values had to be excluded as statistically non-relevant singularities. Consequently, in both cases, significant precipitation amounts were recorded outside the mountain area, primarily in the southern and south-eastern regions of the country, including the Subcarpathian Hills, the Romanian Plain and the Dobrudjan Plateau. However, significant precipitation amounts were also recorded locally in the Transylvanian Depression, the Western (Pannonian) Plain and the Moldavian Subcarpathian Hills, showing that both dynamic factors and local topography may greatly influence pluviogenetic processes.

The maximum values of **Rx20min** index in Romania (**Fig. 4**) vary between 19.4 mm (at Joseni, in the Eastern Carpathians) and 60 mm (at Bacău, in the Moldavian Subcarpathian Hills). The highest Rx20min value at Bacău was recorded on July 20th, 2002 and during the exact same rainfall event, the country's maximum records of Rx30min (74.8 mm) and Rx1hr (106.3 mm) have also occured at the Bacău WS (**Fig. 5** and **Fig. 6**).

These extreme values resulted from an intense atmospheric instability associated with a long-wave trough extending from north-western to south-eastern Europe, thus facilitating the advection of moisture from the western basin of the Black Sea and contributing to the development of Cumulonimbus clouds. This synoptic pattern is characteristic of summer convective storms and has been previously studied by Dobri et al., 2017, but a more detailed analysis of this synoptic event, including several reanalysis maps could be accessed from www.wetter3.de and www.metoffice.com.

However, if excluding the Bacău WS case, a clearer spatial pattern emerges in the distribution of the Rx20min, **Rx30min and Rx1hr indices**, with the highest precipitation amounts being recorded in Romania's southern and south-eastern areas, where rainfall exceeded 50-60 mm in 30 minutes and 80 mm in one hour. These regions are particularly prone to extreme rainfall events due to the higher atmospheric instability triggered by the Mediterranean cyclones (Ion-Bordei, 1983; Garabă & Sfîcă, 2015), as well as to the long-wave troughs and cut-off low systems, specific of the mid-latitude North-Atlantic air-circulation (Dobri et al., 2017). In some coastal areas, however, the proximity of the Black Sea seems to have a rather inhibiting effect on convection, leading to much lower sub-hourly precipitation extremes as compared to the inland areas.

Thus, significant Rx30min values occurred in Eastern Romanian Plain, at Grivița (65.1 mm/September 5th, 1992) and Slobozia (62.8 mm/June 13th, 2020) WSs. In the case of Grivița WS, the value was recorded due to the atmospheric instability triggered by an Atlantic cyclone's long-wave trough, which finally turned into a cut-off low system. In the case of Slobozia WS, from 2020, the Black Sea played a significant role by supplying water vapors to a low-pressure system located over its western basin.

The regions with the lowest precipitation amounts include the Transylvanian Tableland area, the Western Hills, most of the intra-Carpathian depressions (as result of a shelter effect), and certain areas along the Black Sea coast. Regarding the areas on the Black Sea coast, though the sea-water bodies are generally known as inhibitors of convective processes, in this case, depending on the atmospheric circulation patterns, the Black Sea can play a crucial role in generating heavy rainfalls by supplying significant amounts of water vapor to the surrounding regions, especially when retrograde cyclones get powerful enough. This was the case on July 15-16, 1994, when 97.2 mm of rainfall was recorded in just one hour at Fetești WS (**Fig. 6**).

