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Brief communication: How extreme was the thunderstorm rain in Vienna on 17 August 2024? A temporal and spatial analysis.

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Abstract. On 17 August 2024, a single thunderstorm cell ~~in Vienna/Austrialed to a rainfall of~~ over Vienna, Austria, produced 107 mm ~~/2h at the weather station of~~ of rainfall within two hours at the "Hohe Warte" weather station, which has ~~been monitoring~~ recorded hourly precipitation since 1941~~-~~—one of the world's longest-running sub-daily precipitation time series~~at this temporal resolution. A comparison with other gauging stations in the area indicates that this amountof rainfall almost doubles~~. This amount, with an estimated return period of approximately 700 years, is nearly twice as large as the second-largest event ~~. A conservative estimate of the return period of this event is approx. 662 years. Full spatial analysiswas conducted on the~~ on record in the greater Vienna area. However, many events are missed by the station network, as shown by radar-based ~~INCA data set, showing that the 20-year return value on a grid cell level ranges between 28–69 mm/2h, further highlighting the rarity of this event.~~ data. The 100-year return values derived from these data range from 61 to 90 mm in two hours, indicating a slightly less extreme event than suggested by the station-only analysis. Although the extreme precipitation time series shows no significant statistical trend, conditioning the return period on average mid-tropospheric temperature reduces the return period from 700 to 300 years, suggesting that climate change increases the frequency of such events.

1 Introduction

On 17 August 2024, an extreme precipitation event occurred in the northwestern parts of Vienna, Austria. A total of 107 mm ~~fell~~ of rainfall was recorded within two full hours~~(and~~, including 94 mm in ~~one hour) at the~~ a single hour, at Vienna's Hohe Warte weather station in ~~Vienna, leading to~~ a loosely built-up residential area. The event triggered local flooding and ~~causing~~ resulted in one fatality (dpa, 2024). ~~The event set new~~ It also set new all-time records for the highest accumulation of 2-hour and 1-hour rainfall at Hohe Warte (GeoSphere Austria, 2024a). ~~Extreme precipitation events like this are expected to~~ Such extreme precipitation events have become more intense due to climate change (Haslinger et al., 2025) and are projected to intensify further, driven by increased ~~water holding capacity at a~~ saturation water vapor pressure at higher air temperature (Seneviratne et al., 2021). Quantifying the return ~~period~~ periods of such sub-daily events is ~~crucial for e.g.~~ critical for water management, e.g. for dimensioning wastewater drainage systems~~and water management in general~~. One obstacle in quantifying these extremes ~~often~~ is the limited length of hourly precipitation records. ~~The earliest records of~~ Systematic sub-daily precipitation ~~start~~ observations mostly began in the 1950s (Lewis et al., 2019), with ~~a few~~ only a few earlier exceptions (e.g. Hobart, Tasmania), ~~making robust estimates of precipitation extremes more challenging. The~~ which constrains the robustness of extreme precipitation estimates. The start of hourly precipitation measurements at Hohe Warte ~~date~~ dates back to 1941, providing a quality-controlled time series ~~,~~ that enables a more robust assessment of sub-daily precipitation extremes in Vienna.

The convective systems ~~associated with such heavy short-term precipitation are typically not only~~ that are responsible for these sub-daily precipitation extremes are typically short-lived ~~but also confined to small areas (~~and extreme rainfall is spatially confined to only a few km~~^{2}). In Germany between~~ ^{2}. This raises the question of whether existing networks of sub-daily rain measurements are sufficient to capture such small-scale events. Between 2001 and 2018, only 17.3% of radar-detected hourly heavy precipitation events ~~(above~~ > 25 mm ~~) detected by radar~~ in Germany were captured by the rain gauge station network (Lengfeld et al., 2020). ~~Across the Alpine region, there is about one station per 80-150 km^2 (Isotta et al., 2014), though this number has decreased in recent years due to improved radar coverage (Lewis et al., 2019).~~ In Austria, around 280 weather stations with sub-daily measurements are operated by GeoSphere Austria (GeoSphere Austria, 2024b), corresponding to one station per 300 km~~^{2}. However, the~~ ^{2}. The station density in Vienna is significantly higher with ~~7 stations in the city resulting in~~ seven stations located within the city limits, equating to one station per 60 km^2. Additionally, several stations ~~right outside~~ situated close to the city borders further increase the likelihood of thunderstorms ~~directly hitting a weather station.~~ being directly recorded by rain gauges.

