



Southern Germany's 100-year flash flood discharge expected to increase by 30 % under an RCP8.5 climate

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Abstract. The frequency and intensity of convective heavy rainfall events are generally assumed to increase in a warming climate. So far, however, it remained difficult to assess the corresponding changes in flash floods. This difficulty resulted from the mismatch between the coarse spatial resolution of global and regional circulation models, which do not explicitly resolve convective processes, and the small spatial extent of flash-flood-prone headwater catchments. Recently, though, the results of several convection-permitting climate models (CPMs) became available for parts of Germany. Our study presents the first attempt to utilize these high-resolution data (1 h, 3 km) for an assessment of flash-flood changes in southern Germany. Based on an ensemble of 6 CPM models, we simulated the runoff for the periods 1971-2000 (historical) and 2071-2100 under the RCP8.5 scenario for the German part of the Danube basin. We then compared the 100-year return levels of rainfall and discharge maxima between these two periods. The results indicate an increase of 100-yr flood return levels for 94% of the Danube subcatchments with a median increase of 30% across all subcatchments under the RCP8.5 scenario.

1 Introduction

Flash floods are typically caused by convective heavy rainfall, and mostly occur in small, mountainous catchments. They are characterized by response times of less than a few hours, leaving little time for early warning. Furthermore, their high flow velocities promote heavy loads of debris which in turn can lead to erratic overtopping and excessive damage to infrastructure and buildings. As a consequence, a significant proportion of flood-related damages and fatalities is caused by flash floods (Barredo, 2007; Llasat et al., 2010; Petrucci et al., 2019; Mohr et al., 2023), despite their typically localized extent. According to the International Disaster Database (CRED/UCLouvain, 2023) for the years 1962-2023, flash floods are the cause of 31% of reported flood related casualties in Europe.

As a result of climate change, numerous studies have projected an increase in the occurrence of heavy rainfall events (Prein et al., 2017; Da Silva and Haerter, 2025; Hundhausen et al., 2024). More specifically, rising temperatures are expected to lead to an increase in the frequency and intensity of convective rainfall events (Berg et al., 2013; Lepore et al., 2015; Ivancic



and Shaw, 2016; Seneviratne et al., 2021; Hundhausen et al., 2024; Bürger and Heistermann, 2025). Consequently, the future occurrence of flash floods is expected to increase as well (Paprotny et al., 2018; Zhang et al., 2019).

Despite such a general expectation of increasing flash flood frequencies, specific quantitative projections are still sparse. The main reason for that is the fundamental mismatch between the coarse spatial resolution of global or regional circulation models (GCMs and RCMs) and the small extent of flash-flood prone catchments (tens to hundreds of km²). Due to their coarse spatio-temporal resolution, common GCMs or RCMs use parameterised convection and are therefore unable to adequately represent and resolve those convective processes responsible for flash floods. This inability is in contrast to the importance of high-resolution rainfall products in the analysis of these floods. This was recently underlined by Voit and Heistermann (2024a) who showed that flood peaks can vary by a factor of two or more with identical amounts of mean catchment rainfall – merely due to the spatio-temporal distribution of rainfall.

Convection-permitting climate models (CPMs) offer a potential solution to this problem (Ahrens, 2003). With a spatial resolution of only a few kilometers (typically around 3 km), they fit the spatial scale of flash-flood prone basins. Using GCMs as boundary conditions, CPMs typically operate at a regional scale, and are designed to explicitly resolve deep convection (Purr et al., 2021; Rybka et al., 2023; Hundhausen et al., 2024). This ability, however, comes at a high computational cost which is why corresponding simulation experiments are mostly limited to relatively small spatial domains and short time periods (Ahrens and Leps, 2021). Only recently, the results of various simulation experiments became available for all of Germany (Purr et al., 2021; Rybka et al., 2023) or for its southern part (Hundhausen et al., 2024) which allow for the comparison of a heavy rainfall climatology at the end of the 20th century to a climatology at the end of the 21st century under the RCP8.5 scenario.

