Heavy Precipitation Events of Various Durations Across Germany: A Station-Based Assessment of Spatial and Temporal Variability Using the Block Maxima Method

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Abstract. As heavy precipitation events (HPEs) pose substantial risks to natural and human systems, a growing body of research has focused on their behaviour under ongoing climate change, hypothesising that rising air temperature can have a pronounced influence on precipitation patterns, including HPEs of various durations. Recent observational and modelling studies suggest that this influence tends to be particularly strong for short-duration HPEs, albeit their assessment appears challenging due to limited availability of precipitation data with both high temporal resolution and long-term observational records. Therefore, in this study, we made use of recently collected, digitised, and quality-controlled 5-minute precipitation data from rain-gauge stations across Germany in order to assess the spatial and temporal variability of HPEs of nine durations ranging from 5 minutes to 7 days. Using the block maxima method, we confirmed that the spatial and temporal variability of annual maximum precipitation totals (AMPTs) is strongly duration-dependent. While the medians of short-duration AMPTs calculated for individual stations are relatively evenly distributed across Germany, those of medium- and long-duration AMPTs increasingly reflect the influence of topography. Moreover, short-duration AMPTs exhibit higher and spatially scattered event to event variability, contrasting with the relatively consistent and regionally organised event to event variability observed for long-duration AMPTs. The duration-dependent nature of AMPTs is further reflected in their long-term variability. While positive trends prevail for AMPTs with durations of 1 to 7 hours, trends for AMPTs with durations of 3 to 7 days are more balanced or even slightly negative, depending on the investigation period. Yet, statistically significant – both positive and negative – trends are relatively rare and sensitive to changes in the measurement system and investigation period.

1 Introduction

Heavy precipitation events (HPEs) pose substantial risks to natural and human systems, contributing to floods, landslides, and soil erosion, with potentially devastating impacts on economies, infrastructure, and human health (IPCC 2021). These risks are very likely to increase under ongoing climate change, also due to rising population exposure to HPEs and their secondary effects (Chen et al. 2020; Liu et al. 2020; Chen & Sun 2021). On a local scale, population exposure is expected to be particularly high in urban areas. This is due to sealed surfaces and limited drainage capacity, which make urban areas vulnerable to short-duration, but high-intensity, precipitation events that tend to overwhelm drainage infrastructure and lead to severe

high-impact flash floods (Francipane et al. 2021; Iliadis et al. 2023, Zhao et al. 2023). On the other hand, long-duration HPEs are typically responsible for prolonged and widespread flooding, which affect large catchments and cause sustained disruption to regional infrastructure and services (Jia et al. 2022; Fryirs et al. 2023; Cremonini et al. 2024). A good illustration of their

35 impacts can be provided by two well-documented HPEs that occurred recently in Germany. In May 2016, a short-duration precipitation event hit the small municipality of Braunsbach, located in the federal state of Baden-Württemberg in southern Germany. According to estimates by Ziese et al. (2016), the area received around 90 mm of precipitation within one hour. This resulted in an extraordinarily severe flash flood accompanied by mobilisation of sediments and debris that blocked streets with layers up to three metres thick and contributed to overall monetary losses of around EUR 104 million (Bronster et al. 2017;

40 Laudan et al. 2017). In mid-July 2021, another well-documented long-duration precipitation event, associated with the low-pressure system "Bernd", caused catastrophic flooding across large parts of Belgium, Germany, and the Netherlands. Between 12 and 15 July 2021, the federal states of North Rhine-Westphalia and Rhineland-Palatinate in western Germany experienced a combination of persistent and recurrent precipitation, with widespread precipitation totals exceeding 100 mm within 72 hours and local maxima surpassing 150 mm within 24 hours (Junghänel et al. 2021; Mohr et al. 2022; Szymczak et

45 al. 2022; Ludwig et al. 2023). In Germany alone, this event led to more than 180 fatalities and overall monetary losses of around EUR 33 billion (Munich Re 2025).

This high-impact nature of HPEs has motivated a growing body of research, with particular emphasis on their behaviour under ongoing climate change. At the core of this research lies the hypothesis that rising air temperature – and the resulting increase in atmospheric water vapour content of roughly 6.0 to 7.0 % per 1 °C of air warming, as described by the Clausius-Clapeyron

50 (CC) relationship – can have a pronounced influence on precipitation patterns, including HPEs. This CC-based thermodynamic argument is commonly used in the scientific literature to interpret increasing trends observed in various characteristics of HPEs. As an example, increasing trends in annual maximum daily precipitation totals were reported by Westra et al. (2013). Their global-scale analysis, based on station data from the period 1900-2009, revealed that nearly two-thirds of stations showed increases in annual maximum daily precipitation totals, with the median intensity of extreme precipitation changing in

55 proportion to changes in global air temperature at a rate of around 5.9 to 7.7 % per 1 °C, depending on the method applied. Similar conclusions can be drawn from the more recent study by Sun et al. (2021). Based on station data from the period 1900-2018, the authors confirmed that annual maximum totals of both 1-day and 5-day precipitation increased at around two-thirds of stations across global land areas. The median intensity of extreme precipitation changing in proportion to changes in global air temperature amounted to 6.6 and 5.7 % per 1 °C for the annual maximum precipitation totals of 1-day and 5-days,

60 respectively. An alternative approach was proposed by Papalexiou & Montanari (2019), who introduced a method for investigating a predefined number of HPEs – equal to the number of years in the time series, but not restricted to one event per year – arguing that this allows for a more accurate representation of weather and climate extremes than the conventional block maxima method. Their global scale analysis, based on station data from the period 1964-2013, revealed increasing trends in the frequency of daily HPEs at 60.3 % of stations, while trends in intensity were less evident. Further evidence for changes

65 in characteristics of HPEs is provided by satellite data. Using multiple global satellite precipitation products, Roca et al. (2022)

and Konrad et al. (2025) showed that extreme precipitation totals – defined by the 99.5th to 99.9th and the 99.9th percentiles, respectively – exhibit scaling with 48 hour lagged sea surface temperature that is close to CC expectations. Analogous behaviour is also reproduced in climate model simulations, implying that the observed increases in various characteristics of HPEs are not limited to the historical period but are projected to continue – or even accelerate – by the end of the 21st century

70   (Asadieh & Krakauer 2015; Donat et al. 2019; Thackeray et al. 2022).

However, emerging evidence suggests that the CC relationship is more applicable to long-duration HPEs (daily to multi-day events) than to short-duration HPEs (hourly to sub-daily events) (Lenderink et al. 2017; Martel et al. 2020; Wood & Ludwig 2020). A comprehensive review of short-duration HPEs – covering the current state of knowledge, existing challenges, and suggested directions for future research – was provided by Fowel et al. (2021). In particular, this paper focused on the

75   INTENSE project ("Intelligent use of climate models for adaptation to non-stationary hydrological extremes"), within which, for instance, sub-daily precipitation data were collected to form the Global Sub-Daily Rainfall Dataset (Blenkinsop et al., 2018; Lewis et al., 2019). Based on the review of INTENSE studies, Fowel et al. (2021) concluded also that short-duration HPEs can increase at much faster rates than long-duration HPEs – in some regions, even at rates up to three times higher than would be expected from the CC relationship, a pattern often referred to as "super-CC scaling". Similar signals have been detected in

80   more recent studies by Ayat et al. (2022), Purr et al. (2022), Buda et al. (2024), and Da Silva & Haerter (2025), although these results exhibit notable regional differences, likely driven by large-scale circulation patterns. In Central Europe, the availability of relatively long station-based data series has encouraged detailed investigations of HPEs, especially with regard to their long-term variability. As an example, Zeder & Fischer (2020) examined daily precipitation data from 940 stations across Austria, Germany, Switzerland, and the Netherlands, finding that long-duration HPEs (1-day events) became more intense at

85   many stations during the period 1901-2013. However, their results also revealed pronounced spatial heterogeneity, with predominantly positive trends over Switzerland and the Netherlands, whereas trends across Austria and Germany showed a more complex spatial pattern. This pronounced spatial heterogeneity, together with the availability of recently collected and digitised 5-minute precipitation data for Germany, motivates a more detailed, countrywide assessment of HPEs. As a point of comparison, Bauer & Scherrer (2024) reported for Switzerland alone positive trends in the frequency and intensity of

90   long-duration HPEs (1-, 3-, and 5-day events) at the majority of the stations, also during the period 1901-2023. Notably, this study extended its analysis to short-duration HPEs with durations of 10 minutes and 1 hour, albeit only for the period of 1981-2023 due to data availability constraints. This limited availability of precipitation data with high temporal resolution – primarily for earlier decades – remains one of the key barriers in advancing our understanding of short-duration HPEs. Importantly, this issue affects even regions with relatively dense station networks, where precipitation data with high temporal

95   resolution are often missing, inconsistent, or only available for recent decades.

Therefore, in this study, we make use of the recently collected, digitised, and quality-controlled 5-minute precipitation data from the rain-gauge stations across Germany in order to assess the spatial and temporal variability of HPEs, using the block maxima method. Our aim is to provide a comprehensive comparison of HPEs of various durations, acknowledging that such events are governed by distinct atmospheric processes and result in differing impacts. In particular, this study focuses on the

100   long-term variability of HPEs, addressing the pressing question of whether such events are becoming more pronounced under ongoing climate change. The paper is structured as follows: Section 2 discusses the availability of station-based precipitation data in Germany as well as outlines the definitions and methods applied; Section 3 presents the results; Section 4 concludes the paper as well as highlights existing challenges and suggested directions for future research.

