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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/Austria led to a rainfall of 107 mm/2h at the weather station of "Hohe Warte", which has been monitoring hourly precipitation since 1941 - one of the world's longest-running precipitation time series at this temporal resolution. A comparison with other gauging stations in the area indicates that this amount of rainfall almost doubles the second-largest event. A conservative estimate of the return period of this event is approx. 662 years. Full spatial analysis was conducted on the 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.

1 Introduction

On 17 August 2024, an extreme precipitation event occurred in the northwestern parts of Vienna, Austria. A total of 107 mm fell within two full hours (and 94 mm in one hour) at the Hohe Warte weather station in Vienna, leading to local flooding and causing one fatality (dpa, 2024). The event set new 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 become more intense due to climate change, driven by increased water holding capacity at a higher air temperature (Seneviratne et al., 2021). Quantifying the return period of such sub-daily events is crucial for e.g. 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 sub-daily precipitation start in the 1950s (Lewis et al., 2019), with a few exceptions (e.g. Hobart, Tasmania), making robust estimates of precipitation extremes more challenging. The hourly precipitation measurements at Hohe Warte date 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 short-lived but also confined to small areas (a few km^2). In Germany between 2001 and 2018, only 17.3% of hourly heavy precipitation events (above

25 mm) detected by radar 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 (GeoSphere Austria, 2024b), corresponding to one station per 300 km^2. However, the station density in Vienna is significantly higher with 7 stations in the city resulting in one station per 60 km^2. Additionally, several stations right outside the city borders further increase the likelihood of thunderstorms directly hitting a weather station.

Although station density in Vienna is significantly higher than in the rest of Austria or Germany, additional information from radar data is becoming increasingly important (Lengfeld et al., 2020). The key advantage of radar is its 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 at ungauged locations (Panziera et al., 2016) and can further be adjusted with gauging stations to increase the accuracy of the radar estimates (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 surface station data with weather radar data in such a way that the observations at the station locations are approximated, while the remote sensing data provides the spatial structure for interpolation.

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 long-term station record at Hohe Warte. Second, it will be compared to nearby stations in Vienna. Finally, the event will be examined spatially using the gridded INCA dataset. These goals are guided by the following research questions:

- How extreme was the precipitation event at Hohe Warte considering the exceptional 84-year time series of hourly precipitation?
- What is the return period of such an event for other stations in the Vienna basin and are there records of any similar events in the neighboring time series?
- Can similar events be identified in the radar-based INCA dataset for Vienna?
- What are the estimated 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

The study area covers Vienna and its surrounding stations. The 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 are operated by GeoSphere Austria and the hourly data is openly accessible through the "GeoSphere Data Hub" (GeoSphere Austria, 2024a) (Table S1 in the supplement). These semi-automatic weather stations ("TAWES") are classified as SYNOP stations. For each

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of the eleven selected stations, the maximum 2-hour precipitation per day was computed to prevent 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 1 x 1 km spatial resolution for the period 2004-2023. To align with the hourly station data, the 15-minute data was aggregated to full hours. Atmospheric data as precipitable water (PWAT) and cloud temperature 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 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 series was used. Missing station values were permitted, as for ten stations the number of missing hourly values was below five %. 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 event description, HRV satellite images from MSG satellites (Schmetz et al., 2002) and weather radar reflectivity 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 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. 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 that peaked at 45 mm during the event. The daily average for the entire day 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 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. 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.

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 UTC, towering cumulus clouds covered large parts of the Vienna woods, a

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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 indicate that the convergence line remained almost stationary for the next 20 to 30 minutes, during which the cell intensified significantly. The strongest rainfall at Hohe Warte occurred 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 gusts of 40 kn at Innere Stadt. 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 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 recorded only six events with 2-hour precipitation sums greater than 50 mm. Considering the maximum events of all eleven stations, these ranged between 38 mm (Stammersdorf) and 62 mm (Hohe Warte). This highlights that the 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 yields a return period of 662 years with a lower quartile (25 % percentile) of 166 years, and a higher quartile (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 a return period of 662 years. Estimating the return level of such an event for all stations in consideration yields estimates ranging from 554 years to over 1000 years.

3.3 Spatiotemporal analysis of INCA

The station-based analysis showed 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 unrecorded events can be investigated using the INCA data set. This will be tackled by a threefold approach. First, extreme events which were measured by gauging stations (the

