A Climate-Informed Regional Weather Generator for Exploring Hydrological Extremes in a Changing Climate

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GFZ Helmholtz-Zentrum für Geoforschung

CLIM X TREME Climate Change and Extreme Events

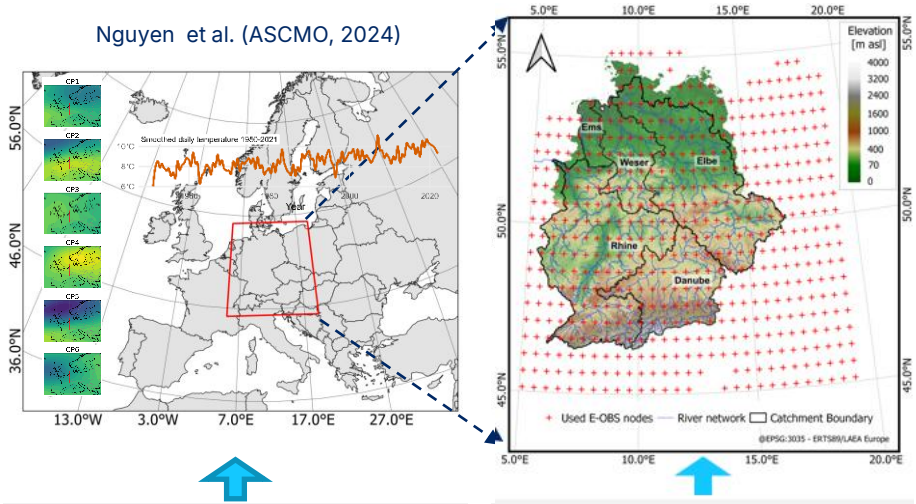
Klima Anpassung Hochwasser Resilienz

HELMHOLTZ

Non-stationary Regional Weather Generator (nsRWG)

nsRWG is a multisite, multivariate stochastic MAR-1 model conditioned on the dynamic (**CP** circulation pattern) and thermodynamic (**t2m**, regional temperature) state of the atmosphere

Nguyen et al. (ASCMO, 2024)



ERA5 msl, surface temperature
6 CPs, 2 seasons (summer and winter)

E-OBS v25.0e; 1950-2021
Daily precipitation, and temperature

$$W(t) = \begin{cases} B_i W(t-1) + C_i \Psi(t), & same\ CP \\ \overline{B}_i W(t-1) + \overline{C}_i \Psi(t), & different\ CP \\ D_i \Psi(t), & t = 1 \end{cases}$$

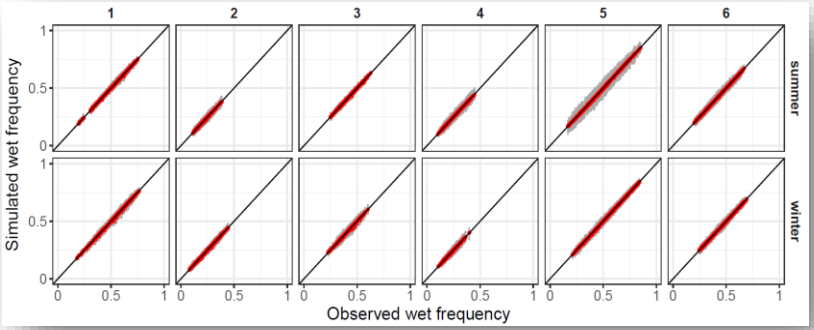
$$P(s,t) \sim \boldsymbol{extGPD}(\kappa, \sigma, \xi) \mid \mathbf{CP}$$
$$\sigma(s,t) \sim \exp(\sigma_o + \sigma_1 * \mathbf{t2m(t)})$$

$$T(s,t) \sim \boldsymbol{N}(\mu, \delta) \mid \mathbf{month}$$
$$\mu(s,t) \sim \mu_o + \mu_1 * \mathbf{t2m(t)}$$

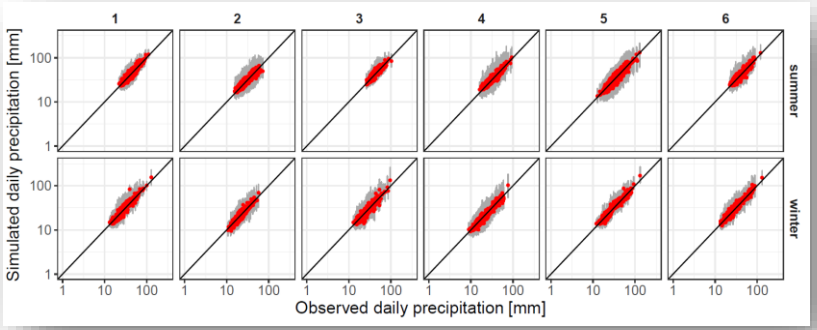
$P(s,t)$: precipitation at location s, time t
$T(s,t)$: temperature at location s, time t
$W(t)$: multivariate standard normal random vector
$\Psi(t)$: ramdom vector of the independent standard normal variable
$B_i, \overline{B}_i, C_i, \overline{C}_i, D_i$: MAR1 parameter matrices (for each CPi)

