Analysis of diurnal, seasonal, and annual distribution of urban sub-hourly to hourly rainfall extremes in Germany

Nasrin Haacke and Eva Nora Paton

ABSTRACT

The timing of short extreme rainstorm, which was usually thought to occur on midsummer afternoons, was investigated to improve future mitigation options for infrastructure and safety from localised flash flooding. Using a peak-over-threshold approach, the timing of 10- and 60-min extreme events was filtered from high-resolution rainfall series assessing diurnal, seasonal, and annual distributions and analysed for spatial variations and prevailing atmospheric circulation types (CTs). The diurnal distribution showed a clear deviation from that of the entire rainfall regime. A complex spatial pattern was identified with distinct timing signatures of storms in the northern (mostly afternoon) and southern regions (a bimodal distribution with a second peak in the early morning) of Germany and a more homogenous diurnal distribution of events across the central regions. Most storms occurred in summer, but 42% of 10-min events occurred outside the summer months (June–July–August). A distinct annual clustering of extremes was identified, which varied distinctly between the 10- and 60-min extremes, indicating that the sub-hourly and hourly events were far from running conterminously. The timing of extreme events on the investigated time scales was not dominated by the occurrence of specific CTs in most cases, suggesting that other factors control these extremes.

Key words | annual variation, circulation types, diurnal variation, extreme rainstorms, seasonal variation, sub-hourly rainfall

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HIGHLIGHTS

- Knowledge about exact timing is essential for urban water management, as these events cause damage at different spatial scales.
- Information on diurnal timing may provide fire brigades and traffic wardens with a clear picture, and seasonal street cleaning could be optimised.
- Timing is important for the planning of scientific monitoring.
- Categorised atmospheric circulation patterns can be used as the first trend indicator for risk assessment.

doi: 10.2166/nh.2021.181

INTRODUCTION

The trend behaviour of daily rainfall extremes has been well studied with a consensus on a significant but regionally varying upward trend in their occurrence (Westra *et al.* 2014; Barbero *et al.* 2019). Fewer studies have analysed hourly or sub-hourly heavy rainstorms due to the general lack of adequate, high-resolution rainfall series over longer periods. Several time-series analyses (De Toffel *et al.* 2008; Müller & Pfister 2011; Guerreiro *et al.* 2018; Kendon *et al.* 2018) have provided evidence on the amplification of rainfall extremes on hourly and sub-hourly timescales over the last two to three decades. Researchers also estimated sub-daily extreme rainfall intensity to change to a greater degree than daily ones towards the end of this century, as atmospheric temperature increases under climate change (Berg *et al.* 2013; Westra *et al.* 2014; Morrison *et al.* 2019). Surprisingly, little is known about the timing of the hourly to sub-hourly rainstorm events for any timeline (day, season, and year). Storms in Central Europe are thought to occur mostly in the late afternoon and to a lesser extent in the late (Meredith *et al.* 2019) or early morning (Ghada *et al.* 2019) and during the summer months (Jacobeit *et al.* 2017; Hofstätter *et al.* 2018; Ghada *et al.* 2019); however, the extent of their occurrence at other times during the day or year has not been studied yet. A similar knowledge gap exists regarding their annual incidence: Are there years with event clusters and others with hardly any events?

The shorter, sub-hourly rainfall extremes are considered problematic for urban water management as their daily counterparts, but for different reasons. Daily extremes can result in a partial or complete failure of urban drainage systems and repeated sewage overflows and urban river flooding often, which affects the entire city area (Fletcher *et al.* 2013). Sub-hourly to hourly extremes cause damage at different spatial scales: blocking, clogging, or overflowing of gutters frequently results in immediate, very localised flooding (Glaser & Stangl 2004; Arnbjerg-Nielsen 2006) which directly impacts the safety of pedestrians, traffic, and infrastructure. The high kinematic energy of the short extremes results in increased splash erosion and leaching of pollutants from abrasive sources such as building facades (Blocken *et al.* 2013; Bollmann *et al.* 2016). Combined with high first-flush concentrations from polluted street surfaces (Poudyal *et al.* 2016), they produce a highly concentrated pollution load sewage overflow into urban rivers.

Knowledge of the timing of the trigger events is essential to make the resulting nuisances manageable today and in the future. Information on diurnal timing may provide fire brigades and traffic wardens with a clearer picture of emergency response. Seasonal street cleaning routines can be optimised to minimise the clogging of gutters from various sources, such as organic litter production, which is known to be highly seasonal (Duncan 1995) and peaks when trees bloom and shed their leaves (in moderate climates normally in April/May and autumn, respectively). Knowledge of the likely timing of extremes is also essential for the planning of any future scientific monitoring campaign that may aim to quantify the dynamics of urban flash floods and diffuse pollution *in situ* (De Vitry *et al.* 2017).

The objective of this study is to address the current knowledge gap in the timing of short and heavy rainstorms. For a set of 22 urban centres, we selected the largest 10- and 60-min extreme events exceeding a predefined threshold. We then assessed their (1) diurnal distributions, (2) seasonal distributions, and (3) annual distributions over the past 20 years across Germany. Sub-hourly trend analysis was hampered until early 2000, when an increasing number of rainfall stations provided sub-hourly information (Brieber & Hoy 2019). This study was limited to 22 stations with adequate data quality since 2000 from urban regions homogeneously distributed over Germany. The resulting analysis period of 20 years is considered too short for reliable trend analysis and appropriate risk assessment concerning changing climate dynamics, such as increased heat waves (Fenner *et al.* 2018), which might drive very localised convective rainstorm patterns. However, we additionally categorised large-scale atmospheric circulation patterns (CPs), which co-occurred with extreme events, as a first trend indicator for future risk assessment.

Although studies presented here are for urban regions across Germany, this study also presents sorting methods and corresponding R routines, which can be readily transferable to other regions in Europe or beyond, where the timing of sub-hourly extremes is, to the best of our knowledge, equally understudied.