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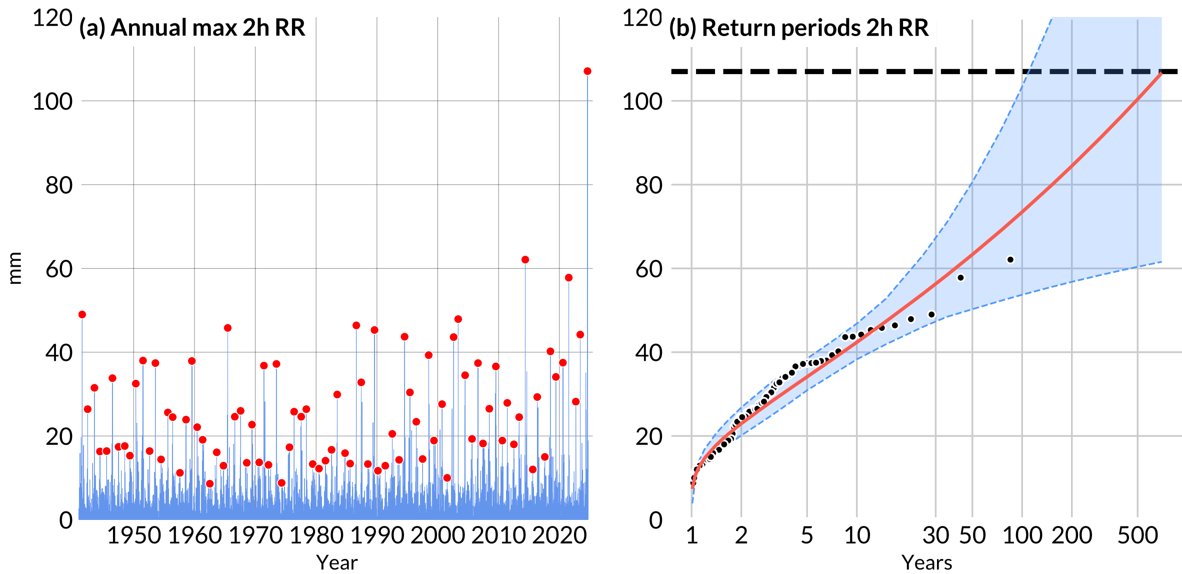

Figure 1. Extreme values statistics from station Hohe Warte. (a) Annual maxima of 2-hour precipitation totals. (b) Return period of 2-hour precipitation totals at Hohe Warte using data from 1941-2024 based on the MLE approach. Blue shading indicates the 95 % confidence interval. The dashed black line highlights the record-breaking 107 mm.

five events with the largest 2-hour precipitation sum), are analyzed regarding their spatial patterns (Figure 2). For the record-breaking event of August 2024, the station Hohe Warte was clearly in the center of the precipitation core (Figure 2a). An area of 17 km^2 was hit by more than 75 mm of rainfall, and 4 km^2 by more than 100 mm. For the events in 2014 (Figure 2b), 2010 (Figure 2d), and 2008 (Figure 2e at least one weather station was close to the precipitation hotspot. For the 2021 event (Figure 2c), however, the precipitation center was not recorded by any station. We note that the 2-hour precipitation totals in this case originate from multiple distinct storms.

This leads us to our second analysis, which utilized the spatially distributed INCA data set to investigate extreme events of 2-hour precipitation at the grid cell level. We found that no events in the period 2004-2023 surpassed a precipitation maximum of 100 mm, but 10 events exceeded 75 mm within two hours. The maximum area with precipitation above 75 mm was 15 km^2 on 17 July 2021 (Figure 2c. The strongest event not featured in the station-based analysis above was on 9 August 2014 with an area of 13 km^2 exceeding 75 mm of precipitation. For the period 2004-2023, we identified a total of 55 events that exhibited 50 mm or more within two hours. Compared to only six cases of >50 mm recorded at weather stations, we conclude that the number of extreme events sampled by the stations is likely underrepresented.

Lastly, we compare an extreme value analysis of the INCA data set to the same analysis using station data. An annual maximum time series of 2-hour precipitation sums is built for the INCA data set and for all stations between 2004 and 2023. Note that not all stations have data for the full range; these were excluded from this analysis. As only 20 years of INCA data

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are available, we focus on analyzing 20-year return periods for a robust estimate. Figure 3 shows the mean estimate and the confidence levels 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 event of 2-hour precipitation range from 28 mm to 69 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 an event like the one in August 2024 might correspond to a 20-year return period.

This result from INCA highlights two key points. First, even in a relatively homogeneous region like Vienna, INCA detects considerably more extreme events than recorded by the stations 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. Nevertheless, our analysis demonstrated that this event was indeed extremely rare, as the 84-year record of Hohe Warte, other sub-daily precipitation measurements in the dense Viennese station network starting around 1990, and the 20-year radar-based INCA data set give no indication that a similar event was ever recorded in the Vienna basin.

