LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

German Data Science Days 2024
LMU München, 8th March 2024

Assessing the dynamics of extreme events under climate change – big data applications in climate science

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ECRA European Climate Research Alliance CP-CHC Collaborative Programme Changes in the Hydrological Cycle

ClimEx www.climex-project.org

Contents

- Preface… why climate science needs big data
- Current knowledge on Climate Change
- Climate Change and Extreme Events – Perspectives from the ClimEx project
  - Results from process-based modeling
  - Results from machine learning
- Conclusions




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Preface – the benefits of big data for climate impact studies

Utilizing big data enables climate impact studies to (better) assess…:

- uncertainty (data, model, structural, scenario,…)
- natural climate variability (vs. anthropogenic climate change)
- (hydro)meteorological extremes

via, e.g. …

- Single Climate Model Initial Condition Large Ensembles (SMILEs)
- hydrometeorological observations
- process-based modeling systems
- data-driven / machine learning modeling systems

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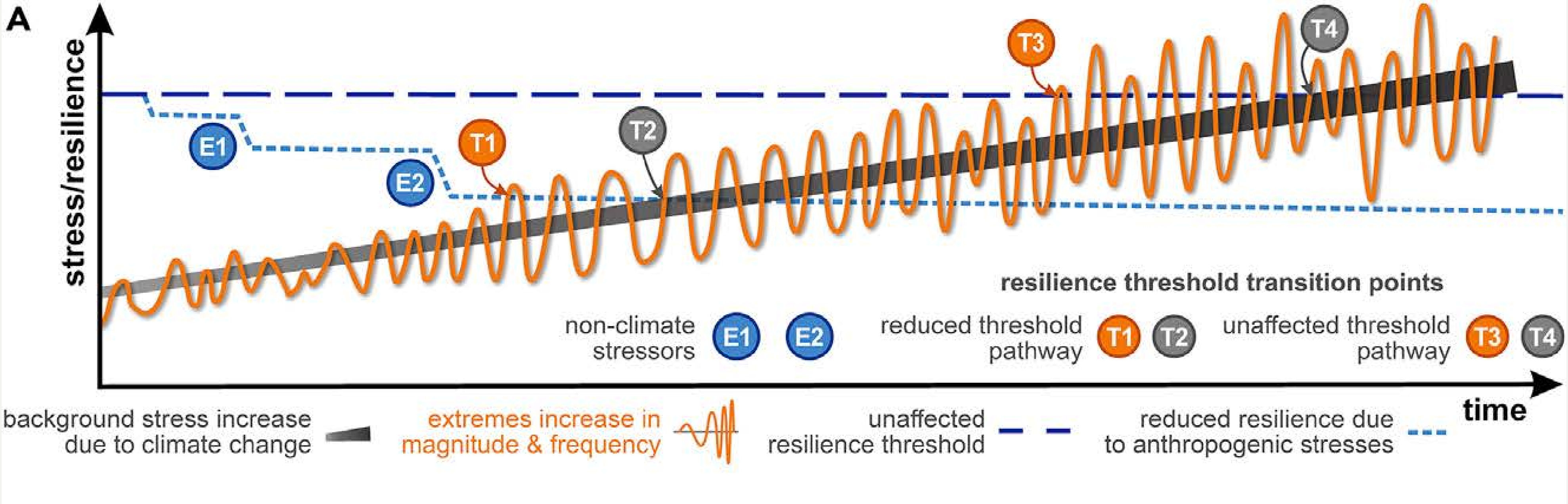
Preface – Climate impact science is complex…

