Interactive Discussion: Author Response to Referee #2 (M. Schleiss)

Brief Communication: On the extremeness of the July 2021 precipitation event in western Germany

Lengfeld et al.
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RC: ***Reviewer Comment***, AR: *Author Response*, □ Manuscript text

Dear Dr. Schleiss,

we would like to thank you very much for your willingness to review this paper, and for your swift, positive and constructive response to the manuscript.

Please find our responses to your comments below. These should be considered as preliminary (part of the interactive discussion). The final implementation of changes also depends on another referee report.

Thanks again for your efforts!

Kind regards,
Katharina Lengfeld (on behalf of the author team)

RC: ***Uncertainty assessment:***
I only found one major issue that needs to be addressed before publication, which is the lack of a proper uncertainty assessment. The authors could and should do more to quantify the uncertainty on the estimated return periods in the GEV, and how this uncertainty propagates to the WEI and xWEI. These are very important issues given the short available data record and the fact that the differences between the top 5 events aren't that large.

AR: We agree that a comprehensive uncertainty analysis of WEI and xWEI would be desirable. In a way this manuscript is also a statement regarding uncertainties as we show how WEI and xWEI values can change when extending the underlying time series.

A comprehensive uncertainty assessment however, as suggested by the referee, is beyond the scope of this study: apart from the quantification of the GEV parameter estimation uncertainty (which is computationally very expensive), the propagation and aggregation of these pixel-wise uncertainties in the computation of WEI and xWEI is anything but trivial, and would entail the development and validation of an adequate methodological approach. Such a development (and its documentation) exceeds the scope of a brief communication and would rather correspond to the format of a "research article". To this end, we would like to refer to the NHESS manuscript guidelines (https://www.natural-hazards-and-earth-system-sciences.net/about/manuscript_types.html):

Brief communications are timely, peer-reviewed, and short (2–4 journal pages). These may be used to (a) report new developments... ...disseminate information and data on topical events of significant scientific

and/or social interest within the scope of the journal....

Having said that, we will provide information in Table 1 about the sensitivity of WEI and xWEI for the top 5 events when leaving the year of occurrence of the event out of the calculation of the GEV parameters as we already have done for July 2021 event. This will allow for a better assessment of the uncertainty introduced by the short time series, which we believe is a major source of uncertainty in this study.

RC: ***On the usefulness and need to rank extremes***
I see value in studying extremes and their characteristics. However, I also wonder how useful it is to rank extremes over a given range of scales. Who needs such a ranking? And what can you really learn from a ranking that keeps changing over time as more data get available? Also, wouldn't such a ranking strongly depend on the lower/upper bounds for the calculation of xWEI?
Suggestion: add some discussion about the practical usefulness of ranking extremes and the scientific/practical limitations of the approach.

AR: The ranking of events is the key to identify events that are exceptional with regard to a specific property (and hence "metric", in this case WEI or xWEI). Identifying such exceptional (high-ranking) events, in turn, is a relevant exercise for various reasons: to understand their occurrence and impacts, which are often fundamentally different from other (lower ranking) events, or to prioritise resources for event-based case or attribution studies. Furthermore the public often demands a "putting-into-context" of these events which can be communicated by ranks. The identification and characterisation of the most severe past events can help to adjust mitigation measures as these events can be used as benchmarks for further analysis.

For clarification, we suggest to change around line 106:

> Hence, the resulting rankings should not be over-interpreted, especially if we consider uncertainties regarding the radar rainfall estimation, the estimation of return periods and the selection of the spatial domain. ..... Nevertheless, ranks can help to compare events and serve as a tool to communicate an events extremeness to the public. Practically the identification and selection of these outstanding events can be used as benchmarks for further analysis and mitigation measures.

We agree with the referee that the choice of lower and upper bounds (in space and time, if we understand correctly) highly influences the values of the xWEI. For this study we used the same 200 x 200 km bounding box for all the different events, as we did in our previous paper (Voit and Heistermann, 2022), where we also discussed the choice of the spatial domain and considered durations in detail. While these choices are arbitrary to some extent, they are all the more important to make events comparable across space and time, and hence to allow for a ranking.