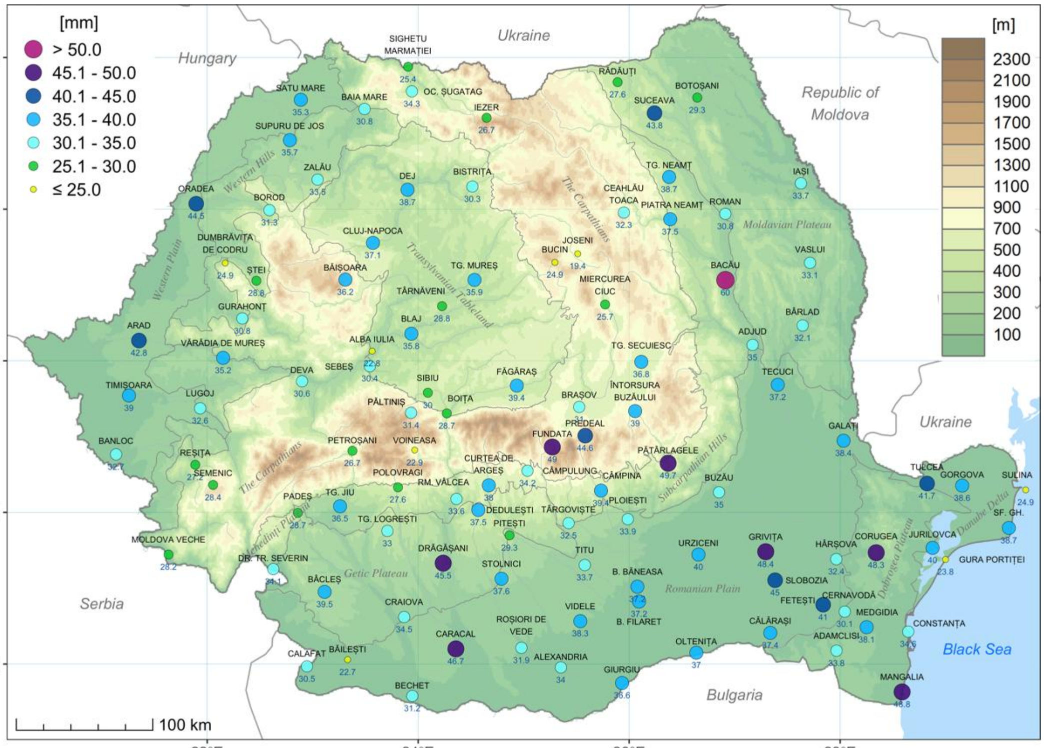

Fig. 4. Spatial distribution of the maximum precipitation amount during 20 minutes *(Rx20min)* in Romania.

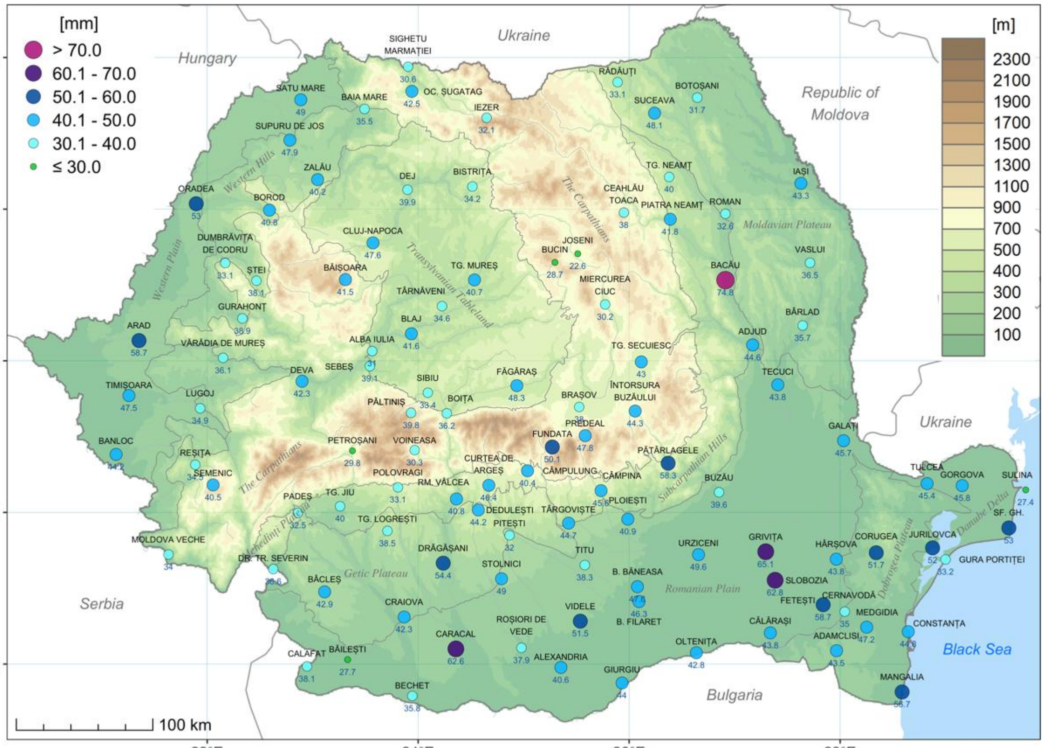

Fig. 5. Spatial distribution of the maximum precipitation amount during 30 minutes (*Rx30min)* in Romania.