~~Although station density in Vienna is significantly higher than in the rest of Austria or Germany, additional information from radar data is~~ Nevertheless, additional observations from weather radars are becoming increasingly important ~~(Lengfeld et al., 2020). The~~ in hydrology (Lengfeld et al., 2020). A key advantage of ~~radar is its~~ radars is their ability to provide full spatial coverage, ~~except where it is obstructed by topographical feature (Germann et al., 2022). In this context, radar data has proven effectiveness in estimating return levels~~ enabling the estimation of return levels even at ungauged locations (Panziera et al., 2016)~~and can further be adjusted with gauging stations to increase the accuracy of the radarestimates (Rosin et al., 2024)~~. By adjusting radar-derived precipitation estimates with in-situ gauge data, errors in purely radar-based rainfall estimates can be mitigated (Goudenhoofdt and Delobbe, 2009; Rosin et al., 2024). GeoSphere Austria's operational nowcasting tool, "Integrated Nowcasting through Comprehensive Analysis" (INCA) (Haiden et al., 2011)~~follows a similar approach , by combining~~ , follows this approach by combining a rainfall field derived from spatially interpolated surface station data with ~~weather radar data in such a way that the observations~~ a radar-derived precipitation field. The combined field is optimized so it matches the rain gauge measurements at the station~~locations are approximated~~'s locations, while the remote sensing data ~~provides~~ provide most of the spatial structure ~~for interpolation~~of the field.

The objective of this study is to quantify the exceptional nature of the 2-hour precipitation event in Vienna on 17 August 2024. ~~First, the event will be analyzed using the~~ To this end, we proceed in three steps: (i) analyzing the long-term ~~station~~ sub-daily precipitation record at Hohe Warte~~. Second, it will be compared to nearby~~ , (ii) comparing the event with observations from other stations in Vienna~~. Finally, the event will be examined spatially using the gridded INCA dataset. These~~ , and (iii) examining its spatial characteristics using the INCA data set. Our goals are guided by the following research questions:

- How extreme was the ~~precipitation event at Hohe Warte~~ event at Vienna Hohe Warte, considering the exceptional 84-year time series of hourly precipitation?
- What ~~is the return period~~ are the return periods of such an event ~~for~~ at other stations in the Vienna basin, and are there records of ~~any similar~~ comparable events in the neighboring time series?
- Can similar events be identified in the radar-based INCA ~~dataset~~ data set for Vienna?
- What are the estimated 100-year return levels of 2-hourly precipitation for the INCA data set~~for a return period of 20 years~~, and do they align with the station data?

2 Data and ~~Methods~~methods

The study area ~~covers~~ encompasses Vienna and its surrounding stations~~. The~~ , covering approx. 1700 km^2. This region has average annual precipitation ranging from 550 mm to 800 mm, with values increasing toward the Vienna Woods in the west (Isotta et al., 2014). The rain gauges used are operated by GeoSphere Austria and the hourly data is openly accessible through the web portal "GeoSphere Data Hub" (GeoSphere Austria, 2024a) (station metadata in Table S1 in the supplement). ~~These~~ Most of these semi-automatic weather stations ("TAWES") are classified as SYNOP stations. For each of the ~~eleven selected stations, the maximum~~ selected eleven stations we analyzed the complete available record - from the onset of hourly rainfall measurements through the end of 2023 - and derived the daily maximum of 2-hour precipitation ~~per day was computed to prevent~~ to avoid selecting multiple, auto-correlated ~~events from selecting multiple~~time steps within the same event. ~~The final year of each time series was 2023.~~

~~For spatially distributed fields, the precipitation analysis of the Integrated Nowcasting through Comprehensive Analysis (INCA) system is used (Haiden et al., 2011). The INCA data set is available on a 15-minute temporal timestep and a~~ As gridded precipitation field we used the analysis from the standard 15-minute INCA version. The data are available at a 1 x 1 km spatial resolution for the period 2004-2023. To ~~align with the~~ ensure consistency with hourly station data, the 15-minute ~~data was~~ values were aggregated to full ~~hours. Atmospheric data as~~ hourly totals (e.g., 00-01 UTC, 01-02 UTC). Furthermore, total precipitable water (PWAT~~) and cloud temperature~~ ; column-integrated amount of water vapor from the surface to the top of the atmosphere) and average temperature between the pressure levels 500 hPa and 700 hPa ("cloud temperature" as in Formayer and Fritz (2016)) were obtained from the ERA5 data set (Hersbach et al., 2020). ~~Extreme value analyses were conducted using the R (R Core Team, 2024) package (Gilleland and Katz, 2016) for all analyses except the station analysis of Hohe Warte, which was conducted with the Python package "pyextremes" (Bocharov, 2024). For stations with records shorter than 25 years, a peak over threshold approach~~