2 Data and Methods

2.1 Availability of Station-Based Precipitation Data Across Germany

This study builds on station-based precipitation data, with a temporal resolution of 5 minutes, which were collected, digitised, and quality-controlled at the Deutscher Wetterdienst (DWD) as part of the research project MUNSTAR (German: "Methodische Untersuchungen zur Novellierung der Starkregenstatistik für Deutschland"; Junghänel et al. 2022). This project aimed to revise both the data foundation and methodological framework of Germany's official heavy precipitation statistics, known as KOSTRA-DWD (German: "Koordinierte Starkniederschlagsregionalisierung und -auswertung des DWD"), cumulating in the publication of its updated version, KOSTRA-DWD-2020, in early 2023 (Junghänel et al. 2023). However, the newly processed high-resolution precipitation data not only enabled the revision of KOSTRA-DWD, but also opened up new opportunities for advancing our understanding of HPEs.

To support the main aim of this study, we selected 237 stations with continuous 5-minute precipitation data series ending in 2020, which enables a robust assessment of the spatial and temporal variability of HPEs and, at least partially, inferences about their long-term variability. These stations met the following two data-availability criteria: (a) data completeness was assessed for each year at a given station following the KOSTRA-DWD-2020 methodology and only years with at least 70 % available 5-minute precipitation data between March and October and at least 75 % available 5-minute precipitation data between April and September were considered representative; and (b) only stations with at least 30 such representative years were included in this study. Around 84 % of the stations selected in this way belong to the DWD network, while the remaining 16 % are operated – either fully or partially within the measurement series – by various partner networks listed in the Acknowledgments. To enhance the robustness of our findings, we further expanded the data foundation by incorporating additional DWD stations that provide precipitation data with temporal resolutions of 7 hours and 1 day – note that the 7-hour precipitation data originate from standard sub-daily measurements, routinely conducted in Germany at 07:00, 14:00, and 21:00 MEZ. Figure 1 shows that the number of stations – regardless of their temporal resolution – fluctuates considerably over time, reaching its highest level after the year 1970. From the early 1970s onwards, the data foundation comprises around 160 to 215 stations with 5-minute resolution, 350 to 410 stations with 7-hour resolution, and 850 to 1000 stations with 1-day resolution. Figure 2, in turn, indicates that the spatial distribution of the stations is relatively well balanced across all temporal resolutions, although the stations with 5-minute resolution, due to their smaller number, occasionally exhibit larger distances between each other, for example in the western part of the Northwestern Lowlands or the northern part of the Western Lowlands. Moreover, temporal resolution of precipitation data influences the length of the data series, with median values of around 55 years for stations with

5-minute resolution, 56 years for stations with 7-hour resolution, and 69 years for stations with 1-day resolution. Finally, as a consequence of Germany's topography, lowland stations clearly outnumber those located in upland and mountainous regions.
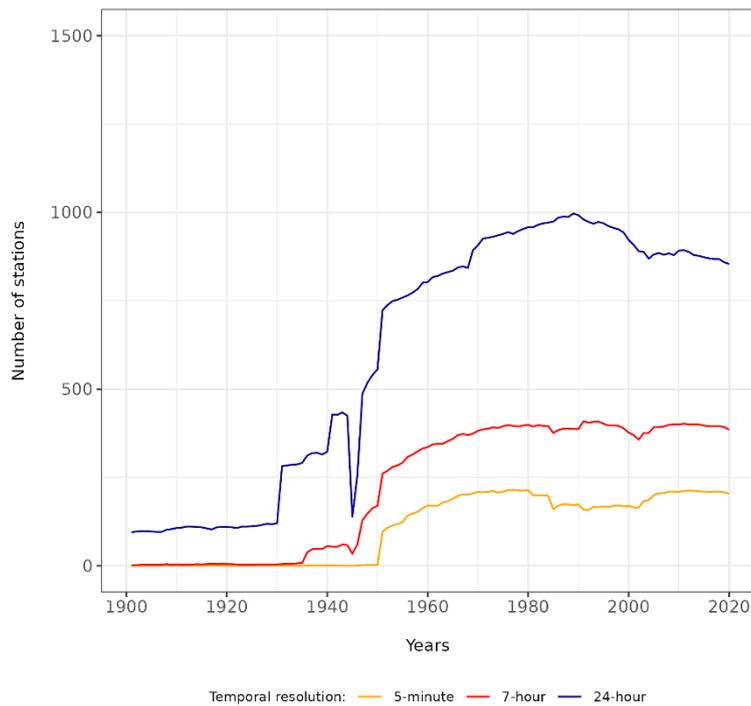
Figure 1: Temporal distribution of the number of stations selected according to the data availability criteria described in Section 2.1. Colours indicate temporal resolution of the precipitation data: 5-minute, 7-hour, and 1-day.
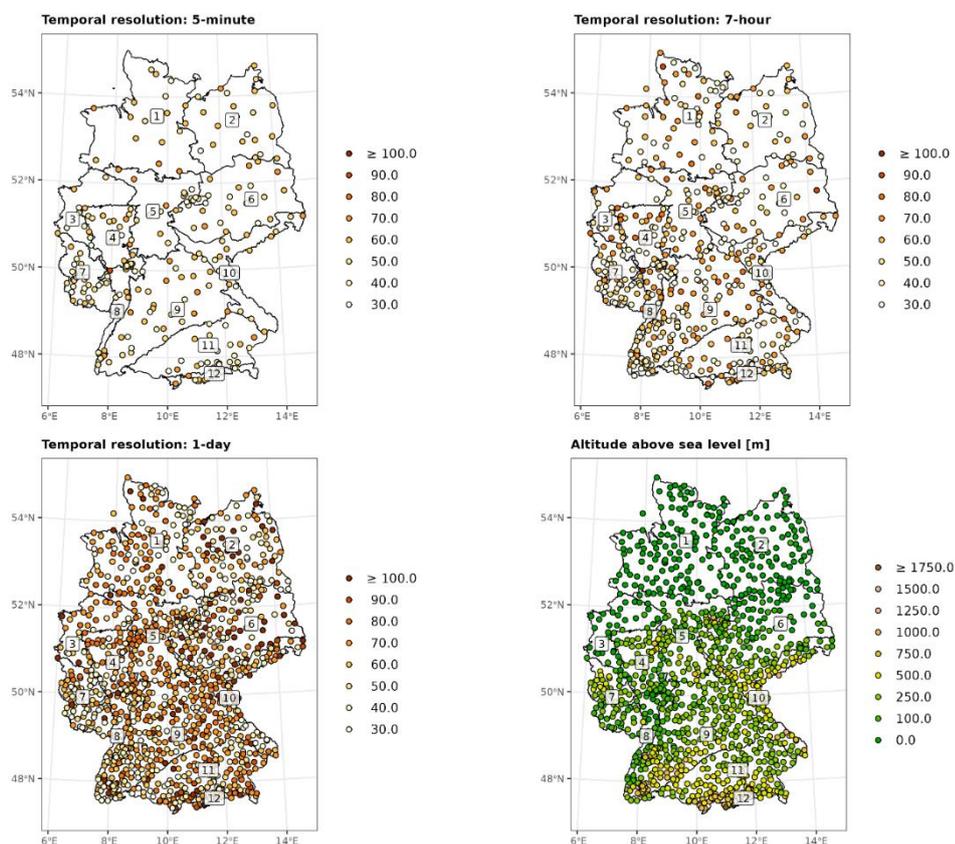
Figure 2: Spatial distribution of stations selected according to the data availability criteria described in Section 2.1, with the colour of each circle indicating the number of years in the data series. Results are shown separately for the three temporal resolutions of the precipitation data: 5-minute, 7-hour, and 1-day. In addition, the map in the bottom right shows the altitude above sea level [m] for all selected stations. Black borders and numbers indicate natural regions in Germany, based on the classification of Meynen and Schmithausen (1959): (1) Northwestern Lowlands, (2) Northeastern Lowlands, (3) Western Lowlands, (4) Uplands east of the Rhine, (5) Central Uplands and Harz, (6) Eastern Valleys and Hills, (7) Uplands west of the Rhine, (8) Upper Rhine Lowlands, (9) Southwestern Uplands, (10) Eastern Uplands, (11) Alpine Foothills, and (12) Alps.

2.2 Definition and Identification of Heavy Precipitation Events

A review of the scientific literature reveals a wide range of definitions for heavy and extreme precipitation events. Typically, these are based on either the block maxima or the peak-over-threshold method, each with its own advantages and limitations. While the block maxima method captures only a single event within a defined time period – potentially overlooking other significant events, the peak-over-threshold method relies on a somewhat subjectively chosen threshold, which – if poorly defined – can lead to biased or unstable results, particularly when further applying extreme value theory (Camuffo et al. 2020; Bücher & Zhou 2021; Tabari 2021). In order to ensure consistency with the most recent version of Germany's official heavy precipitation statistics KOSTRA-DWD-2020, we adopted the block maxima method in this study, while acknowledging that other methods may also be appropriate depending on the scientific context. This study focuses on nine durations, which broadly

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represent annual maximum precipitation totals (AMPTs) of short (5, 30, and 60 minutes), medium (3, 7, and 12 hours), and
155 long (1, 3, and 7 days) durations.

