Supplementary Material

A Data and Methods

Heavy precipitation statistics: KOSTRA

KOSTRA (*Koordinierte Starkniederschlagsregionalisierung und -auswertung*; latest version KOSTRA-DWD-2010R; Malitz and Ertel, 2015; Junghänel et al., 2017) is a gridded data set of roughly $8\times8\,\mathrm{km}^2$ horizontal resolution containing precipitation statistics for Germany provided by the German Weather Service (DWD). It is based on ground-based observational station data interpolated to the regular grid for duration levels below 24 hours and on HYRAS-DE for longer intervals. KOSTRA provides statistics on different duration levels ranging from 5 minutes to 72 hours and return periods between 1 year and 100 years. It is widely used in Germany for precipitation–runoff estimations and the dimensioning of facilities.

Antecedent Precipitation Index

As mentioned in PART1, antecedent wetness conditions can be an important driver for the precipitation–runoff response in a river basin. An established quantity to describe the preconditions is the Antecedent Precipitation Index (API; e.g., Kohler and Linsley, 1951; Viessman et al., 2002). API is a weighted summation over N days prior to the event day using a weighting factor k. In line with PART1 and previous studies (e.g., Heggen, 2001; Schröter et al., 2015), we use $N = 30$ days and $k = 0.9$. For PART2, API is applied to the daily HYRAS-DE data set. For the statistical analyses, a normalized version NAPI is defined as follows:

$$\mathrm{NAPI} = \frac{\mathrm{API}(x,y,t)}{\mathrm{cAPI}(x,y,d)} - 1\,, \tag{1}$$

where (x,y) denotes the grid point position, t is the day of interest, and d is the corresponding calendar day of t between 1 January and 31 December. cAPI is the climatological mean over the entire time series of HYRAS-DE on the corresponding calendar day d. By subtracting 1, NAPI is centered around zero, meaning that negative values describe drier conditions and positive values wetter conditions than the climatology.

High resolution climate model simulations: KIT-KLIWA

Table S1. Driving GCMs of the KIT-KLIWA CPM simulations with related references and used realization, and the 30-year time periods that corresponds to the global warming level of $+2\,^\circ$C (GWL2) and $+3\,^\circ$C (GWL3) based on the method of Teichmann et al. (2018).

GCM	Reference	Realization	GWL2	GWL3
MPI-ESM-LR	Giorgetta et al. (2013)	r1i1p1	2029–2058	2052–2081
EC-EARTH	Prodhomme et al. (2016)	r12i1p1	2026–2058	2051–2080
CNRM-CM5	Voldoire et al. (2013)	r1i1p1	2029–2058	2052–2081
HadGEM2-ES	Collins et al. (2011)	r1i1p1	2016–2045	2037–2066

B Classification in the historical context

Table S2. Heaviest precipitation events in Germany between 1951 and 2021 based on daily HYRAS-DE and the empirical heavy precipitation event criterion $\mathrm{HPE_{crit}}$ (sorted in descending order regarding the area A, $\mathrm{rk_{HPEcrit}}$; see Sect. 2.3.2). The events are the same as shown in excerpts in Figures 2, 3, 4, and S1. Given are the mean precipitation amount $\overline{R}$ averaged over A, the maximum grid point precipitation R_{max} within A, the API value averaged over A and its deviation from the corresponding climatology NAPI, the PSI value, the rank according to the PSI $\mathrm{rk_{PSI}}$, the maximum return interval of areal precipitation T_{max} regarding LAERTES-EU and related area $A_{\mathrm{T_{max}}}$ at which T_{max} is reached (derived from Fig. 5). **Bold numbers** represent the maximum of the corresponding column, except for $A_{\mathrm{T_{max}}}$ as a range is given in this case.

