

# How intermittency affects the rate at which rainfall extremes respond to changes in temperature

Final response to reviewers and editor  
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I would like to thank the reviewers and the editor for their valuable comments and suggestions for improving the quality of this paper. I have taken each comment into consideration and performed all necessary changes (with the exception of a few minor technical issues explained below). In the following, please find a point-by-point description of the main changes made during revision together with references to the corresponding page numbers and sections.

## **Main changes to the paper:**

- I went over the whole paper again to make sure the term “intermittency” was clearly defined and that the difference between intermittency (i.e., a statistical summary of the lacunarity of rain) and the actual physical processes responsible for it (e.g., evaporation, advection, convergence and formation of precipitation) was clear.

- In the introduction, I added a sentence about the difference between large-scale and small-scale intermittency with some new references to the literature:

*“Indeed, beyond a few hours of aggregation time scale, total rainfall amounts often turn out to be more correlated to storm duration and intermittency rather than peak rainfall intensity (e.g., Azad and Sorteberg, 2017; Lamjiri et al., 2017). And while the discrete, episodic nature of precipitation may be most apparent at larger scales (e.g., days, weeks or months), its effects can be observed down to the microscale (e.g., Kumar and Foufoula-Georgiou, 1994; Ignaccolo et al., 2009; De Michele and Ignaccolo, 2013; Mascaro et al., 2013).”*

- I added more details in Section 4.1 about the physical mechanisms responsible for producing intermittency in rain. In the same section, I also added the additional explanation suggested by Reviewer 1 for why the scaling of extremes might change above 22-23 degrees Celsius:

*“Another explanation could be the existence of strong moisture limitations in the regions surrounding the rainfall and upwind thereof. The atmosphere might have capacity to hold more water at higher temperatures, but the land surfaces have no additional moisture to give, causing the relationship between temperature and rainfall extremes to change. The key parameter in this case is the rate at which new precipitable water can be evaporated and brought in from surrounding regions, which increases with temperature but will be limited by advection velocities and moisture availability at nearby land surfaces. A simple calculation of daily mean evaporation rates with temperature using the approximation provided by Linacre (1977) confirms this hypothesis, showing that although mean evaporation rates increase steadily with temperature, the rate of increases slows down at higher temperatures. Even in cases of unlimited moisture supply, evaporation rates remain small compared with precipitation rates. Thus, once all the water in a column of air has been rained out, the dominant factors controlling precipitation totals at scales beyond one hour are likely to be dynamical in nature. Intermittency, although it is not a physical quantity, can be viewed as a summary statistic of the combined effect of all dynamical processes at work in rainfall. As such, it can help better understand*

*the response of rainfall extremes to changing temperatures beyond simple Clausius-Clapeyron scaling.”*

- I changed the text in the data and methods section to clarify the difference between the full USCRN dataset (which contains stations outside of the U.S.) and the subset used for analysis (which only contains data in the U.S.).

*“The full weather station network consisted of 232 different stations spread across the United States, Canada and Siberia. However, only a small subset of these stations were kept for the analysis. Specifically, only the time series with at least 20 valid positive rainfall values in at least 20 different temperature classes between 5 and 30 degrees Celsius at the 24h aggregation time scale were kept. This drastically reduced the number of stations, from 232 to 99. A map with the 99 stations satisfying all these criteria is shown in Figure 1.”*

- In the data and methods section, I added a sentence explaining why aggregation was performed over overlapping time windows.

*“The main reason for using overlapping time windows during aggregation was to better account for the fact that the starting time of an aggregation time period is arbitrary. By contrast, non-overlapping time windows would have resulted in many large precipitation accumulations to be missed.”*

- In section 4.1 (pages 9-10) I added information about the uncertainty on the estimated scaling rates, as suggested by the editor. Average uncertainties on estimated scaling rates were 1.8 - 2.7% for the model without intermittency and 1.3 - 1.7% with intermittency. However, individual uncertainties on scaling rates for selected stations and time scales can be as high as 5%, as illustrated by the station *FL-Everglades-City-5-NE*. I did not perform any formal statistical testing as I felt this was not real needed here to get the message: there are obvious differences between the two methods at larger scales and not so much at the smaller scales.

*“In the model without intermittency, scaling rates rapidly decrease with Delta t from approximately 4.37% at the hourly time scale to -0.45% at the 24h scale. The average uncertainty affecting the estimated scaling rates at a given time scale (among all stations) is between 1.8% and 2.7% and increases with Delta t. [...] After correcting for intermittency, the effect of temperature becomes visible again and results are much closer to what can be expected from the Clausius-Clapeyron relationship. Still, there appears to be a small decrease of the scaling rate with Delta t after correction for intermittency from 8.0% at the hourly scale to 5.70% at the 24h scale. The latter however, can be explained by the relatively small sample sizes and is well within the range of uncertainty (average uncertainty of 1.3 - 1.7% per time scale, increasing with Delta t).”*

*“The stations with the strongest scaling rates overall (both at the hourly and daily time scales) were *FL-Sebring-23-SSE* (12.96% +/- 3.4% without intermittency and 14.70% +/- 1.74% with intermittency) and *FL-Everglades-City-5-NE* (12.42% +/- 5.15% respectively 13.04% +/- 2.41%), both situated in a humid tropical climate famous for large and intense warm season thunderstorms”*

- Following up on the suggestion by the editor, I added an additional sentence at the end of the conclusion mentioning the necessity to perform more in-depth analysis of the joint and conditional distribution of the triplets of rainfall (R), temperature (T) and intermittency (I) for all rainfall quantiles, and not just the extremes:

*“A more detailed and systematic analysis of the joint probability distribution of (R,T,I) and pairwise conditional density functions for all values of rainfall accumulations (and not only for the upper quantiles) might also be beneficial to better understand how rainfall amounts, temperature and intermittency are linked across scales.”*

**Technical/notational remarks:**

All suggested changes have been performed with the exception of the following:

- Equations 2 and 3: ‘ni’ should actually read  $n_i$  (subscript i as it is an index), otherwise it will appear as if n is multiplying by i.

*Response: There is no need for a subscript here as this is indeed a multiplication.*

- Equations 5, 7: The hierarchy of brackets would be recommended:  $[\ ]$  rather than  $(\ )$ .

*Response: Square brackets are not recommended here. For functions, it’s better to use  $()$ .*

- While the author presented the relations for all the 99 stations using boxplots, it would be better if they are presented in maps to understand the spatial variations better. Perhaps, as discussed in section 4, the author can divide the scaling exponents under different temperature gradients and then maps the exponents.

*Response: Maps containing the results of the 99 stations would have been possible. I tried this in some of the earlier versions of the paper (before initial submission). However, I felt it was hard to interpret these (due to strong variations in space, scales and temperatures) and to draw any strong conclusion from them. The boxplots on the other hand provide a much clearer summary of the data.*

- Editor comment: figures have to be improved to make them presentation quality.

*How exactly? Some suggestions for improvement would be welcome.*