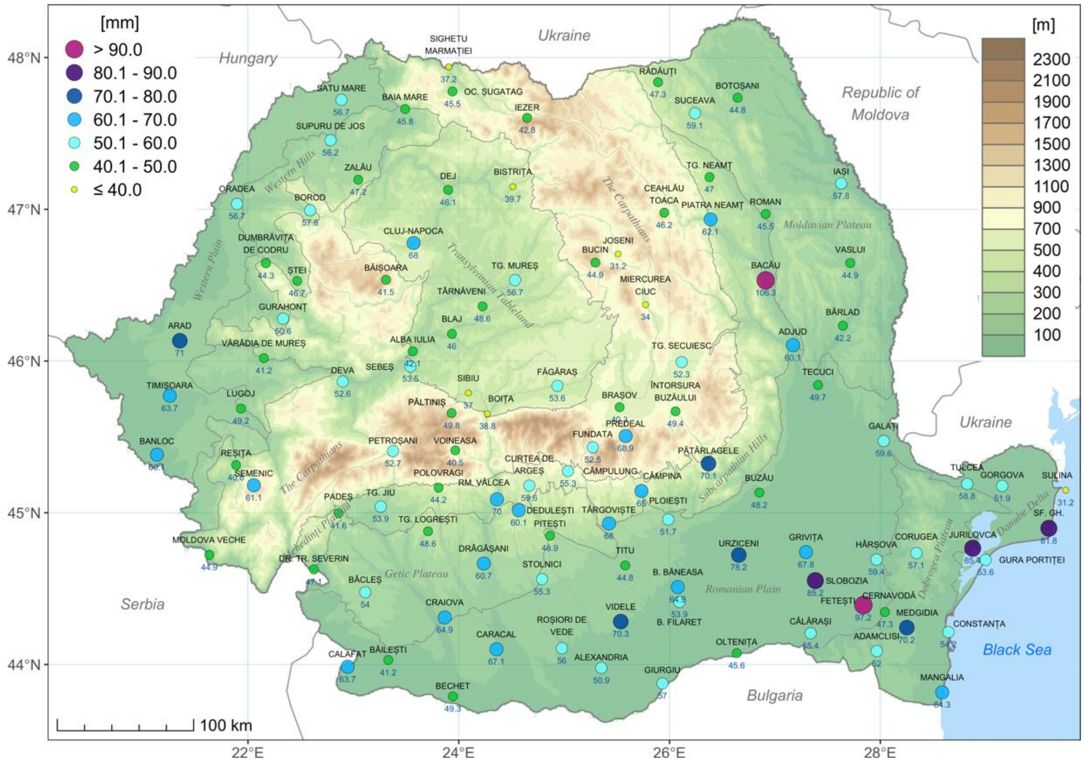

Fig. 6. Spatial distribution of the maximum precipitation amount during one hour (*Rx1hr)* in Romania.

4.2. Observed trends in sub-hourly maximum precipitation amounts in Romania

The spatial distribution of extreme rainfall amounts in Romania, for any sub-hourly duration considered in this study (**Fig. 7-11**), reveals complex patterns with both increasing and decreasing trends scattered across the country.

Overall, 52.3% of the analyzed weather stations recorded decreasing trends, 41.5% recorded increasing trends and for 6.2% of the WSs no trend was identified (as an average value for all durations).

The differences are, nevertheless, particularly interesting in some regions like the South-East one, where stations in close proximity one to another show opposing trends, some even with statistically significant changes and high magnitudes. This situation could be due to the fact that short-lived extreme precipitation events are often driven by convective storms, which are highly limited to a rather small area and cause nearby stations to record opposite trends, especially in flat terrain areas.

The spatial distribution of maximum precipitation trends in south-eastern Romania, particularly in the Dobrudjan Tableland area, exhibits a significant variability, with adjacent weather stations recording (statistically significant) contrasting trends. This complex pattern could be attributed to several interrelated factors: the local climatic conditions, the land-sea interactions and the topographical effects. The region's topography, with varying elevations along the shoreline of the Black Sea, plays a crucial role in modulating precipitation amounts. That's why coastal areas may experience different rainfall amounts and intensities as compared to inland locations, due to sea breezes and moisture availability. Additionally, subtle elevation changes can influence the development and movement of convective cells, contributing to the observed spatial variability.

Moreover, for the Black Sea shore, the trends in sub-hourly precipitation extremes are similar to the trends of several daily indices analyzed by Croitoru et al. (2013).

On the contrary, Romania's Western Plain has a notable cluster of decreasing trends around Arad WS, with significant changes (Rx10min), while the nearby areas like Reșița and Semenic show increasing trends, obviously due to their location at higher altitudes.