DATA AND METHOD

Study area

Germany is in the temperate climate zone in the transition zone between the maritime climate of Western Europe and the continental climate of Eastern Europe. Weather is dominated by the prevailing circulation types (CTs) in this transition zone and leads to the following climatic differentiations in Germany: (1) oceanic climate from the Atlantic in the west, (2) maritime climate in the north, (3) continental climate in the east and southeast, and (4) subtropical climate in the southwest.

Data availability

A total of 22 urban meteorological stations with precipitation records for 10- and 60-min aggregation times (representing 10- and 60-min events) were available from the German Weather Service (Climate Data Center) for the period 2000–2019, which fulfilled data consistency standards (less than 10% of missing data) and a homogenous distribution across Germany. One hour of no precipitation was chosen as a separator for two events to ensure independence from events. Information about the prevailing CTs and CPs after Hess & Brezowsky (1969) was provided in daily resolution by the German Weather Service.

Threshold selection

The IPCC (2012) defines a climate extreme as the occurrence of a value of a climate variable above (or below) a threshold value near the upper (or lower) end of the range of observed values of the variable. For the selection of extremes (extreme precipitation in this study), three conceptual approaches exist: the peak-over-threshold approach, the percentile-based approach, and the block maxima approach. The peak-over-threshold approach considers all values exceeding a certain threshold, i.e. a fixed threshold with a specifically associated impact (Sulikowska & Wypych 2020). Thresholds can vary depending on the geographical context, researcher or manager goals, or other factors (McPhillips *et al.* 2018). The difficulty of using this approach lies in the choice of threshold.

Percentile-based thresholds can be derived from statistical cumulative density functions generated from the observed data or some conceptual distributions for precipitation extremes (such as generalised extreme value) and define a given part of the observations (e.g. upper 10, 5, and 1% if using the 90th, 95th, or 99th percentile) as ‘extreme’. This approach is limited by the fact that the frequency of occurrence is assumed to be known and that identified extremes are not necessarily ‘extreme’ because of their impact (IPCC 2012; Sulikowska & Wypych 2020). The block maxima approach consists of dividing the observation period into non-overlapping periods of equal size (i.e. weeks, months, seasons, and years) and restricts attention to the maximum observation in each period (Gumbel 1958). The new observations created thus follow an extreme value distribution. By using this approach, however, relevant high observations may be ignored, and some lower observations are retained.

In this study, the peak-over-threshold approach was favoured as it allows the identification of events by a certain value of interest, without ignoring relevant events or including irrelevant events. It also provides a regional comparison of actual rainstorm magnitudes entailing urban flash flood hazards across Germany for the same rainfall depth, intensity, and duration. A fixed threshold will also allow a subsequent nationwide coordinated approach for the testing and planning of mitigation measures.

Extreme events were extracted using a threshold of 10 mm for 10-min and 20 mm for 60-min extreme events. Both thresholds were derived from recent studies on sub-daily extreme rainfall by Peterson (2005), Zhang & Zhai (2011), and Westra *et al.* (2014) and were shown to have a specific impact on urban flooding by Guerreiro *et al.* (2018). By using these thresholds, a total of three hundred and nine 10-min storms and one hundred and eighty-five 60-min storms were identified at the 22 stations within the last 20 years.

Different total numbers of events were identified for the stations varying between three 10-min (six 60-min) events for List auf Sylt and seventeen 10-min (twenty-eight

60-min) events for Munich. An apparent increase in storm number is evident from north to south for both durations (Figure 1); no clear variation in storm number was found from west to east.

Atmospheric CTs and CPs

Atmospheric CTs summarise the wind direction, humidity, pressure, and thermal properties of air masses, describing the fundamental processes that link large-scale atmospheric conditions with near-surface climate phenomena (Ghada *et al.* 2019). One of the defining features of CTs is the wind direction of the air mass advection as summarised in Table 1. The table also comprises the atmospheric CPs associated with each CT (see Werner & Gerstengarbe (2010) for an in-depth description of each CP). Each sampled storm event was assigned to the prevailing atmospheric CTs and CPs on that day (Figure 1). All major CTs and a total of