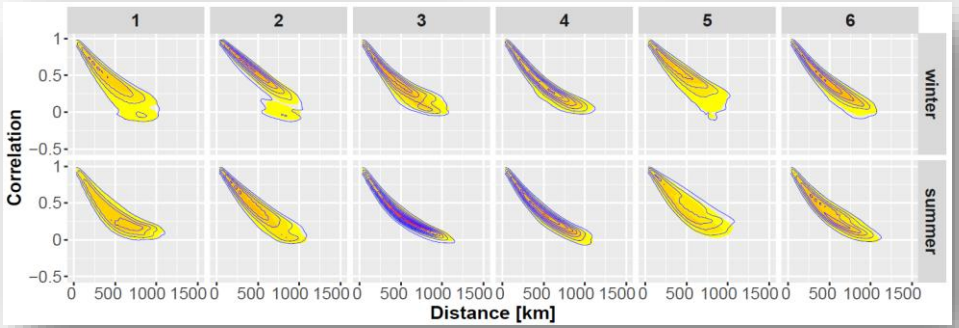
nsRWG Validation (for the Central European setup)

Wet frequency



Extreme daily precipitation (99.5th)





Nguyen et al. (ASCMO, 2024)

Spatial correlation

Shaded color: observation
Contour lines: simulation

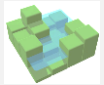
Applications of the Regional Weather Generators

Regional Flood Model (RFM)

0 Weather circulation patterns

1 Regional weather generator (nsRWG)

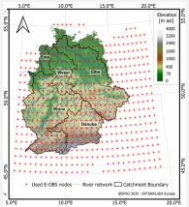
2 Hydrological model (mHM-UFZ)



3 Regional inundation model (RIM)

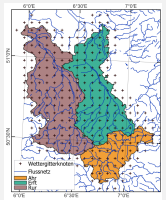
4 Flood loss model (FLEMO*)

A



Germany-wide setup

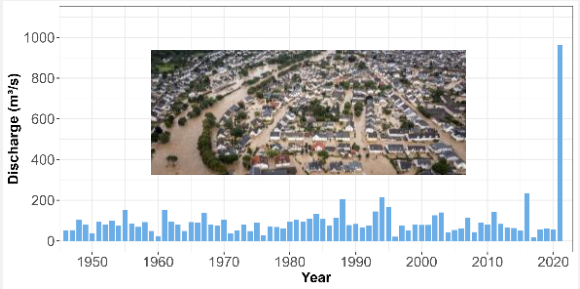
B



Ahr, Erft Rur setup

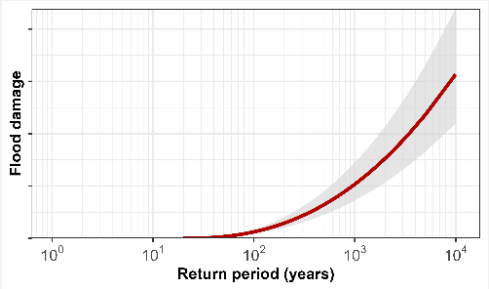
What can we do with it?

1 Understanding and simulating Black Swans B

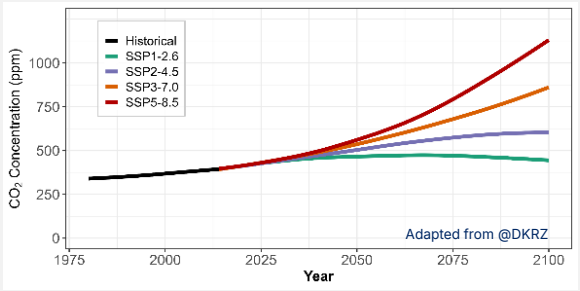


Merz et al. (KAHR Buch, 2025)

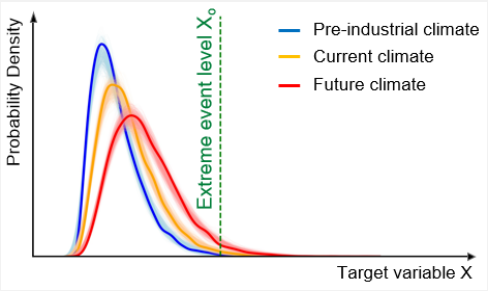
2 Quantifying large-scale flood risk A



3 Projecting flooding in a warmer world A



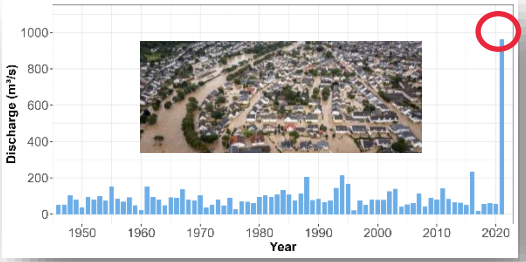
4 Attributing extreme events B



Nguyen et al. (EGU, 2025)