But while CPMs offer a promising perspective to project future changes in convective heavy rainfall at high spatial and temporal resolution, the resulting consequences for the occurrence of flash floods are by no means self-evident. This is because of the complex process chain that transforms a rainfall event to a catchment's discharge response at any cross-section in the stream or river channel. First, the transformation of rainfall to quick (surface or near-surface) runoff is highly non-linear, and governed by the interaction of landscape properties such as land use, soil and antecedent wetness. Second, the concentration of quick runoff components in the landscape essentially represents a convolution of the rain field in space and time, mainly as a function of catchment topography and surface roughness. Altogether, the assessment of how a change in heavy rainfall climatology translates to the occurrence of flash floods requires a corresponding hydrological model.

The degree to which hydrological assessments of climate change can benefit from CPM forcings is still subject to discussion. While various studies have confirmed the usefulness of CPM results for hydrological impact studies (e.g., Schaller et al., 2020; Davis et al., 2022; Tamm et al., 2023; Poncet et al., 2025), Wagner et al. (2025) found no added value in comparison to a model in which convection was parameterized (see also a comprehensive review in Table 1 of Wagner et al., 2025). Obviously, the outcome of such an evaluation will depend on the spatial and temporal extent of the analysis, on the target variable (e.g., average water balance versus extreme events), and on the corresponding reference (benchmark) model. In order to account for the stochastic nature of extreme convective events and resulting flash floods, any comparison of historical and future



climatologies should aim at maximizing the length of the analysis period and as well as the size of the study area in order to increase the robustness of the resulting extreme value statistics (e.g. Poncet et al., 2025).

In this study, we aim to assess future changes in extreme convective rainfall and resulting floods across all small headwater catchments in the German part of the Danube basin under the RCP8.5 scenario (Representative Concentration Pathways, 2071-2100, business as usual, high emission scenario). With the resulting large study area of more than 56,000 km², we aim to account for the aforementioned stochasticity in the occurrence of flash floods: we do not interpret the rate of change for each basin individually, but target the median rate of the change across all small catchments in the study area. For our analysis, we collected a CPM ensemble with six members from different institutions and projects in Germany (Purr et al., 2021; Rybka et al., 2023; Hundhausen et al., 2024) that have only become available in the recent years, and use this ensemble as an input to a hydrological model that was specifically designed to parsimoniously simulate the response of small headwater basins to heavy rainfall events of short duration Voit and Heistermann (2024a). For each ensemble member, each subbasin, and each simulation period (historical: 1971-2000, future: 2071-2100), we then obtain the 100-year return levels for rainfall at 1h and 6h durations as well as the 100-year flash flood discharge. On that basis, we quantify the change of the 100-year return levels from the historical to the future period across all headwater catchments of the Danube basin. By only looking at the rate of change between the historical and the future period, we implicitly account for any precipitation bias in the CPM simulations, as e.g. reported by Hundhausen et al. (2024).

2 Data

2.1 Study area

The study area is the German part of the Danube catchment (Fig.1) which is located in the federal states of Bavaria and Baden-Württemberg, and is the third largest catchment in Germany (59.630 km²). The Danube is formed from two source rivers (Brigach and Breg), that originate in or at the edge of the Black Forest, and leaves Germany towards Austria after the city of Passau. The study area is characterised by a temperate climate, with topography ranging from alpine to mid-mountain regions, including also karst plateaus and glacial forelands. While the hydrology is strongly affected by snow melt seasonality, the occurrence of flash floods is exclusively governed by convective precipitation events in the summer.

2.2 CPM-Ensemble

The CPM ensemble consists of the four members (KIT-KLIWA) provided by the Karlsruhe Institute of Technology (KIT), one member by the German Weather Service (Deutscher Wetterdienst, DWD hereafter) and one member by the Goethe University Frankfurt (GUF-ECE). All members are based on COSMO-CLM simulations driven by different CMIP5 global climate models (GCMs) under the RCP8.5 scenario, with a temporal resolution of 1 hour. The standard CMIP data reference syntax (rNiMpL) is used to describe the ensemble members: rN is the realization number, iM indicates the initialization method and pL indicates the physics version (Taylor et al., 2011). In this study, each ensemble member is referred to by an ID that consists of the

