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Brief communication: Contextualizing the September 2024 extreme precipitation in Austria within the climatological record

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Abstract. From 12–16 September 2024, Vb-type cyclone 'Boris' brought persistent heavy precipitation and strong winds to Central and Eastern Europe. Northeastern Austria was particularly affected, with several pre-Alpine regions exceeding 300 mm in five days, and numerous station records broken. Using station and gridded observations, we benchmark five-day total precipitation against historical extremes and estimate return periods. We find that 6.6 % of Austria experienced totals at least 50 % above previous records, with maxima around 162 % higher. Several stations exhibit return periods of hundreds of years. The event is unprecedented in the Austrian observational record, underscoring its exceptional severity and climatological rarity.

1 Introduction

From 12 to 16 September 2024, an intense cyclone named 'Boris' (also referred to as 'Anett' by the German Weather Service, DWD) produced exceptional, long-lasting precipitation, flooding, and strong winds across parts of Central and Eastern Europe (Green et al., 2025). The system originated as a surface low over the Gulf of Genoa and progressed towards Hungary, closely following the classical Vb storm track (van Bebber, 1891; Messmer et al., 2015; Hofstätter et al., 2018), which is well known for extreme precipitation in northeastern Austria (Hofstätter et al., 2016, 2018). A concurrent blocking high-pressure system stretching over Western Russia inhibited the cyclone's eastward progression and helped sustain multi-day precipitation over the region (Komma et al., 2025).

The northeastern pre-Alpine area of Austria experienced near-continuous rainfall with sustained rates around $10\,\mathrm{mm\,h^{-1}}$ and peaks up to $20\,\mathrm{mm\,h^{-1}}$. Although typical of convective storms, such intensities are rare in widespread, stratiform-dominated events and, critically, have not previously persisted this long in pre-Alpine regions during the Austrian observational period.

Hydrological and geomorphic impacts ranged from flash floods in small catchments to severe flooding and flood waves on medium-sized rivers, notably the *Große Tulln*, *Perschling*, and *Traisen*, as well as on the large stream of the *Danube* (Komma et al., 2025), along with extensive mass movements. Hydrogeomorphic responses included hillslope-channel coupling and landslides, most prominently in the *Pielach Valley*. Considering the total precipitation and spatial extent, this event ranks alongside the major Central European summer floods of 1899, 1997, 2002, 2005, and 2013, all of which are linked to Vb-like

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synoptic situations (Blöschl et al., 2013; Hofstätter et al., 2018; Haslinger et al., 2025; Komma et al., 2025). Beyond Austria, the Czech Republic, Slovakia, and southwestern Poland were among the most affected regions (Kimutai et al., 2024; Green et al., 2025).

The September 2024 event has already been examined from several complementary perspectives, including storyline attribution indicating anthropogenic intensification (Athanase et al., 2024), dynamical analog-based attribution suggesting increased shoulder-season frequency (Riboldi et al., 2026), and impact assessments of mass-movement responses such as debris flows (Pánek et al., 2025; Tichavský et al., 2026). Return periods of total precipitation have been estimated using a non-stationary extreme value model based on block maxima (Kimutai et al., 2024), but uncertainties inherent to the standard 100-year time-series limit the conclusiveness of these estimates. The findings suggest that events of this magnitude now represent a 'new tail' of the distribution, complicating return-period estimation from historical records using frequentist methods.

Here, we place the Austrian precipitation extremes into a climatological context. Specifically, we aim to elucidate the climatological outlier characteristics by (i) evaluating the total precipitation across the event compared to historical gridded records and (ii) more robustly estimating return periods, including uncertainties, for ten stations with the highest accumulated precipitation during the event.

