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Apparent Heavy Tails of Sub-Daily Precipitation Explained by the Coexistence of Lighter-Tailed Processes

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Key Points:

- An apparent contradiction between physical arguments and statistical results for sub-daily precipitation is examined on a large data set
- Due to coexistence of processes, the tail of extremes for durations of 1–6 hr appears heavier than the one of the individual components
- A mixture of stretched exponential tailed processes explains the apparent power-type tails found by extreme value statistics

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Extreme value theory is routinely applied to estimate rainfall frequency for several accumulation periods. Typically, it is found that sub-daily precipitation has power-type tails, meaning that the probability of observing increasingly large magnitudes decreases as a power law. Physical arguments, however, suggest it should have lighter, stretched exponential, tails. Here, we reconcile these perspectives showing that part of the contradiction is caused by precipitation process heterogeneity. We examine hundreds of sub-daily precipitation records in the Greater Alpine Area, for which a classification of storms into homogeneous types is available. We find that an apparent heavy-tail behavior is reported at scales of 1–6 hr, and is explained by the coexistence of stratiform and convective processes, both characterized by stretched exponential tails. Our results challenge the assumptions which justify the use of extreme value theory for sub-daily precipitation, with important implications for how design values are determined.

Plain Language Summary

This study addresses the discrepancy between statistical and physical arguments regarding extreme sub-daily rainfall. We analyze hundreds of sub-daily precipitation records in the Alpine region with classified storm types. We reveal that process heterogeneity is important in determining sub-daily precipitation statistics, determining a violation of the assumptions behind the extreme value theorem. The study reconciles statistical observations with physical understanding, emphasizing the importance of considering the heterogeneity of precipitation processes in extreme event analysis and prediction. The results of this research have implications for hydrological engineering and risk assessment practices.

1. Introduction

Extreme value theory has been widely applied to characterize the probability distribution of extreme sub-daily and daily precipitation (Coles, 2001; Gaetan et al., 2025; Katz et al., 2002). A key finding from these analyses is that precipitation exhibits a power-type tail, where the probability of observing particularly large intensities decreases with magnitude following a power law (Nerantzaki & Papalexiou, 2019; Papalexiou & Koutsoyiannis, 2013; Serinaldi & Kilsby, 2014). This characteristic implies a higher likelihood of extreme events compared to distributions with lighter tails, such as the exponential distributions. This statistical interpretation appears to conflict with physical arguments based on atmospheric dynamics and thermodynamics, which suggest that precipitation magnitudes over fixed temporal aggregations should have lighter, stretched exponential tails (Frisch & Sornette, 1997; Wilson & Toumi, 2005). In fact, stretched exponential tails for precipitation have been supported by observations (Marra et al., 2023; Papalexiou, 2022; Papalexiou et al., 2018), leading to the development of non-asymptotic extreme value approaches (Marani & Ignaccolo, 2015). However, the discrepancy between statistical findings and physical expectations has sparked debate in the scientific community and raised questions about the suitability of both extreme value theory and non-asymptotic approaches to model precipitation extremes (Marra et al., 2023; Schmith et al., 2025; Serinaldi et al., 2025).

One explanation for this contradiction is the slow convergence of stretched exponential tails to the asymptotic limit of the extreme value theorem. In fact, non-asymptotic samples from stretched exponential tails appear to belong to the Fréchet type of extreme value theory, that has power-type tails (Papalexiou & Koutsoyiannis, 2013; Wilson & Toumi, 2005), instead of the Gumbel type, that has exponential tail, toward which they asymptotically converge. However, on some occasions which include sub-daily precipitation, these stretched exponential tails