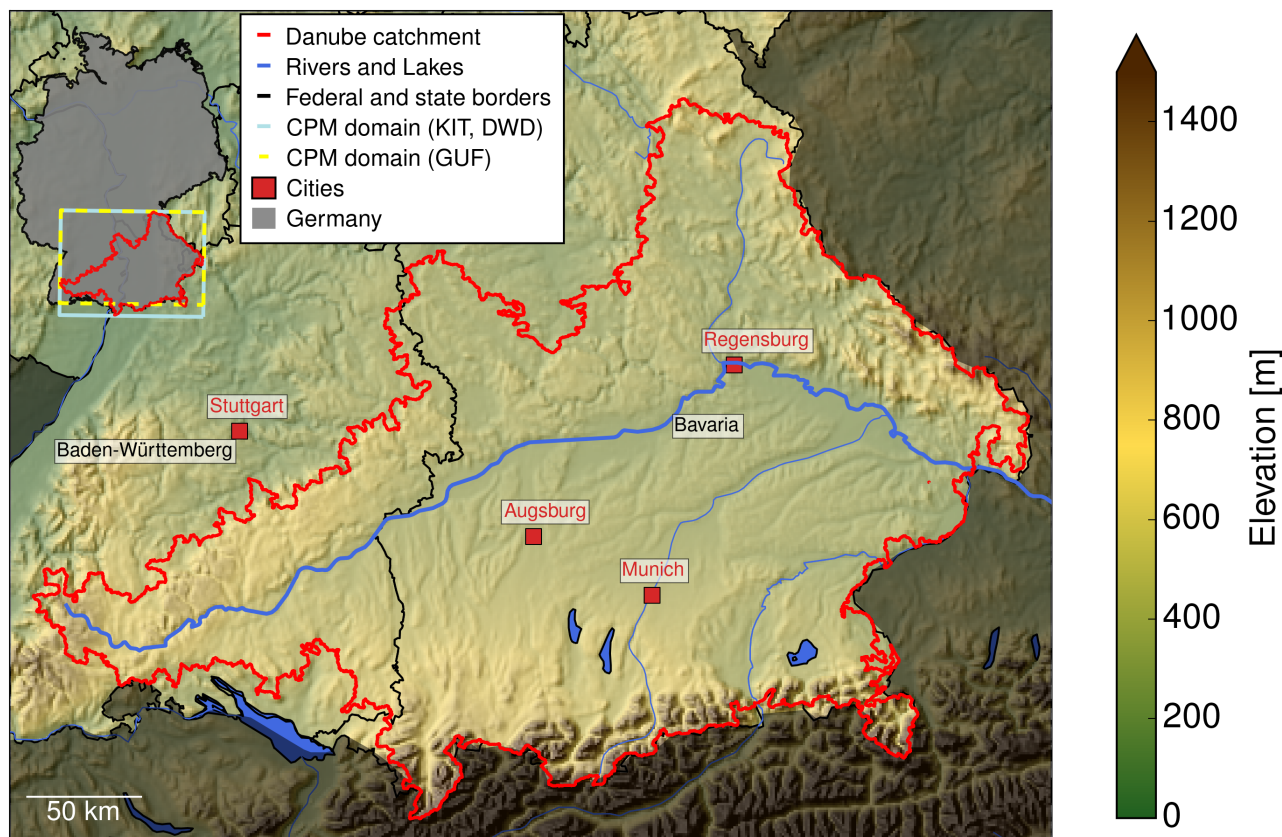


Figure 1. German part of Danube catchment (red line). Upper left: position of the catchment within Germany. Blue: Danube river and tributaries and lakes, red squares: cities, black: federal and state borders. Light Blue: CPM domain of the KIT and DWD ensemble members. Dashed yellow: domain of the CPM GUF ensemble member.

name of the institution that carried out the experiment and the forcing GCM. For further references and a summary of the CPM ensemble refer to Table 1. ΔT describes the average global warming in comparison to the historical period (1971-2000). Please note that the references provided in this table provide, for each ensemble member, a detailed description with respect to the forcing GCM as well as corresponding CPM settings and parameterisation, so that we will not go into further detail in this regard. The approximately 36 km southernmost part of the Danube catchment is not covered by GUF-ECE.

2.3 Terrain and elevation data

The following datasets were used to set up the hydrological model.

- **Digital elevation data:** We obtained flow paths and the resulting subbasins as well as the travel time distribution with the subbasins based on the EU-DEM. This DEM is a fusion of the SRTM (Shuttle Radar Topography Mission) and the

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Table 1. Description of the CPM ensemble used in this study.