2 Data & Methods

2.1 Data

We use two data sets from Austria's national weather and climatological service, GeoSphere Austria: (i) SPARTACUS, a 1 km daily gridded precipitation data set covering the period 1961 to 2024 (Hiebl and Frei, 2018; GeoSphere Austria, 2020), and (ii) semi-automatic station data (TAWES; GeoSphere Austria, 2024). The ten stations with the highest recorded five-day precipitation during 12–16 September were selected for analysis (Tab 1, Fig 1a). We used SPARTACUS to assess the climatological spatio-temporal characteristics of the event, and station data to estimate return periods.

2.2 Event characterization and climatological assessment

We quantify the event by using five-day total precipitation:

$$\mathrm{Rx5day}_y = \max_y \left(\sum_{j=i}^{i+4} \mathrm{RR}_j \right), \tag{1}$$

with RR as daily total precipitation for all days i in a given year y, yielding annual maximum five-day total precipitation (Lehner and Schlögl, 2026).

For each SPARTACUS grid cell, we compare the 2024 five-day maximum ($\mathrm{Rx5day}_{2024}$) to the historical record for 1961–2023, denoted $\mathrm{Rx5day}_{\mathrm{rec}} = \max_{1961-2023}(\mathrm{Rx5day})$, and map the percent exceedance δ:

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Table 1. The ten stations with the highest five-day total precipitation during 12–16 September 2024 (coinciding with Rx5day for 2024). Return-period estimates are reported with 95 % confidence intervals. Stations with very short record lengths (and thus highly uncertain return-period estimates) are marked with an asterisk; their return-period estimates are omitted to preclude unreliable conclusions.

Rank	Station name	$\mathrm{Rx5day}_{2024}$ [mm]	Previous historic record [mm]	Return period [year]	Record length [years]
1	Lilienfeld/Tarschberg	417	273 (Jul 1997)	107 (49, 261)	33
2	St. Poelten/Landhaus	409	207 (Jun 2009)	579 (254, 1571)	88
3	Langenlebarn	397	143 (Jun 2009)	1563 (558, 5387)	62
4	Lunz/See	390	310 (Sep 2007)	35 (18, 73)	31
5	Reichenau/Rax	337	256 (Sep 2007)	254 (129, 557)	124
6	*Unterach am Attersee**	327	152 (Aug 2023)	–	6
7	Oberndorf/Melk	326	222 (Jun 2009)	134 (65, 309)	48
8	Weyer	320	246 (Jan 2013)	53 (30, 100)	57
9	*Schwarzau im Freiwald**	315	68 (Aug 2023)	–	3
10	Baernkopf	310	131 (Jun 2009)	118 (47, 348)	22

$$\delta = 100 \times \frac{\mathrm{Rx5day}_{2024} - \mathrm{Rx5day}_{\mathrm{rec}}}{\mathrm{Rx5day}_{\mathrm{rec}}} \tag{2}$$

2.3 Extreme value analysis

Given the stark outlier characteristic of the total precipitation, we adopt a data-efficient peak-over-threshold (POT) approach with the Generalized Pareto Distribution (GPD; Pickands, 1975), which performs more robust under such conditions. We employ a spatial Bayesian hierarchical framework (Cooley et al., 2007) implemented in Stan via R (R Core Team, 2025) using `rstan` (Guo et al., 2025). To strengthen inference and sharpen uncertainty estimates across heterogeneous record lengths, we pool information across stations to estimate a common GPD shape parameter ξ (Hosking and Wallis, 1997), while allowing station-specific scale parameters σ_s and thresholds u_s. For exceedances $Y_{st} > u_s$ we thus assume $Y_{st} - u_s \sim \mathrm{GPD}(\sigma_s, \xi)$. For comparison, we also fit a Bayesian Generalized Extreme Value (GEV; Fisher and Tippett, 1928) model to annual maxima series with a fixed shape parameter.

The decision to pool ξ was informed by two diagnostics: (i) All stations observed their highest-ever recorded Rx5day on 2024-09-16, indicating strong co-occurrence at high but finite thresholds within a common extremal regime. (ii) Bivariate tail-dependence analysis (Coles et al., 1999; Coles, 2001) in conjunction with qualitative checks against regional physioclimatic delineations (Lehner et al., 2025), revealed no statistically significant inter-station differences at $\alpha = 0.05$.