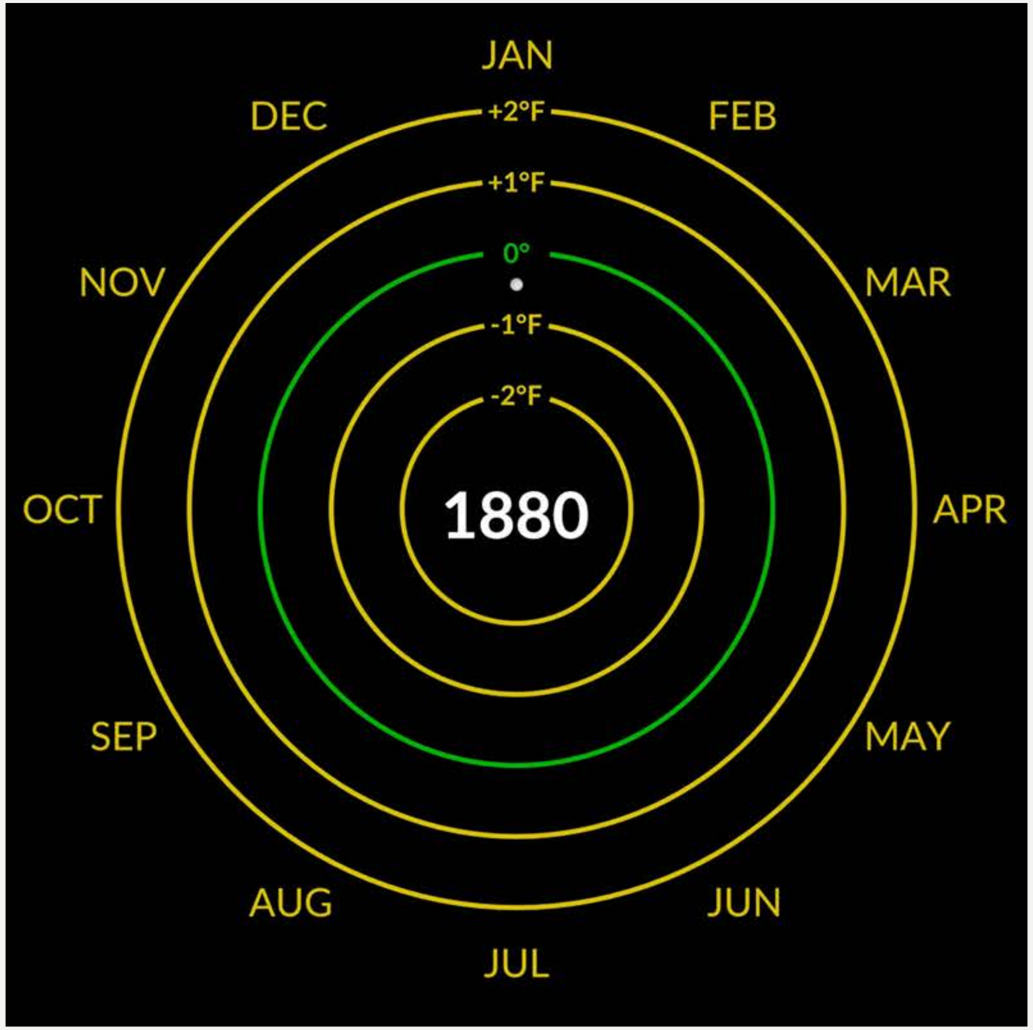
Anthropogenic Stresses on (the World's Large) Rivers