ID	GCM	RCM	experiment	resolution	global ΔT	reference
KIT-MPI	MPI-ESM-LR	COSMO5.0-CLM9	r1i1p1	2.8 km	3.52	Hundhausen et al. (2023)
KIT-ECE	EC-EARTH	COSMO5.0-CLM9	r12i1p1	2.8 km	3.53	Hundhausen et al. (2023)
KIT-CNRM	CNRM-CM5	COSMO5.0-CLM9	r1i1p1	2.8 km	3.50	Hundhausen et al. (2023)
KIT-HAD	HadGEM2-ES	COSMO5.0-CLM9	r1i1p1	2.8 km	4.62	Hundhausen et al. (2023)
DWD-MIROC5	MIROC5	COSMO5.0-CLM16	r1i1p1	3.0 km	3.35	Rybka et al. (2023)
GUF-ECE	EC-EARTH	COSMO5.0-CLM7	r12i1p1	2.8 km	3.53	Brisson et al. (2021)

ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) and shows a good accuracy for Germany compared to other DEMs (Kramm and Hoffmeister, 2022). The dataset has a resolution of 25 m and is freely available from the Copernicus Land Monitoring Service (European Commission, 2016).

- **Land cover** was derived from CORINE CLC5-2018 (BKG, 2018) which is based on a classification of high-resolution satellite data into 37 land cover classes (for Germany), according to the nomenclature of the European Environmental Agency (EEA). Objects with a minimum size of 5 ha are considered in the classification.
- **Soil data** were obtained from the BUEK 200 (national soil survey at 1:200,000 scale; BGR, 2018), compiled by the Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR) in collaboration with the National Geological Services (Staatliche Geologische Dienste, SGD) based on surveys conducted by individual federal states. For each mapping unit, BUEK 200 provides the areal proportions of dominant soil types along with associated profile information, including texture, bulk density, and other attributes.

3 Methods

3.1 Identifying extreme precipitation

Heavy rainfall events are usually classified by estimating their return period which are, in turn, obtained from extreme value statistics. The generalized extreme value (GEV) distribution is used to model the annual exceedance probabilities of annual maxima for the durations of 1 hr and 6 hrs. The focus on convective events from March-October guarantees for the temporal independence of the annual maxima. The shape parameter is set to 0.1 following the recommendation from Shehu et al. (2023) for an estimation of return periods up to 100 years, and the location and scale parameters of the GEV are individually estimated for each grid point and duration.

3.2 Modelling quick runoff

Flash floods are governed by the formation and concentration of quick runoff components. Therefore, groundwater and evapotranspiration processes can be neglected which immensely simplifies the structure of the required hydrological model. Because



of a general lack of stream flow observations at the flash flood scale, i.e. for small basins and extreme events, we require a model with few parameters that does not require calibration (Gaume et al., 2004; Borga et al., 2014). Consequently, our model consists of two components, which are commonly used in flash flood modelling: (i) the formation of runoff is computed with the Curve Number (CN) method (U.S. Department of Agriculture-Soil Conservation Service, 1972; Natural Resources Conservation Service, 2004) based on land use, soil characteristics and antecedent rainfall; (ii) the concentration of runoff, which is mainly controlled by the topography, is represented by the geomorphological instantaneous unit hydrograph (GIUH) method (Singh et al., 2014; Yi et al., 2022). The flow velocities to derive the GIUH are computed according to Maidment et al. (1996). The model requires the areal average precipitation per subbasin as input. Hence, the subbasins have to be sufficiently small to justify the assumption of a homogeneous rainfall distribution across the catchment. We set outlet points on every stream intersection with a Strahler order of 7 or larger. We restrict our analysis to basins with a size of up to 750 km², because effects of hydro-engineering and channel hydraulics on streamflow propagation become more important with increasing basin size. The remaining 3128 subbasins have a median size of 12.8 km² (25th percentile: 7.5 km², 75th percentile: 22 km²). Because we focus on convective rainfall events, and because our model has no snow routine, we also limit the simulations to the months from March to October.

The prime focus of our model is to capture the timing and magnitude of the flood peaks, and hence to allow for the comparison between the historical and the RCP8.5 projection. The simplified model setup enables us to compute quick runoff for two 30-year periods (historical and RCP8.5) for each of the 6 ensemble members for the whole German part of the Danube catchment. Our model setup for Germany was described, proven and tested in several previous studies (Voit and Heistermann, 2024a, b; Voit et al., 2025) in which we also comprehensively discussed resulting uncertainties. The source code is openly available (Voit, 2024).