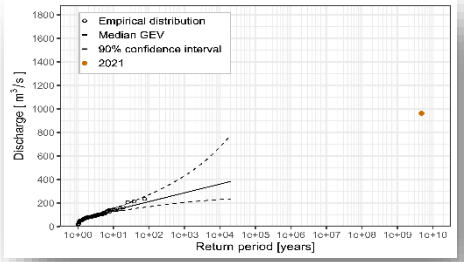
And…

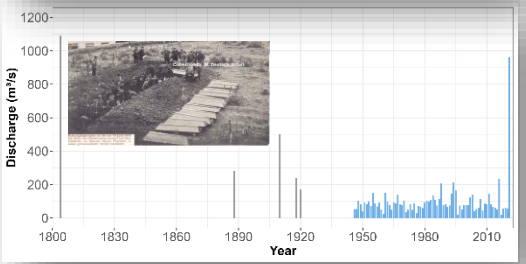
1 Understanding and simulating Black Swans
Example Ahr flood July 2021



Extreme value statistics:

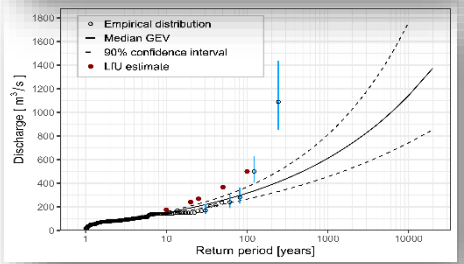
- Flood frequency analysis based on 75 years (1946-2020) of observed streamflow,
- Return period of 2021 flood (~963 m³/s) : ~4 bil years!

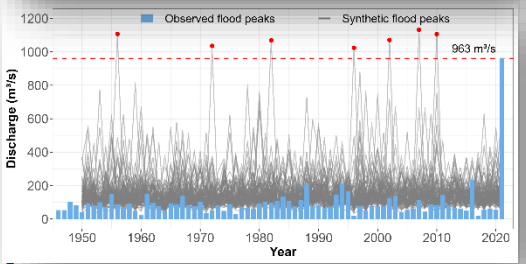




Extreme value statistics incorporating historical floods:

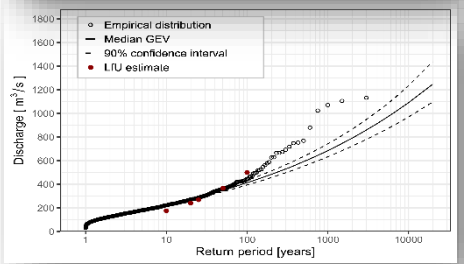
- Integrating 5 historical floods (reconstructed) and 75 years of observed streamflow,
- Return period of 2021 flood: ~8000 years.





Extreme value statistics based on long-term simulation using weather generator and hydrological model:

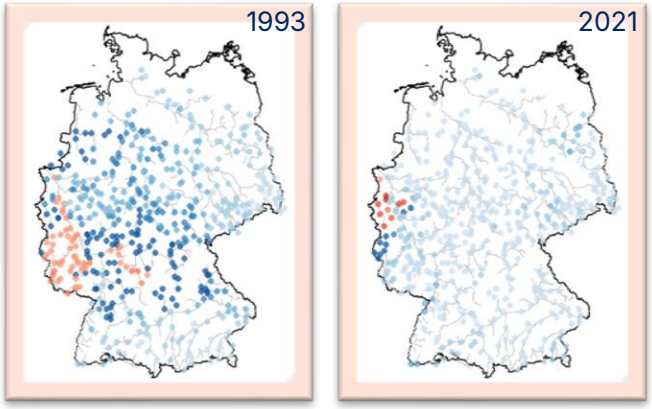
- Hourly synthetic rainfall and streamflow for 12000 years (30 years x 400 realisations),
- Return period of 2021 flood: ~5000 years.



Merz et al. (KAHR Buch, 2025) and Vorogushyn et al. (HyWA, 2022)