2.3 Statistical Methods for Assessing Variability in Heavy Precipitation Events

To gain insight into the spatial and temporal variability of AMPTs, we applied a combination of descriptive statistics and non-parametric trend analysis methods. Spatial variability was assessed by mapping station-based statistics and examining their relationship with altitude. For brevity, this study presents only results based on the median and the coefficient of variation
160 (CV), the latter defined as the standard deviation normalised by the mean and expressed as a percentage. Long-term temporal variability, in turn, was assessed using the non-parametric Mann-Kendall test to detect monotonic trends in AMPTs of various durations, with trend magnitudes estimated using Sen's slope and statistical significance evaluated at the 0.05 level. This method is frequently employed in climate research owing to the advantages of the Mann-Kendall test, such as its applicability to datasets with missing values, insensitivity to outliers, and robustness to non-normal data distributions (Costa et al. 2020;
165 Mallick et al. 2021; Linkinaw et al. 2023). In addition, Locally Estimated Scatterplot Smoothing (LOESS) was applied to visualise gradual changes in AMPTs over time and to identify potential non-linear and non-monotonic trends that may not be adequately captured by the Mann-Kendall test. This method is especially well-suited to uncover underlying temporal structures in noisy or highly variable data and has previously been applied to analyse variability in temperature and precipitation patterns (Wanishsakpong & Notodiputro 2018; Silva et al. 2022; Bauer & Scherrer 2024).

170 ## 3. Spatial and Temporal Variability of Heavy Precipitation Events Across Germany

3.1 General Patterns

An initial overview of AMPTs is provided in Figure 3, which combines box and violin plots to present the overall distribution of AMPTs across all durations, stations, and years considered. As expected, AMPTs increase with duration, clearly reflecting the longer accumulation periods – the median of 5-minute AMPTs amounts to 5.5 mm, while that of 7-day AMPTs reaches
175 73.8 mm. In addition, the visually apparent widening of the interquartile range with increasing duration – together with the changing shape of the violin plots – suggests that long-duration AMPTs may exhibit greater overall variability, potentially due to more pronounced spatial or temporal heterogeneity. However, this appearance is largely a consequence of the inherently different scales of AMPTs of various durations rather than an actual increase in their variability. This is confirmed by CV, which remains relatively stable across all durations, ranging from 41 to 48 %, with slightly higher values observed for
180 short-duration AMPTs (not shown in this paper). Moreover, the severity of individual precipitation events is well illustrated by the highest observed precipitation totals, which also increase with duration – reaching, for example, 25.5 mm for the duration of 5 minutes and 497.5 mm for the duration of 7 days.
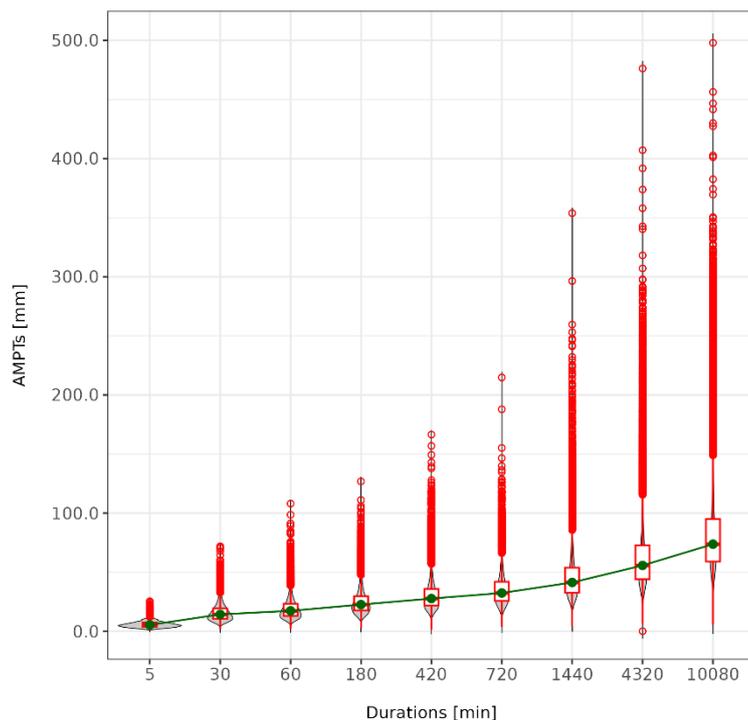
Figure 3: Overall distribution of AMPTs [mm] across all stations and years considered, shown for nine durations representing
185 **short- (5, 30, and 60-minutes), medium- (180, 420, and 720 minutes, i.e., 3, 7, and 12 hours), and long-duration (1440, 4320, and 10080 minutes, i.e., 1, 3, and 7 days) precipitation events. The figure combines box and violin plots. Red boxes represent the interquartile range (IQR), red whiskers extend to 1.5 × IQR, and red open circles mark individual outliers lying beyond IQR. In turn, grey violin plots display a smoothed kernel density of the distribution, with wider sections corresponding to a higher concentration of AMPTs. Green filled circles indicate the median for each duration and are connected by a green line.**

190 Complementing this overall distribution, Figure 4 shows the spatial distribution of the medians of AMPTs calculated for

individual stations, revealing a clear duration-dependent relationship – both the medians and their spatial variability increase

with duration. While the medians of short-duration AMPTs are relatively evenly distributed across Germany, those of

medium- and long-duration AMPTs increasingly reflect the influence of topography. In particular, when considering AMPTs

with duration of one or more days, the highest medians are concentrated in upland and mountainous regions of southern

195 Germany – including the Alps, the Alpine Foothills, the Black Forest in the western part of the Southwestern Uplands, and the

Upper Palatine-Bavarian Forest in the southern part of the Eastern Uplands. These spatial patterns are further complemented

by the distribution of CV, which describes the relative variability of AMPTs across years – and, because the block maxima

method used in this study selects one event per year, also the event-to-event variability at each station. As presented in Figure 5,

its spatial distribution differs clearly between short- and long-duration AMPTs. While short- and medium-duration AMPTs

200 exhibit relatively high and spatially scattered event-to-event variability, long-duration AMPTs tend to be more consistent and

regionally organised. In particular, when considering AMPTs with duration of 3 and 7-days, a clear contrast emerges between