In the North-West of the Transylvanian Depression, Zalău WS records a statistically significant decreasing trend in Rx20min, Rx30min and Rx1hr.

In the Curvature Subcarpathian Hills, particularly around Buzău WS, the trends are exclusively negative, with high magnitudes exceeding 1.5 mm/decade for Rx1hr (**Fig. 11**). This pattern may be attributed to foehn winds in the region, which suppress convective activity and largely limit precipitations.

The mountainous areas (The Carpathians) exhibit mixed trends, likely due to orographic effects, which can enhance or suppress convective activity based on local wind patterns, moisture availability and elevation gradients (Ion-Bordei, 1988). The presence of opposing trends over relatively short distances suggests that local topography plays a critical role in determining precipitation patterns at sub-hourly scales.

The **Rx5min index** has decreasing trends at most of the WSs located in the Romanian Plain, Dobrudja and Moldova Plateaus, but also on large areas in the Transylvanian Tableland (**Fig. 7**). The highest negative magnitudes, exceeding 0.6 mm/decade, occur at Corugea, Hârșova, Botoșani and Arad WSs. The trends of Rx5min are statistically significant only in the Dobrudjan Plateau. Increasing trends of this index mostly occur in the western regions of the country, but also in the Central Moldavian Plateau and on the Black Sea coast. However, the positive magnitudes hardly exceed 0.3 mm/decade.

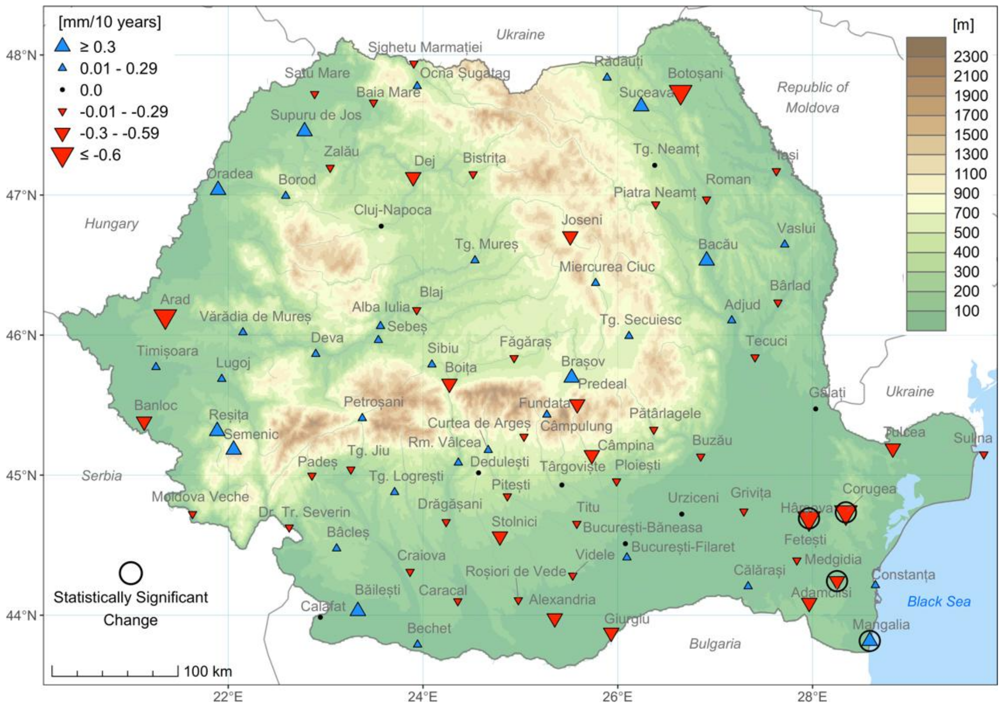

Fig. 7. Long-term trends in the maximum precipitation amount during 5 minutes (*Rx5min*) in Romania for the period 1970-2021.

Regarding the trends of the **Rx10min index** (**Fig. 8**), it should be noted that the positive trends have higher magnitudes in the extra-Carpathian regions and are statistically significant at three WSs. Statistically significant positive trends also occurred for Rx5min and Rx20min indices, but only for one WS.

During the trend analysis, we observed that the sign of the trend does not usually vary at the same WS significantly. This pattern becomes more reliable when increasing the duration of the analysed indices (e.g. Rx20min, Rx30min, Rx1hr, in this study).