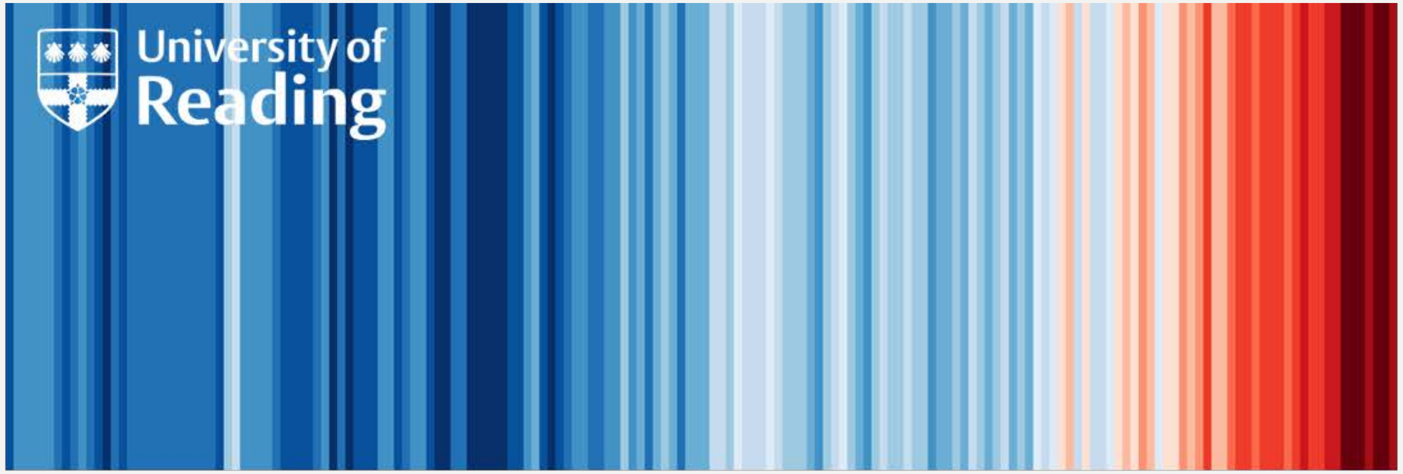
Schematic showing the influence of progressive climate change and decreasing resilience due to other stressors (E1 and E2, such as damming and sediment mining) that could cause resilience thresholds to be crossed under the presence of increasing extreme events (T1 and T3), as well as the slower background stress of climate change (T2 and T4)

(Best and Darby, *One Earth*, 2020)

What can we take from observations?

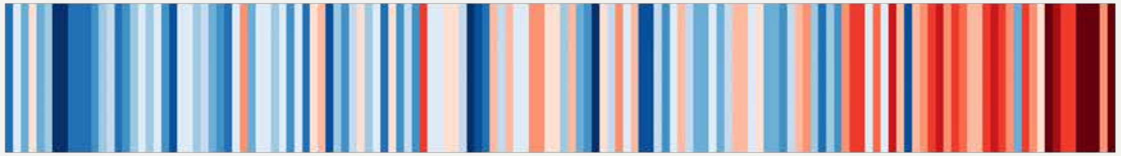


Ed Hawkins © NASA's Scientific Visualization Studio

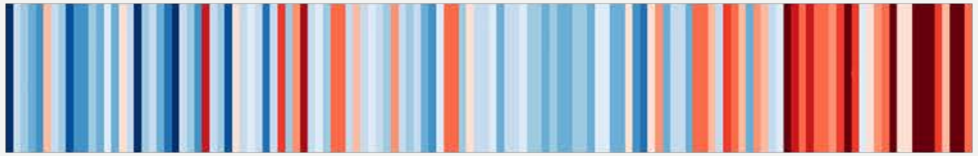


Climate Stripes - Global (1850 – 2021)

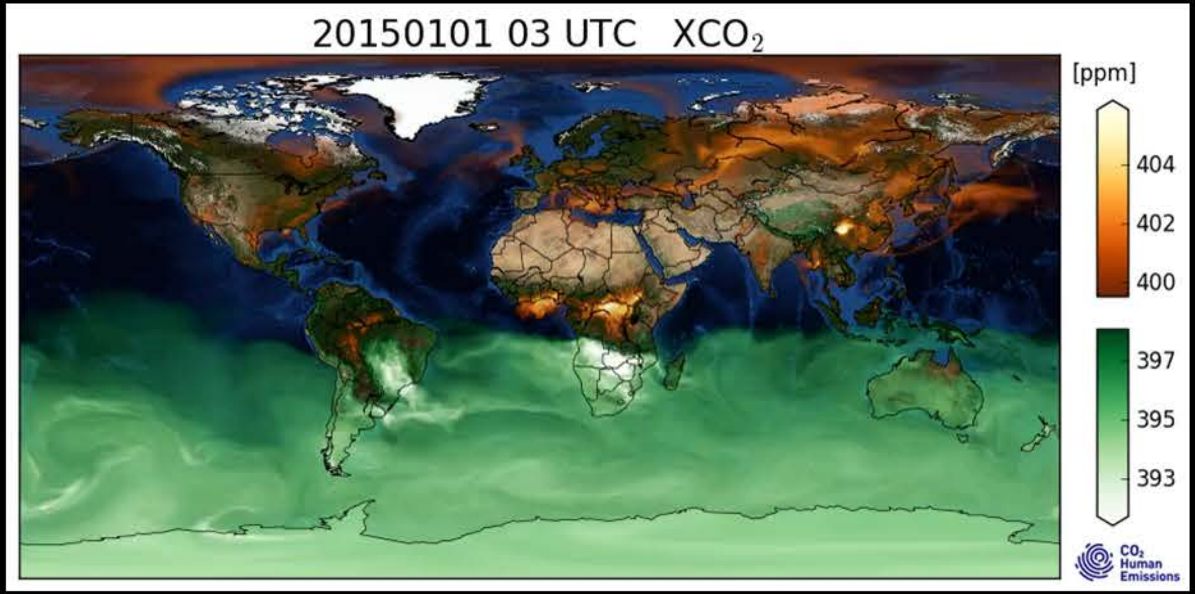
Climate Stripes - Germany (1880 – 2022)