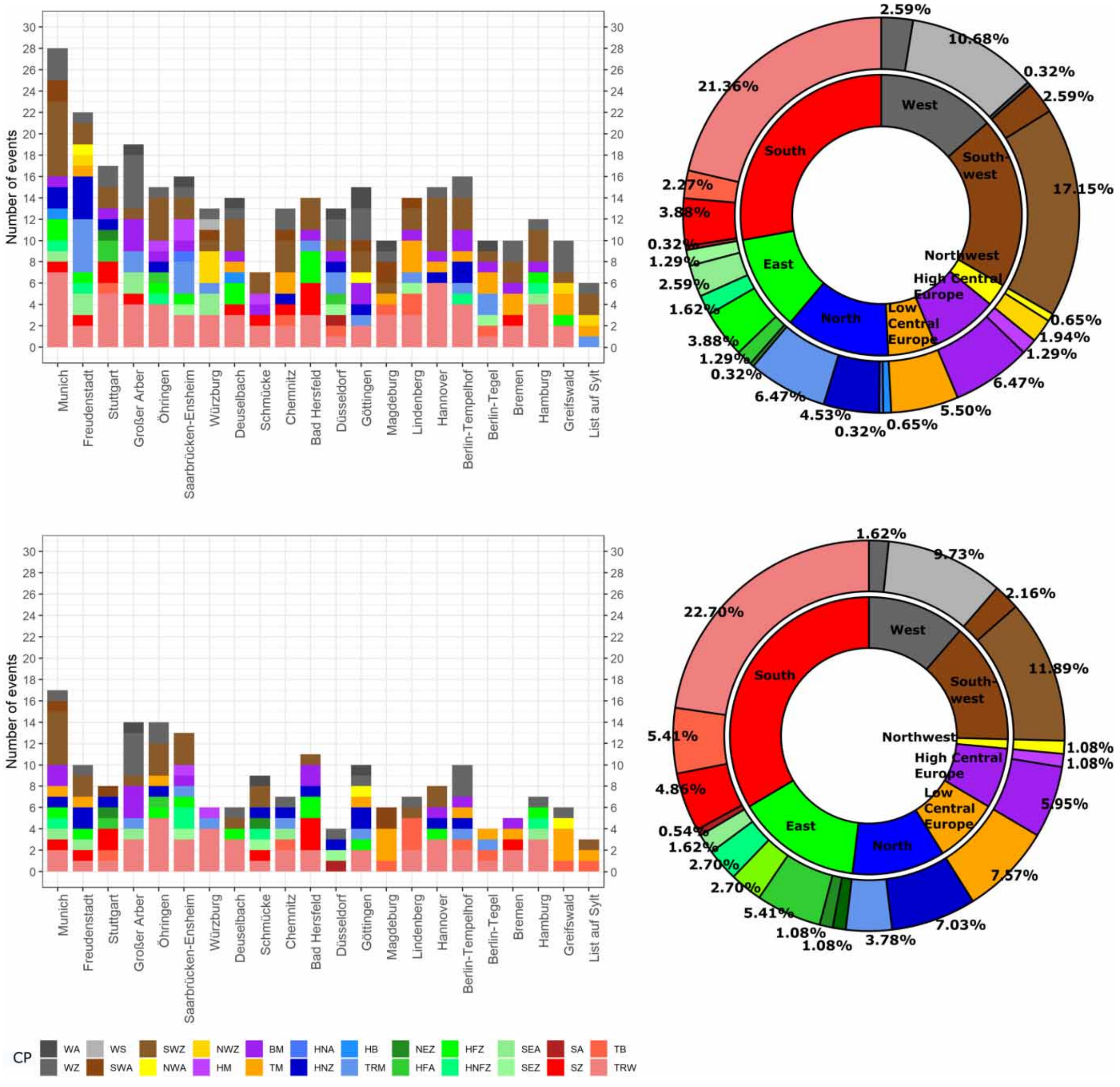

Figure 1 | Frequency distribution of extreme 10-min (upper row) and 60-min (lower row) rainfall events at all stations sorted from south to north. Circular plots show the percentage of CTs and CPs that co-occurred during the storms. All acronyms are explained in Table 1.

Table 1 | Large-scale atmospheric CTs and CPs according to Werner & Gerstengarbe (2010)

Large-scale atmospheric CT	Atmospheric CP
West	WA: westerly, anticyclonic WZ: westerly, cyclonic WS: westerly, south-shifted
Southwest	SWA: south-westerly, anticyclonic SWZ: south-westerly, cyclonic
Northwest	NWA: north-westerly, anticyclonic NWZ: north-westerly, cyclonic
High Central Europe	HM: high over Central Europe BM: zonal ridge across Central Europe
Low Central Europe	TM: low over Central Europe
North	HNA: Icelandic high, ridge Central Europe HNZ: Icelandic high, trough Central Europe TRM: trough over Central Europe
East	NEZ: north-easterly, cyclonic HFA: Scandinavian high, ridge Central Europe HFZ: Scandinavian high, trough Central Europe HNFZ: high Scandinavian Iceland, trough Central Europe SEA: south-easterly, anticyclonic SEZ: south-easterly, cyclonic
South	SA: southerly, anticyclonic SZ: southerly, cyclonic TB: low over the British Isles TRW: trough over Western Europe

This table shows patterns identified in this study only.

23 (20) CPs were detected to co-occur during the 10- and 60-min extreme storms. Most storms occurred with air mass inflow from the southern directions (28 and 34%, with a trough over Western Europe (TRW days) being the most dominant pattern), followed by air masses approaching from south-western (20 and 14%) and western (14 and 11%) directions. There appears to be no difference regarding CTs co-occurring with extreme events between the northern part (potentially influenced by large water bodies) and the southern part of Germany (influenced by the Alps) (Figure 1).

Analysis tools

Statistical analysis was performed using the statistical software R (R Development Core Team 2018). An R routine for the automatic identification, calculation, and visualisation of diurnal, seasonal, and annual extremes for multiple time series was developed and is available for the research community under an R Cran GUI public licence.

RESULTS

Diurnal distribution of heavy storm events

The majority (79%) of storm events occurred in the afternoon and evening (12:00–22:00) with peaks around 15:00 and 16:00/20:00 for the 10- and 60-min extreme events, respectively (Figure 2). A considerably smaller amount occurs in the first half of the day homogeneously distributed over the early hours. Median values of diurnal timing for individual stations (red marks in Figure 2) vary significantly between individual stations ranging between 9–17:00 (10-min) and 10–20:00 (60-min) storms. Stations can be grouped into three dominant patterns of timing: (1) an accumulation of events over 12 h, emerging predominantly in the afternoon and evening (10 of 22 for 10-min and four of 22 for 60-min); (2) a bimodal distribution of events in the early morning (more than one event) and afternoon with a higher and denser concentration in the afternoon (four of 22 for 10-min and eight of 22 for 60-min); and (3) a homogenous distribution of events over 24 h (seven of 22 for 10-min and 10 of 22 for 60-min).

The spatial distribution across Germany of the three timing patterns (Figure 3) reveals that the north-western region (e.g. Hamburg, Bremen, Hannover, and List auf Sylt) has most of its events in the afternoon and evening, and almost no precipitation in the early hours (blue pie charts in Figure 3). The southern region (e.g. Munich, Freudenstadt, and Groß Arber) is dominated by the second timing pattern with two peaks: the major one being in the evenings (yellow pie charts). More homogenous distribution of events around the clock can be observed in the west and centre of Germany (red pie charts). However, deviations of these spatial patterns of timing were noticeable across the middle section of Germany.