2 Flood risk in Germany in the present climate

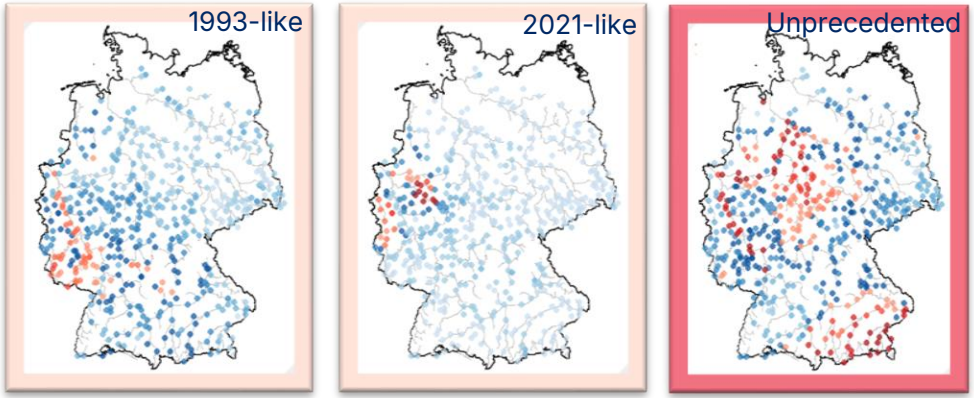
Observed floods *(1950 – 2021)*



HQ-Class

- <HQ2
- <HQ5
- <HQ10
- <HQ20
- <HQ50
- <HQ100
- <HQ200
- <HQ500
- <HQ1000
- >=HQ1000

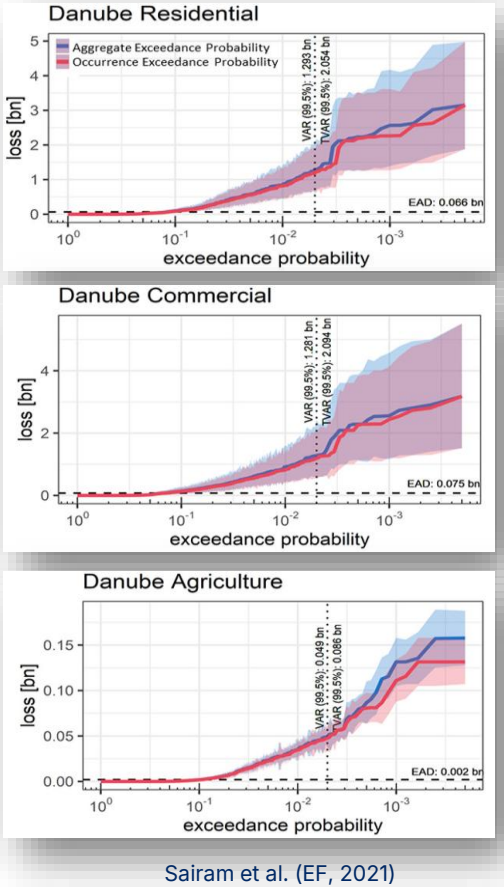
Synthetic floods (*Same period)*



Nguyen et al. (TdH, 2024)

RFM

Flood risk curves



Sairam et al. (EF, 2021)

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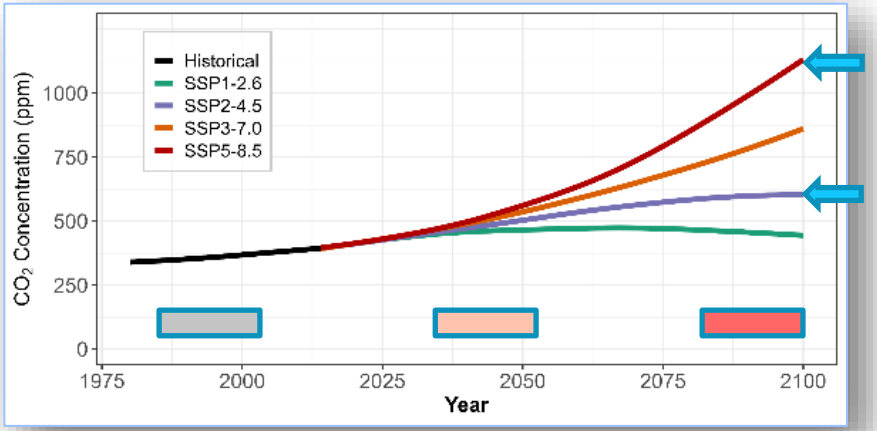
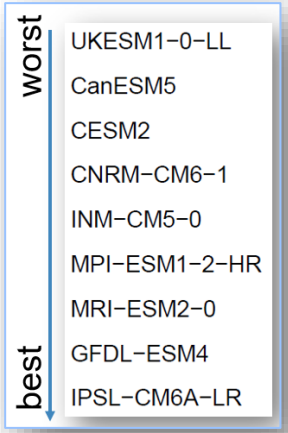
3 Projecting floods for future climate

- 2 Shared Socio-economic Pathways (**SSP245 and SSP585**)
- **9 selected GCMs** with highest "skill" from CMIP6
- Historical "control" period **1985-2014**
- 2 projection periods, each 30 years (**2031-2060, 2071-2100**)

Indirect downscaling of future climate using the nsRWG.