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the western and eastern parts of Germany – higher values of CV are observed in the east, where annual precipitation totals are generally lower.
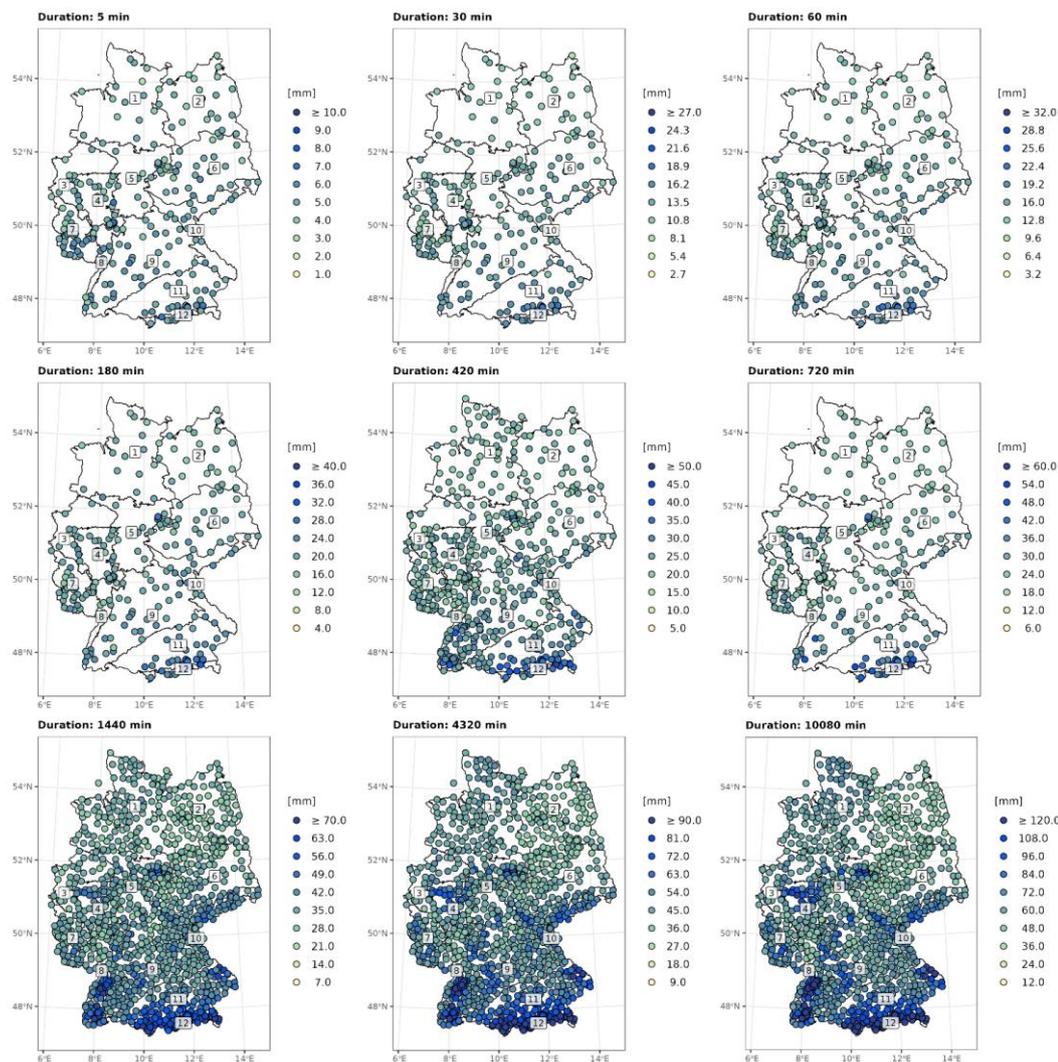
Figure 4: Spatial distribution of stations selected according to the data availability criteria described in Section 2.1, with the colour of each circle indicating the median of AMPTs [mm] calculated for an individual station. Results are shown for nine durations representing short- (5, 30, and 60 minutes), medium- (180, 420, and 720 minutes, i.e., 3, 7, and 12 hours), and long-duration (1440, 4320, and 10080 minutes, i.e., 1, 3, and 7 days) precipitation events. As in Figure 2, black borders and numbers indicate natural regions in Germany.
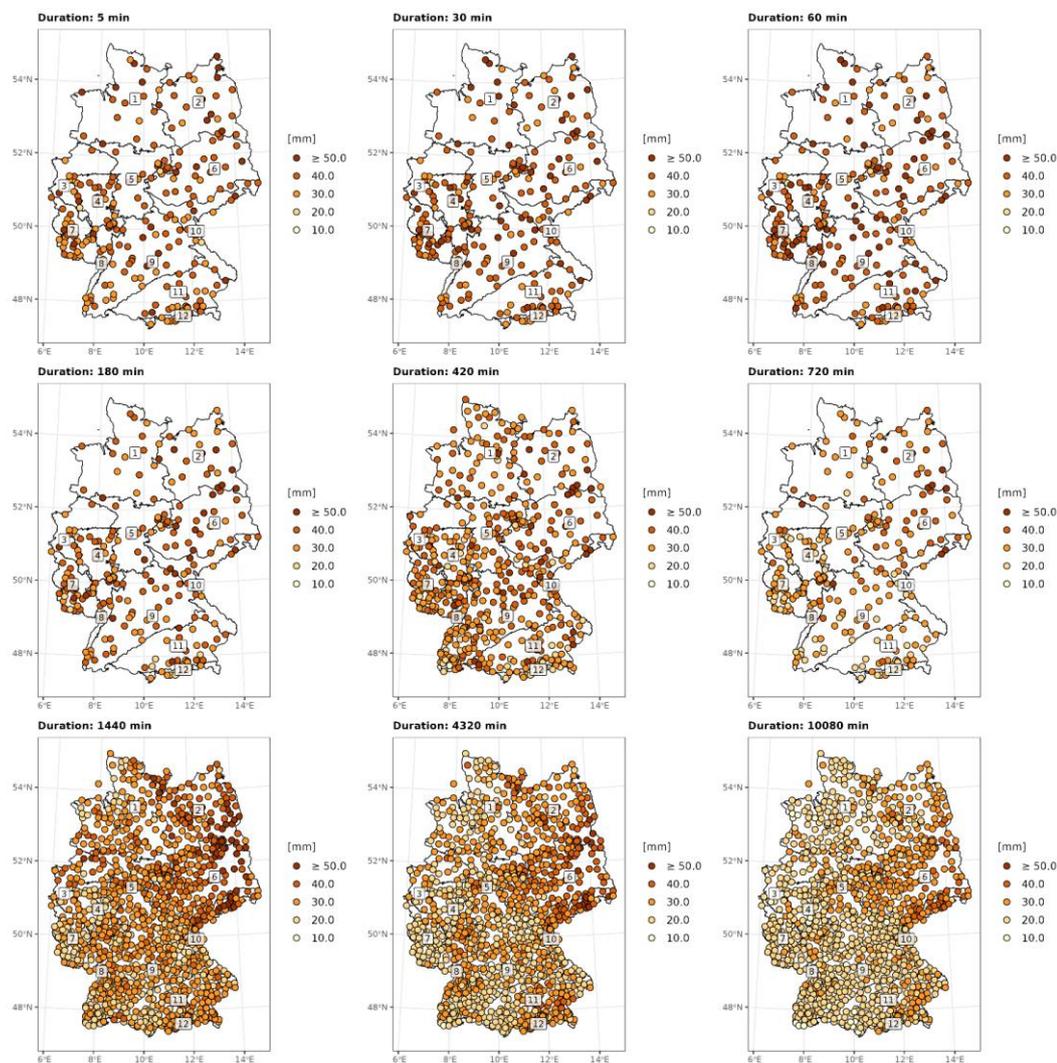
Figure 5: Spatial distribution of stations selected according to the data availability criteria described in Section 2.1, with the colour of each circle indicating CV of AMPTs [%] calculated for an individual station. Results are shown for nine durations representing short- (5, 30, and 60 minutes), medium- (180, 420, and 720 minutes, i.e., 3, 7, and 12 hours), and long-duration (1440, 4320, and 10080 minutes, i.e., 1, 3, and 7 days) precipitation events. As in Figure 2, black borders and numbers indicate natural regions in Germany.

Beyond describing the spatial and temporal patterns, a joint analysis of the medians and CV sheds some light on the dominant atmospheric processes governing precipitation events of various durations. Short-duration AMPTs, which exhibit uniform spatial distribution and relatively high, but spatially scattered, event-to-event variability, appear to be associated with small-scale convective processes triggered by highly unstable local thermodynamic conditions. These localised thermodynamic processes – including intense surface heating and low-level moisture convergence – very likely contribute to the isolated and short-lived nature of short-duration precipitation events, in line with the observed patterns in median and CV. Conversely, long-duration AMPTs tend to affect large regions, yielding more spatially coherent and regionally organised

patterns in both median and CV. This points to the dominance of large-scale atmospheric processes in their development – including frontal structures, slow-moving low-pressure systems, and Vb cyclones (van Bebber 1891) – all of which can persist for several days and generate widespread, topographically modulated precipitation. This reasoning can be substantiated by the main findings of our previous study, which applied a then new numerical method for classifying circulation patterns over Central Europe, known as "Großwetterlagen for Reanalyses" (Palarz et al. 2024). According to that study, short-duration HPEs are closely linked to small-scale convective processes that can develop under a relatively wide range of circulation conditions – including not only cyclonic but also anticyclonic circulation patterns, while long-duration precipitation HPEs are typically associated with more persistent cyclonic circulation patterns.