Diurnal timing cannot be linked directly to specific prevailing atmospheric CTs (presented by colour coding in Figure 2), i.e. none of the CPs dominate during early

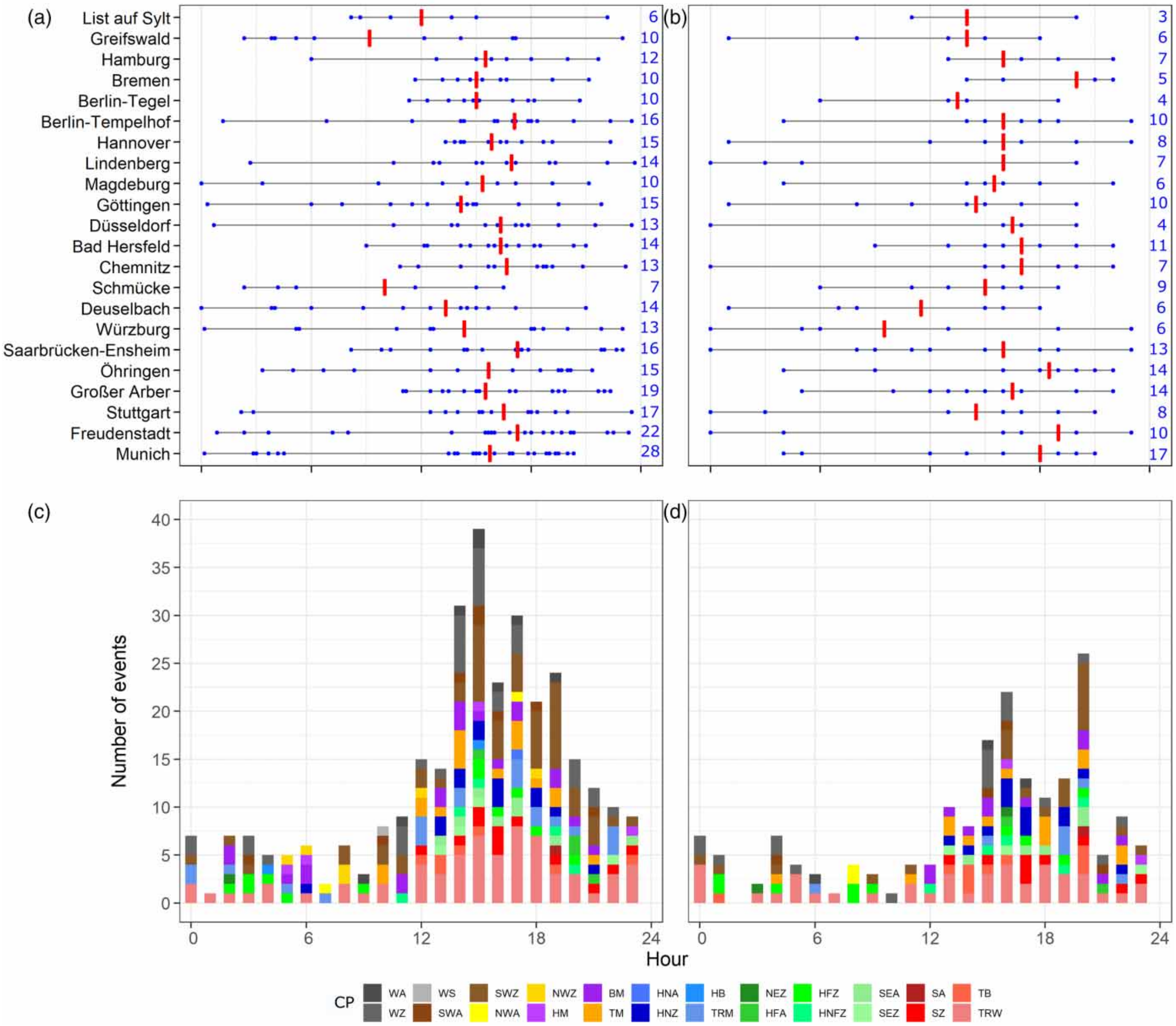

Figure 2 | Diurnal distribution of short-duration heavy storm events across Germany of (a) 10-min duration (≥10 mm) and (b) 60-min duration (≥20 mm). Red mark represents the median, and the number of events is given in blue. Hourly frequency distribution, including information about prevailing CTs and CPs, is shown for 10-min events in (c) and 60-min events in (d). All acronyms are explained in Table 1. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2021.181.

morning or afternoon storms. Heavy rainstorms co-occurred around the clock with eastern, southern, south-western, and western CTs. However, it is notable that the low central type co-occurred mostly with storms during the afternoon, but not during night and morning hours. For 10-min events, the northwest type only co-occurred during the day, and for the 60-min storms, the north and high central east type only co-occurred in the afternoon and evening.

Storms associated with the most frequent CT, the south-western circulation, tended to co-occur mostly with the circulation pattern SZ (cyclonic southerly) in the afternoon. However, the TRW (trough over Western Europe) pattern co-occurred with storms around the clock.

Seasonal distribution of heavy storm events

In total, 58% (10-min) and 83% (60-min) of storms occurred in the summer months (June, July, and August) with a median date on the 9th of July (Julian day 190) and the 11th of August (Julian day 223) for 10- and 60-min events, respectively (Figure 4). Most heavy rainfall events (84% of 10-min and 99% of 60-min events) occurred between May