Thresholds were chosen to balance bias and variance, seeking enough exceedances for stable estimation while remaining within the GPD's asymptotic tail. Systematic testing favoured a station-specific threshold corresponding to the 98.5th percentile, consistently outperforming non-pooled baseline models in leave-one-out cross-validation.

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To mitigate the strong serial autocorrelation in rolling five-day total precipitation, we declustered the individual time-series using the runs method (Coles, 2001). We estimated the extremal index using the k-gaps model (Süveges and Davison, 2010) across candidate run lengths k and chose a common $k = 13$ days near the stabilization range of the extremal index ($\approx 10-13$ days). Very short records (Schwarzau, Unterach) were less informative for this diagnostic, but were treated consistently with $k = 13$.

Robustness of the threshold and declustering choices was assessed by refitting the hierarchical GPD across thresholds from the 95th to 99.5th percentiles and run lengths from 5 to 13 days. The pooled shape parameter increased from $\xi = 0.14$ at the 95th percentile to $\xi = 0.23$ at the 98th percentile threshold and then remained stable at higher thresholds (approximately $0.22 \leq \xi \leq 23.5$). Varying k had negligible impact. The sensitivity analysis supports the threshold selection and indicates that exceedances above the 98th percentile lie within the GPD's asymptotic regime.

3 Results & Discussion

3.1 Climatological spatio-temporal assessment

The 2024 maximum five-day total precipitation field highlights the event footprint, with the ten stations recording the highest event totals annotated by rank (Fig. 1a). The pre-Alpine region of northeastern Austria was most affected, with widespread five-day total precipitation exceeding 250 mm and localized maxima from about 300 mm to just over 400 mm. Such intensities are typically confined to areas north of the Alpine main ridge and to southern Alpine regions where orographic lifting is strongest (Seibert et al., 2007). Comparable values are also found in other mountainous regions affected by the event, such as in the Czech Republic (Český hydrometeorologický ústav, 2024). This indicates strong synoptic and convective forcing as a main driver of these high precipitation intensities, given that effects from orographic lifting are weaker in pre-Alpine areas.

In 2024, 32.1 % of the study area set a new Rx5day record compared to the period since 1961. About 6.6 % exceeded the previous record by more than 50 %, and approximately 0.55 % more than doubled it (Fig 1b). For comparison, the corresponding shares for exceeding at least 1 times, 1.5 times, and 2 times the previous record were 11.1 %, 0.84 %, and 0 % in 1997, and 23.7 %, 3.45 %, and 0.05 % in 2002, respectively. The maximum local increase in Rx5day for 2024 reached about 162 %, versus 72.3 % in 1997 and 109.4 % in 2002, underscoring 2024 as a clear spatial outlier with far more widespread and pronounced five-day precipitation records.

The exceptional precipitation intensity is further reflected in the daily total precipitation on September 14–15 at *St. Pölten* and *Langenlebarn*, which reached 225 mm and 216 mm, respectively. These rank as the second and third highest daily total precipitation in the entire history of the Austrian meteorological monitoring network, surpassed only by the precipitation-prone Loibl station (Carinthia, 1097 m), which recorded 233 mm on September 4, 2009.

