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

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Abstract.

The weather extremity index (WEI) and the cross-scale WEI (xWEI) are useful parameters for determining the extremeness of precipitation events. Both rely on the estimation of return periods and, therefore, the estimation of GEV parameters. When including the year 2021 in this estimation, the devastating event in July 2021 drops from first to fourth place regarding the WEI compared to all events between 2001 and 2020, but remains the most extreme regarding the xWEI. This emphasizes that it was extreme across multiple spatial and temporal scales, and the importance of considering different scales to determine the extremeness of rainfall events.

1 Introduction

In July 2021, an extreme precipitation event took place in western Germany (Fig. 1) and neighbouring countries which caused one of the most severe natural disasters in Germany and Europe. In Germany, more than 180 people lost their lives (more than 140 in Rhineland-Palatinate, and more than 40 in North Rhine-Westphalia). According to Munich Re, loss and damage amounted to EUR 46 billion (MunichRE, 2022), 33 billion in Germany alone. The German Insurance Association (GDV) reported a new record of EUR 8.2 billion insured flood losses for a single event (GDV, 2021). Numerous studies have been published since the event, e.g. related to meteorological, hydrological, and impact-related aspects (Mohr et al., 2022), hydro-geomorphological processes (Dietze et al., 2022), or early warning (Fekete and Sandholz, 2021; Thieken et al., 2022a). With regard to the extremeness of the event's precipitation, Germany's national meteorological service (Deutscher Wetterdienst; DWD hereafter) estimated return periods of well over 100 years for large parts in North Rhine-Westphalia and Rhineland-Palatinate (Junghänel et al., 2021). Mohr et al. (2022) reported return periods of more than 700 years over large areas.

Junghänel et al. (2021) and Dietze et al. (2022) highlighted that an important feature of the July 2021 precipitation event was not only a high rainfall accumulation at a large spatial extent, but also the occurrence of high return periods at various durations as well as a remarkable heterogeneity in space. In order to account for such complex events, and to formalize the quantification of their extremeness, Müller and Kaspar (2014) had suggested (in this journal) the weather extremity index (WEI). The WEI identifies the spatial and temporal scale at which an event was most extreme and allows to quantify the extremeness (rarity) of an event. It has been increasingly used since then (Gvoždíková et al., 2019; Minářová et al., 2018), and was also established as

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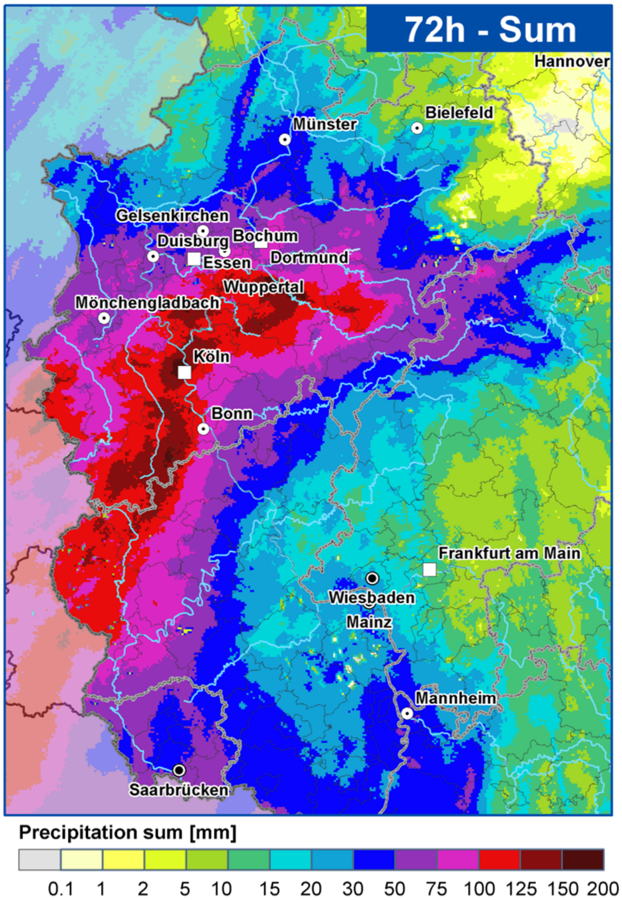

Figure 1. Accumulated rainfall of the precipitation event from 12. July, 5:50 UTC to 15.July 2021, 5:50 UTC based on RADKLIM v2017.002 (Winterrath et al., 2018b)

a routine measure of extremeness by the DWD (Lengfeld et al., 2021). Based on the German operational radar data, DWD has quantified the WEI of the event to be 229 log(yr)km. With this value, the event outranked all other events based on radar data that were previously classified in the period from 2001 to 2020.