Extreme value analysis was ~~chosen, where the number of selected events was determined as three times the available years for each station. For all other stations and the INCA data set an annual maxima time serieswas used~~conducted by a peaks over threshold (POT) approach. Each time series (rain gauges and INCA) was limited to the months May to September, and the $k*nyear$ largest maximum daily 2-hour precipitation events were selected. We set $k=3$, and $nyear$ denotes the number of available years of the respective time series. Missing station values were permitted, as for ten stations the number of missing hourly values was below ~~five~~5 %. ~~The parameters of the generalized extreme value (GEV) distribution and the Generalized Pareto (GP) distribution were estimated by maximum likelihood (ML)and L-Moments. Confidence intervals were derived using a parametric bootstrap approach for the L-Moments estimates and a normal approximation for the ML estimates~~For the estimation of return periods, a regional frequency approach (RFA) was chosen (Hosking and Wallis, 1997), as preliminary results showed that this approach yields the most robust results compared to single-site estimates by L-moments or maximum likelihood. In the RFA framework, L-moments of the initial eleven stations were computed and weighted by the length of the station record for estimation of the (regional) parameters of the Generalized Pareto distribution (GPD). Three stations with large deviations from the regional L-moment estimates were discarded from the analysis to ensure a homogeneous study area. The 100-year return period for the INCA data set was computed using the index quantile function and weighting it by the mean of the POT-series for each grid cell. Confidence bounds (2.5 %, 25 %, 75 %, 97.5 %) for the eight remaining stations and each INCA grid cell were estimated by a Monte-Carlo simulation. Finally, a distributional Bayesian regression was set up to account for a possible increase in precipitation extremes conditional on cloud temperature. All statistical analyses were performed in R (R Core Team, 2024) using the packages lmomco (Asquith, 2024), lmomRFA (Hosking, 2024), and bamlss (Umlauf et al., 2018).

For the event description, ~~HRV~~ High-Resolution Visible (HRV) satellite images from MSG satellites (Schmetz et al., 2002) and weather radar ~~reflectivity~~ data (reflectivity and Doppler radial velocity) from the Austrian radar network operated by Austro Control (Kaltenböck, 2012) were used.

3 Results and discussion

3.1 Synoptical situation and event description

On 17 August 2024, Central Europe was in a moderate southwesterly flow regime (≈25 kn) between a 500 hPa ~~through~~ trough extending over Western Europe and a ridge over Eastern Europe (Figure S1a in supplement). At the surface, the pressure gradients were weak and wind speeds in Vienna were around 5 kn from the Northeast, but changing to a southwesterly wind above 900 hPa. Prior to the event, a 2 m dewpoint of 19 °C and a maximum 2 m air temperature of nearly 33 °C indicated a warm and humid boundary layer. The 12 UTC radiosonde measurement showed a surface-based Convective Available Potential Energy (CAPE) of ≈1500 J/kg and entrainment CAPE of ≈1100 J/kg (Figure S1b in Supplement). Moisture availability was exceptionally high throughout the troposphere, as evidenced by ~~a Precipitable Water (PWAT , also known as the column-integrated amount of water vapor from the surface to the top of the atmosphere) value~~ ERA5-derived PWAT that peaked at 45 mm during the event. The daily average ~~for the entire day~~ on 17 August was 42.4 mm, which ranks as the third-highest daily mean value for August in the period 1941–2024. The 1991–2020 average for mid-August is 27 mm. From a climate change perspective, PWAT has been shown to increase by approx. 6 % per 1°C rise of ~~surface~~ 2 m air temperature in Europe (Wan et al., 2024).

Furthermore, the 2-hourly average temperature between 500 hPa and 700 hPa was ~~at a high~~ 273 K, which ~~corresponds to a 1.5-year event~~was the maximum value of all extreme precipitation events from the extreme value analysis, and only eight events recorded a temperature higher than 272 K. While the unstably stratified, warm, and humid troposphere provided favorable conditions for heavy thunderstorms, the vertical wind shear was rather weak (0-6 km shear of 21 kn), which hindered storm organization and updraft longevity.