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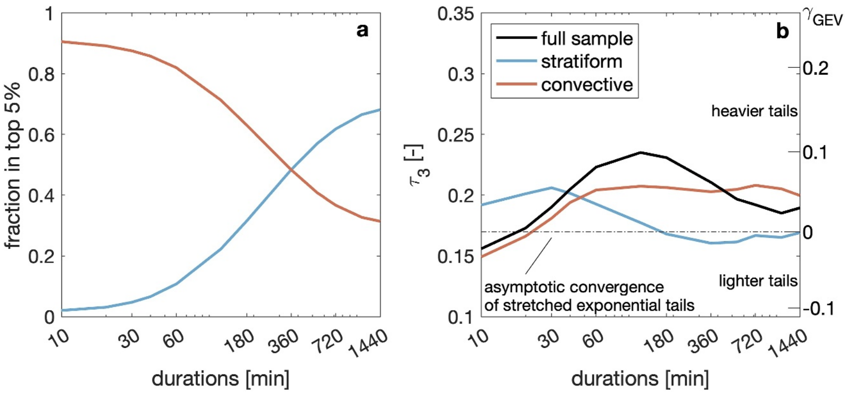

Figure 1. The coexistence of lighter-tailed processes lead to apparent heavy tails of extreme sub-daily precipitation. (a) Average fraction of stratiform and convective events among the observed storms exhibiting largest 5% of the intensities at different durations. (b) Average tail heaviness of observed annual maxima from stratiform (blue) and convective (red) storms and from the full sample (black) measured by the third L-moment ratio τ_3, the corresponding shape parameter of a generalized extreme value distribution is shown in the secondary y-axis (γ_{GEV}).

supported by physics remain too light to explain the observed extremes, causing distrust in physics-based approaches (Marra et al., 2018, 2023; Poschlod, 2021; Schmith et al., 2025).

We hypothesize that part of the discrepancy between statistical findings and physical expectations is due to the heterogeneity of precipitation-generating processes (Cavanaugh et al., 2015; Laaha et al., 2025; Marra et al., 2019). Extreme precipitation can result from various atmospheric mechanisms, each with distinct characteristics and intensity distributions (Berg et al., 2013; Houze, 2014). e.g., convective precipitations tends to produce short-duration extremes (e.g., sub-hourly and hourly), while stratiform processes tend to generate extremes over longer time scales (e.g., multi-day). This heterogeneity of the precipitation generating process could violate the fundamental assumption of extreme value theory that the sample extremes are derived from a single process and that they are therefore representative of a unique population. To overcome this discrepancy, there have been proposals to use mixture distributions to model hydro-meteorological extremes (Kjeldsen et al., 2018; Rossi et al., 1984), but these still rely on the asymptotic assumptions of extreme value theory and do not fully reconcile the discrepancy with atmospheric physics.

The coexistence of different precipitation processes could be non-negligible in a range of durations of critical interest and may influence the overall statistics of extreme precipitation in ways that are not fully captured by the current classical extreme value approaches. Here, we investigate the impact of process heterogeneity on sub-daily precipitation extremes, and we assess whether the coexistence of processes with stretched exponential tails, supported by physics, can explain the observed statistics.

2. Methods

We use data from 310 Alpine climate stations with at least 20 years of precipitation recordings at 10-min resolution in Switzerland, Austria and Italy (see Figure S1 in Supporting Information S1), a region with complex topography and diverse precipitation regimes. We separate temporally independent precipitation storms using 24 hr of consecutive dry (<0.1 mm/10 min) intermissions, following Marra et al. (2020), and we retain only storms lasting at least 30 min. Each storm is associated with a dominant precipitation process according to the storm typology by Papacharalampous et al. (2025), which uses a k-medoids algorithm based on four storm features: total precipitation, maximum intensity at 10 min, total length of the storm, intra-storm variability. It accounts for five types of events (see Figure S2 in Supporting Information S1). Here we focus on the "convective" and "stratiform" types because they are the ones that contribute most to extreme precipitation. The "short stratiform" type accounts for the residual storms that complement to 1 the proportions shown in Figure 1, but were found to have no impact on the overall statistics. The other types have no contribution to heavy precipitation.

For each independent storm, the largest accumulation of precipitation observed during different aggregation intervals is extracted using running windows with steps of 10 min. The average precipitation intensity is then calculated by dividing these accumulations by the duration of the aggregation interval. These are the "ordinary events" in the terminology of Marra et al. (2020). We explored durations of 10, 20, 30, 40 min, 1, 2, 3, 6, 9, 12, 18, 24 hr. Therefore, each storm at each station is associated with a storm type, and with a set of precipitation magnitudes, one for each duration. To quantify the contribution of convective and stratiform processes to heavy precipitation at different durations, we identify the storms that caused the largest 5% of precipitation magnitudes at each duration and quantify the proportion of event types in these heavy events.