3.3 Assessment of changes in flash flood hazard

For each basin and each 30-year period of each CPM ensemble member, we extracted the annual maximum flood peaks and fitted a generalized extreme value distribution (GEV) to these data. We then calculated the 100-year return level. With only 30 annual maxima, the fit of the GEV distribution can be highly uncertain and may lead to implausible parameter estimates, especially for the shape parameter. Based on the suggestions of Morrison and Smith (2002) and Merz et al. (2022), we hence excluded basins from the analysis for which the estimated shape parameter falls outside the range of -0.3 to 0.5. Table S1 in the supplement summarizes the number of basins with a valid shape parameter for each ensemble member. A higher shape value indicates a more heavy-tailed GEV distribution, whereas a negative shape value implies the existence of an upper bound on possible flood magnitudes.

The short 30-year simulation period limits the applicability of extreme value statistics. However, the members of our CPM ensemble describe alternative scenarios of how the future regional climate could evolve. Heavy rainfall events in these ensemble members can be assumed to be independent - and so can the annual maxima derived from the different ensemble members. Building on this idea, we additionally fit GEV distributions by pooling the annual maxima from all ensemble members for each basin, as also suggested by Ruff and Pfahl (2023). That way, our GEV fits should become more robust, and instead of



Table 2. Median and 95 % confidence interval of the ratios (future/historical) displayed in Fig. 2 for all ensemble members and the pooled dataset.

CPM	100-yr 1h prec.	100-yr 6h prec.	100-yr flood peak	max. flood peak
KIT-MPI	1.19 ±0.005	1.21 ±0.005	1.18 ±0.018	1.24 ±0.016
KIT-ECE	1.25 ±0.005	1.28 ±0.005	1.24 ±0.019	1.28 ±0.017
KIT-CNRM	1.24 ±0.005	1.31 ±0.005	1.26 ±0.020	1.32 ±0.015
KIT-HAD	1.26 ±0.005	1.27 ±0.005	1.26 ±0.020	1.34 ±0.017
DWD-MIROC5	1.25 ±0.005	1.25 ±0.005	1.28 ±0.017	1.20 ±0.016
GUF-ECE	1.13 ±0.005	1.18 ±0.005	1.21 ±0.022	1.22 ±0.017
pooled data	1.25 ±0.002	1.26 ±0.002	1.30 ±0.008	1.27 ±0.012

computing the mean return level as a mean from all ensemble members, we obtain the mean return level from the GEV fit that is based on the pooled dataset (similar to Voit et al., 2025). Please see section 5 for a discussion of limitations of this approach as it could violate the assumption of homogeneity.

155 Since the peak discharge for a return period of 100 years is of fundamental importance for flood risk management, we focus our analysis on the resulting changes of the 100-year return level (for both rainfall and discharge) between the historical (1971-2000) and the future (2071-2100) period.

4 Results and Discussion

4.1 Effect of climate change on extreme precipitation events

160 Across all ensemble members and all pixels within the Danube catchment, the median of the ratios of the 100-year return level between the future (RCP8.5) and the historical period is larger than one, indicating that the 100-year extreme precipitation depth will increase in the future for both durations (1h and 6h, Fig. 2). For the 1 h duration, the median of the ratios across all pixels ranges between 1.13 (GUF-ECE) and 1.26 (KIT-HAD). For the 6 h duration, the median ratio is between 1.18 (GUF-ECE) and 1.31 (KIT-CNRM).

165 We could not identify clear spatial patterns of changes in extreme rainfall for the six ensemble members. However, we include Figures S1 and S2 in the supplement which show the spatial distribution.