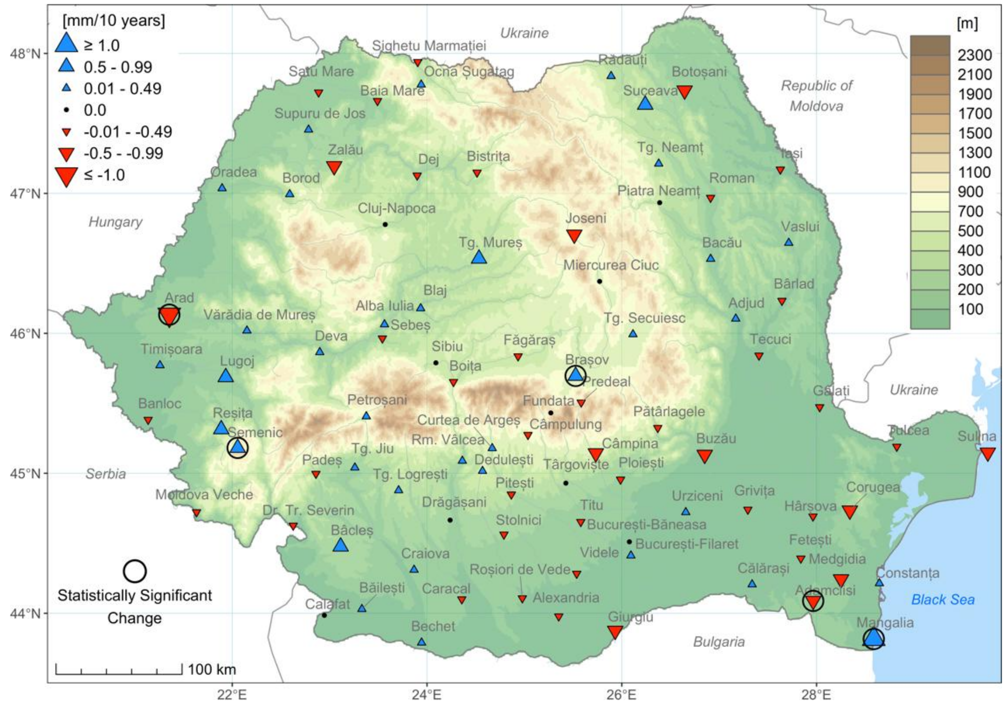

Fig. 8. Long-term trends in the maximum precipitation amount during 10 minutes (*Rx10min*) in Romania for the period 1970-2021.

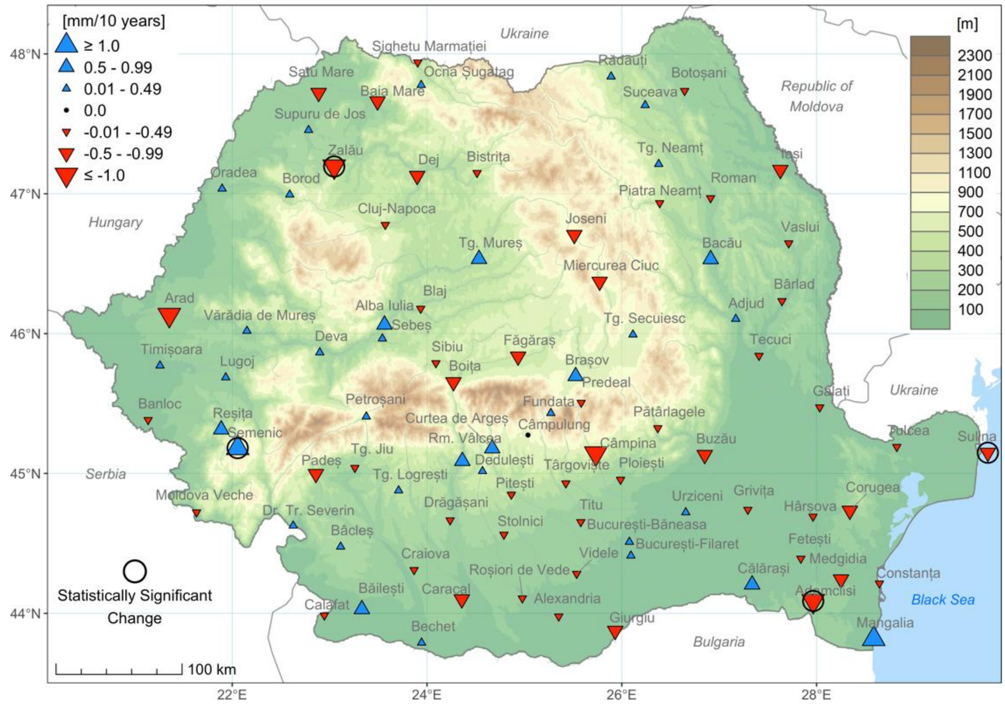

Fig. 9. Long-term trends in the maximum precipitation amount during 20 minutes (*Rx20min*) in Romania for the period 1970-2021.