To measure the tail heaviness of the observed extremes in the closest way possible to extreme value theory approaches used in practice, we focus on the annual maxima. At each station, we extract the maximum value of each year from (a) the entire time series, (b) the series of convective events only, and (c) the series of stratiform events only. We quantify tail heaviness using the third *L*-moment ratio (τ_3) of these annual maxima series, that is, the ratio of the third and second *L*-moment (Hosking, 1990). *L*-moments are routinely used for the estimation of extreme-value distributions (Nerantzaki & Papalexiou, 2019) due to their good performances also in presence of smaller samples (∼20–40 years) such as those used in the present study. The third *L*-moment ratio is theoretically a measure of skewness, however, for positively skewed distributions *L*-skewness is strongly correlated with *L*-kurtosis and can thus be used as a proxy for *L*-kurtosis. Note that we don't use directly *L*-kurtosis because the sample size is small and we observe large fluctuations. We provide the *L*-kurtosis figures in Supporting Information S1 (Figure S3).

We model stretched exponential tails for the ordinary convective and stratiform events using two-parameter Weibull distributions with cumulative distribution function $F(x) = 1 - e^{-(x/a)^b}$. We estimate the parameters using a least squares linear regression in Weibull transformed coordinates (Marra et al., 2020). Note that estimating the shape parameter with this method is generally unbiased. Specifically, we performed a Monte Carlo simulation and observed that the bias for typical shape parameters and sample sizes is about one order of magnitude lower than the estimation uncertainty. We focus on the tails by left-censoring the values below the 95th percentile, meaning that we retain the values lower than this threshold for the parameter estimation by treating them as non-exceedances. Numerous previous studies validated this approach based on Weibull tails for the description of the statistics of extreme precipitation (e.g., Araujo et al., 2023; Marra et al., 2019, 2020, 2023).

To quantify the tail heaviness of extremes emerging from the stretched exponential tails of convective and stratiform events and from their mixture, we use Monte Carlo simulations. A direct computation is theoretically possible but requires the numerical integration of the inverse cumulative distribution function, which for the case of the mixture needs to be done numerically, leading to unfeasible computation times. We generate 10^5 synthetic years from the examined distributions (convective only, stratiform only, or both) according to the proportions observed and the average number of annual events for the given type. We then extract the annual maxima of these synthetic series and compute the third *L*-moment ratio of the annual maxima.

To assess the potential impact of heterogeneity on estimates based on extreme value theory, we generate 10^5 synthetic years from a mixture of processes that matches the average characteristics of 2-hr events across the examined stations in terms of parameters of the stretched exponential tails of convective and stratiform events and of annual number of convective and stratiform events. We estimate the parameters of the generalized extreme value (GEV) distributions describing the full sample as well as the individual event types using the method of the *L*-moments (Hosking, 1990). We then estimate extremes predicted using a mixture of GEV distributions, considering the proportion of annual maxima belonging to the two types.

3. Results

First, we examine, for each climate station, the events that caused the largest 5% intensities at each duration, to assess whether they were mostly associated with stratiform or convective processes. As expected, almost all heavy storms at 10 min are associated with convective events, while stratiform events are negligible (Figure 1a). Increasing duration, the proportion of convective events decreases, reaching ∼35% at 24 hr, while the proportion of stratiform events increases to ∼65%. On average, the proportions of the two types are comparable at durations of about 6 hr. Interestingly, 10% of the heavy events on an hourly scale are already classified as stratiform.