$\mathrm{rk_{HPEcrit}}$	Date	A (km^2)	$\overline{R}$ (mm)	R_{max} (mm)	$\overline{\mathrm{API}}$ (mm)	NAPI	PSI	$\mathrm{rk_{PSI}}$	T_{max} (a)	$A_{\mathrm{T_{max}}}$ (km^2)
1	8 Aug. 1978	**20 851**	124.6	183.9	17.63	0.13	**2.40**	1	> **1000**	7000 – 20 000
2	17 Jul. 2002	13 099	91.5	152.0	34.47	0.87	2.20	2	100	30 000 – 40 000
3	12 Aug. 2002	10 826	**138.8**	**262.0**	50.03	1.78	1.68	5	> **1000**	500 – 1000
4	29 Jun. 2017	10 225	91.2	175.2	25.69	0.81	1.70	4	20	10 000 – 20 000
5	14 Jul. 2021	8354	100.2	154.3	62.90	1.59	0.80	23	50	15 000 – 20 000
6	26 Aug. 2010	7151	113.6	153.8	46.08	1.32	1.02	18	50	6000 – 8000
7	29 Jun. 1981	7017	93.0	138.8	36.78	0.74	1.22	15	20	12 000 – 25 000
8	18 Jul. 1987	6750	110.3	141.4	29.55	1.42	1.47	7	20	3000 – 5000
9	8 Jul. 1954	6616	109.6	212.9	91.51	3.40	1.11	17	50	3000 – 5000
10	30 Jun. 2021	3943	137.7	192.0	7.50	–0.44	1.56	6	100	1000 – 1500
11	27 Aug. 1989	3876	81.3	96.5	20.74	0.05	1.14	16	10	15 000 – 20 000
12	9 Jul. 2021	3676	70.2	78.8	13.29	–0.21	1.25	13	1	50 000 – 60 000
13	22 Jul. 2011	2740	80.7	105.6	56.03	2.84	0.96	20	< 1	–
14	29 Aug. 1969	2139	92.5	121.3	21.26	0.52	1.35	11	10	7000 – 10 000
15	21 May 1999	1738	134.6	196.2	84.77	3.19	0.74	25	50	2000 – 3000
	12 Jun. 1993	1738	81.7	114.4	38.73	1.44	1.01	19	10	20 000 – 30 000
17	4 Aug. 1983	1671	92.9	107.8	19.71	0.27	1.43	8	5	5000 – 15 000
	27 Sep. 1965	1671	83.7	97.9	13.46	–0.37	0.77	24	1	5000 – 15 000
19	16 Jul. 1965	1470	99.2	130.9	82.40	3.13	1.23	14	2	8000 – 15 000
	28 Jul. 2000	1470	86.5	100.7	29.52	0.96	0.94	21	2	3000 – 5000
21	15 Jul. 1956	1136	96.2	119.1	36.73	1.49	1.42	9	5	15 000 – 50 000
	27 Oct. 1998	1136	74.1	85.6	52.86	1.71	1.36	10	2	6000 – 80 000
23	9 Jul. 1954	1069	102.0	133.3	**110.15**	**5.30**	1.76	3	10	20 000 – 50 000
24	18 Jul. 2002	1002	97.4	124.4	80.62	2.96	1.27	12	1	1000 – 2000
	1 Jun. 2016	1002	87.7	118.2	45.44	1.32	0.84	22	1	1000 – 2000
	4 Sep. 1995	1002	85.2	108.6	28.73	0.18	0.42	26	< 1	–