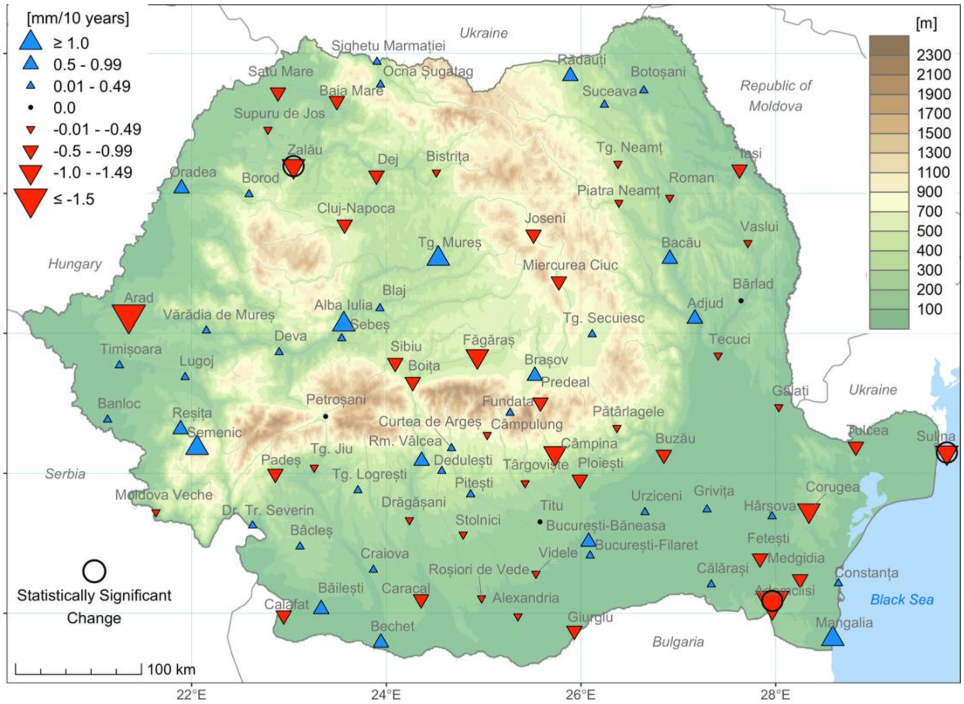

Fig. 10. Long-term trends in the maximum precipitation amount during 30 minutes (*Rx30min*) in Romania for the period 1970-2021.