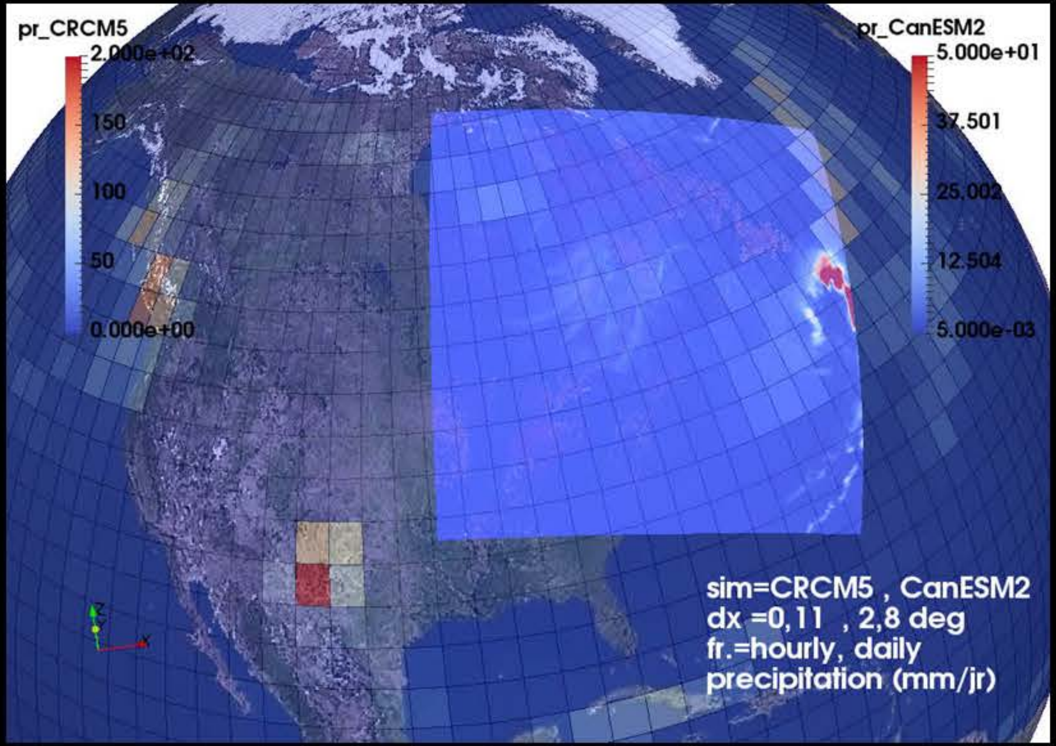
Climate Stripes - USA (1895 – 2022)