4.2 Effect of climate change on flash floods

For each ensemble member (section 2.2), we modelled discharge series for the Danube basin for the time slices 1971-2000 (historical) and 2071-2100 (RCP8.5). We then extracted, for each subbasin and period, the annual maximum series, fitted the
 170 corresponding GEV parameters, and identified the corresponding 100-year return level. Figure 2 reveals a future increase of the 100-year flood for all ensemble members under the the RCP8.5 scenario. The median ratios between the future and the historical 100-year flood ranges between 1.18 (KIT-MPI) and 1.28 (DWD-MIROC5). Note that the number of subbasins for

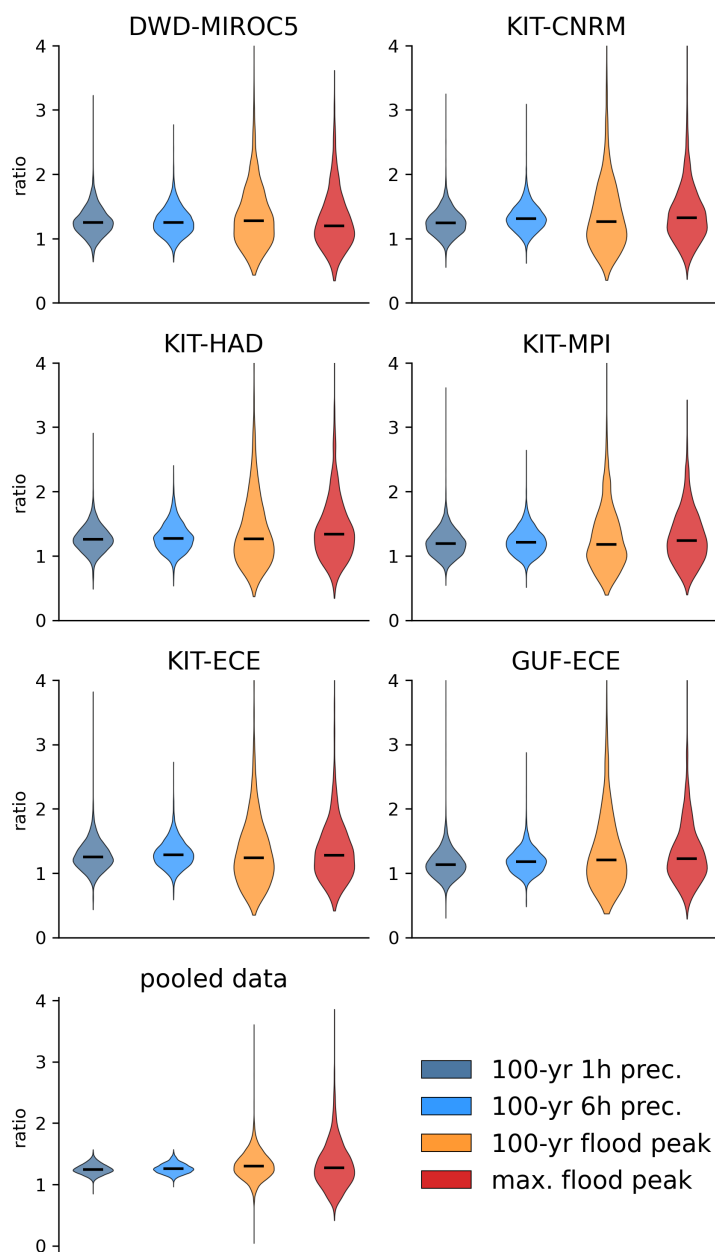


Figure 2. Ratios between RCP8.5 and historical 100-year return levels of 1h (grey), 6h (blue) rainfall, 100-year return level flood peak (orange) and maximum flood peak (red) for every pixel (1h and 6h rainfall) or catchment (flood peak) within the Danube catchment and every member of the CPM ensemble and the pooled dataset. Median is shown in black.

each ensemble member might slightly differ from the maximum number of 3128 subbasins because we only included basins with an estimated shape parameter within the range of -0.3 to 0.5 (see section 3.3). Table 1 in the supplement shows the



175 exact number of subbasins considered for each ensemble member. For the sake of completeness, Figure S3 shows the spatial distribution of the changes in 100-year return levels for each ensemble member, Figure S4 for the pooled dataset. However, we could not discern any noticeable spatial pattern for any of the ensemble members. In all cases, except for DWD-MIROC5 and the pooled dataset, the the median ratio between the future and the historical *maximum* flood is even higher than the *median* ratio between the future and the historical 100-year flood.