RC: ***Alternative approaches***
One limitation of WEI and xWEI is that they do not really tell us anything about how extreme an event was relative to others. Furthermore, the metrics involve the fitting of a GEV model, which comes with large uncertainty. Perhaps a different metric or different way of quantifying relative extremeness across scales should/could be considered?
Suggestion: add a few words about possible, alternative approaches to WEI and xWEI.

AR: We are not sure whether we correctly understand the referee's statement that "one limitation of WEI and xWEI is that they do not really tell us anything about how extreme an event was relative to others." – as it is exactly what these indices were designed for. There are different concepts of quantifying the extremeness of heavy precipitation events. "Simple" return periods or the exceedance of thresholds at gauges might be the most

common ones, but do neither reflect the spatial extent of an event, nor give any information at which duration the event was most extreme. More advanced concepts like the Precipitation Severity Index (Caldas-Alvarez et al. 2022) consider the spatial extent, but also do not acccount for different durations explicitly. Another index was introduced by Ramos et al. (2017) which is based on precipitation anomalies and spatial extent of an event. None of these concepts considers and combines the co-occurrence of extremeness of an event at different duration levels, neither do these concepts identify the spatial and temporal scale on which an event was most extreme. So while we agree that WEI and xWEI are uncertain quantities, they have been shown to be useful measures for assessing and comparing the extremeness of heavy precipitation events - which is why we chose these measures in the context of this study. As this is a brief communication, we would prefer not to elaborate on alternative metrics in the introduction, since this would distract too much from the actual topic.

RC: ***Temporal structure***
Some information about the temporal structure of the July 2021 event would help the reader understand why this event was extreme over multiple scales, and how the water was distributed over time.
Suggestion: show a time series and/or give some information about peak rainfall rates, intermittency and standard deviation of rainfall rate over time for a fixed location. Fig1 covers the spatial aspect but there is no information about the time aspect so far.

AR: We will add barplots with temporal evolution of the hourly precipitation in four districts that were hit by the July 2021 event as shown in the figure below. The radar observations have a spatial resolution of 1 km x 1 km. We show the maximum hourly precipitation within each district to better understand temporal structure and will add the following to the description of the event in line 15:

> The temporal development of the event (Fig. 1 right) indicates heavy precipitation on several temporal scales from showers of a few hours up to continuous rainfall for more than a day.

RC: ***Stationarity assumption***
There is an implicit stationarity assumption behind the whole study that should be mentioned.
Suggestion: Clearly mention the assumptions underlying your approach and the consequences they could have on the calculation of return values and (x)WEI. To reassure readers, I suggest you check whether there a trend in the precipitation extremes data over time. You can check this by fitting alternative GEV models with time-dependent shape or scale parameters and applying model selection based on likelihood ratio tests or AIC.

AR: We will mention in the methods section of the revised manuscript that stationarity of the underlying GEV distribution is assumed when estimating the GEV parameters. The dataset of 21 years of data is not long enough for a reliable analysis of instationarity (even if we have to assume it exists). At the same time, the shortness of this times series makes stationarity a pragmantic and viable assumption. We will comment on this issue around line 66 of the revised manuscript.

RC: ***Equation 1***
Please provide units for all quantities (A, T and E). What does the index i represent? The text does not say. Same for the index t. Please use ln() instead of log() to avoid ambiguity about the base of the logarithm.

AR: i represents a grid point of the radar composite, t is used for a given duration in the original paper of Müller and Kaspar, where the extremity is defined. We agree it is more clear to use ln instead of log. We will change this and explain t, i and add the units.