Recently, Voit and Heistermann (2022) argued in their contribution to this special issue that the WEI could be supplemented in order to account for events that are not only extreme at a distinct spatial and temporal scale. Instead, such events could be extreme across various scales - a feature that also appeared to characterize the July 2021 event. Hence, Voit and Heistermann defined the cross-scale weather extremity index (xWEI), and found that, on the basis of xWEI, the July 2021 event outranked other extreme events by far.

However, the estimates of WEI and xWEI that have so far been obtained for the July 2021 event by the DWD and Voit and Heistermann (2022) share a limitation: the parameters of the underlying generalized extreme value (GEV) distributions were estimated based on the RADKLIM data set - a reanalysis of DWD's procedure for radar-based quantitative precipitation

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estimation. As the RADKLIM data used for that purpose did not yet contain data from 2021, the July 2021 event was not included in the estimation of GEV parameters. The extremeness of the event might hence have been overestimated.

In June 2022 the DWD published the updated RADKLIM reanalysis (Winterrath et al., 2018b) which now includes data from 2001 to 2021. This provides the opportunity to re-assess, in this brief communication, the extremeness of the July 2021 event on the basis of the most recent homogeneous radar reanalysis, using both the established WEI and the xWEI as a supplement to account for extremity across scales.

In section 2, we introduce the underlying datasets, RADOLAN, RADKLIM and CatRaRE. Section 3 summarizes the concept and the computation of the two extremity indices, WEI and xWEI. In section 4, we present an assessment of the five highest ranking extreme events in the most recent RADKLIM dataset, and the changes introduced by including the data from 2021. Section 5 summarizes our findings and highlights implications for research and risk management.

2 Data

Our analysis of the July 2021 event is based on two different sets of gauge-adjusted, hourly precipitation data: (i) The operational RADOLAN-RW product (RADOLAN, 2022) always uses the most recent algorithms for data processing and is available in realtime; (ii) RADKLIM (RADKLIM v2017.002, see Winterrath et al., 2018a, b), in turn, is a reanalysis of radar data since 2001: it is based on a homogeneous set of algorithms, includes advanced climatological corrections, and uses additional hourly and daily rainfall data from rain gauges that were not available in realtime.

Based on RADKLIM, DWD provides a Catalogue of Radar-based heavy Rainfall Events (CatRaRE) containing rainfall events in Germany of 11 durations between 1 and 72 hrs since 2001 that exceed DWD's warning level 3 for severe weather in terms of precipitation rate. A detailed description of the catalogue and its parameters can be found in Lengfeld et al. (2021), the data can be accessed via Lengfeld et al. (2022).

3 Methods

Müller and Kaspar (2014) defined the so-called weather extremity index WEI that takes into account the affected area A and the rareness of an event (in form of the return period T) for various durations. At a given duration D, the extremity $E_{t,A}$ amounts to:

$$E_{t,A} = \frac{\sum_{i=1}^{n} log(T_{D,i})}{A} \cdot \frac{\sqrt{A}}{\sqrt{\pi}}. \quad (1)$$

The maximum $E_{t,A}$ over all durations is then defined as WEI and determines the spatial extent and duration of the most extreme stage of an event.

We use two different combinations of radar data and GEV parameter estimates: (1) The realtime setup with estimation of GEV parameters based on RADKLIM data from 2001 to 2020 (not including the July 2021 event) combined with operational hourly rainfall sums from RADOLAN and (2) the climatological setup with estimation of GEV parameters based on RADKLIM data from 2001 to 2021 combined with reprocessed hourly rainfall sums from RADKLIM. The differences between the