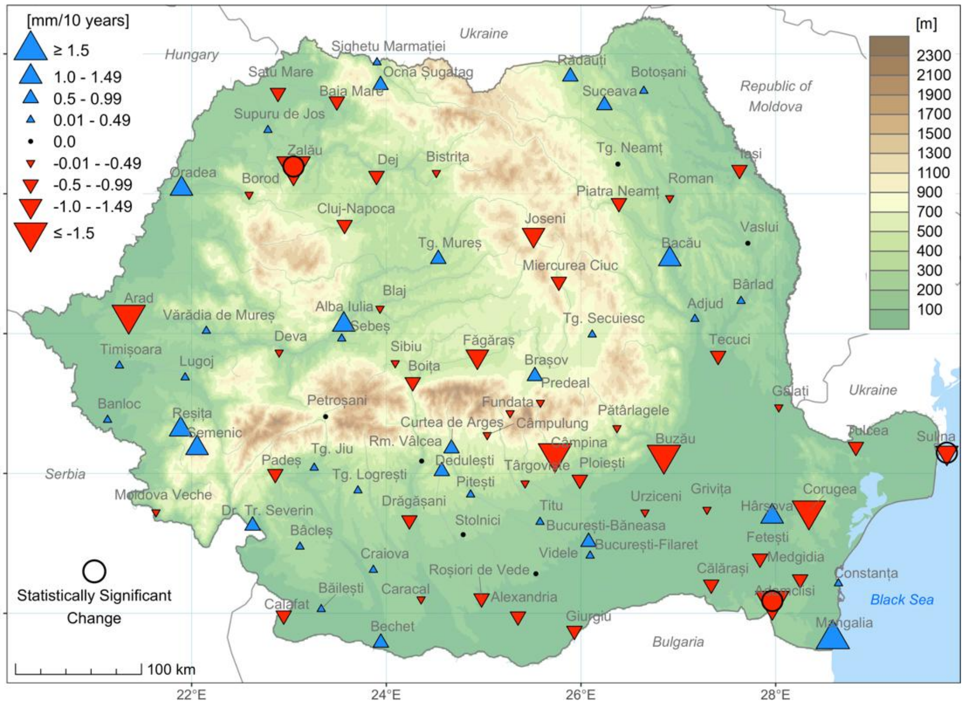

Fig. 11. Long-term trends in the maximum precipitation amount during one hour (*Rx1hr*) in Romania for the period 1970-2021.

Furthermore, we can notice that the greater the duration of the index gets, the higher the magnitude of the negative trends becomes. Thus, the negative trend clusters occurring in the North-West of the country, in the Curvature Subcarpathian Hills and the Dobrudjan Plateau are better highlighted by the **Rx30min and Rx1hr indices** (**Fig. 10** and **Fig. 11**). For these two indices, the negative rate of change exceeds 1.5 mm/decade at several WSs.

4.2.1. Observed trends in sub-hourly maximum precipitation amounts in Bucharest

București-Filaret is one of the three weather stations that provide meteorological observations for Romania's capital, Bucharest. It holds the longest sub-hourly precipitation record in the country, with measurements dating back to 1898. However, 23.2% of the data is missing over the entire 125-year period analysed in this paper. Even so, the remaining 96 years of observations offer a valuable basis for examining long-term patterns in sub-hourly precipitation.

To explore these patterns, five plots were produced to visualize the interannual variability of the maximum precipitation amounts corresponding to the five indices used in the national-scale analysis (**Fig. 12**). Each plot includes a simple linear regression trend line as well as the breakpoints identified using the *strucchange* R package (Zeileis et al., 2002). This method allowed us to analyse all available data while excluding missing values, and to detect structural changes in precipitation trends.

For most indices (Rx10min, Rx20min, Rx30min, and Rx1hr), the breakpoint analysis identified two periods characterized by increasing trends. The earliest segment, covering years prior to 1920, exhibits a particularly steep increase for these four indices. After 1920, the upward trend becomes more moderate. Although the overall trend is positive for all indices, the Rx5min series shows a decreasing trend between 1898 and 1951. Given the substantial gaps in the record, especially consecutive missing years, it is difficult to provide a robust explanation for this behaviour.

Nevertheless, one conclusion is clear: extreme short-duration rainfall events have occurred both in the early historical period and in recent decades, as illustrated by the maximum 20- and 60-minutes precipitation amounts (**Fig. 12**).