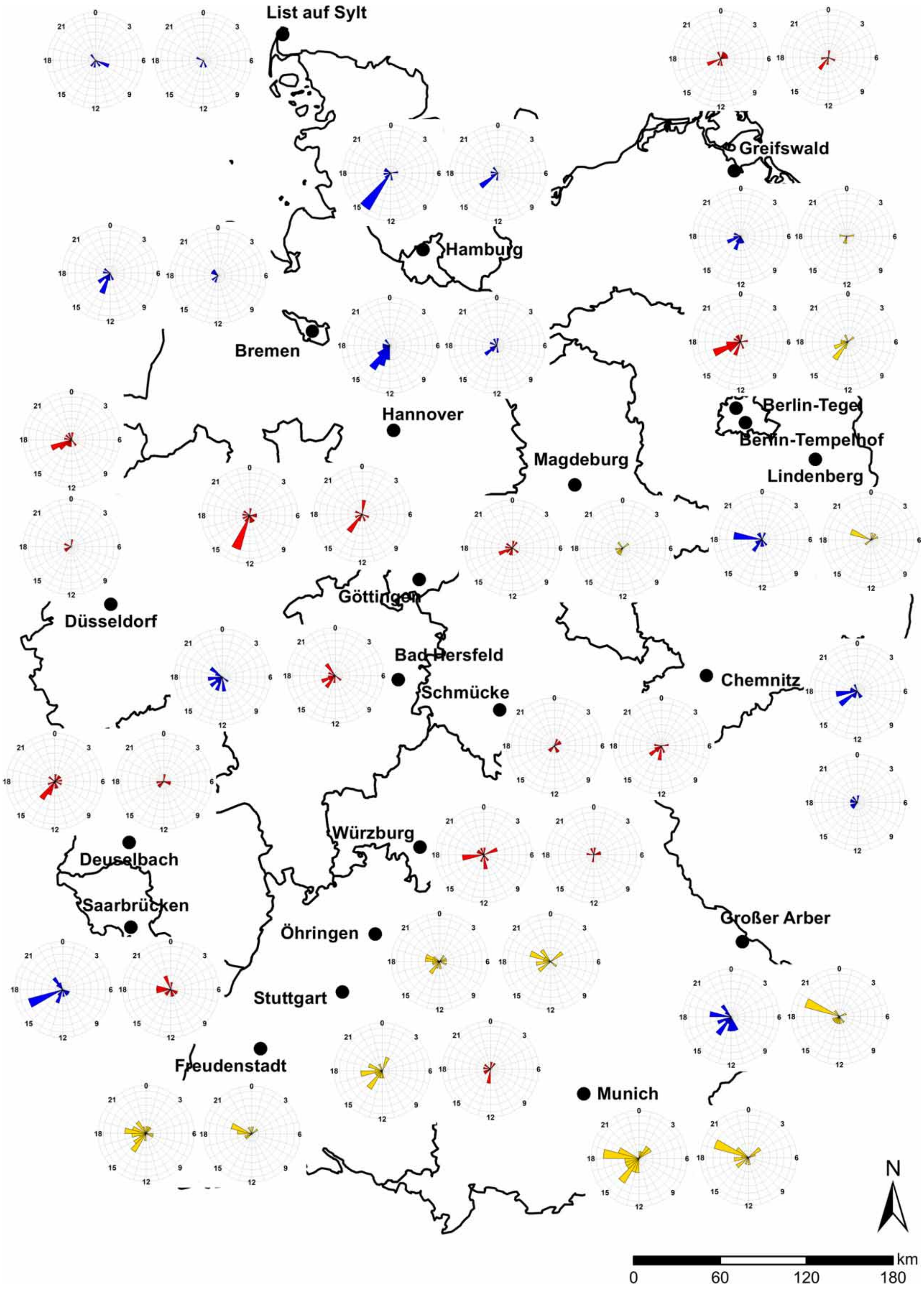

Figure 3 | Diurnal frequency distribution of short-duration heavy storm events across Germany. The pie chart represents 24-h clock, whereby left pie charts represent 10-min events (≥10 mm), and right pie charts represent 60-min events (≥20 mm). Colours represent classifications: blue = accumulation of events over 12 h, yellow = bimodal distribution, and red = homogeneous distribution. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2021.181.