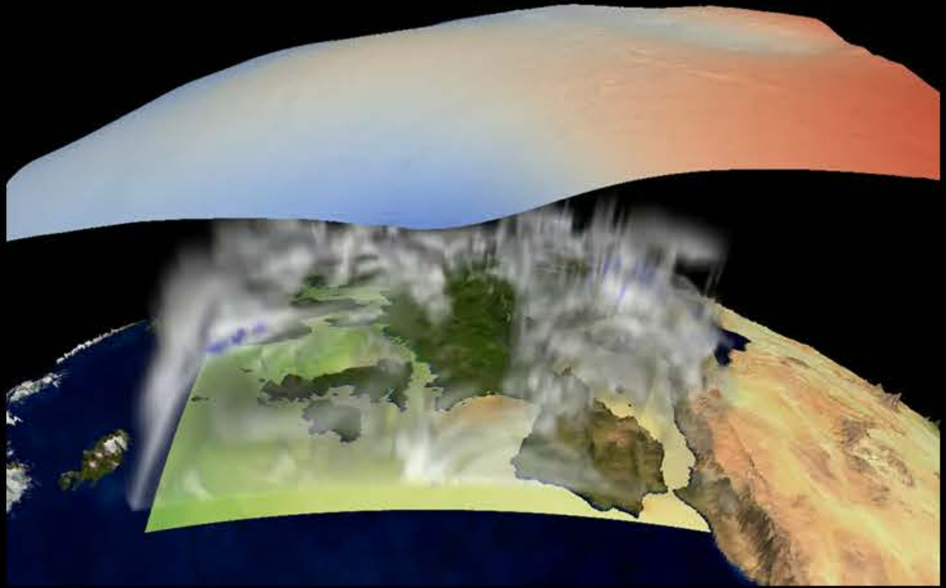


Climate models … huge data

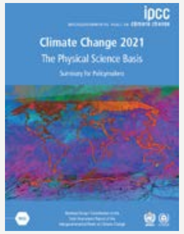


https://www.che-project.eu/news/animation-co2-variability



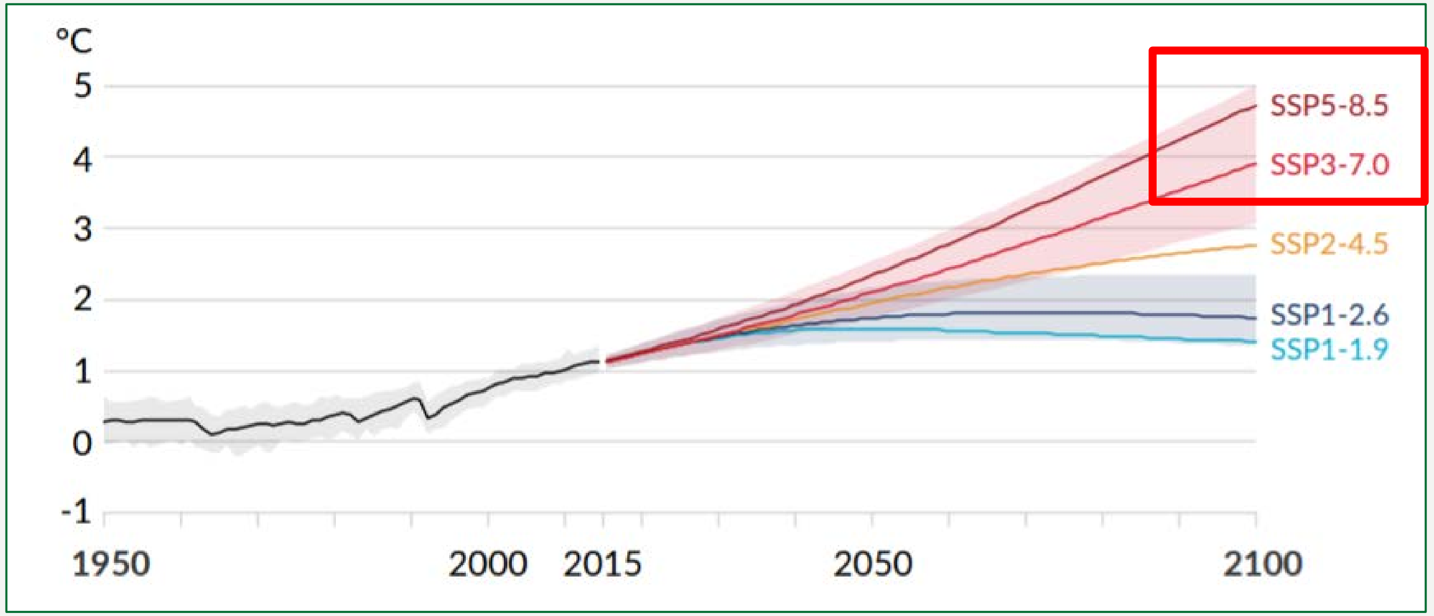