3.2 Long-term variability

As a first step toward assessing the long-term variability of AMPTs, we examined the direction and statistical significance of monotonic trends computed using the Mann-Kendall test and Sen's slope estimator. Figure 6 summarises these results, including all durations, stations, and years considered, and shows that positive trends prevail across all durations. The fraction of stations exhibiting positive trends – both significant and non-significant – peaks at almost 90 % for durations of 5 and then decreases gradually to around 53 % for duration of 7 days. However, the very high fraction of stations indicating statistically significant positive trends for 5-minute AMPTs – amounted to around 55 % – raised the hypothesis that this pattern may be driven by data inhomogeneities rather than by physically plausible changes in precipitation dynamics. To investigate this issue, we followed the methodology described by Coles (2001) and Shehu et al. (2023), applying the Akaike Information Criterion to evaluate whether the long-term tendencies of AMPTs are best captured by an abrupt jump coinciding with the documented transition from analogue to digital measurement systems, a linear trend, or stationarity. Our results confirmed that, particularly for short-duration AMPTs, a large fraction of stations indicates abrupt jumps – for 5-minute AMPTs, approximately 54% of stations indicate such discontinuities, whereas this fraction decreases rapidly with increasing duration, reaching about 21% for 1-hour AMPTs (not shown in this paper). To ensure the reliability of our findings, all formal assessments were therefore restricted to AMPTs with durations of one hour or longer. Results for 5 and 30-minute AMPTs – which, owning to their short accumulation periods, are especially prone to inhomogeneities associated with the transition from analogue to digital measurement systems – are omitted from inference but are displayed in the following figures for completeness. These inhomogeneities are primarily due to the fact that older rain recorders commonly used in Germany were limited to measuring maximum intensities of approximately 2.7 mm/min, whereas modern instruments can register intensities of approximately 5 to 20 mm/min. Consequently, replacing an older gauge with modern device may introduce an artificial increase in the maximum registrable intensity. Since the intensity of heavy precipitation generally decreases with increasing duration, these inhomogeneities predominantly affect very short durations, while longer durations (from one hour onwards) remain largely unaffected.
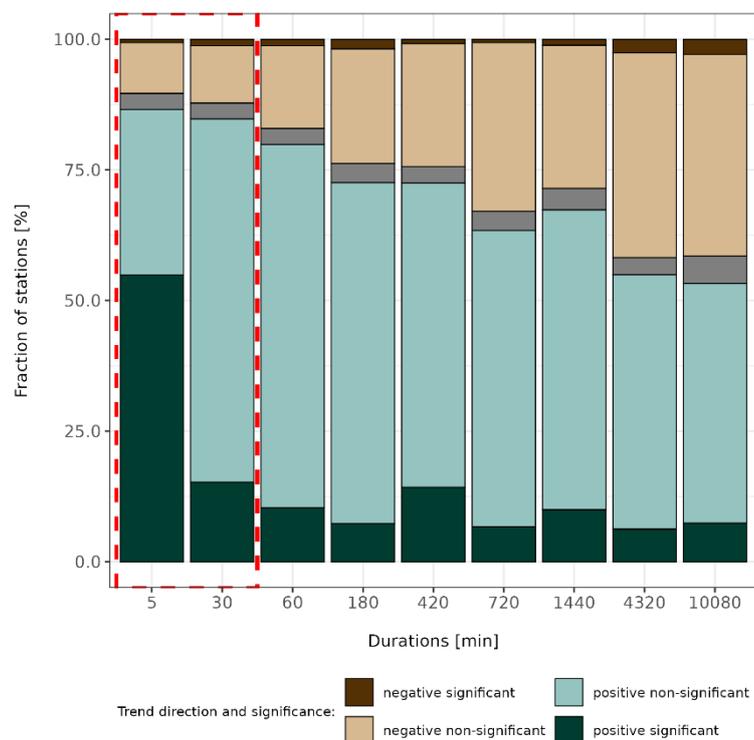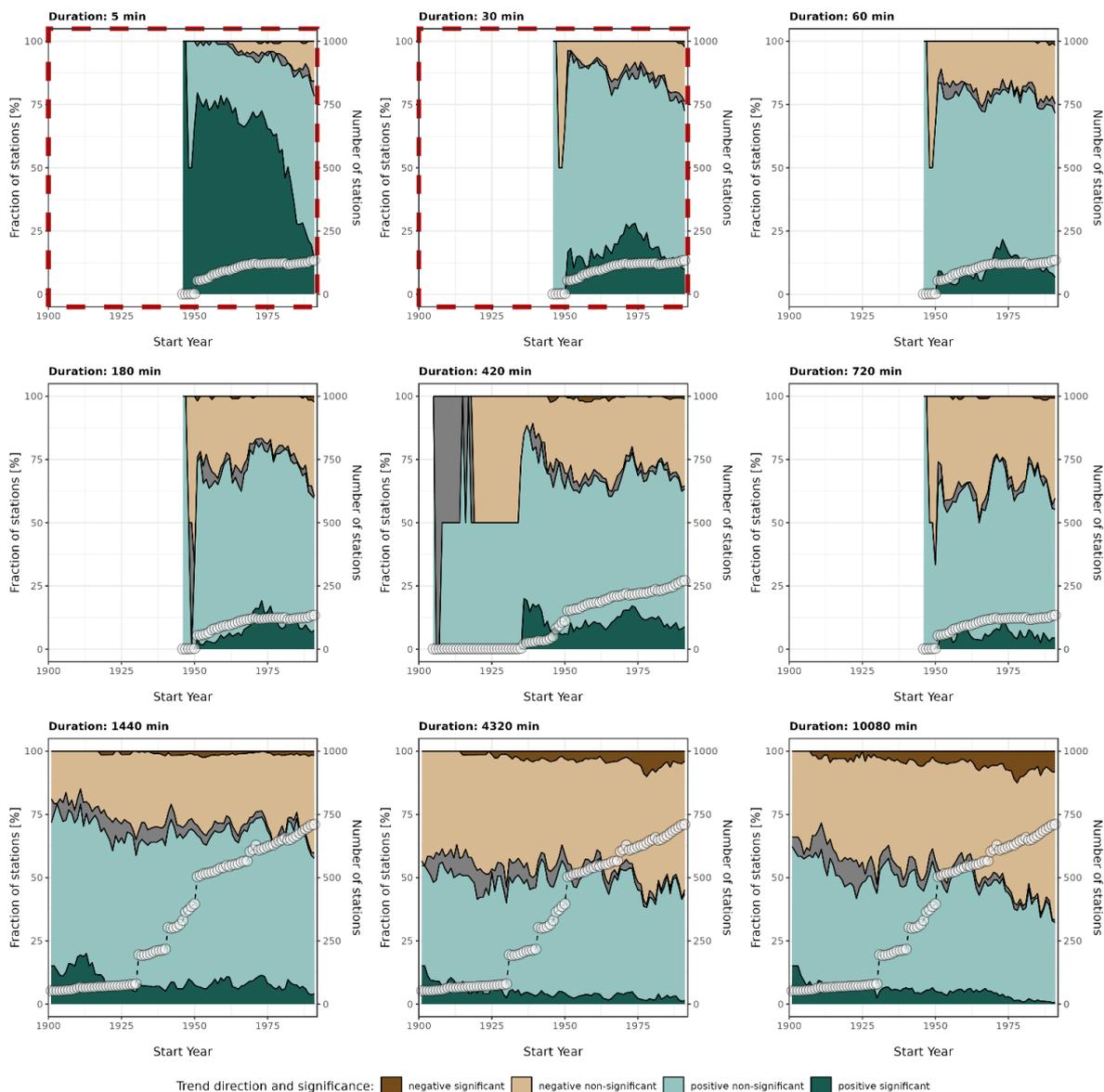
Figure 6: Fraction of stations [%] selected according to the data availability criteria described in Section 2.1 that exhibit different trend directions and significance in AMPTs, shown for nine durations representing short- (5, 30, and 60 minutes), medium- (180, 420, and 720 minutes, i.e., 3, 7, and 12 hours), and long-duration (1440, 4320, and 10080 minutes, i.e., 1, 3, and 7 days) precipitation events. Colours indicate the direction and statistical significance of the monotonic trends computed using the Mann-Kendall test and Sen's slope estimator. Grey shading denotes stations for which no relevant trend was identified, i.e., stations with a change of less than 0.1% per year relative to the long-term median AMPTs. Only stations with at least 90 % data availability for AMPTs in the respective time periods are included. Note that, in this figure, the stations do not share a uniform investigation period for trend analysis. The 5- and 30-minute durations are highlighted by a red dashed frame to indicate the increased uncertainty of trend estimates at very short accumulation periods, which are particularly prone to inhomogeneities associated with the transition from analogue to digital precipitation measurement systems.

While restricting the formal assessment of trends to AMPTs with durations of one hour or longer mitigates the impact of the inhomogeneities outlined above, the resulting trends remain sensitive to other sources of uncertainty. In particular, Figures 7 illustrates how the direction and statistical significance of the monotonic trends vary with the start year used for the trend analysis, while the end year is fixed at 2020 – the final year of precipitation data considered in this study. When focusing on AMPTs with durations of 1 to 7 hours, a clear predominance of positive trends is observed across most start years with relatively high station availability, yet the majority of these trends are not statistically significant. A different picture emerges for AMPTs with durations of 3 to 7 days, for which the fraction of stations exhibiting positive and negative trends is more balanced. For AMPTs with a duration of 7 days and start years fixed in the late 1970s or 1980s, negative trends even slightly outnumber positive ones. Moreover, as the start year is moved progressively further back in time, the fraction of stations exhibiting positive trends in 1- and 7-day AMPTs increases when both statistically significant and non-significant trends are

275   taken into account. This pattern may suggest that longer investigation periods help to reveal more robust signals of temporal variability in AMPTs, although it remains challenging to separate physically plausible changes in precipitation dynamics from sampling effects arising from the varying number of stations included in the trend analysis. Nonetheless, the fraction of stations exhibiting statistically significant trends – both positive and negative – is relatively low across all durations and start years considered. The highest fraction of statistically significant positive trends is observed for 1-, 3-, and 7-hour AMPTs, at around

280   15 to 20 % for analyses starting in the 1970s, and for 1-day AMPTs, at around 12 to 22 % for analyses starting in the 1900s. Conversely, statistically significant negative trends are most frequent for 3- and 7-day AMPTs, at around 6 to 11 % and 8 to 13 %, respectively, for analyses starting in the late 1970s and early 1980s. Typically, however, the fraction of stations with statistically significant positive trends does not exceed 15 %, while statistically significant negative trends are generally observed at fewer than 5 % of stations, for most investigation periods with a relatively large sample of available stations.
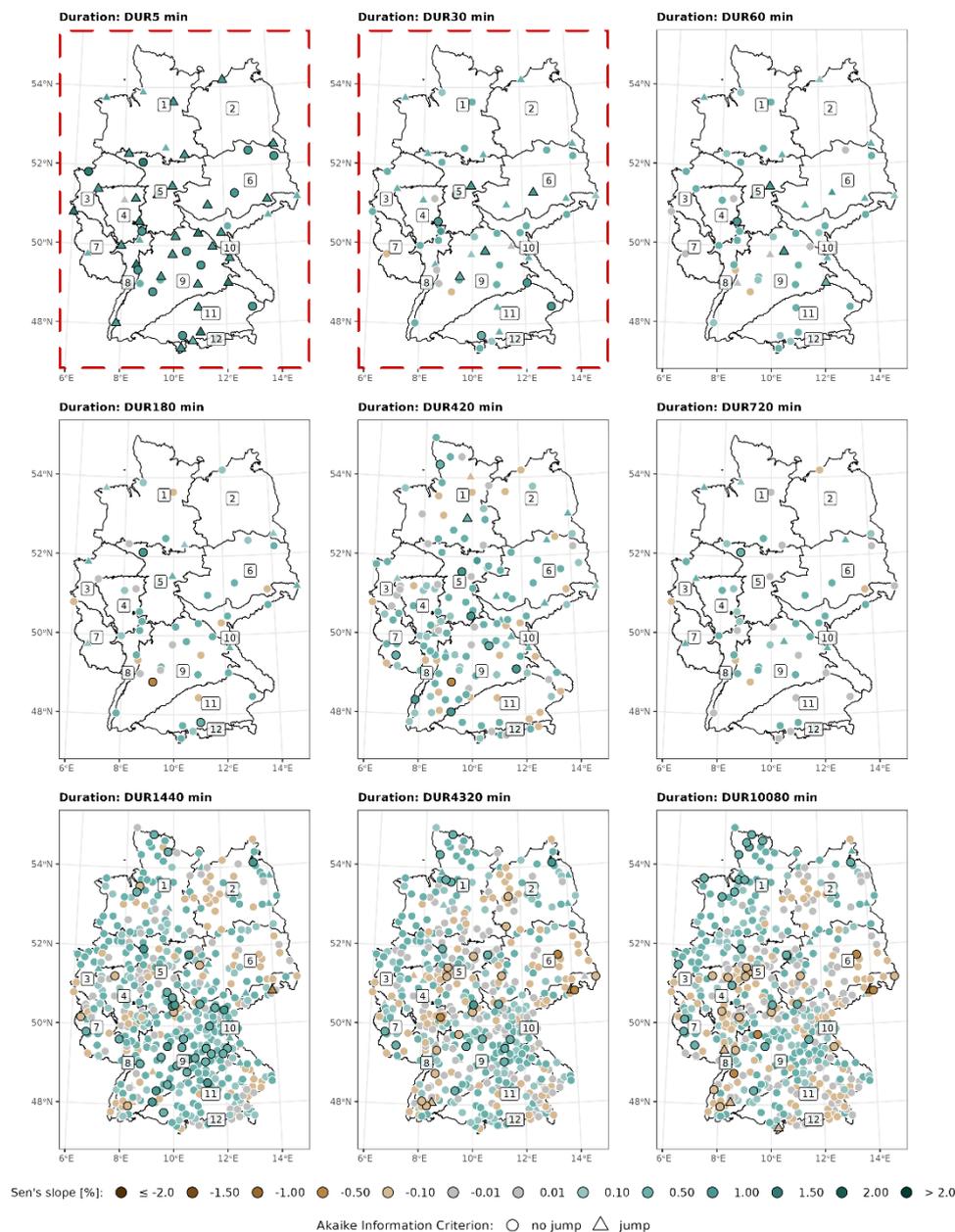
Figure 7: Fraction of stations [%] selected according to the data availability criteria described in Section 2.1 that exhibit different trend directions and significance in AMPTs depending on the start year used for the trend analysis, while the end year is fixed at 2020. Colours indicate the direction and statistical significance of the monotonic trends computed using the Mann-Kendall test and Sen's slope estimator. Grey shading denotes stations for which no relevant trend was identified, i.e., stations with a change of less than 0.1% per year relative to the long-term median. Only stations with at least 90 % data availability for AMPTs in the respective time periods are included. In addition, white filled circles connected by a dashed line show the number of stations used for the trend analysis for each time period. Results are shown for nine durations representing short- (5, 30, and 60 minutes), medium- (180, 420, and 720 minutes, i.e., 3, 7, and 12 hours), and long-duration (1440, 4320, and 10080 minutes, i.e., 1, 3, and 7 days) precipitation events. Only stations with at least 90 % data availability for AMPTs in the respective time periods are included. The 5- and 30-minute durations are highlighted by a red dashed frame to indicate the increased uncertainty of trend estimates at very short accumulation periods, which are particularly prone to inhomogeneities associated with the transition from analogue to digital precipitation measurement systems.