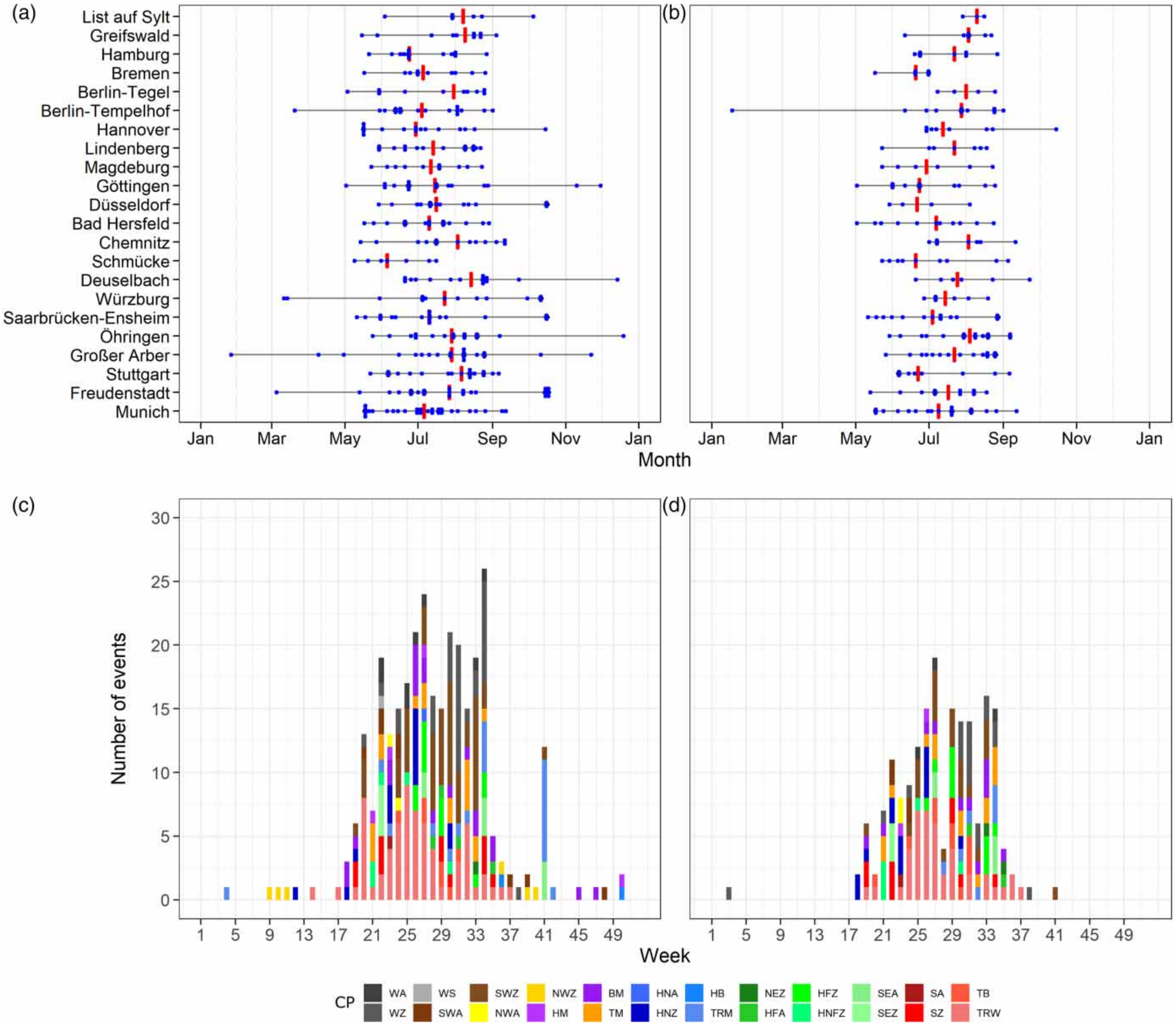

Figure 4 | Seasonal distribution of short-duration heavy storm events across Germany of (a) 10-min duration (≥10 mm) and (b) 60-min duration (≥20 mm). Red mark represents the median. Weekly frequency distribution, including information about prevailing CTs and CTs, is shown for 10-min events in (c) and 60-min events in (d). All acronyms are explained in Table 1. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2021.181.

and September, whereas a significantly smaller proportion (for the 60-min event, only one event at the station in Berlin) occurred in the autumn and winter months from October to April. Stations, with a wider seasonal range of the occurrence of 10-min events, are mainly located in the southern part of Germany.

The seasonal timing of heavy rainstorm events shows some interesting co-occurrence patterns with CTs. Outliers, outside the summer months, co-occur mostly with north-western and high central CTs. For the 10-min event, there exists a strong relation between northern circulation and 10-min events in the autumn months. During the entire summer months, all CTs except the north-western type were detected to co-occur during individual storms; the western type tends to be more pronounced in the second summer half.

Annual distribution of heavy storm events

For the 10-min events, the largest number of storms occurred in the years 2005 and 2017 (23 and 24 storms, respectively). In 2015, the smallest number of storms (six) was identified. The average annual storm number was around 15; no trend was detected over the 20 years of data.

For the 60-min events, the largest number of storms were consecutively detected from 2016, 2017, and 2018 (14, 14, and 19 storms, respectively), whereas in the years 2004 and 2015, only three and two storms occurred (Figure 5). The plot of annual events in Figure 5(d) shows a clear trend. A Mann–Kendall trend test indicated an increase in the occurrence of storm events (Mann–Kendall test statistic τ: 0.491, $p < 0.01$, $N = 20$) with a statistically significant trend slope (after the Theil–Sen approximation) of 0.5%, equivalent to an increase of 0.5 events/year or 10 events over the investigation periods. The trend test was carried out over a short period of 20 years, so care needs to be taken when interpreting these results.

The annual variations of 10- and 60-min events differ notably, not only concerning their trend behaviour but also their annual clustering. In the years with the most 60-min events, we detected average or below-average numbers of 10-min events and *vice versa*. This effect is particularly visible for the year 2004, where twenty 10-min but only three 60-min extreme events were detected. The large