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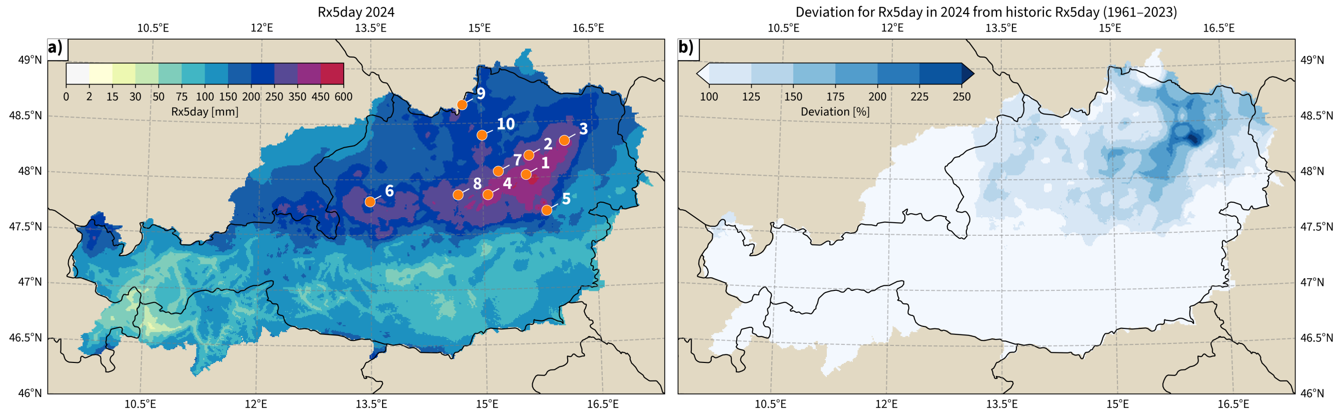

Figure 1. Climatological spatial characteristics of the September 2024 event: (a) five-day maximum precipitation (Rx5day) for 2024, with the ten stations recording the highest totals during 12–16 September 2024 annotated by rank, and (b) the percent deviation of 2024 Rx5day from the historical baseline (1961–2023), highlighting the pronounced pre-Alpine outlier characteristic.

3.2 Return-period estimation

Tail dependence diagnostics at the 99th percentile for the four longest records (stations ranked 2, 3, 5 and 8 in Tab 1) indicate significant extremal correlation ($0.3 \leq \chi \leq 0.55$), strongly supporting regional pooling of the GPD shape parameter. Although $0.58 \leq \bar{\chi} \leq 0.77$ points to weakening dependence toward the asymptotic limit, the strong empirical dependence indicates that large-scale synoptic systems (as in September 2024) behave as spatially coherent events across the study area.

Hierarchical GPD fitting produced stable, highly informative posteriors with little numerical sampler noise and all Markov chains converging to the same distribution. The pooled posterior shape parameter converged to $\xi = 0.23$ with a standard deviation of $s = 0.05$, demonstrating a heavy tail in the Fréchet domain. Independent GEV fits agree closely, with $\xi = 0.19$ ($s = 0.03$), reinforcing confidence in the heavy-tailed Fréchet regime and in the model. This behaviour is consistent with physical arguments linking increased atmospheric moisture loading to Fréchet-type tails (Faranda et al., 2024).

Model behavior is illustrated by the upward-curving return-level plots on a logarithmic x-axis (Fig 2b), which is an indicator of the Fréchet-type heavy tailed nature of the posterior distribution in that climatic region. Uncertainty bands (bootstrapped 95% confidence intervals) are generally narrow despite some relatively short station records, reflecting hierarchical borrowing of strength whereby longer series stabilize estimates of both ξ and σ of the shorter ones. However, the shortest records, *Schwarzau* (3 years) and *Unterach* (6 years), benefit less from this stabilizing effect. Even under a POT framework, effective sample sizes remain small. Return-period estimates inferred from these short series, which substantially exceed the record length, should therefore be treated with caution and regarded as indicative ranges, with relative rankings being more defensible than their absolute magnitude. Nonetheless, including very short records is fundamentally justified within the Bayesian hierarchical framework with spatial pooling. Adding these series leaves the shared shape parameter essentially unchanged, demonstrating robustness, while the scale and station-level return periods appropriately reflect the associated uncertainty. For

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example, at the three-year *Schwarzau* record, the posterior return period of 12 years is consistent with the station's average behavior but is accompanied by a very wide credible interval (3–162 years). Because the extreme event occurred coherently across stations, these short records provide genuine signal to the pooled tail and help stabilize the joint extreme-value distribution, thereby reducing posterior return period estimates and their uncertainty across the network. Thus, despite their brevity, retaining such series leverages spatial information while transparently propagating uncertainty, whereas excluding them would discard observed informative extremes and weaken inference. Rather than introducing noise, these records enhance the spatial regularization of the model.