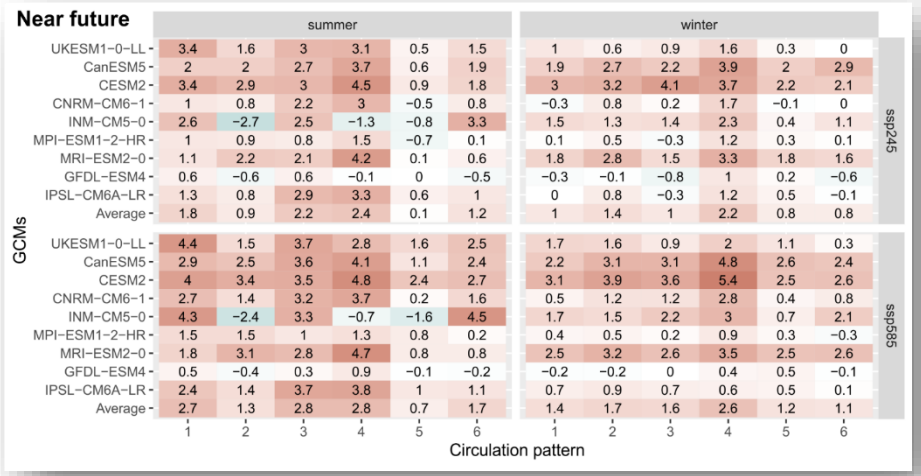


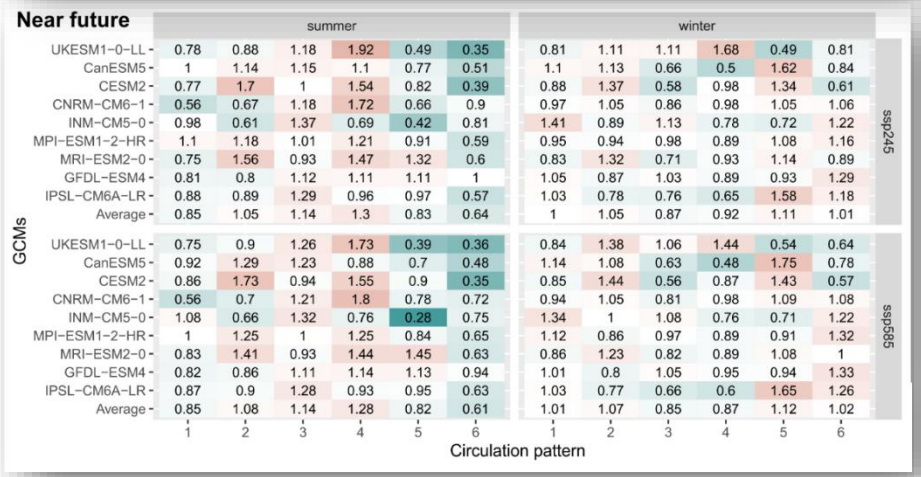


3 Project floods for future climate

Change in regional temperature

Change in frequency of circulation patterns





Nguyen et al. (ASCMO, 2024)

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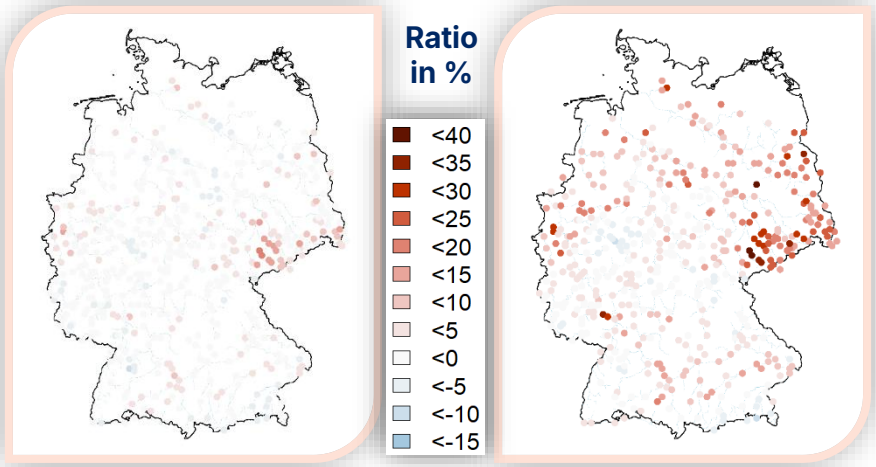
3 Projecting floods for future climate