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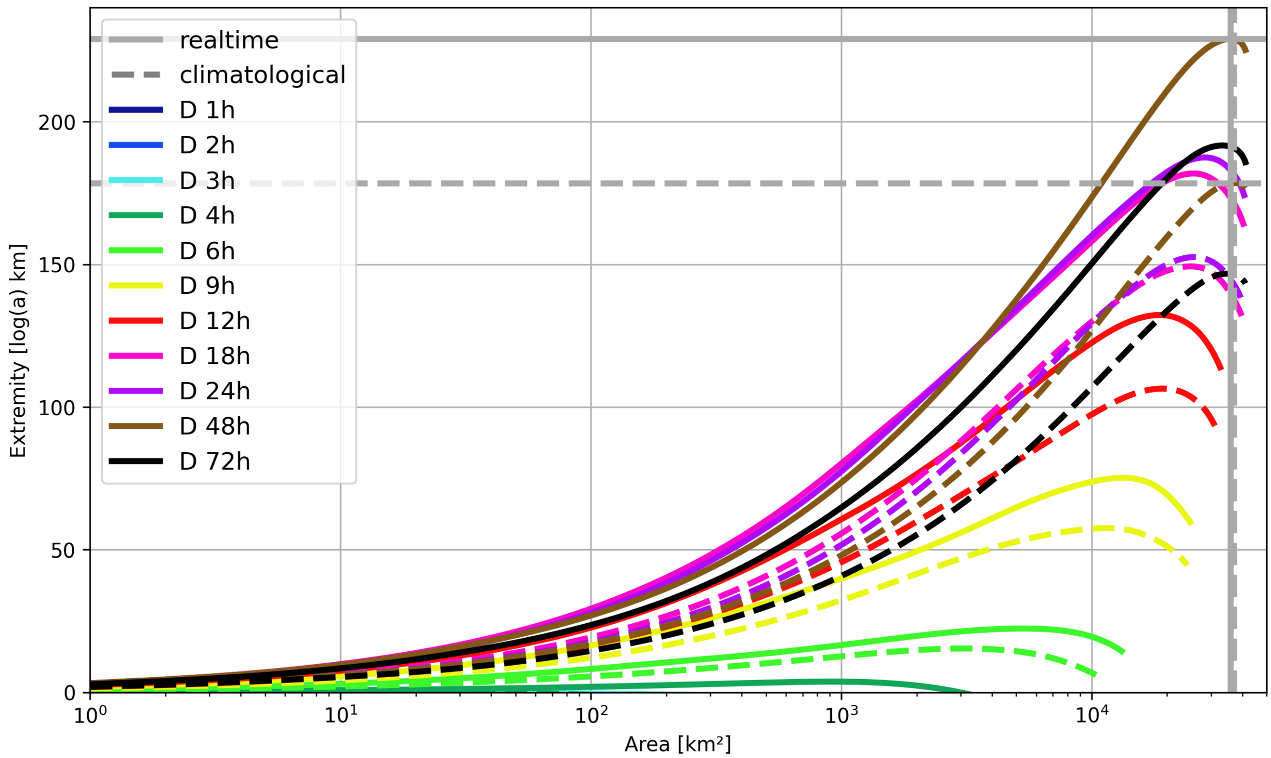

Figure 2. WEI calculated for 14 July 2021, 23:50 UTC, with operational RADOLAN data and GEV parameters obtained from RADKLIM 2001-2020 (realtime setup: solid lines) and from reprocessed RADKLIM data (Version 2017.002) and GEV parameters from RADKLIM 2001-2021 (climatological setup: dashed lines)

RADOLAN and the RADKLIM data do not influence the results significantly (not shown here). Therefore, the focus of this study lies on including or excluding data from 2021 in the estimation of GEV parameters.

The retrieval of xWEI was documented in detail by Voit and Heistermann (2022). The fundamental idea of xWEI is to integrate the extremeness E_{tA} across spatial scales and all regarded duration levels instead of searching for a maximum of E_{tA}. This integration is, again, based on the aforementioned E_{tA}-curves which, for each duration, display E_{tA} across spatial scales. We now interpret these curves in a 3-dimensional coordinate system in which the x-axis represents the area, the y-axis the duration, and the z-axis E_{tA}. Together, these curves span a surface. The volume underneath this surface corresponds to the cross-scale extremeness (xWEI) of an event (Voit and Heistermann, 2022).

4 Results

Figure 2 illustrates how the E_{tA}-curves changed after the most recent RADKLIM reanalysis was included in the estimation of GEV parameters in the "climatological" setup: as expected, E_{tA} reaches lower values across all durations and areas than in the

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Table 1. The five most extreme precipitation events in CatRaRE v2022.01, according to the weather extremity index (WEI), and the corresponding cross-scale weather extremity (xWEI) values for the same events. In parenthesis we show the change of the indices in comparison to the values previously obtained with the realtime setup (without including the year 2021 in the GEV parameter estimation). Duration and area specify the duration and area at which the event reached its maximum extremity, $\overline{R}$ is areal average of the event's rainfall depth.