The observed five-day total precipitation of the September 2024 event, when expressed using empirical return periods based on Weibull plotting positions, lies well above the uncertainty bounds of the extreme value model, confirming the event's exceptional severity (Fig 2b,d,f; Tab 1). Several return-period estimates are extremely large, notably at *St. Pölten* (≈ 600 years) and *Langenlebarn* (≈ 1600 years). This raises the valid concern of whether the model is accurate and robust enough to not consider these values as artifacts or a single-event bias. While agreement between the GPD and GEV estimates supports these magnitudes, uncertainty necessarily increases when extrapolating well beyond the record lengths. Conversely, some stations yield comparatively modest return periods, such as *Lunz* (34 years) or *Weyer* (53 years). This pattern aligns with weakening extremal dependence at high quantiles, as indicated by $\bar{\chi} < 1$: stations share a common heavy tail in the Fréchet regime regionally, but the most extreme intensities can decouple from the regional mean at the distribution limits due to localized effects and hydrometeorological responses. Such localization of extreme peaks under regional synoptic forcing is consistent with tributary synchronization and hydrological controls (Komma et al., 2025).

4 Conclusions

This study characterizes the 12–16 September 2024 extreme precipitation associated with the extratropical Vb-Cyclone 'Boris' as an exceptionally rare outlier for the pre-Alpine region of northeastern Austria. Five-day total precipitation set widespread records of up to 162 $\%$ above historical maxima, with two stations registering the second- and third-highest one-day sum on record (225 mm and 216 mm). Precipitation events of this intensity (in both duration and magnitude) are unusual outside the Alps, where orographic lifting typically concentrates the most intense precipitation.

Using a robust regional extremal framework that spatially pools stations, we fitted Hierarchical Bayesian peak-over-threshold (GPD) and annual maxima (GEV) models. Both approaches converged on a common regional shape parameter in the heavy-tailed Fréchet regime, with $\xi = 0.19$ (GEV) and $\xi = 0.23$ (GPD), indicating a stable climatic feature across the investigated stations rather than an artifact of threshold choice or outlier influence.

Diagnostics – including declustering, Markov chain Monte Carlo convergence, threshold stability (ξ stable within $0.15 - 0.25$) and confirmed spatial asymptotic dependence ($\chi > 0$) – support the robustness of large modelled return periods. Nonetheless, these should be interpreted as robust indicators of extreme rarity rather than precise frequency estimates, due to the inherent uncertainty of extrapolating beyond the record length.