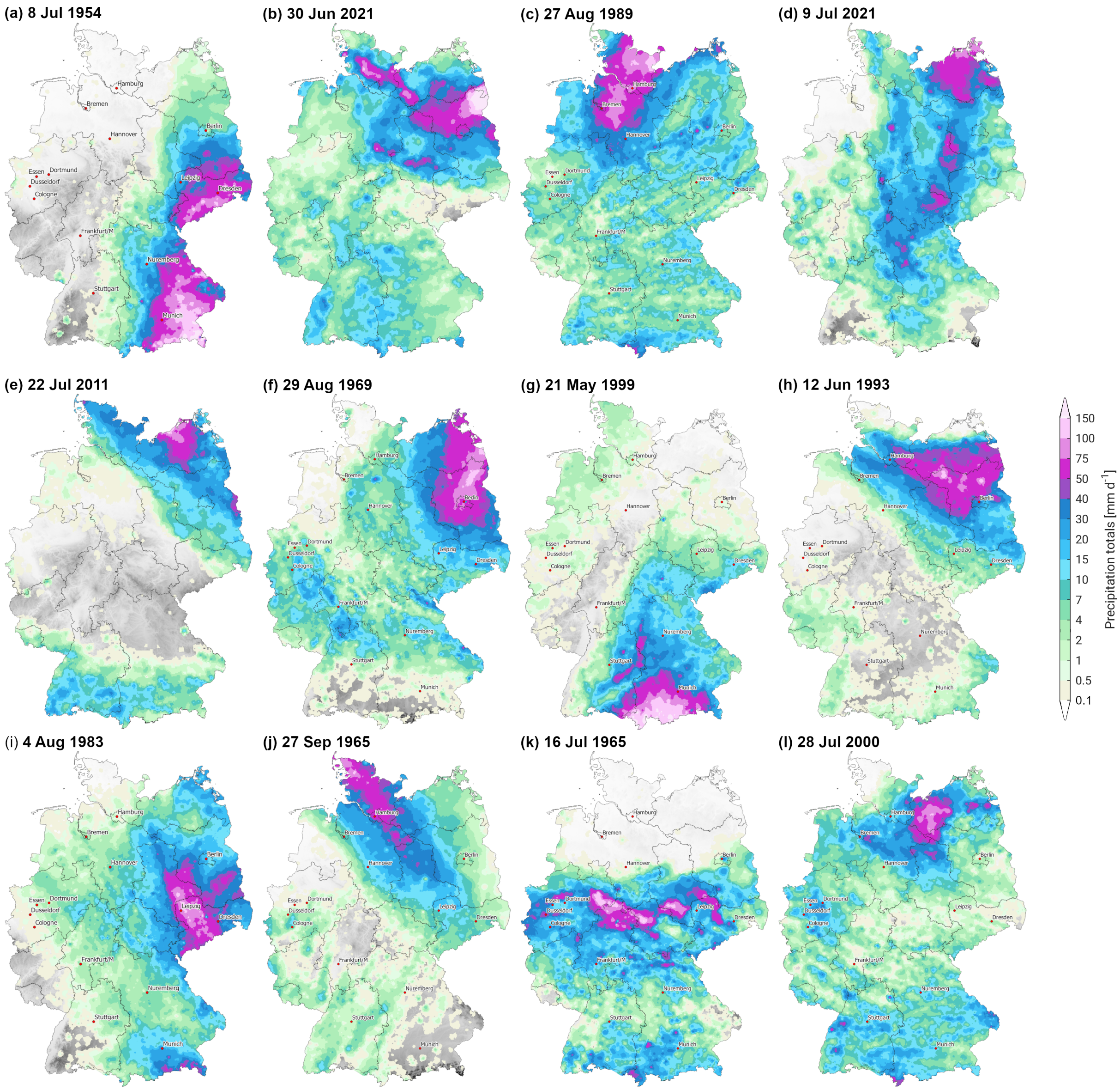

Figure S1. Same es Fig. 2, but for the heavy precipitation events in Germany ranked 9th (a) to 20th (l) according to the HPE_{crit} criterion (based on daily HYRAS-DE data, 1951 to 2021). See also Table S2 with further statistic.

C Relation to climate change

Table S3. Relative increase of daily precipitation Δ (in % per degree global warming) for different return periods (RP) calculated from the reference period (1971 to 2000) to GWL2 and from the reference period to GWL3. The mean was calculated over all ensemble members and all grid points within CReg or LReg, respectively.

RP (in a)	Δ_{CReg} (in %)		Δ_{LReg} (in %)	
	GWL2	GWL3	GWL2	GWL3
1	6.2	5.6	6.3	5.4
3	7.3	6.8	7.5	6.5
5	7.9	7.5	8.1	7.0
10	8.8	8.4	9.0	7.8
30	10.3	10.1	10.7	9.2