For short durations up to about 30 min the annual maxima of the entire time series ("full sample" in Figure 1) tend to share the tail heaviness of convective events, a behavior that can somehow be expected, given the dominance of convective events at short durations. For durations longer than about 6 hr, the full sample has tail heaviness

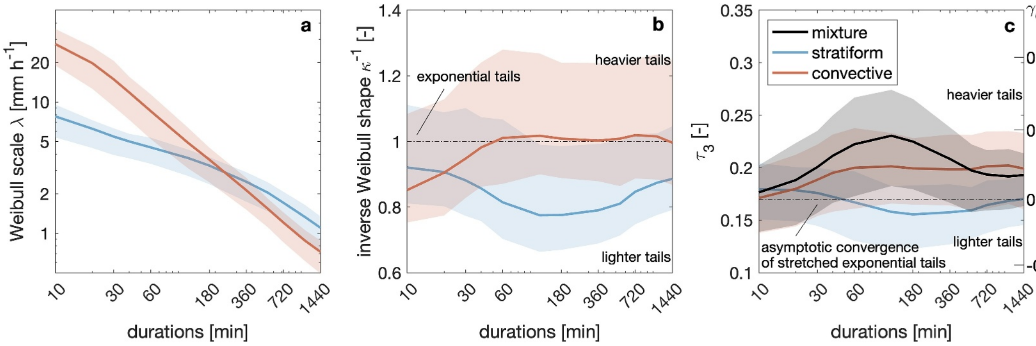

Figure 2. A mixture of Weibull-tailed processes explains the observed tail heaviness. (a) Scale parameter of the stretched exponential distributions describing heavy events from stratiform (blue) and convective (red) storms as a function of duration. (b) Inverse shape parameter of the stretched exponential distribution describing heavy events from stratiform (blue) and convective (red) storms as a function of duration. (c) Tail heaviness, measured by the third L-moment ratio τ_3, of annual maxima sampled from the Weibull distributions describing the tails of stratiform (blue) and convective (red) events. The tail heaviness of annual maxima sampled from the mixture of these Weibull tails is also shown (black). In all panels, solid lines show the average and shaded areas the inter-quartile range across the climate stations.

roughly halfway between convective and stratiform events. However, for intermediate durations between 1 and 6 hr, the tail heaviness of the full sample tends to be higher than those of both convective and stratiform events.

We then assess whether these findings can be reconciled with the stretched exponential tails predicted by physics. We estimate the stretched exponential tails describing stratiform and convective events, whose parameters are shown in Figure 2. We see that convective events have typical magnitudes (measured here by the scale parameter of the Weibull distribution, Figure 2a) markedly greater than the ones of stratiform events for durations below approximately 1 hr, while the typical magnitudes of convective and stratiform events are similar for durations greater than 1 hr. The tail heaviness of the two processes (measured by the inverse of the Weibull shape parameter) is typically close to exponential, or sub-exponential for the case of stratiform events, and relatively uniform for durations above approximately 1 hr.

These stretched exponential tails explain well the tail heaviness of the observed extremes belonging to these two types (Figure 1b vs. Figure 2c), aside from an underestimation of the tail heaviness of stratiform events at durations below 3 hr (where the estimation for observational data might be affected by measurement discretization). Using the Monte Carlo approach, we then estimate the tail heaviness of annual maxima that emerge from mixtures of stretched exponential tails with the observed characteristics and proportions (black line in Figure 2c). The mixture of stretched exponential tails, as predicted by physics, explains well the tail heaviness of the observed annual maxima across all the durations, including the apparent heavier-tail region observed between 1 and 6 hr (Figures 1b and 2c).

The proportions of different processes in Figure 1a, however, is not sufficient to explain the emergence of heavy tails in the full sample. To fully understand these apparent tails, it is necessary to consider the tails of the individual processes as well as their typical scales. Stratiform events tend to have lighter tails than the convective events across most durations, but their scale become comparable already at durations as short as 1 hr (Figure 2), increasing the chances of having stratiform events among the annual maxima. In general, even in absence of differences in tail heaviness, mixing distributions with different scales may lead to apparent heavy tails, at least non-asymptotically.