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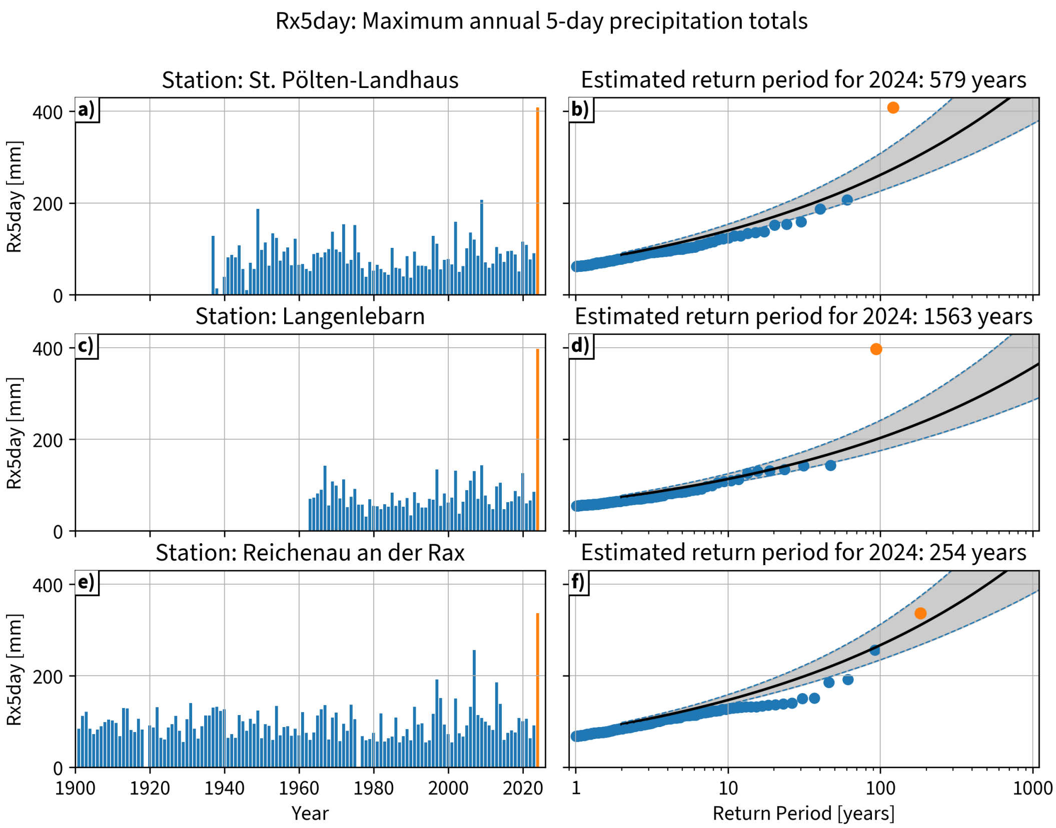

Figure 2. Observed annual Rx5day block maxima of stations (a) *St. Pölten*, (c) *Langenlebarn* and (e) *Reichenau*. Panels (b,d,f) show the estimated return levels for the same stations based on the fitted GPD (solid black line) with corresponding bootstrapped 95%-confidence intervals. Dots indicate the observed Rx5day threshold exceedances. Note the extreme outlier position of the Rx5day value of the year 2024 (orange), despite the overall goodness of the fit.

Our findings align with other studies in Central Europe that confirmed the event's extreme nature (e.g. Kimutai et al., 2024). Our Bayesian analysis with pooled station data shows that a standard 100-year data-series often under-samples the far tail, thereby underscoring the value of spatial pooling for robust regional return-period estimation.

Further research could investigate localized controls, such as embedded convective lifting, orographic lifting, or lake-effect processes, to investigate the decoupling of individual stations from the regional average at very long return periods.

Overall, the event was exceptionally rare for the pre-Alpine northeastern Austria region and likely surpassed the 100-year design threshold at most stations, underscoring the unprecedented nature of the five-day total precipitation from cyclone 'Boris'. Together, these findings demonstrate both the utility of regional pooling and the importance of accounting for local controls when assessing future extreme-precipitation risk.

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Code and data availability. The code supporting this analysis is available on GitHub at https://github.com/seblehner/brief-comm-sept24-extreme-precip. A part of the extreme value analysis was supported by using AI as code suggestion tool; all code was carefully verified manually. All data is openly available on zenodo at https://doi.org/10.5281/zenodo.19346127.

Author contributions. Conceptualization: SL, HS, KH; data curation: SL, HS; formal analysis: SL, HS, MS; investigation: SL, HS, TSG, KH, MS; methodology: SL, HS; supervision: KH, MS; Writing (original draft preparation): SL, HS, MS; Writing (review and editing): SL, HS, TSG, KH, MS.

Competing interests. MS is a member of the Editorial Board of Natural Hazards and Earth System Sciences.

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