RC: ***Table 1***

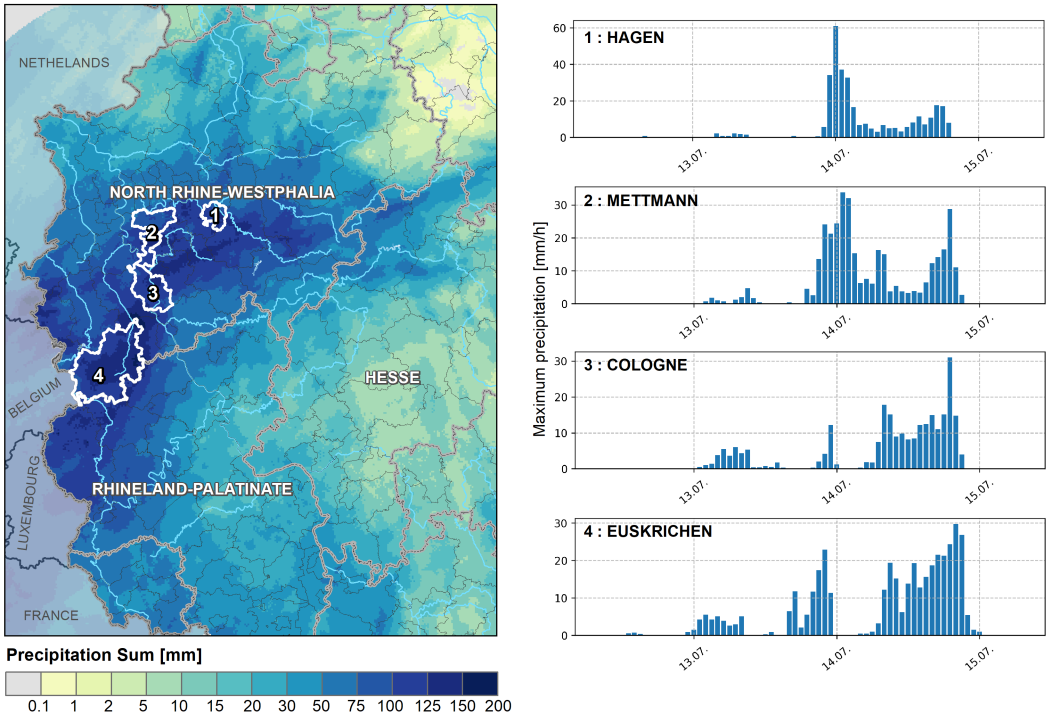

Figure 1: Suggested revised version.

Table 1: please provide units for WEI and xWEI

AR: We will add log(a) km as the unit for the WEI in Table 1. xWEi is dimensionless.

RC: ***Table 1: I struggle to understand what you mean by "Duration". The caption says that the "Duration" is the timescale at which the maximum extremity was reached. But there are only two values (24h and 48h) for 5 events. I would have expected each event to have a peak at a different time scale. More generally, I think it would be useful to clarify what you consider to be an "event" and what the difference is between the "Duration" and the length of an "event". For example, is the average precipitation depth calculated at the event scale or over the duration indicated in the table?***

AR: We use the term "duration" in its standard meaning in hydrometeorology and extreme value statistics: the "duration" (or "duration level") is the length of a reference time interval over which the cumulative precipitation depth or the mean precipitation intensity is determined which could then be subjected to further (extreme value) analysis (as in intensity-duration-frequency curves, IDF). In this study, we analysed 11 different duration levels (1, 2, 3, 4, 6, 9, 12, 18, 24, 48 and 72 hours) in order to obtain the maximum corresponding return periods over the entire length of the event; and indeed, the 5 most extreme events according to the WEI all have the largest extremity at a duration level of 24 or 48 h. Again, for the computational details, we have to refer to the literature in terms of Lengfeld et al. (2021) and Voit and Heistermann (2022). In contrast to the referee's statement, we did not use the term "length of an event" in the manuscript, but in fact we need to define such a length for our analysis as it sets the time window in which we compute the return periods for the abovementioned duration levels. While the length of an event could be considered as the time span between

the first and the last raindrop, we admit that its definition involves some level of arbitrariness in determining the times of start and end. In any case, the length of an event could be shorter than an hour, but also longer than 72 hours, and is hence independent of the duration levels.