4. Discussion

Asymptotically, the tail heaviness of a mixture converges to the tail heaviness of the component that has the heaviest tail. At the shortest temporal aggregation of 10 min, an apparent contradiction occurs, as the stratiform events tend to have tails heavier than the convective events, although convective events are the ones dominating the extremes—an observation also reported, indirectly, by Berg et al. (2013). The much smaller magnitude of the stratiform events at these scales, however, prevents these heavier tails from emerging. In the asymptotic limit, stretched exponential distributions converge to exponential tails. Nevertheless, as seen above, when the

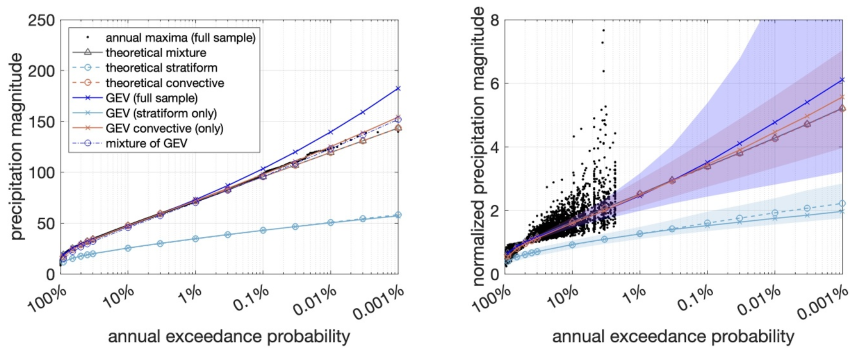

Figure 3. Non-convergent heterogeneous processes lead to biased extreme value theory estimates. (a) Synthetic annual maxima (we generate 10^5 years) from a mixture of convective and stratiform processes generated from the average properties of the observed events at 2-hr duration. The generalized extreme value (GEV) estimate based on extreme value theory for the full sample overestimates the magnitude of the most extreme events, because of the heterogeneity and the non-convergence to the asymptotic limit. The figure also shows the GEV estimates of the two processes separately, demonstrating the impact of non-convergence alone: stretched exponential tails heavier than exponential (convective case) are overestimated by GEV (convergence to exponential is from above), while stretched exponential tails lighter than exponential (stratiform case) are underestimated by GEV (convergence to exponential is from below). The mixture of GEV obtained considering the two processes separately overestimates extremes similarly to the GEV of convective processes. (b) Similar results obtained from the observed data at each climate station. Solid lines show the average GEV estimates and shaded areas show the inter-quartile range across the climate stations. At each stations, annual maxima and quantiles are normalized over the median annual maximum. The mixture of GEV is not shown here.

population is composed of two groups each with stretched exponential tail, the resulting overall tail appears heavier than the individual ones. These observations confirm the notion that, when examining extreme precipitation, we are far from the asymptotic convergence required by the extreme value theorem. While the reported findings refer to the examined area, a mid-latitude region with rough orography close to the Mediterranean, qualitatively similar results are to be expected in all situations in which multiple processes with diverse statistics contribute to the local extremes. These include seasonal maxima instead of annual maxima as well as other regions and climatologies. The magnitude of the impact on the tail heaviness and the quantitative explanation based on the mixture of Weibull tails, however, will depend on the characteristics of the local precipitation regime.

The third *L*-moment ratio shown in Figures 1b and 2c can be directly related to the tail limiting type of the extreme value theorem (Hosking, 1990). As the asymptotic assumption of the theorem is likely not verified, as just seen, estimates of rare sub-daily to daily extreme precipitation obtained using extreme value theory on this heterogeneous sample (or on stretched exponential tails processes in general) could be biased. Indeed, when we generated very long synthetic time series from stretched exponential tails that resemble the coexistence of stratiform and convective events of our observations, we confirmed that the estimates based on extreme value theory tend to overestimate the most severe extremes (Figure 3). Comparing the GEV estimate from the full sample (blue) with the GEV estimate from convective events only (solid red), we see that the overestimation due to the heterogeneity is more important than the one due to non-convergence alone (measured by the difference between the solid red and the dashed red) mentioned by Wilson and Toumi (2005), Papalexiou and Koutsoyiannis (2013), Marra et al. (2023) and others. Considering the heterogeneity of processes, however, is not sufficient to reproduce observations, as shown by the estimates obtained using the mixture of GEV distributions (dash-dotted blue line in Figure 3), which shows an overestimation similar to the one of the GEV of convective storms related to the non-convergence of stretched exponential tails to the asymptotic limit. Figure 3 also demonstrates the impact of the non-convergence of stretched exponential tails to the asymptotic limit. Stretched exponential tails heavier than exponential (convective case) converge to exponential from above, and are overestimated by GEV (compare solid and dashed red line), while stretched exponential tails lighter than exponential (stratiform case) convergence to exponential is from below, and are underestimated by GEV (solid and dashed light blue lines).