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To further investigate the spatial distribution of the monotonic trends in AMPTs, we analysed their regional distribution for three different start years – 1951, 1971, and 1991 – while, as before, keeping the end year fixed at 2020. Figures 8 to 10, which

300   display the percentual magnitude of the Sen's slope estimates relative to the long-term median of AMPTs, along with statistical significance and the presence or absence of abrupt jumps identified using the Akaike Information Criterion, reveal discrepancies emerging between short- and medium-duration AMPTs on the one hand, and long-duration AMPTs on the other. While the former tends to show uniform and mostly positive trends, the latter indicates more spatially contrasting patterns. Especially, for the short-term investigation period (1991-2020, Figure 10), 3- and 7-day AMPTs show a pronounced regional

305   structure, with negative trends concentrated in parts of southern, south-eastern, and western Germany. These include regions such as the Southwestern Uplands, the Eastern Uplands, the northern part of the Alpine Foothills, and the northern part of the Uplands east of the Rhine. Many of these negative trends are statistically significant and not associated with detected abrupt jumps in the data series, suggesting robust, climate-related signals in long-duration AMPTs. However, this pattern weakens considerably in the medium-term period (1971-2020, Figure 9) and is no longer evident in the long-term period (1951-2020,

310   Figure 8). For the long-term period, Sen's slope estimates typically range between −0.5 % and +0.5 % per year, but they increase markedly when the investigation period is shortened, reaching values exceeding ±1.5 % per year in some local hotspots. In some of these hotspots, however, the high magnitudes of Sen's slope estimates coincide with detected abrupt jumps and should not be interpreted as signals driven only by physically plausible changes in precipitation dynamics. When considering the influence of altitude and topography, no systematic relationship was found with either the direction or the

315   statistical significance of monotonic trends in AMPTs. Although long-duration precipitation events generally exhibit higher AMPTs in upland and mountainous regions, the direction and significance of their trends appear largely independent of both altitude and topography, implying that large-scale circulation patterns likely play a more prominent role in shaping their long-term variability.
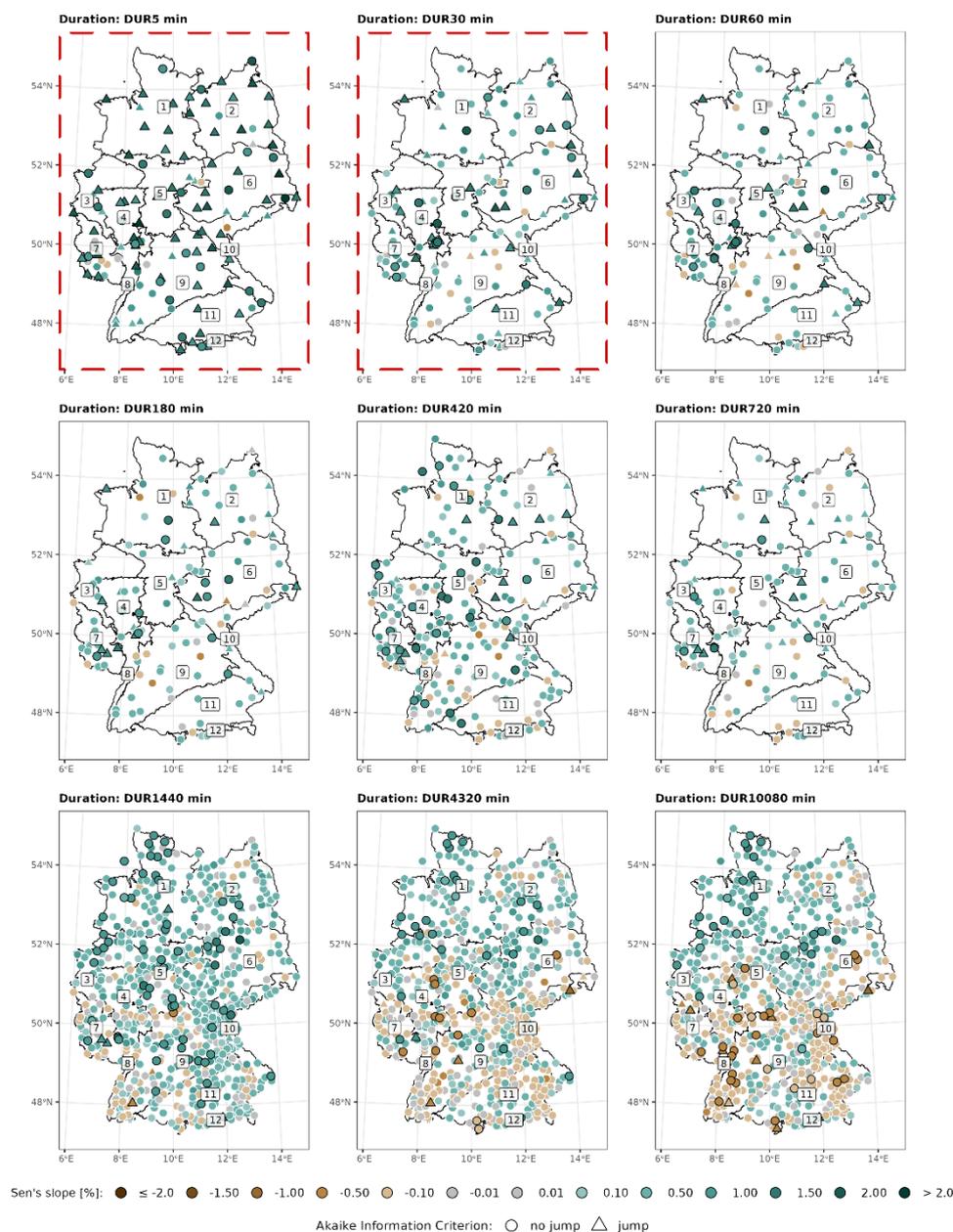
Figure 8: Spatial distribution of stations selected according to the data availability criteria described in Section 2.1, with the colour of each circle or triangle indicating the trend magnitude in AMPTs [%, per year relative to the long-term median of AMPTs] for the period 1951-2020, computed using the Mann-Kendall test and Sen's slope estimator. Circles represent time series without an abrupt jump identified by the Akaike Information Criterion, whereas triangles represent time series with such jumps. Black borders around circles or triangles indicate statistical significance at the 0.05 level. Results are shown for nine durations representing short- (5, 30, and 60 minutes), medium- (180, 420, and 720 minutes, i.e., 3, 7, and 12 hours), and long-duration (1440, 4320, and 10080 minutes, i.e., 1, 3, and 7 days) precipitation events. Only stations with at least 90 % data availability for AMPTs in the respective time periods are included. As in Figure 2, black borders and numbers indicate natural regions in Germany. The 5- and 30-minute durations are highlighted by a red dashed frame to indicate the increased uncertainty of trend estimates at very short