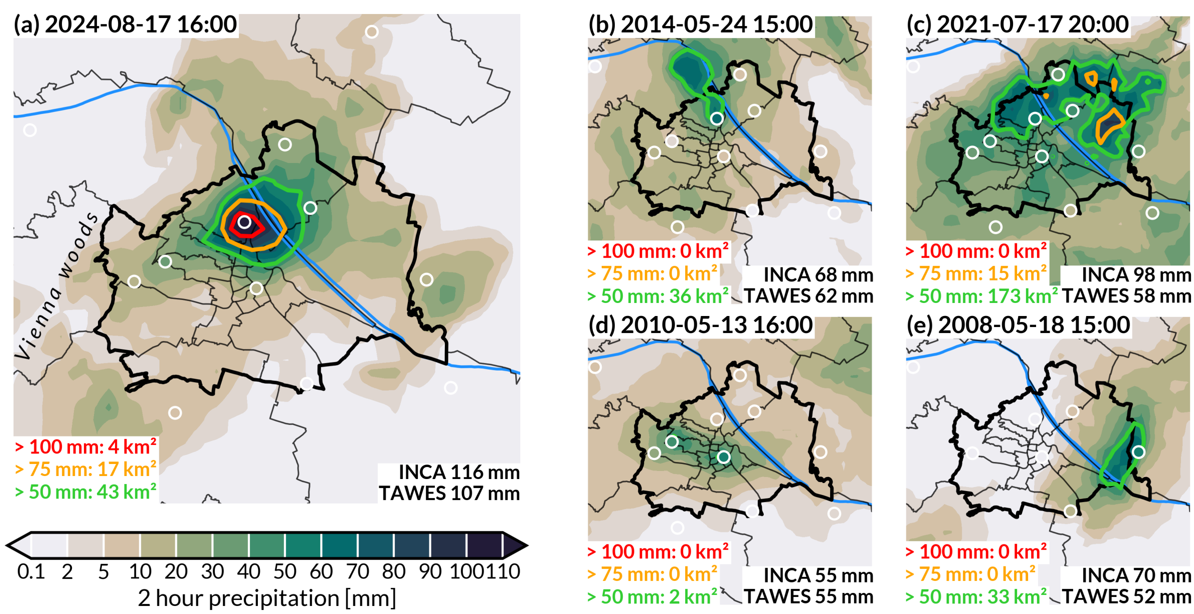

Figure 2. INCA precipitation totals (mm) for the five highest 2-hour rainfall events recorded at TAWES weather stations in Vienna and its surroundings since 2004. Dots with white contours indicate TAWES locations, with the dot fill color corresponding to the station rainfall measurement. Green, orange, and red contours indicate areas where 2-hour rainfall in INCA 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.

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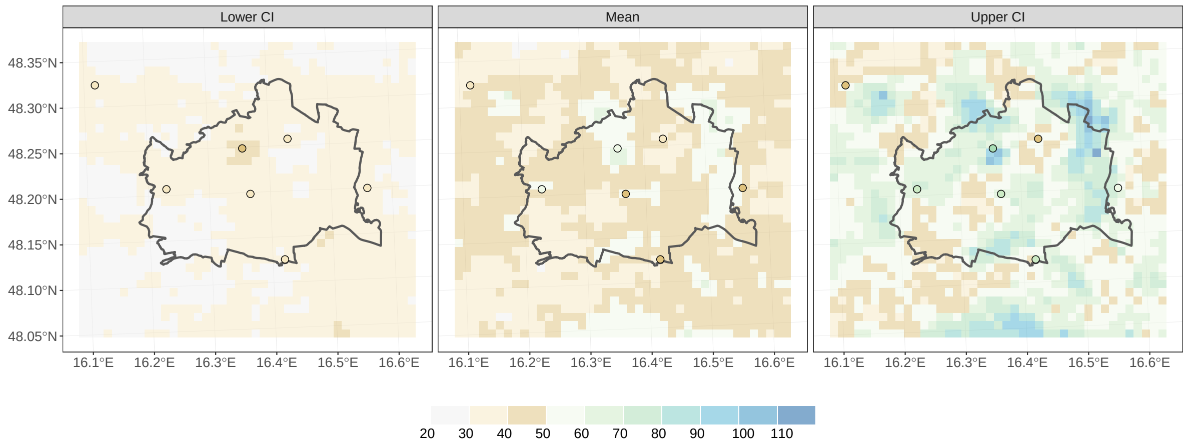

Figure 3. Estimation for a 2-hour precipitation event with a return period of 20 years for the INCA data set (2004-2023) shown with the background colors and for each station (2004-2023) represented by colored dots. An annual maxima series was built for each pixel and station. The central panel shows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

4 Conclusions

We analyzed the record-breaking 107 mm precipitation event over two hours on 17 August 2024 using the time series from Hohe Warte in Vienna, which offers exceptionally long hourly observations dating back to 1941. A thunderstorm's precipitation core hit the station, leading to an event with a return period of 662 years with a 25 % percentile of 166 years and a 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. No other event since 2004 exceeded 62 mm at any station in the study area. Given the long return period of such an event and 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 of extreme precipitation return periods is essential for public engineering. It is crucial for 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.

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 INCA data set used for spatial analysis is primarily a nowcasting product. While it is expected to outperform pure radar data 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 in the INCA code base may have introduced additional 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 INCA data used in this study can be downloaded at https://doi.org/10.5281/zenodo.14500708.

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

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