Around 11:00 UTC (13:00 local time), HRV satellite images showed isolated thunderstorms forming over the Lower Austrian Prealps ≈ 60 km southwest of the city. By ~~1200~~ 12:00 UTC, towering cumulus clouds covered large parts of the Vienna woods, a hill range extending from the Prealps to the western city districts. At 13:00 UTC, multiple thunderstorm cells developed in this area~~near Vienna~~. Shortly afterward, an outflow boundary originating from decaying thunderstorms approx. 100 km northwest of Vienna reached the city, establishing a convergence line between westerly and easterly winds along the foothills of the Vienna woods. The strong convergence contributed to the rapid development of a new thunderstorm cell in the northwest part of Vienna, first appearing on weather radar images at 13:45 UTC. TAWES measurements and Doppler radar data indicate that the convergence line remained ~~almost~~ nearly stationary for the next 20 to 30 minutes, during which the cell intensified significantly. The strongest rainfall at Hohe Warte ~~occurred~~ was recorded from 14:20 to 14:40 UTC, with 10-minute rain totals of 24.1 mm and 26.7 mm, respectively. At the same time, a microburst produced maximum wind gusts of 40 kn at Innere Stadt, a weather station in the city center 5 km to the southeast of Hohe Warte. By 15:00 UTC, the storm cell began to weaken, but light stratiform precipitation from the dissipating storm cluster continued for another 3 hours. The highest 2-hour precipitation sum was 110 mm from 13:50 to 15:50 UTC, or 107 mm for the two full hours from 14:00 to 16:00 UTC.

3.2 Station-based analysis

~~Figure 1a) shows the annual~~ Prior to 2024, only two events in 2014 (62 mm) and 2021 (58 mm) exceeded 50 mm within two hours at the station Hohe Warte (see Fig. 1a for daily maxima of 2-hour precipitation ~~sums for the observation period~~ from 1941 to 2024~~(for the estimation of the return periods the year 2024 was left out~~). The block bootstrapped Mann-Kendall trend test by Önöz and Bayazit (2012) revealed no significant trend in the time series. ~~Except for two events in 2014 (62 mm) and 2021 (58 mm), none of the events exceeded 50 mm at the station Hohe Warte.~~ In their respective observation periods, all eleven stations in the ~~area of Vienna and nearby~~ study area recorded only six events with 2-hour precipitation sums greater than 50 mm. Considering the maximum events of all eleven stations, these ranged ~~between~~ from 38 mm (Stammersdorf~~) and~~, sub-daily measurements starting in 2008) to 62 mm (Hohe Warte, excluding the record-breaking event). This highlights that the August 2024 event was not only extraordinary at the Hohe Warte station but also unprecedented across any station in the Vienna basin.

In a second step, we estimated the return period of the event, which is visualized in Fig. 1b. Since the results for computing these extremes are highly sensitive to individual events, we calculated the return period ~~with two different approaches: maximum likelihood estimation (MLE) and L-Moments (LM). For both estimates, the event itself was excluded from the time series. The MLE estimate~~ based on a regional frequency analysis, which should give a more robust estimate for such extremes. The year 2024 was excluded for each time series, and thereby the record-breaking event itself. This yields a return period of ~~662~~

~~years with a lower quartile~~ almost 700 years (699 years) for the station Hohe Warte. The interquartile range for a 107 mm/2 h event spans from 507 years (25 %~~percentile) of 166 years , and a higher quartile~~) to 1383 years (75 %~~percentile)of 9, 572 years. Considering the LM estimate, we obtain a return period of 5~~), ~~384 years , and the quartiles range from 926 years to 356,447 years. A broader confidence level would result in infinite values for the upper confidence limit. The more robust L-Moments approach underestimates the extremes of our time series, whereas the MLE procedure overestimates them, this highlights that even the conservative estimate of the MLE approach obtains~~ whereas the confidence bounds range between 184 years (2.5 %) and 3424 years (97.5 %). Including the year 2024 in the analysis would still result in a return period ~~of 662 years~~ exceeding 500 years (528 years). Estimating the return level of such an event for ~~all stations in consideration yields~~ each of the other stations in the Vienna basin yields mean estimates ranging from ~~554~~ over 473 years to over 1000 years.