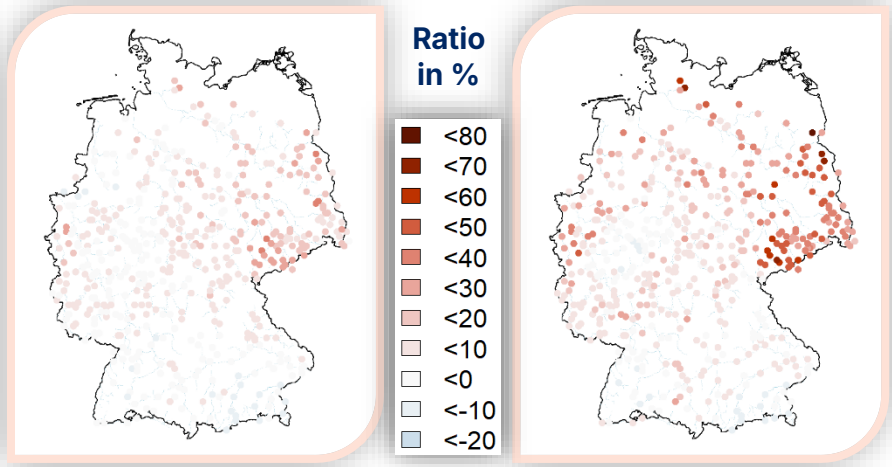
HQ100



SSP245 2031-2060

SSP585 2071-2100

HQ1000

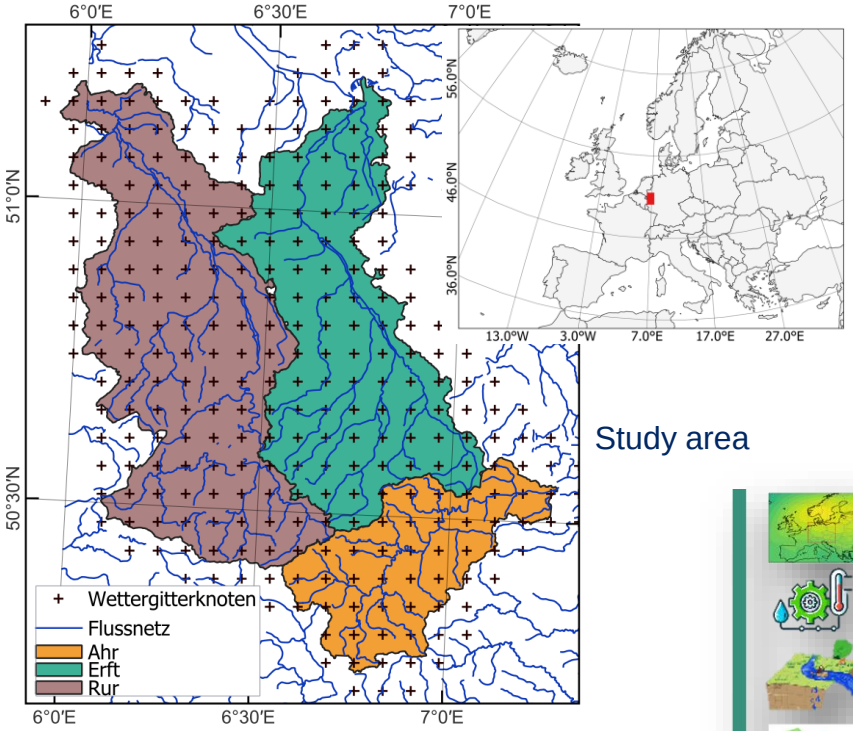


SSP245 2031-2060

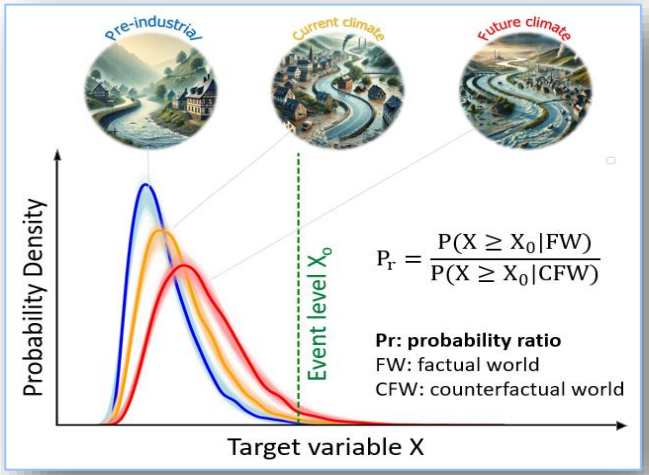
SSP585 2071-2100

Nguyen et al. (TdH, 2024)

4 Impact attribution of the Ahr flood event July 2021



Study area



Attribution framework

0 Weather circulation patterns

1 Regional weather generator (nsRWG)

2 Hydrological model (mHM-UFZ)

3 Regional inundation model (RIM)

4 Flood loss model (FLEMO*)

- 6 GCMs (DAMIP)
- 12,000 years
- 1d-maxima precipitation
- Flood peak
- Inundation extent and area, affected buildings
- Flood loss

Merz et al. (KAHR Buch, 2025) and Nguyen et al. (in preperation)