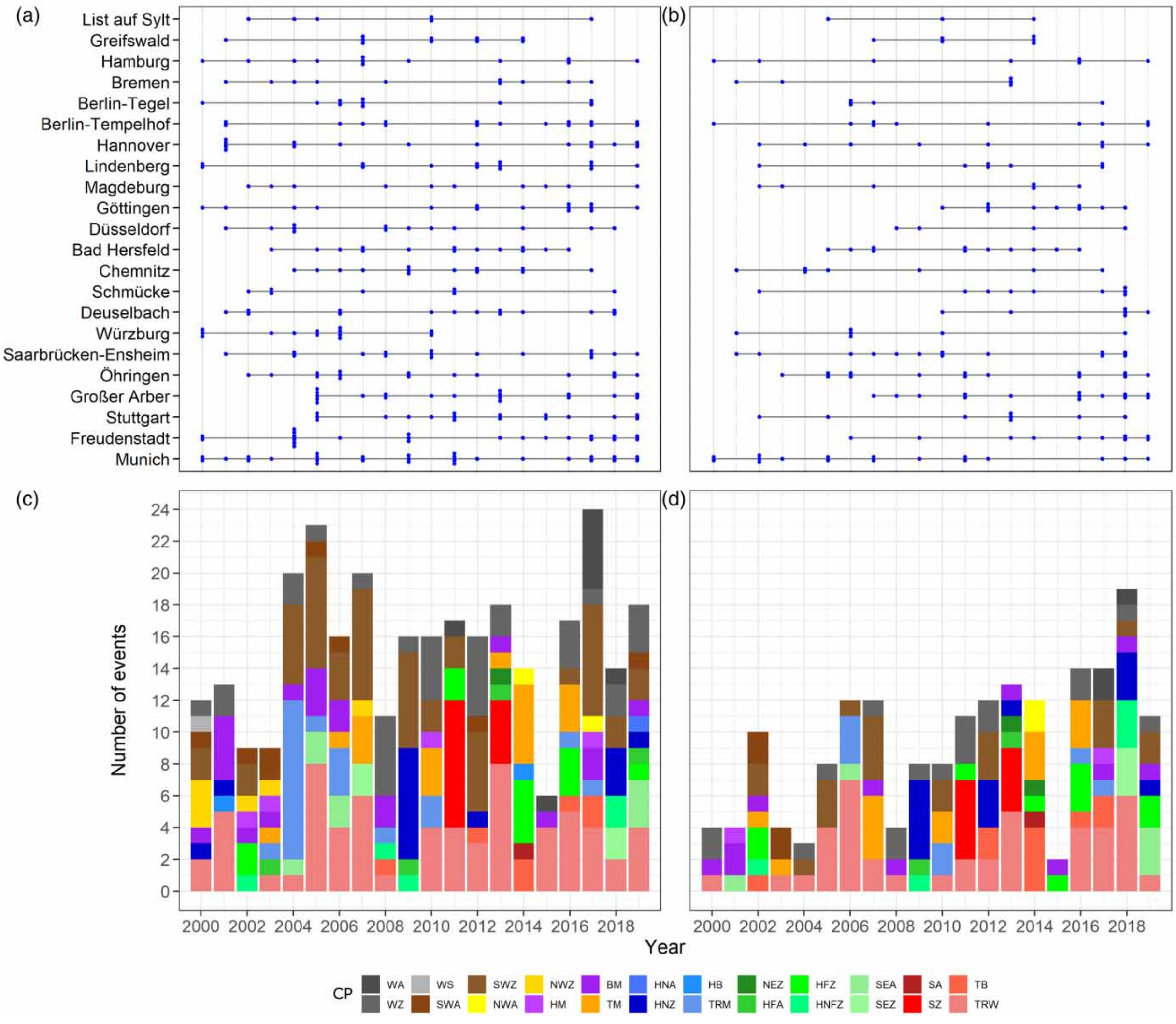

Figure 5 | Annual distribution of short-duration heavy storm events across Germany of (a) 10-min duration (≥10 mm) and (b) 60-min duration (≥20 mm). Red mark represents the median. Annual frequency distribution, including information about prevailing CTs and CPs, is shown for 10-min events in (c) and 60-min events in (d). All acronyms are explained in Table 1. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2021.181.

number of storms that occurred in 2018 is particularly interesting, as it was a year mostly famous for being particularly dry over the entire summer months throughout Germany.

In the years with the largest number of storm events, storms were associated with a wide range of different CTs. The 10-min extreme storms in 2005 and 2017 co-occurred mostly with southwest and southern CTs, whereas the 60-min extreme storms in the years 2016, 2017, and 2018 were associated with CTs in all directions.

DISCUSSION

Timing of extreme events

The *diurnal* distribution was quantified in this study for extreme events only. In contrast, many previous studies on diurnal distributions quantified the frequency and amount distribution for the entire (hourly) rainfall regime, including low-to-moderate hourly rainfall values (e.g. Yaqub *et al.* 2011; Mandapaka *et al.* 2013; Ghada *et al.* 2019). Other studies used a percentile-based approach looking at the most extreme events only (e.g. Meredith *et al.* 2019). These studies confirmed a peak in rainfall amount in the late afternoon to late evening hours for study areas in Central Europe. However, a direct comparison of their results with the here-used peak-over-threshold selection of extreme events is limited. Ghada *et al.* (2019) investigated the geographical patterns associated with the diurnal cycle across Germany. They did not find differences in peak distributions regarding latitude, longitude, and elevation for average hourly rainfall (but larger differences with rainfall frequency). However, their study included all hourly rainfall amounts >0.2 mm, which does not compare well to our threshold value of 20 mm (for 60-min events) for event selection.

This study showed that the diurnal distribution of extreme events does not follow the diurnal distribution of rainfall if all and not only extreme rainfall events were considered. Instead, we were able to distinguish more complex spatial patterns with distinct timing signatures of storms that differed between the northern (mostly afternoon) and southern regions (a bimodal distribution with a second peak in the early morning) of Germany. The afternoon peaks are caused by classical convection mechanisms (Ghada *et al.* 2019). Whereas the morning peaks may be attributed to the accumulation of humidity at lower levels during the night and complex topography, for example, as found in southern Bavaria towards the Alps with distinct peaks in early morning storm events in Munich. Proximity to water bodies may result in a similar effect and explain the morning peak in the northeast (e.g. Greifswald at the Baltic Sea), but this explanation is not valid for the diurnal timing in the north-western part of Germany where no pronounced morning peaks were detected in most cases.

Our *seasonal* distribution of extreme events confirmed previous knowledge that storms occurred mainly during the summer months of June–July–August (Darwish *et al.* 2018; Ghada *et al.* 2019 for the UK). At the same time, our study showed that 42% of 10-min events (17% of 60-min events) occurred outside the summer months, most of them in May and September (26% of 10-min and 16% of 60-min events), and a smaller portion in the winter. A recent study by Darwish *et al.* (2018) identified a shift of extreme events from the summer to autumn months, which might lead to an intensification of event incidents. However, the total number of detected autumn extremes in this study was considered too small for trend analysis to yield reliable results.

To our knowledge, no studies have analysed the *annual* areal distribution of sub-hourly extremes across Germany or Europe over the last decades. A general trend increase of hourly extremes was detected by de Toeffel *et al.* (2008) and Müller & Pfister (2011) for extremes with durations from 1- to 30-min for individual station series, but neither study analysed the concurrence of extremes in specific years. We found a statistically significant trend increase of the 60-min storm events across Germany; however, this result should not be overvalued as the analysis was based on only 20 years of data, considered too short for climate-relevant trend analysis.

The fact that the annual variations and trend behaviour of 10- and 60-min extreme events differed notably suggests that the sub-hourly temporal scaling cannot be neglected. Distinctively different annual behaviours, as we detected for several years, for example for 2004, when nearly seven times more 10-min events occurred, confirm that the 10- and 60-min extremes are far from running conterminously.