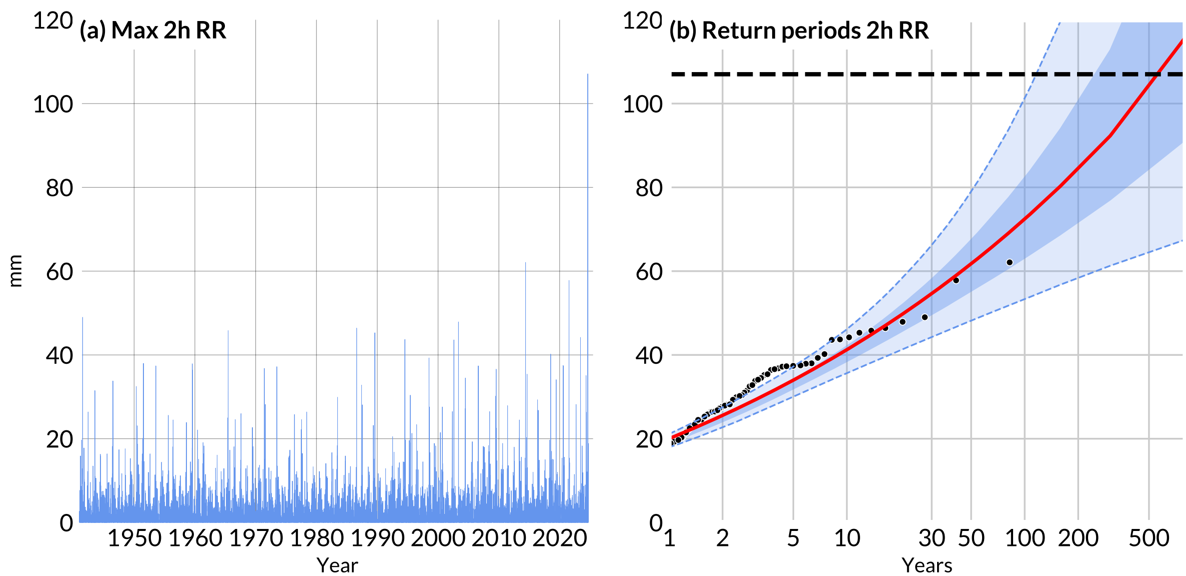

Figure 1. Extreme values statistics ~~from~~ for station Hohe Warte. (a) ~~Annual~~ Daily maxima of 2-hour precipitation totals. (b) Return period of 2-hour precipitation totals at Vienna Hohe Warte using ~~data~~ observations from 1941-2024 based on the ~~MLE~~ RFA approach. ~~Blue~~ Light blue shading indicates the 95 % confidence interval, darker blue shading indicates the 25% and 75% percentiles and the red line the mean estimate. The horizontal dashed black line highlights the ~~record-breaking~~ 107 mm ~~.~~ from 17 August 2024.

Changes in extreme (convective) precipitation can also be linked to an increase in temperature due to the Clausius-Clapeyron scaling. Based on ERA5 reanalyses, mean summer cloud temperature (700 hPa to 500 hPa) has been increasing for Vienna, particularly since the 1980s. Estimating the return period for extreme precipitation conditional on cloud temperature can give additional insights into the future likelihood due to progressing climate change. This conditional approach yields a return period of approx. 300 years, which is substantially lower than the approx. 700 years for the stationary model, suggesting an impact of climate change on such events.

3.3 Spatiotemporal analysis of INCA

The station-based analysis ~~showed~~ indicated that 2-hour precipitation events larger than 50 mm are extremely rare in the Vienna basin. One possible explanation could be the low chances of a thunderstorm precipitation core being recorded by gauging stations, despite the high station density in Vienna. ~~The possibility of these~~ Potentially unrecorded events can be investigated using the INCA data set~~. This will be tackled by~~ , which we will use in a threefold approach. ~~First, extreme events which were measured by gauging stations (the~~

First, we analyze the spatial patterns of the five events with the largest 2-hour precipitation ~~sum), are analyzed regarding their spatial patterns (Figure~~ sums observed at gauging stations (Fig. 2). For the ~~record-breaking event of~~ August 2024 ~~,~~ event, it is evident that the station Hohe Warte was ~~clearly~~ in the center of the precipitation core (~~Figure~~ Fig. 2a). ~~An~~ Based on INCA, an area of 17 km^2 was hit by more than 75 mm of rainfall, and only 4 km^2 by more than 100 mm. For the events in 2014 (~~Figure~~ Fig. 2b), 2010 (~~Figure~~ Fig. 2d), and 2008 (~~Figure 2e~~Fig. 2e) at least one weather station was close to the precipitation hotspot. For the 17 July 2021 event (~~Figure~~ Fig. 2c), however, the precipitation center was not recorded by any station, and the INCA maximum of 98 mm exceeds the station maximum by 40 mm. We note that the 2-hour precipitation totals in this case ~~originate~~ originated from multiple distinct ~~storms~~storm cells.