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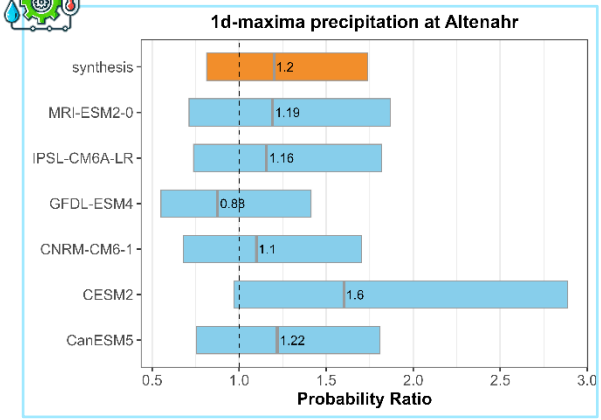
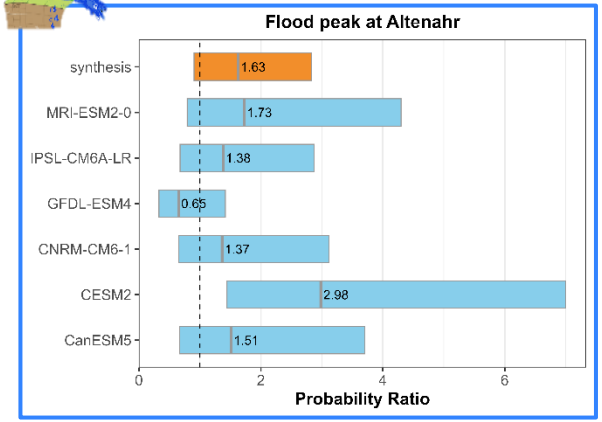
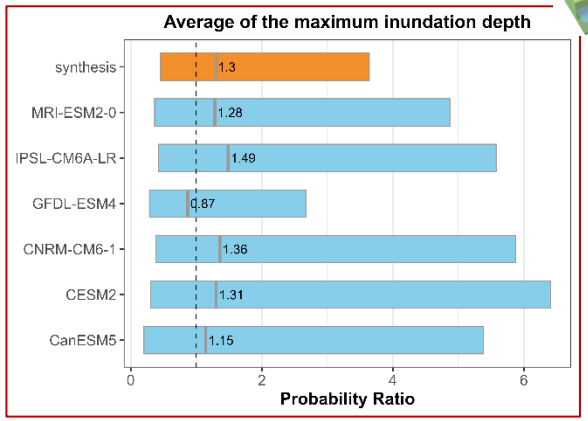
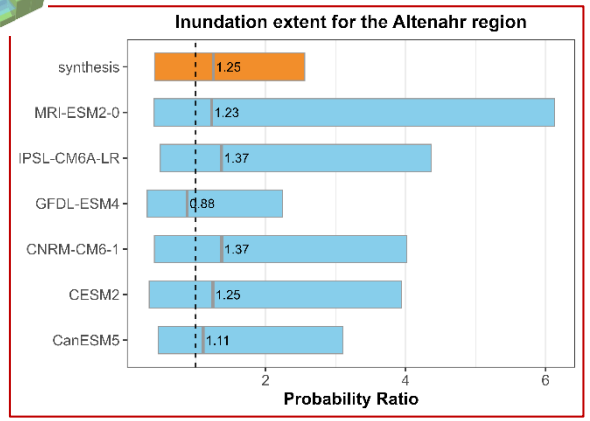
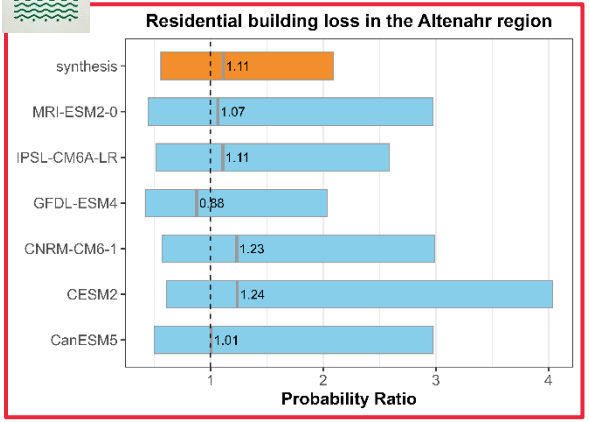




Overall, these findings suggest that anthropogenic climate change **has increased the likelihood of events like the July 2021 flood** and demonstrate the potential of the RFM framework for end-to-end flood impact attribution.



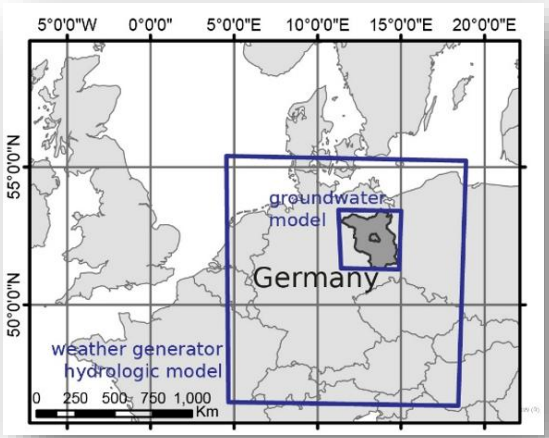




Merz et al. (KAHR Buch, 2025) and Nguyen et al. (in preperation)