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accumulation periods, which are particularly prone to inhomogeneities associated with the transition from analogue to digital precipitation measurement systems.
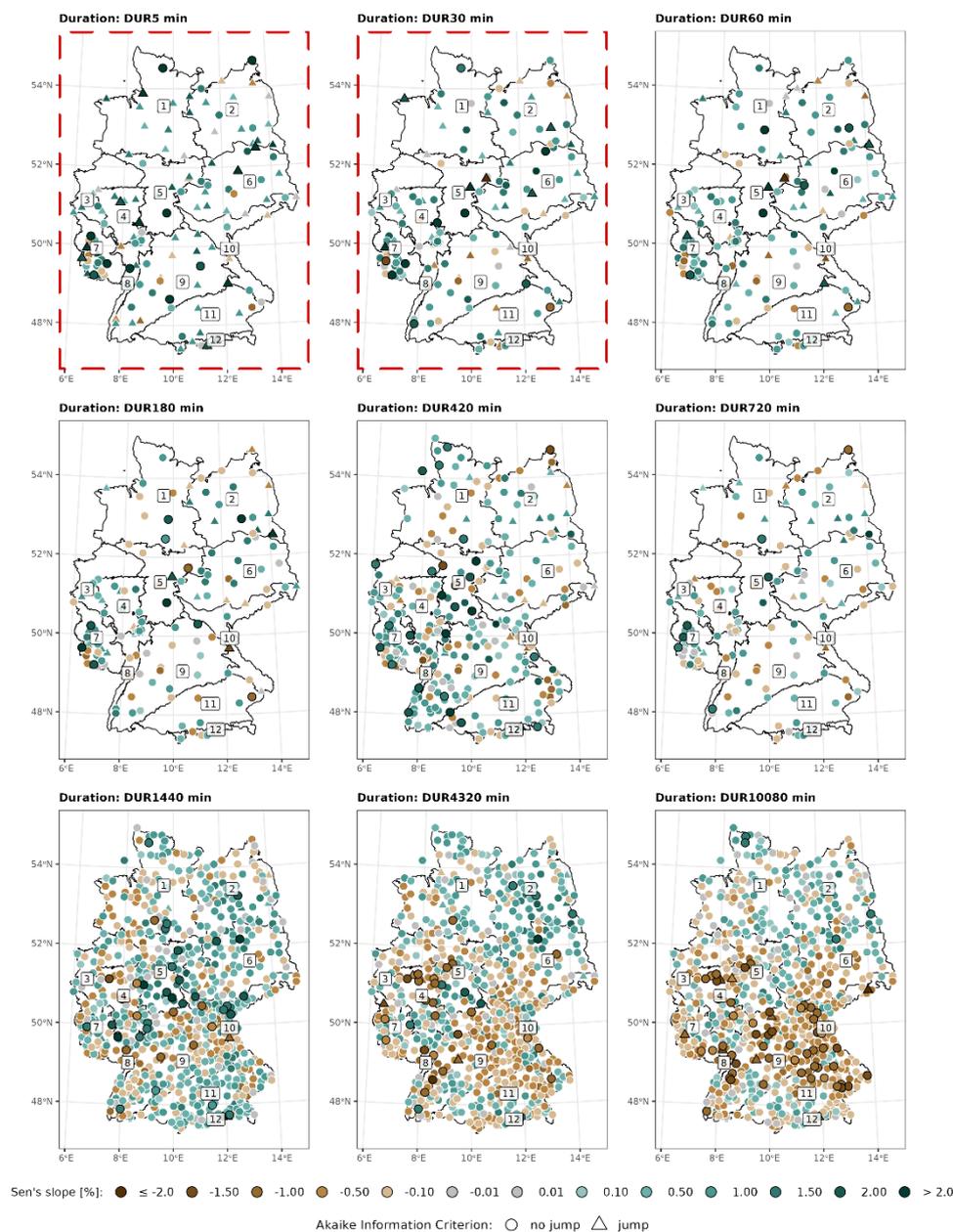

Figure 9: Spatial distribution of stations selected according to the data availability criteria described in Section 2.1, with the colour of each circle or triangle indicating the trend magnitude in AMPTs [%, per year relative to the long-term median of AMPTs] for the period 1971-2020, computed using the Mann-Kendall test and Sen's slope estimator. Circles represent time series without an abrupt jump identified by the Akaike Information Criterion, whereas triangles represent time series with such jumps. Black borders around circles or triangles indicate statistical significance at the 0.05 level. Results are shown for nine durations representing short- (5, 30, and 60 minutes), medium- (180, 420, and 720 minutes, i.e., 3, 7, and 12 hours), and long-duration (1440, 4320, and

17

340 10080 minutes, i.e., 1, 3, and 7 days) precipitation events. Only stations with at least 90 % data availability for AMPTs in the respective time periods are included. As in Figure 2, black borders and numbers indicate natural regions in Germany. The 5- and 30-minute durations are highlighted by a red dashed frame to indicate the increased uncertainty of trend estimates at very short accumulation periods, which are particularly prone to inhomogeneities associated with the transition from analogue to digital precipitation measurement systems.


Figure 10: Spatial distribution of stations selected according to the data availability criteria described in Section 2.1, with the colour
345 of each circle or triangle indicating the trend magnitude in AMPTs [%, per year relative to the long-term median of AMPTs] for the period 1991-2020, computed using the Mann-Kendall test and Sen's slope estimator. Circles represent time series without an

abrupt jump identified by the Akaike Information Criterion, whereas triangles represent time series with such jumps. Black borders around circles or triangles indicate statistical significance at the 0.05 level. Results are shown for nine durations representing short- (5, 30 and 60 minutes), medium- (180, 420, and 720 minutes, i.e., 3, 7, and 12 hours), and long-duration (1440, 4320, and 10080 minutes, i.e., 1, 3, and 7 days) precipitation events. Only stations with at least 90 % data availability for AMPTs in the respective time periods are included. As in Figure 2, black borders and numbers indicate natural regions in Germany. The 5- and 30-minute durations are highlighted by a red dashed frame to indicate the increased uncertainty of trend estimates at very short accumulation periods, which are particularly prone to inhomogeneities associated with the transition from analogue to digital precipitation measurement systems.

In light of the clear sensitivity of the direction and statistical significance of the monotonic trends to start year used in the trend analysis, we further examined the long-term variability of AMPTs in more detail. To this end, we applied the LOESS with a 42-year smoothing window to AMPTs of all stations with at least 70 consecutive representative years, as defined in Section 2.1, ensuring a sufficiently long temporal perspective for detecting potential signs of decadal or longer fluctuations. As shown in Figure 11, which displays the LOESS smoothers for both individual stations and the median across all stations considered, the results once again highlight the duration-dependent nature of AMPTs, reinforcing our previous findings. While the LOESS-smoothed time series computed for short-duration AMPTs – including again the 5- and 30-minute durations – exhibit pronounced temporal variability, accompanied by a relatively uniform range of values across all stations, the corresponding time series for long-duration AMPTs display a much more stable temporal pattern alongside greater station-to-station divergence, with the highest and clearly outstanding values stemming from rain-gauge stations located at high altitudes in the Alps and the Black Forest. Moreover, for short-duration AMPTs, the median of LOESS-smoothed time series reveals some indications of decadal fluctuations, with higher values during the 1950s, a downward tendency from the 1960s through the 1970s, and a renewed upward trend thereafter. This pattern is most evident for durations of 5 and 30 minutes and gradually diminishes with increasing duration, culminating in a largely stable median of the LOESS-smoothed time series for AMPTs of 1 day and longer, implying an absence of both robust monotonic trends and decadal fluctuations. Similar results were reported by Bauer & Scherrer (2024), who, based on station data from Switzerland, found, on the one hand, stable median values for 1-day AMPTs over the period 1901-2023 and, on the other hand, upward trends in 10-minute AMPTs over the period 1981-2023 – a pattern consistent with the increase observed in this study. We assume that the decadal fluctuations in short-duration AMPTs may be explained by changes in the behaviour of large-scale circulation patterns, potentially reinforced by an intensified convective response to anthropogenic warming, as hypothesised by Bauer & Scherrer (2024), particularly affecting summertime AMPTs of short durations. However, the evident increase identified in the LOESS-smoothed time series during the 1980s and 1990s may also be attributable – at least in part – to the transition from analogue to digital measurement systems, which took place at many rain-gauge stations during the 1990s.
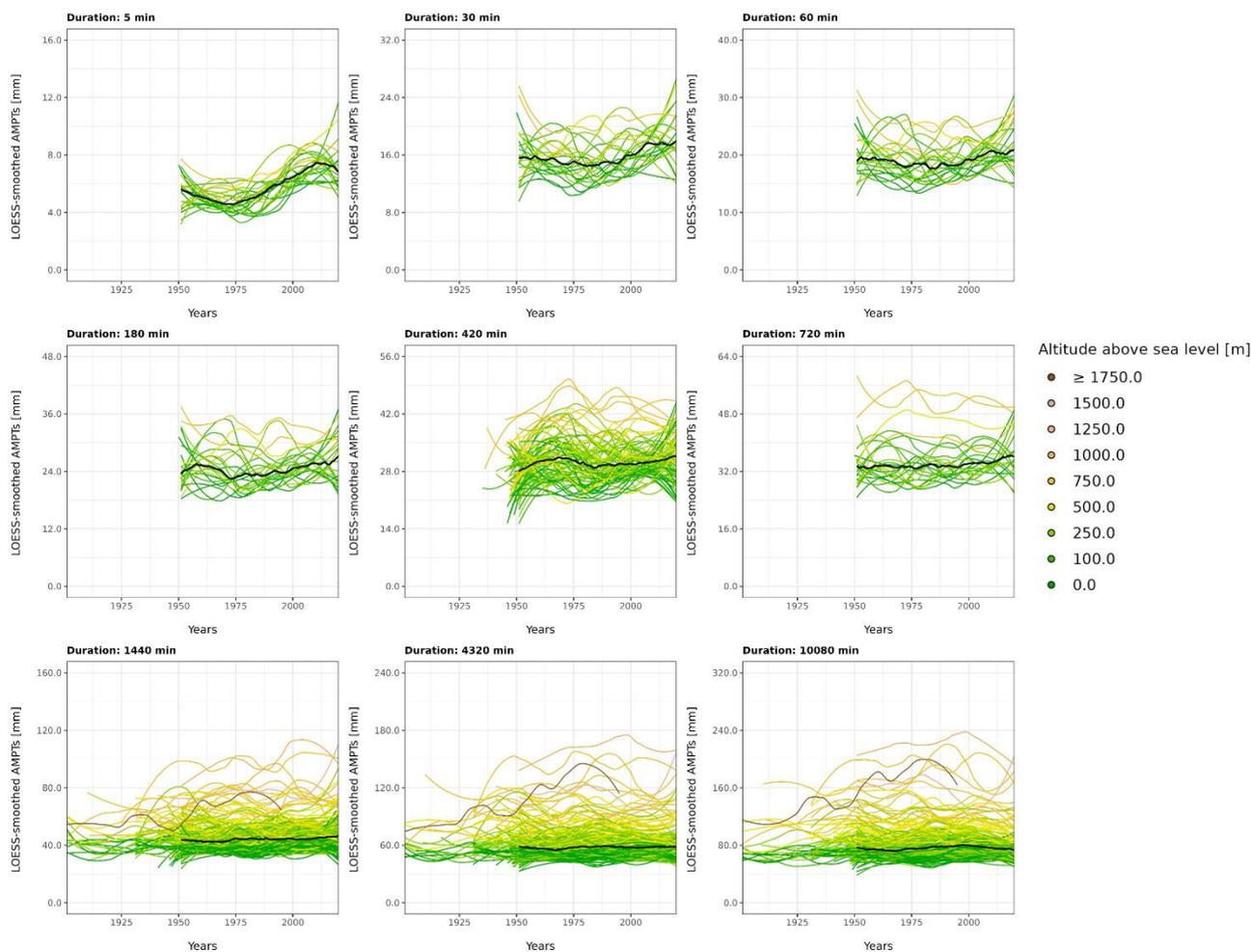
Figure 11: LOESS-smoothed time series of AMPTs [mm] for all stations with at least 70 consecutive representative years selected according to the data availability criteria described in Section 2.1 – a 42-year smoothing window was applied. Each coloured line represents the time series of one individual station, with the line colour indicating its altitude above sea level [m], while the black line denotes the median across all stations considered. Results are shown for nine durations representing short- (5, 30, and 60 minutes), medium- (180, 420, and 720 minutes, i.e., 3, 7, and 12 hours), and long-duration (1440, 4320, and 10080 minutes, i.e., 1, 3, and 7 days) precipitation events.