This leads us to our second analysis, which utilized ~~the spatially distributed INCA data set~~ INCA to investigate extreme events of 2-hour precipitation at the grid cell level. We found that no ~~events~~ event in the period 2004-2023 surpassed a precipitation maximum of 100 mm, but ~~10~~ six events exceeded 75 mm within two hours. The maximum area with precipitation above 75 mm was ~~15~~16 km^2 on 17 July 2021 (~~Figure 2e~~Fig. 2c). The strongest event not featured in the station-based analysis above was on ~~9 August 2014 with~~ 3 June 2020 with a maximum 2-hour precipitation of 87 mm south of Vienna and an area of ~~13~~7 km^2 exceeding 75 mm~~of precipitation~~/2 h. For the period 2004-2023, we identified a total of 55 events ~~that exhibited~~ > 50 mm~~or more within two hours~~/2 h. Compared to only six cases of > 50 mm/2 h recorded at weather stations, we conclude that the number of extreme events sampled by the stations is likely underrepresented. Further, only 15 events > 50 mm/2 h were observed by INCA in the years from 2004 to 2013, but 40 events from 2014-2023, indicating either a trend in extreme precipitation events or a possible inhomogeneity in the data set.

Lastly, we compare an extreme value analysis of the INCA data set to ~~the same analysis using~~ station data. ~~An annual maximum time~~ A POT series of 2-hour precipitation sums is built for the INCA data set ~~and for all stations~~ between 2004 and 2023. The regionalized parameters of the GPD were used as the index rainfall distribution for each INCA grid cell. Note that not all ~~stations have data for the full range; these were excluded from this analysis. As only 20 years of INCA data are available, we focus on analyzing 20-year return periods for a robust estimate. Figure~~ grid cells may be well represented by the RFA approach. To assess this, the deviations of the L-moments from the regionalized L-moments were computed, and only about 11% of the grid cells exceeded the critical threshold of the discordancy measure (Hosking and Wallis, 1997). Fig. 3 shows the mean estimate and the confidence levels of a 100-year return level for INCA and the stations. Generally, the return periods of the station data align with those of the INCA data set. For the mean estimate, the values for a ~~20-year~~ 100-year event of 2-hour precipitation range from ~~28~~60 mm to ~~69~~91 mm within the domain.

~~The significant uncertainty of these events is underscored by the upper confidence interval, which suggests that maximum values observed in the northern parts of Vienna could indicate that~~ The upper confidence bounds (97.5 %) of a 100-year event would already include an event like the one in August 2024 ~~might correspond to a 20-year return period.~~ in the northern parts of Vienna.

~~This result from INCA~~ Interestingly, the spatial pattern of 100-year return levels in the Vienna area shows no west–east gradient and thus does not reflect the climatological annual precipitation distribution - extreme precipitation events do not seem to be favored along the hilly Vienna woods. Some recent studies have investigated the influence of urban areas on precipitation and found local enhancements in or downwind of big urban areas (McLeod et al., 2017; Torelló-Sentelles et al., 2024). Proposed mechanisms of this enhancement are changes in the local atmospheric circulation similar to a land-sea breeze and modifications of cloud and nuclei condensation through pollutants (Amorim and Villarini, 2024). However, no such effect has been documented for the Vienna area yet, and our results also do not allow conclusions in this regard.

Our spatiotemporal analysis highlights two key points. First, even in a relatively ~~homogeneous~~ densely measured region like Vienna, INCA detects considerably more extreme events than ~~recorded by the stations~~ the in-situ station network due to its full spatial coverage. Second, the ~~shorter 20-year observation period of INCA, compared to the 84-year period covered by station data, leads to a broader confidence interval, further complicating the assessment of the event~~ upper confidence bounds of a 100-year event for INCA already encompass such an event, indicating that station-based records may overestimate return periods. Nevertheless, our analysis demonstrated that this event was indeed extremely rare~~, as~~ : neither the 84-year ~~record of Hohe Warte , other~~ Hohe Warte record, the sub-daily precipitation measurements ~~in the dense Viennese station network starting around~~ from Vienna's dense station network available since 1990, ~~and~~ nor the 20-year radar-based INCA data set ~~give no indication that a similar~~ indicate that a comparable event was ever recorded in the Vienna basin.