Our results partially explain the underestimation of extremes from non-asymptotic methods reported in previous studies. e.g., Marra et al. (2023), Schmith et al. (2025) and Poschlod (2021) observed that in northern Europe, the stretched exponential tails predicted by physics were too light to explain the observed statistics of daily precipitation. Similarly, Marra et al. (2018) reported systematic underestimates of extremes for a range of sub-daily durations when using stretched exponential models. We showed that the coexistence of stratiform and convective processes can explain these observations, a hypothesis suggested already by Marra et al. (2018).

It should be noted that temporal non-stationarity in the precipitation processes such as the ones induced by the ongoing climate change (e.g., IPCC, 2023) could impact the apparent tail heaviness in a manner which is qualitatively similar to the one of heterogeneity highlighted here (e.g., Abdelmoaty & Papalexiou, 2023; Nguyen et al., 2025). Quantitatively, however, climate change impact is negligible with respect to the mixing of heterogeneous processes. In fact, using information from Dallan et al. (2024), climate change impact can be conservatively constrained to be smaller 5% over the 40 years spanned by our database, which is approximately one order of magnitude smaller than the differences imputable to the mixing of heterogeneous processes highlighted here.

The classification of the storms we use is based on the local precipitation time series, and aims at focusing on the dominant physical process during the intense portion of the storms. In principle, other classifications are possible, for instance based on synoptic circulation or large-scale atmospheric configurations, although their relation to the local precipitation tends to be more nuanced. The observation that stratiform events appear to have heavier tails than convective at 10 min, while confirmed by other studies (e.g., Berg et al., 2013), could be affected by the classification into types. In fact, few large cases, or even one, that are misclassified may inflate the apparent tail heaviness of one type rapidly, especially at short time scales. At longer scales, the averaging would smooth out such effects.

5. Conclusions

We analyze hundreds of sub-daily precipitation records to assess whether process heterogeneity can explain the contradiction between the heavy tails found by extreme value theory for sub-daily precipitation and the stretched exponential tails predicted by atmospheric physics. We find that process heterogeneity is an essential component of extreme sub-daily precipitation statistics. The apparent power-type tail reported by extreme value theory can be explained by the coexistence of non-convergent stretched exponential processes. Notably, the heavier tails observed at scales of 1–6 hr are explained by a mixture of lighter-tailed processes. These results further reconcile the discrepancy between statistical findings and physical expectations in the statistics of extreme sub-daily precipitation. This highlights once more the importance of including information on the understanding of physical process under study (as e.g. in Basso et al., 2021; Fischer, 2018), instead of only relying on statistical asymptotic theory based on assumptions which might not match the actual data generating process.

On a range of sub-daily durations that include the hourly scale, the coexistence of convective and stratiform events contributes to violating the assumptions of the extreme value theorem. Due to the stretched exponential nature of precipitation tails, which have an extremely slow convergence, and to the coexistence of processes with different scales and tails, precipitation extremes are far from converging to the extreme value theorem limit. Assuming asymptotic convergence on these non-convergent heterogeneous samples may lead to an overestimation of the probability of particularly large extremes.

Extreme precipitation statistics constitutes the basis of the modeling chains used for hydrological and hydraulic design, water resources management, risk management, and insurance/reinsurance. We find that process heterogeneity in extreme precipitation is important already at hourly scales and concerns a range of scales of utmost importance for all these applications. These results may have important implications for how design values are determined. We advocate the explicit consideration of process heterogeneity and of physical arguments in our extreme value models as a way to develop resilient and sustainable strategies.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Source code and data to reproduce the study are freely available from Marra (2025): https://doi.org/10.5281/zenodo.17185624.