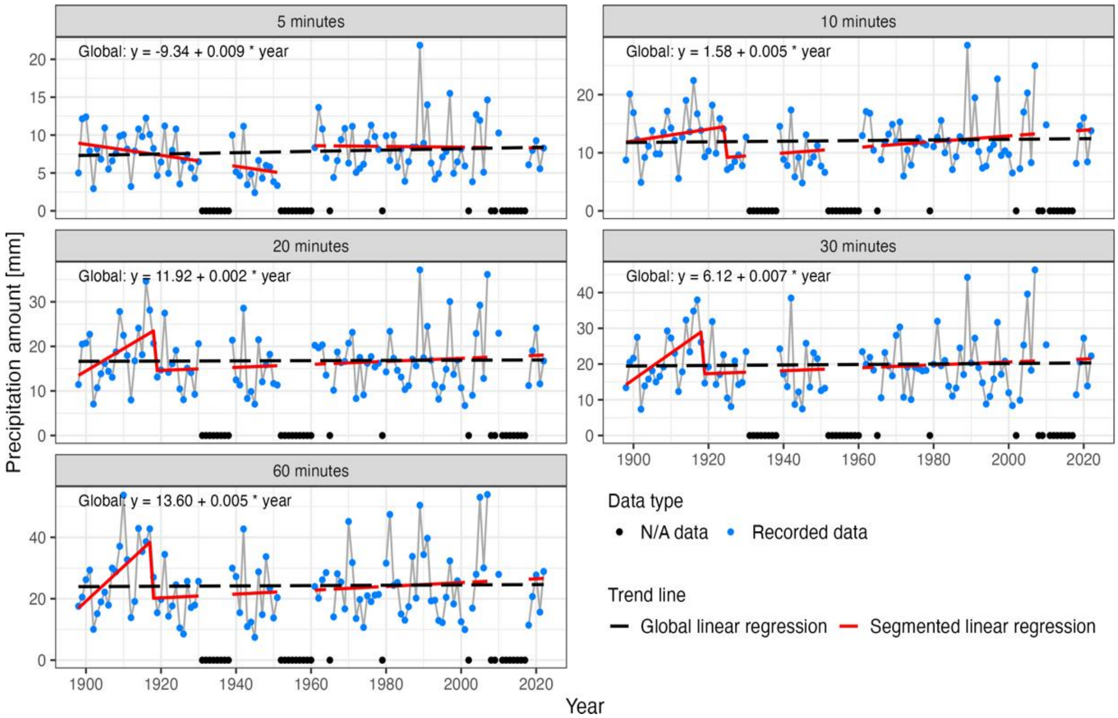

Fig. 12. Long-term trends in the sub-hourly maximum precipitation amounts at București-Filaret weather station for the period 1898-2022.

5. DISCUSSION

This study provides a comprehensive assessment of sub-hourly precipitation extremes in Romania, offering new insights into their climatology and temporal trends. Our findings highlight the spatio-temporal variability of short-duration extreme rainfall events, thus confirming their increasing intensity in several regions. These results align with previous studies that documented rising trends in extreme precipitation on a daily basis (Croitoru et al., 2013, 2015; Micu et al., 2016, 2021), reinforcing concerns over the intensification of short-term convective storms.

The observed trends in sub-hourly precipitation extremes demonstrate considerable heterogeneity across Romania. This variability is consistent with findings from other European studies (Casanueva et al., 2014; Erić et al., 2021; Berényi et al., 2023), which emphasize the influence of local geographic and climatic factors on precipitation dynamics.

Several synoptical processes may explain the observed trends. The increase in extreme rainfall amounts in southern and south-eastern Romania can be attributed to the combined effects of Mediterranean cyclones, long-wave troughs and cut-off low-pressure systems (Ion-Bordei, 1983; Dobri et al., 2017), which may enhance atmospheric instability, fostering convective developments that lead to extreme short-duration precipitation events. Additionally, the Black Sea's influence on moisture advection may amplify rainfall intensity along coastal regions, particularly under specific circulation patterns.

The complex orographic influences within the Carpathian Mts. introduce additional spatial variability, as upslope and downslope airflows affect precipitation distribution (Ion-Bordei, 1988).

The comparison between sub-hourly and daily extreme precipitation indices suggests that high-resolution data provide a more detailed understanding of rainfall dynamics. Previous studies (Busuioc et al., 2015, 2017; Lakatos et al., 2021) emphasized the importance of high temporal resolution datasets for detecting subtle changes in extreme rainfall. Our study dwells on this perspective, showing that sub-hourly trends may differ from those observed at daily scales due to the nature of convective precipitation processes.

6. CONCLUSIONS

This study provides a detailed assessment of sub-hourly precipitation extremes in Romania, highlighting both their climatological characteristics and temporal trends. The highest recorded values reached 29.3 mm in 5 minutes at Făgăraș (1991) and 106.3 mm in one hour at Bacău (2002), demonstrating the intensity of short-duration rainfall events.

The trend analysis over the 1970-2021 period reveals a complex spatial distribution, with both increasing and decreasing trends scattered across the country. The south-eastern region, particularly the Dobrudjan Tableland area, exhibits notable variability, with adjacent weather stations showing very contrasting trends, influenced by local climatic conditions, land-sea interactions, and topography. While some areas in southern and western Romania display significant decreasing trends, such as around Arad, Zalău and in the Curvature Subcarpathian Hills, other locations, including Reșița and Semenic, show significant increasing trends. In mountainous areas, the trends are mixed, likely due to orographic effects modulating convective activity.

Our findings emphasize the importance of high-resolution precipitation data for detecting local changes in extreme rainfall patterns and for understanding their hydrological implications. The documented regional variability and the increasing frequency of short-duration extreme rainfall events, combined with Romania's high exposure to flash floods, underscore the need for more localized flood risk management strategies and adaptive urban planning measures to enhance climate resilience.

Additionally, future research should focus on refining climate projections at high temporal resolutions to enhance predictive capabilities for extreme precipitation events.

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