In summary, we suggest to use "duration level" instead of duration in the revised manuscript, in order to highlight the difference to "length of an event" (which is, however, not mentioned in the manuscript).

RC: ***Table 1: it would be useful to indicate the change in WEI and xWEI for the other events as well. I understand that you are primarily interested in the changes for the July 2021 event. However, I also think that it's important to convey a general sense of how sensitive the WEI and xWEI metrics are to the inclusion/exclusion of particular year of data.***

AR: The WEI and xWEI for the other events did not change with the updated GEV parameters when including/excluding the year 2021 in the GEV parameter estimation. We will mention this in the manuscript. In addition, we will compute the GEV parameters for the other four events without the year of their occurrence and add the WEI and xWEI for the events based on these parameters to get an idea of its sensitivity to the length of the time series (see also the comment by referee 3).

RC: ***Min/Max bounds for integration***
Section 3: For the calculation of WEI and xWEI, please clearly state the minimum/maximum bounds you took for integrating over the duration and area.

AR: To keep the results comparable we used the same bounds for the computation of the xWEI as in our previous study (Voit and Heistermann, 2022): Duration levels from 1 h - 72 h and a bounding box of 200 km * 200 km around the centroid of the event (Bad Neuenahr). For the WEI the whole area affected by the event as defined in CatRaRE is taken into account for the calculation (Lengfeld et al., 2021).
We will add this information in line 77.

RC: ***l.87 The term "characteristic" duration was not properly defined.***

AR: We normally use the term "characteristic duration" for the durations at which an event has the highest extremity. In this brief communication we used the term in line 87, only. We suggest to replace it by the following:

> This event had the largest extremity at a duration of 24 hrs...

RC: ***l.103: I don't understand why the July 2021 could be considered a compound event. Please justify.***

AR: The referee is right that this point needs further explanation and clarification. Thieken et al. (2022) highlighted the flood events resulting from the August 2002 event in Saxony as a compound inland flood. During this event we observed extreme rainfall at rather short durations which caused flash floods as well exceptional rainfall at longer durations (especially at the 48h duration) which caused fluvial floods and most likely led to an increased runoff coefficient due to the already saturated soils. We expect a similar behaviour for the July 2021 floods with different flood types most likely overlaying and amplifying each other, with the added complexity of hydrogeomorphic processes at various time scales (see Mohr et al. 2022 and Dietze et al. 2022). According to the definition below, as well as to the definition of the IPCC (Seneviratne et al. 2012), we are therefore inclined to describe these floods as "compound inland floods". However, we agree that the question whether the concept of a "compound event" could also apply to a precipitation event such as the one in July 2021 should be subject to further discussion within the scientific community. To clarify this point we changed the sentence in line 102 to:

Thieken et al. (2022) framed the Elbe flood event that followed the August 2002 precipitation (rank 1 in Tab. 1) as a "compound inland flood", in the sense of different flood mechanisms overlaying and amplifying each other. Similar observations were made for the July 2021 event (e.g. Mohr et al. 2022). Given the exceptional xWEI values of both the August 2002 and the July 2021 events, it might be worth to discuss, in the future, whether heavy precipitation events that are extreme across scales could be framed as hydro-meteorological compound events.

RC: ***According to Leonard et al. (2014), "A compound event is an extreme impact that depends on multiple statistically dependent variables or events". According to Zhang et al. (2021), compound extremes are defined as 1) two or more extreme events occurring simultaneously or successively, 2) combinations of extreme events with underlying conditions that amplify the impact and 3) a combination of events that are not extreme individually but lead to an extreme event or impact when combined.***
In the case of the July 2021 event, I do not see why this event should be labeled as "compound". It just appears to have been extreme over multiple spatial and temporal scales at the same time. Please elaborate!

AR: We refer to our previous answer.

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