180 While DWD-MIROC5 exhibits the largest median increase of 100-year return levels (1.28), the confidence intervals suggest that there is no significant difference between the median ratios for DWD-MIROC5, KIT-CNRM, KIT-HAD, and KIT-ECE. Only for GUF-ECE and KIT-MPI, the median ratios between the 100-year return levels is significantly, though not substantially, lower. These results are consistent with the median ratios of the 100-year return levels for 1h and 6 h rainfall. Between the two rainfall durations, the increase in the 100-year return level of 1h rainfall seems to be slightly more decisive for the increase in
185 the 100-year return level of floods ($R^2=0.52$) than the increase of the 100-year return levels of 6h rainfall ($R^2=0.38$). However, we should be careful not to overinterpret the differences between the ensemble members.

For individual basins, the spread between ensemble members can be substantial, which can be attributed to the fact that the actual spatial realisation of extreme precipitation events within a 30-year simulation period is a random process. A 30-year window is not long enough to ensure to guarantee a robust GEV fit, or, in other words, the extrapolation of the 100-year return
190 level is highly uncertain. Consequently, very large or very small ratios most likely reflect an unstable GEV fit. This is also why we preferred the median instead of the mean ratio between the 100-year return levels as a metric of change.

To address this source of uncertainty, we combined, for each subbasin, the annual maximum series of all ensemble members in order to fit the GEV distribution and estimate the 100-year return level (see section 3.3). This approach considerably reduces the spread of the ratios across all subbasins (due to more robust GEV fits, results not shown). The resulting median ratio
195 between the future and historical 100-year return level amounts to 1.30 ± 0.008 which is even higher than the median ratio obtained for the individual ensemble members while the confidence interval is narrower. It remains unclear why the median ratio for this combined dataset is higher. Yet, due to the much more robust GEV fits, we consider this value more reliable than the median ratio obtained for the individual ensemble members or any aggregate metrics resulting from these individual median ratios.

200 We could not identify any remarkable spatial patterns for any of the individual ensemble members, nor for the pooled data set (Fig. S3 and Fig. S4) Increased return levels show no, or only weak correlations with basin size, soil and land use (characterized by the curve number) and topography (mean slope and mean and standard deviation of the elevation).

5 Limitations

While we attempted to address the climate model uncertainty by using a multi-model CPM ensemble, it should be clear that
205 this attempt is limited in various aspects. First of all, an ensemble with six members still has to be considered small. Yet, this is all we could collect in terms of CPM simulations under an RCP8.5 climate for our study region. In fact, the decision to focus our analysis on the Germany part of the Danube basin was made exactly because it maximized the number of available CPM

simulations. Then again, our results with regard to the changes in heavy precipitation and flash flood peak discharge are quite consistent across ensemble members which increases our confidence in the results.

210 While numerous studies have already investigated the representation of extreme rainfall at short durations (e.g. Rybka et al., 2023; Purr et al., 2021; Hundhausen et al., 2024), it still remains unclear whether the spatio-temporal structure of extreme precipitation events in climate projections can be considered "realistic". This is a critical issue since previous studies (e.g. Voit and Heistermann, 2024a) have shown that the spatio-temporal rainfall distribution is essential for the formation of flash flood peaks. This issue is, however, beyond the scope of the present study as it is very challenging not only to "measure" changes
215 in spatio-temporal rainfall event properties, but also to assess how such changes would propagation through a hydrological model.

Furthermore, CPMs tend to show a wetness bias (Hundhausen et al., 2024; Prein et al., 2015). In our analysis, we attempt to address this bias by not evaluating the 100-year return levels directly, but by assessing the *ratios* between the return levels between the historical and RCP8.5 simulations.

220 Furthermore, changes in land use could affect the hydrological processes, but are assumed to be stationary in our study. Additionally to the inherent uncertainty of our hydrological model (see Voit and Heistermann, 2024a; Voit et al., 2025, for an extensive discussion), 30 years of modelled data limit the robustness of the statistical analysis. For this reason we restricted our analysis to the 100-year return levels, even though, in regard to extremes, higher return levels would be of interest. We also addressed the limited length of the analysis periods by excluding implausible GEV fits (see Supplement 3) and by pooling the
225 annual maxima series of all ensemble members which led to a remarkable increase in the robustness of the GEV parameter estimates per subbasin. While we consider this approach as very helpful, one might argue that such pooling could violate the assumption of homogeneity required for the GEV parameter estimation. We are confident, however, that the distributions resulting from the different ensemble members are sufficiently homogeneous, given the consistency of the median ratios. More importantly, we hypothesize (but cannot prove) that the error introduced by any potential inhomogeneities is lower than the
230 error introduced by the small sample size of only 30 annual maxima per sample.