4 Conclusions

In this study, we made use of recently collected, digitised, and quality-controlled 5-minute precipitation data from rain-gauge stations located across Germany in order to assess the spatial and temporal variability of HPEs of various durations, using the block maxima method. Building on this high-resolution data foundation, it has been confirmed that AMPTs exhibit clear duration dependence in their spatial and temporal variability, which may be attributed to the distinct atmospheric processes that govern them. The duration-dependent nature of HPEs manifests most clearly when examining the medians of AMPTs, which increase with duration, clearly reflecting the longer accumulation periods. This is accompanied by a corresponding

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increase in the spatial variability of the medians of AMPTs calculated for individual stations and a shift in the spatial distribution of their event-to-event variability, as indicated by CV. The latter tends to be higher and more spatially scattered for short- and medium-duration AMPTs, but becomes more consistent and regionally organised for longer durations. Together, these differences are indicative of the dominant atmospheric processes governing HPEs of various durations. While short-duration HPEs appear to be associated with small-scale convective processes triggered by highly unstable local thermodynamic conditions, the development of long-duration HPEs is shaped by large-scale atmospheric processes – including frontal structures, slow-moving low-pressure systems, and Vb cyclones (van Bebber 1891) – all of which can persist for several days and generate widespread, topographically modulated precipitation. As described in Section 3.1, this reasoning can be substantiated by the main findings of our previous study, indicating that short-duration HPEs are closely linked to small-scale convective processes that can develop under a relatively wide range of circulation conditions, while long-duration HPEs are typically associated with more persistent cyclonic circulation patterns (Palarz et al. 2024). Moreover, the same study also revealed comparable spatial patterns of HPEs, despite discrepancies in the data and methods applied. Specifically, the Catalogue of Radar-based Heavy Rainfall Events, used in that analysis, is based on reprocessed, rain gauge-adjusted data from the DWD radar network and – by applying the peak-over-threshold method – identifies HPEs lasting between 1 hour and 3 days for the period of 2001 onwards. Yet, both studies indicate that short-duration HPEs are relatively evenly distributed across Germany, while long-duration HPEs increasingly reflect the influence of topography, predominantly affecting upland and mountainous regions. Similar conclusions were also drawn by Lengfeld et al. (2020), who analysed the comparable radar-based data from the period 2001-2018 and found that HPEs lasting between 1 and 4 hours show a uniform distribution across various topographical conditions. However, a detailed comparison of those studies remains challenging due to the differing characteristics of station- and radar-based precipitation data. A promising future research direction lies in integrating the strengths of both data sources – combining the accuracy and long observation coverage of station data with the spatial completeness of radar data – while minimising their respective limitations. Some initial efforts in this direction are already underway within our research group, including the development of a hybrid version of KOSTRA-DWD, which aims to combine station- and radar-based data to produce robust heavy precipitation statistics for Germany.

The duration-dependent nature of HPEs is further reflected in their long-term variability. Positive trends prevail across nearly all durations; however, several sources of uncertainty can limit the robustness of their interpretation. In particular, short-duration AMPTs are especially prone to inhomogeneities resulting from artificial shifts induced by changes in station settings – most notably the transition from analogue to digital measurement systems – with nearly half of the 5-minute AMPTs exhibiting abrupt jumps identified using the Akaike Information Criterion. Furthermore, the direction and statistical significance of the monotonic trends remain sensitive to the start year used in the trend analysis, underscoring the importance of both the length and positioning of the investigation period. Nonetheless, for durations between 1 and 7 hours, the fraction of stations exhibiting positive trends prevails across most start years, whereas for durations between 3 and 7 days, the fraction of stations with positive and negative trends is more balanced, with some shorter investigation periods even showing a slight tendency towards negative trends. Yet, statistically significant trends remain relatively rare across all durations and periods

considered – typically not exceeding 15 % for positive and 5 % for negative trends. At least to some extent, these findings are consistent with the results presented by Scherer et al. (2016), Zeder & Fischer (2020), and Bauer & Scherrer (2024), and align with the overall global tendency of around two-thirds of stations exhibiting positive trends in 1-day AMPTs (Westra et al. 2013, Sun et al. 2021). Also, Zeder & Fischer (2020) pointed to a pronounced intensification of 1-day AMPTs, with

430 predominantly positive trends, of which only around 12 % were statistically significant, while the fraction of significantly negative trends remained below 2 %. On the other hand, Bauer & Scherrer (2024) emphasized the duration-dependent nature of the monotonic trends across Switzerland, concluding that for the period 1981-2023, AMPTs of short durations (from 10 minutes to 3 hours) exhibit positive trends, while the trends gradually decrease with increasing duration and become negative for AMPTs of one day or longer. Nonetheless, our study also highlights key data-related challenges that must be addressed to

435 enable more reliable trend analysis. As precipitation data with high temporal resolution are prone to inhomogeneities resulting from artificial shifts induced by changes in station settings, there is a pressing need for further development and comprehensive comparison of data homogenisation methods tailored specifically to heavy and extreme weather and climate events. This methodological gap appears to have received relatively little attention in the literature and may help explain the absence of a homogenisation stage in some studies on HPEs, including those by Scherer et al. (2016), Zeder & Fischer (2020), and Bauer

440 & Scherrer (2024), where such procedures were also constrained by limited availability of station metadata. A further challenge lies in the demonstrated sensitivity of the monotonic trends to the length and positioning of the investigation period, which underscores the need to further extend data series – particularly through the digitisation of historical precipitation data with high temporal resolution. Together, these two efforts can substantially advance our understanding of HPEs – by improving knowledge of their dynamics and strengthening the statistical basis for trend analysis – thereby supporting evidence-based

445 climate adaptation strategies, as well as more effective operational monitoring and early warning system.

Code and data availability

The original precipitation time series used in this study are subject to various data access restrictions and therefore cannot be made publicly available in their entirety. Nonetheless, large parts of these data are publicly available via the Climate Data Center of the Deutscher Wetterdienst at https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/.

450 Additional precipitation data, along with associated metadata, can be obtained from the responsible partner institutions upon reasonable request and subject to the applicable data use regulations.

The annual maximum precipitation totals, together with the corresponding model selection results based on the Akaike Information Criterion (AIC), were derived from the original precipitation time series using the R package Nextreme available at https://github.com/DWA-A-531/Nextreme. To further support reproducibility of the analyses presented in this paper, the

455 derived data products – specifically the AMPTs, the associated AIC-based model selection results, and the station metadata – as well as the R code required for data processing, statistical inference, and figure generation, are publicly available at Zenodo under https://doi.org/10.5281/zenodo.18606227.

Author contributions

Conceptualization: AP, TJ, JO, TD. Data curation: AP, TJ. Formal analysis: AP, TJ. Funding acquisition: TJ, TD, FK.
460 Methodology: AP, TJ, JO. Project administration: TJ, TD, FK. Supervision: TJ, TD, FK. Visualization: AP. Writing – original draft: AP. Writing – review & editing: AP, TJ, JO, TD, FK.

Competing interests

The authors declare that they have no conflict of interest

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