Rank	Region	Date	ID	Duration [h]	Area [km^2]	$\overline{R}$ [mm]	WEI	xWEI
1.	Saxony	August 12-13, 2002	1798	24	48420	87	208	2855
2.	Lower Saxony	July 24-26, 2017	17961	48	54287	85	188	2121
3.	Lower Saxony	July 17-19, 2002	1239	48	45053	85	180	2402
4.	West-Germany	July 13-15, 2021	24193	48	41177	91	179 (-50)	3134 (-597)
5.	Berlin/Brandenburg	June 29-30, 2017	17695	24	33927	72	165	2577

"realtime" setup. On average, maximum E_{tA}-values are 20-30$\%$ lower for all relevant durations. The overall structure of the E_{tA}-curves remains dominated by long durations between 12 and 72 hours. Shorter durations of 4 to 6 hours do not reach E_{tA} values of 100 log(yr)km, durations up to three hours are less pronounced. The most extreme stage for the July event is in both cases reached for a duration of 48 hours.

Tab. 1 puts WEI and xWEI of the five most extreme events according to CatRaRE v2022.01 into context, and also shows the changes of WEI and xWEI for the July 2021 event, depending on which setup was used for quantification. For the July 2021 event, the values of WEI and xWEI changed from 229 to 179 log(yr)km (-50), and from 3731 to 3134 (-597). Based on the updated WEI values, the July 2021 event no longer outranks all other events, but now ranks at the 4th position. The most extreme event according to the WEI with a value of 208 log(yr)km occurred in Saxony in August 2002 and led to the devastating flood along the Elbe river. This event had a characteristic duration of 24 hrs and precipitation of 87 mm in these 24 hrs averaged over the affected area. The events in second and third place in July 2017 and 2002 both lasted 48 hrs and are, thus, more comparable to the July 2021 event. Their WEI is only slightly higher with 188 log(yr)km and 180 log(yr)km, respectively. Both events have lower mean precipitation values of 85 mm compared to the July 2021 event with 91 mm, but larger spatial extents. This underlines the sensitivity of the WEI to the affected area. With regard to the updated xWEI, however, the July 2021 event (still) appears as the most extreme event out of these five. If ranked according to xWEI, the Saxony 2002 event would be on second rank, followed by the Berlin 2017 event and the two events in Lower Saxony (2002 and 2017).

5 Conclusions

Based on the weather extremity index (WEI) and the cross-scale weather extremity index (xWEI), we re-assessed the extremeness of the disastrous heavy rainfall event which took place in western Germany in July 2021. To that end, we used the most recent reanalysis of DWD's weather radar data (RADKLIM).

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While the impact of the July 2021 event was unique, our analysis reveals that it was just the fourth most extreme event in the period from 2001-2021, according to the WEI. Before having included the recent RADKLIM data in the GEV parameter estimation, the event had been considered the most extreme. According to the xWEI, however, we found that the July 2021 event still outranks all other events within the recent RADKLIM dataset. This emphasizes, on a formal basis, previous reports that one of the key features of the July 2021 event was its extremeness across spatial and temporal scales. Following Thieken et al. (2022b), the July 2021 event could be considered a hydro-meteorological compound event.

But while the xWEI implies that the July 2021 event in fact outranked others, we need to acknowledge that the top ranking events are relatively close both in terms of WEI and xWEI. Hence, the resulting rankings should not be over-interpreted. Indeed, the highest ranking events appear quite similar with regard to their extremeness. Their occurrence in very different regions of Germany suggests that such types of events could effectively take place anywhere in Germany, and might be considered as hydro-meteorological reference events for disaster risk management throughout the country. The *impact* of such events on the ground, however, will vary dramatically based on governing hydrological and hydro-geomorphological processes as well as exposure and vulnerability. This is demonstrated by the two extreme events that occurred in Lower Saxony, the impacts of which appeared to be less severe, or at least were less visible in the national media. We hence consider it important to assess the potential impacts of such events anywhere across Germany or Central Europe.

Code and data availability. The RADKLIM dataset is publicly available at the DWD open data servers: https://dx.doi.org/10.5676/DWD/RADKLIM_RW_V2017.002 (Winterrath et al., 2018b) as well as the CatRaRE catalog (https://dx.doi.org/10.5676/DWD/CatRaRE_W3_Eta_v2022.01) (Lengfeld et al., 2022). The code and exemplary data for the computation of xWEI is published in following repository: doi.org/10.5281/zenodo.6556463 (Voit, 2022).

Author contributions. All authors conceptualized the study, KL and PV carried out the statistical analysis, KL prepared the figures, all authors prepared the manuscript.

Competing interests. The contact author has declared that neither of the authors has any competing interests.

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