6 Conclusions

The ensemble members largely agree on the overall increase of the return levels of 1h- and 6h precipitation, as well as on the increase of the 100-year return level for floods in small basins. In our view, the use of the pooled dataset of annual maximum series from all ensemble members allows for the most reliable aggregate analysis of the ensemble. The pooled dataset indicates
235 that 94 % of subcatchments in the Danube basin will experience an increase of the 100-year return levels under the RCP8.5 scenario. Looking at the median of all catchments, the future (2071-2100) 100-year flash flood peak discharge will increase by 30 % in comparison to the historical one (1971-2000). This number is well in line with the widely discussed Clausius Clapeyron (CC) scaling according to which extreme quantiles of extreme rainfall intensities increase by 7 % per degree K of global warming. This rate was just recently confirmed for stratiform and convective rainfall extremes in Germany (Da Silva and Haerter, 2025). With warming rates between 3.4 to 4.6 K by the end of the century under the RCP8.5 scenario (see Tab. 1),
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a CC scaling of $7\% K^{-1}$ would correspond to an increase of extreme rainfall quantiles (such as the 100-year 1h rainfall) by a factor of 1.25–1.32. While it is interesting to note that the 100-year return level appears to change at a similar rate of 1.3, we should be careful not to overinterpret this finding, given the large uncertainties along the analysis chain. Still, our results should encourage future research to take a closer look at the CC scaling with regard to high flash flood quantiles. It basically suggests
245 that flash flood extremes scale similarly to short-duration rainfall extremes. The occurrence of such behaviour will certainly depend on how the hydrological model converts rainfall to runoff ("runoff coefficient") under extreme rainfall conditions.

We would also like to put an increase of the 100-year flash flood discharge by 30% a little bit into a risk management perspective. Please consider, for the sake of illustration, a "typical" GEV distribution (shape=0.3, location=5, scale=4.5): for such a distribution, a flood with a peak that is 1.3 times higher than the 100-year return level would correspond to a return
250 period of 210 years. In the terminology of the European Unions Floods Directive, today's "low probability"-flood (i.e. the 200-year flood in Germany) would hence become the "medium probability"-flood of the future. Here, we have to keep in mind that the impact of a flood increases non-linearly with its intensity (or the return period, see e.g. Ward et al., 2011; Vidmar et al., 2025).

With regard to extreme floods, the analysis of higher return periods would be desirable. However, 30-year simulations are
255 too short to reliably extrapolate to higher return periods using extreme value statistics. One solution could be to sample extreme rainfall events from the RCP8.5 ensemble simulations and to use these events for a counterfactual study as done e.g. in Voit et al. (2025). This systematic approach would also reduce the randomness in the spatial distribution of the extreme precipitation and consequent flood events.

Despite the numerous limitations, coupling CPMs with hydrological models might, so far, be the most promising way to
260 estimate the range of future flood peaks and this approach should be helpful for disaster risk management to anticipate the effects of future extreme floods.

Code and data availability. The code for our hydrological model has been recently published for the study Voit and Heistermann (2024a):
https://github.com/plvoit/counterfactual_flash_flood_analysis.

All data used in this study is openly accessible: the EU-DEM is available on request at <https://www.eea.europa.eu/en/datahub/datahubitem-view/d08852bc-7b5f-4835-a776-08362e2fbf4b?activeAccordion=735550>. Alternatively the dataset can be downloaded at <https://web.archive.org/web/20200703221722/https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/elevation/eu-dem-1aea>. The CLC5-2018 land cover data is available at <https://gdz.bkg.bund.de/index.php/default/open-data/corine-land-cover-5-ha-stand-2018-clc5-2018.html>. The soil data is available at https://www.bgr.bund.de/DE/Themen/Boden/Informationsgrundlagen/Bodenkundliche_Karten_Datenbanken/BUEK200/buek200_node.html, all last accessed 09 April 2025.

270 *Author contributions.* Paul Voit and Maik Heistermann conceptualized this study. Paul Voit carried out the analysis with contributions from Marie Hundhausen and Larisa Seregina. Paul Voit produced the figures. Paul Voit and Maik Heistermann wrote the manuscript with contributions from Larisa Seregina, Marie Hundhausen, Hendrik Feldmann and Bodo Ahrens.

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