4 Conclusions

We analyzed ~~the record-breaking~~ an extreme precipitation event in Austria that brought 107 mm ~~precipitation event over two hours~~ within 2 hours when a thunderstorm's precipitation core hit Vienna's Hohe Warte weather station on 17 August ~~2024 using the time series from Hohe Warte in Vienna, which offers~~ 2024. The exceptionally long hourly ~~observations dating back to 1941. A thunderstorm's precipitation core hit the station, leading to an event with a~~ time series from this station dates back to 1941, and an analysis including neighboring stations shows that this event is unprecedented, with an estimated return period of ~~662 years with a~~ approx. 700 years (25% percentile of ~~166 years and a~~ 500 years and 75% percentile of ~~9572 years. Other neighboring stations in the area and the INCA data set show that the rain sum is unprecedented in and around Vienna.~~ 1400 years). No other event ~~since 2004~~ has ever exceeded 62 mm within two hours at any station in the study area. ~~Given the long return period of such an event and the~~ A comparison with the 20-year radar-based INCA data set suggests that station-based return periods may be overestimated, but still does not find any similar event in Vienna.

In the results we did not find significant trends of sub-daily precipitation extremes due to the high variability and mostly short records of sub-daily precipitation extremes, which in combination obscure a possible signal. In contrast, Haslinger et al. (2025)

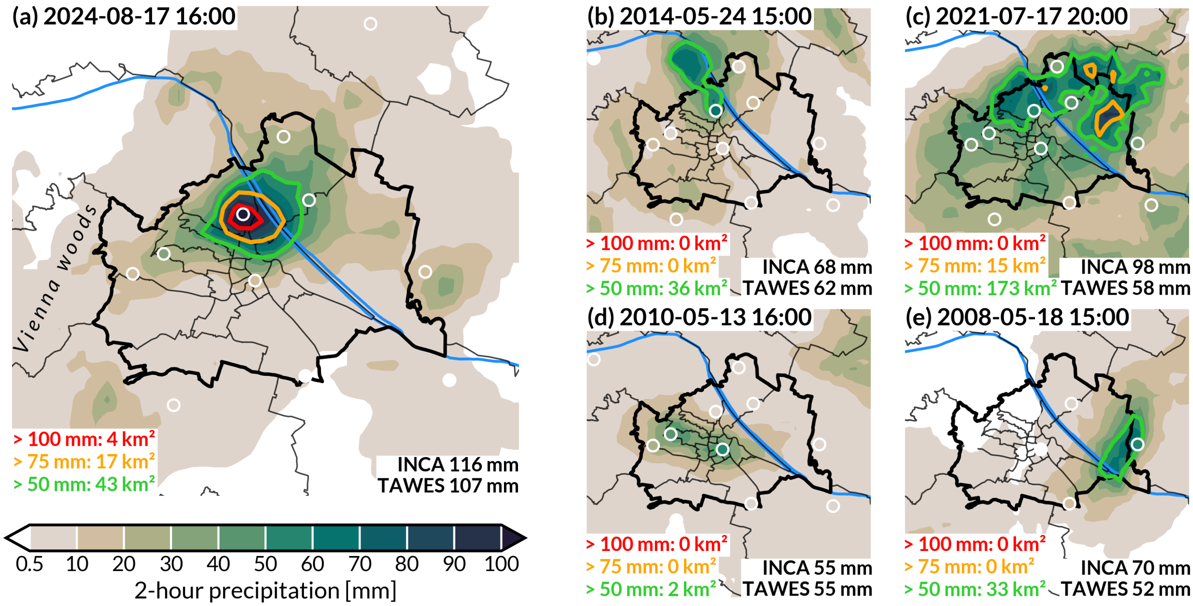

Figure 2. INCA precipitation totals (mm) for the five highest 2-hour rainfall events recorded at TAWES weather stations in Vienna and its surroundings since 2004. ~~Dots with white contours~~ White-contoured dots indicate TAWES locations, with the dot fill color corresponding to the station rainfall measurement. Green, orange, and red contours indicate areas where 2-hour ~~rainfall in~~ INCA rainfall exceeds 50 mm, 75 mm, and 100 mm, respectively. In the right bottom corner of each subplot, maximum values recorded at TAWES stations are contrasted with maximum INCA values.