The large number of storms that were detected in 2018 are particularly interesting. According to Thompson *et al.* (2020), the 2018 drought was one of the longest and hottest recent European droughts with spring and summer precipitation falling below 40% of normal amounts. Concurrently, a higher-than-average number for the 10-min and the largest number of 60-min extremes occurred in this year. In similar hot and dry summers of 2004, 2010, 2013, and 2015 (Hanel *et al.* 2018), no increased numbers of storm events were detected; the opposite was true for 2015, with the smallest overall number of events. A detailed explanation of the underlying process mechanisms is pending.

Atmospheric CTs and extreme events

Atmospheric CTs govern rainfall emergence. However, the correlations between CTs and rainfall incident and timing are more pronounced for low-to-moderate rainfall events rather than extreme events (Ghada *et al.* 2019). Our findings partly confirmed the results by Brieber & Hoy (2019). They found that sub-hourly extremes (15-min events) in Central Germany are frequently generated by warm, humid continental air from Southern and Eastern Europe as well as trough conditions over Western Europe. Beyond that, we saw that CTs from any wind direction might prevail during the selected extreme events, which suggests that other dominant factors influence the convective precipitation occurrence of short extremes as well.

The occurrence of specific CTs did not dominate the timing of extreme events on the diurnal, seasonal, and annual scales. Heavy storms in the afternoon frequently occurred with warm and moist air from south-western directions, as was estimated in the study by Ghada *et al.* (2019) for any hourly rainfall intensities. Some distinct patterns exist between the co-occurrence of northern and central CTs during the day and night storms and for autumn storms, but the number of those cases was too small to derive a clear connection.

The diverse co-occurrence of CTs with identified 10- and 60-min extreme events is remarkable and requires further investigation. High-resolution (convection-permitting) regional climate models, such as those used in Meredith *et al.* (2019) or the analysis of atmospheric circulation anomalies versus soil moisture–temperature coupling as done by Liu *et al.* (2020), could be employed to study the overall extreme climatic behaviour, for example, for the year 2018, which was particularly dry and hot, and to show the largest areal number of 60-min storms. Only a process-based approach, beyond the scope of this study, will allow the identification of the underlying mechanisms that led to the generation of multiple CT-storm combinations that occurred in that year.

Future research and way forward

Three major areas of research on the timing of extremes remain: the modulation of extreme event occurrence due to CTs, orography, large water bodies, and urban influences (e.g. reported by Lorenz *et al.* 2019); a potential change of timing due to climate change; and the temporal scaling of sub-hourly rainfall.

The modulation of extreme event occurrence cannot be addressed using the available rainfall point data from individual stations. Especially for large cities, which are considered to have an effect on rainfall distribution, more than one point data is required. In this study, two stations were selected for the city of Berlin. Differences can be seen at all timescales; however, a radar-based time-series analysis as described by Mandapaka *et al.* (2013) or Panziera *et al.* (2018) would be better to assess urban and regional signals as a function of storm timing. Currently, homogeneous precipitation time series from radar systems are only available for a period of 16 years in Germany (Lengfeld *et al.* 2019).

For a stringent analysis of changes in extreme timing, much longer time series than 20 years are required, but normally not available in the necessary resolution. Longer rainfall series should also be analysed in uniform with other climate drivers of rainstorms, which showed a clear trend over the last one to two decades and are highly sensitive to convective dynamics such as increasing temperatures with more frequent heatwaves during the summer months (Fenner *et al.* 2018) and increasing the occurrence of westerly CTs (Plavcová & Kyselý 2013). If and how the changing dynamics affect the timing of extremes is not yet clear and beyond the scope of this study.

Finally, the temporal scaling of sub-hourly data needs further research. Whereas the diurnal timing of 10- and

60-min extremes was relatively similar, dissimilarities emerged regarding their annual and seasonal clustering. The distinct differences in timing indicate that the behaviour of hourly and sub-hourly extremes cannot simply be lumped together but need to be analysed separately.

During this analysis, it emerged that the selection of fixed time intervals of sub-hourly extremes may not be an adequate way of dealing with convective storms, as it also does not capture the essence of the entire storm behaviour. For subsequent analysis of short rainstorms relevant for a risk assessment of urban flash floods, we suggest against simply filtering for sub-hourly time steps with extreme intensities, but rather including the entire course of the precipitation hydrograph in the storm selection. Beside the average intensity, the categorisation of such sub-hourly extreme events should also include information on hydrograph shape, peak intensity and duration, and total rainfall amount. Furthermore, further research could include the investigation of changes in the timing of extreme rainfall in urbanised areas in comparison to rural areas.

CONCLUSION

This study sheds new light on the temporal distribution of short heavy rainfall extremes, whose timing cannot be simplified to summer afternoons. However, a complex spatial signature of storms regarding diurnal timing was discovered that differed between the northern (mostly afternoon) and southern regions (a bimodal distribution with a second peak in the early morning) of Germany. Although the most frequent occurrence of events was identified in summer, a significant number occurred between May and September depending on the region. Therefore, the traditional seasonal division of summer (June–July–August) may not be appropriate when analysing extreme events. We identified annual clusters for years with a particularly small and large number of events, but they were not identical for the two aggregation times. This discrepancy and the diverse co-occurrence of CTs require further research on the underlying mechanisms and driving forces of convective storm generation and initiation using, for example, high-resolution convection-permitting regional models for different geographic settings. For future work on the temporal scaling of convective extremes, we hypothesise that the 60-min events share more similarities with daily extremes than with 10-min extremes. We further suggest including the rainfall hydrograph of short extremes in future analysis to capture the essence of the entire convective storm behaviour.

ACKNOWLEDGEMENTS

This work was supported by the Deutsche Forschungsgemeinschaft as part of the research training group Urban Water Interfaces (GRK 2032). I thank Dr Nehls and Dr Otto for useful critiques and for reviewing this study.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 9 December 2020; accepted in revised form 1 February 2021. Available online 25 February 2021