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Supporting Information for "Apparent heavy tails of sub-daily precipitation explained by the coexistence of lighter-tailed processes"

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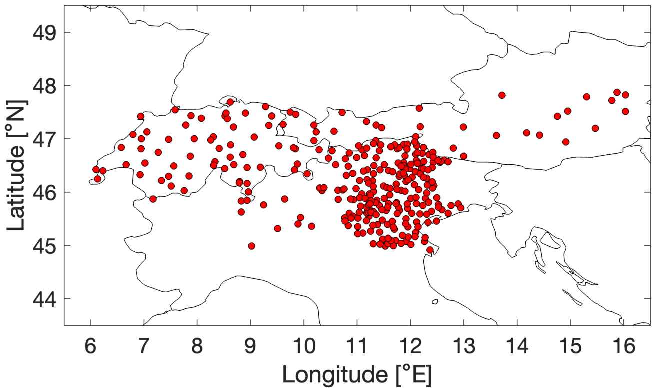

Figure S1. Location of the climate stations used in the study.

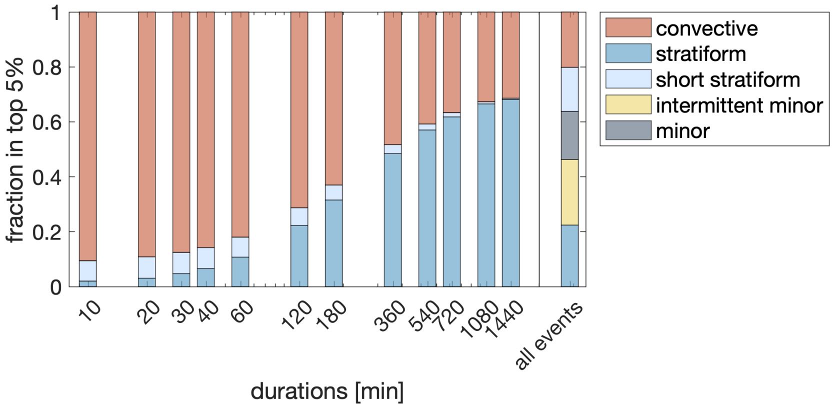

Figure S2. Average fraction of the different storm types exhibiting largest 5% of the intensities at different durations. The rightmost column shows the average fraction for all the storms.

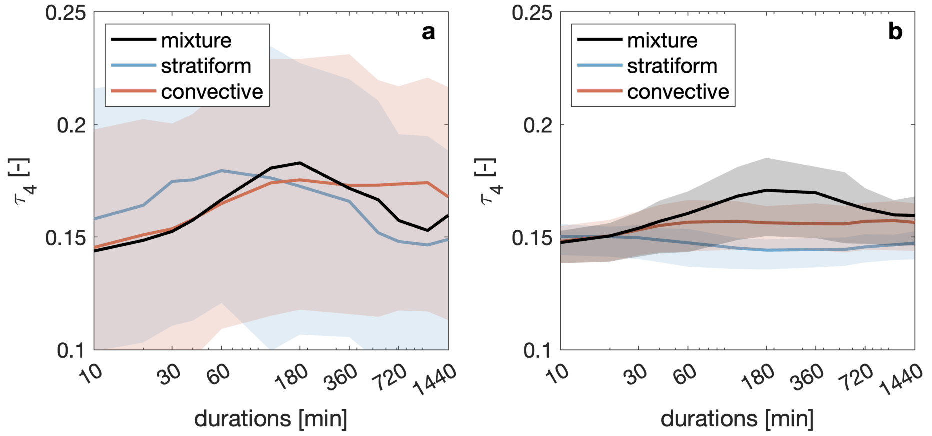

Figure S3. (a) Same as Figure 1b, but for the fourth L-moment ratio (τ_4). (b) Same as Figure 2c, but for the fourth L-moment ratio (τ_4).