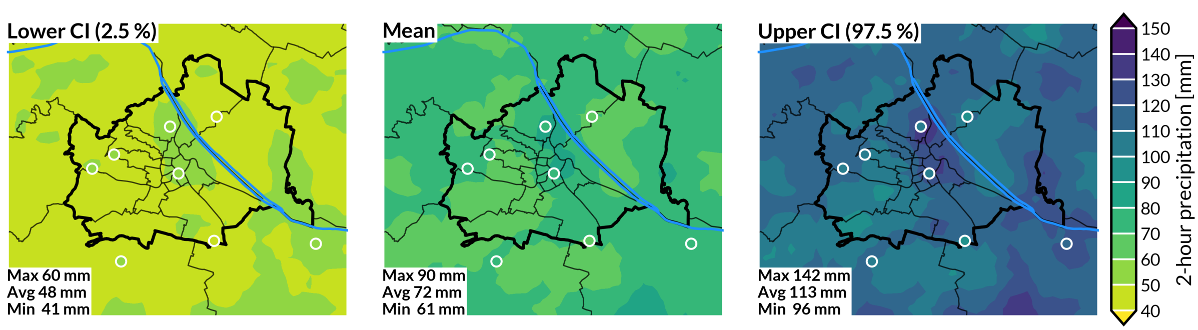

Figure 3. Estimation for a 2-hour precipitation event with a return period of ~~20~~ 100 years for the INCA data set (2004-2023) ~~shown with the background colors~~ and for each station ~~(2004-2023)~~ represented by colored dots. ~~An annual maxima~~ A POT series was built for each pixel and station. The central panel shows the mean estimate, whereas the left (right) panel displays the lower (upper) confidence level (CI), based on a 95 % confidence interval.

recently demonstrated that temporally smoothing the signal of extreme precipitation reveals a statistically significant increase of rainfall anomalies in Austria. Using this approach would yield similar results for our data set. As an alternative approach to assessing a potential climate change impact, we estimated the probability of the 2024 event conditional on cloud temperature, reducing the return period to 300 years. This is substantially lower than for the stationary model (700 years), suggesting that rising temperatures increase the intensity of extreme sub-daily precipitation in Vienna. This finding is in line with other studies such as Meyer et al. (2022) examining the trends in conditions favoring extreme precipitation events~~(Meyer et al., 2022), it can be argued that climate change has increased the likelihood of this event.~~ .

~~A realistic estimate~~ Our analysis demonstrates that including radar data yields additional insights into the return periods of extreme precipitation events. Historical events have been regularly missed by the existing rain gauge network, and their rainfall maxima were sometimes substantially underestimated. Consequently, the use of radar data is essential for obtaining realistic estimates of extreme precipitation return periods~~is essential~~ , which are critical for public engineering ~~. It is crucial for~~ and water management planning, such as designing sewage ~~systems, as extreme events are often not recorded and may be significantly underestimated when relying solely on station data. Our analysis shows that a more comprehensive review of such events can provide deeper insights into their frequency and likelihood.~~ system capacity.

Limitations of this study arise from the length of the time series. Even though the weather station in question has 84 years of hourly measurements, the estimated return period of the event is much larger with a wide confidence interval. The same is true for the INCA data set used for ~~spatial analysis~~ the spatial analysis, which only spans 20 years. Additionally, INCA is primarily a nowcasting product. While it is expected to outperform ~~pure radar data~~ purely radar-derived precipitation estimates in climatological analyses, it may suffer from spatial or temporal inhomogeneity~~. Although INCA, as a gridded dataset, provides complete spatial coverage, it only spans about 20 years, and long return periods are subject to high uncertainty due to the shortness of the archive. Furthermore, continuous improvements~~ , e.g. changes in the INCA code base may have introduced ~~additional temporal inhomogeneities~~ . temporal inhomogeneities (Panziera et al., 2016).

Code and data availability. Code for reproducing the data analysis can be found under https://github.com/katelbach/precipAnalysis. The weather station data and the aggregated INCA data used in this study can be downloaded at https://doi.org/10.5281/zenodo.14500708. Please note that the publicly available INCA data on the GeoSphere Data Hub is the 1-hour version and therefore differs from the 15-minute version used in this study.

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Competing interests. The authors declare that they have no competing interests.

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