5 Groundwater recharge projections

- **Weather circulation patterns**
- **Regional weather generator (nsRWG)**
- **Hydrological model (mHM-UFZ)**
- **Thermal-hydraulic groundwater model (FEFLOW-DHI)**

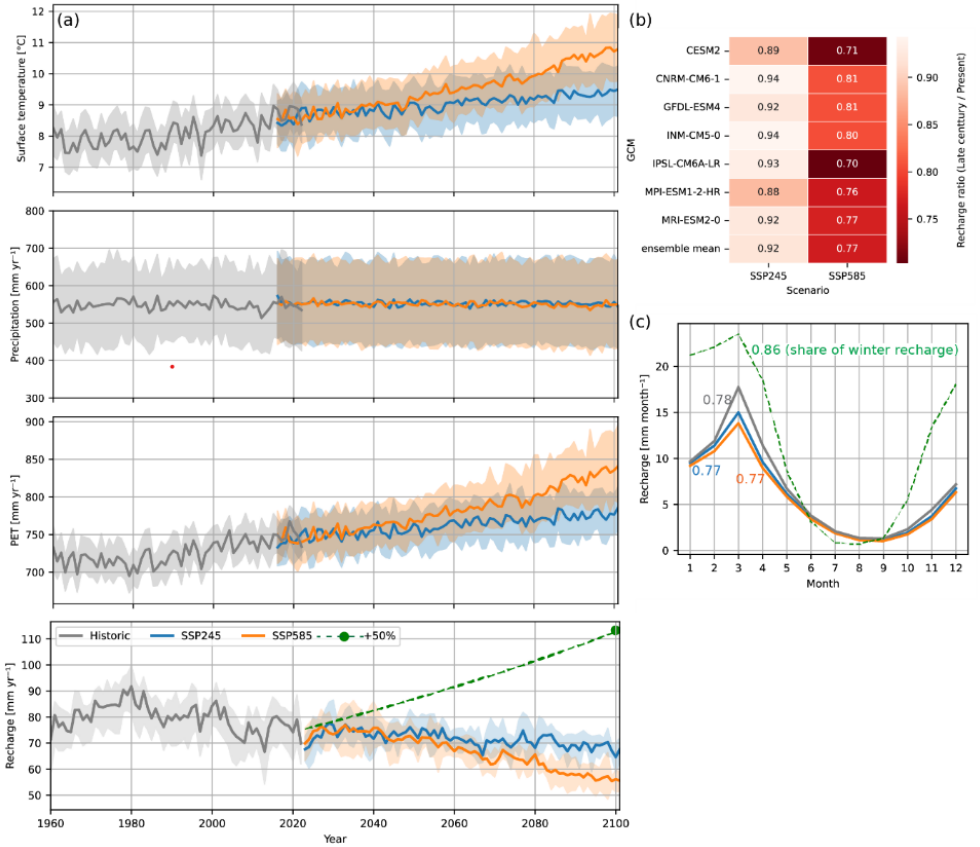


Tsypin et al. (HESS 2025). (under review)

- **Study site**: Brandenburg State, northeastern Germany.
- **Scenarios**: SSP2-4.5 and SSP5-8.5, projected up to the year 2100.
- **Objective**: Evaluate the capability of the non-stationary RWG (nsRWG) to analyze drought conditions (monthly to annual timescales).

5 Groundwater recharge projections (cont.)

Under the high-emissions scenario, a 20 % recharge reduction, from a mean of 75 to 60 mm a-1, causes a 2–5 m water level decline, reducing the area of unconfined aquifer subjected to seasonal temperature fluctuations.



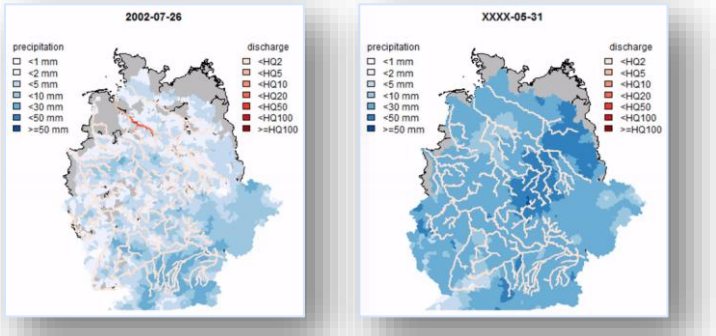
Tsypin et al. (HESS 2025). (under review)

Summary

- We developed a climate-informed, **non-stationary Regional Weather Generator** (nsRWG) conditioned on atmospheric dynamics and thermodynamics.
- Coupled with a full model chain, (e.g RFM) it enables **end-to-end hydrological analysis**.
- The framework simulates both extreme floods and prolonged droughts. It supports:
  - **black-swan flood exploration and flood-risk** (present and future) assessment.
  - **end-to-end attribution** of the July 2021 Ahr flood.
  - also projecting future groundwater recharge in Brandenburg, Germany.

Thank you for your attention!

Contact: dung@gfz.de



Animation by Viet Dung Nguyen

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