Current state of knowledge…



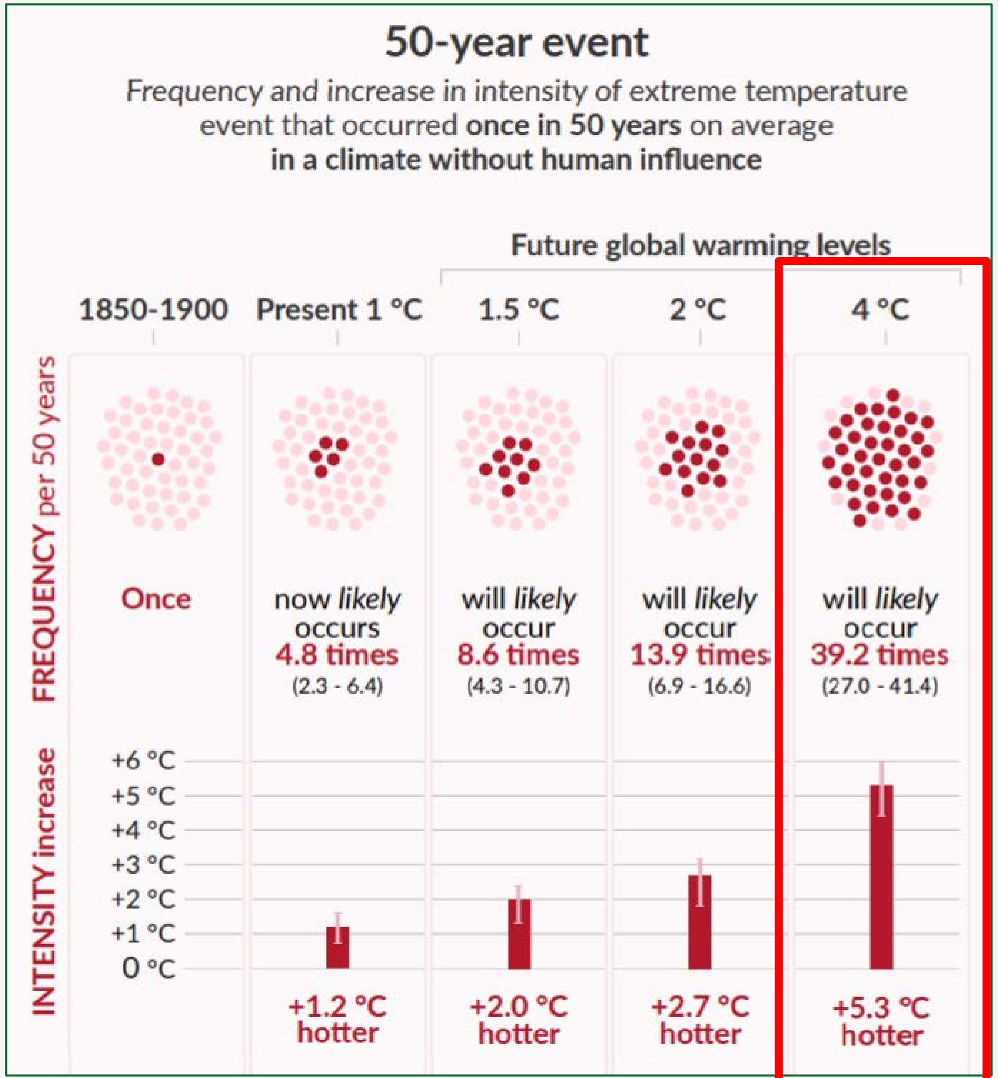
From the 6th Assessment Report of the IPCC (AR6) – 09. Aug 2021:
Scenarios of possible futures

e.g. global temperature change in comparison to 1850-1900



SSP = *Shared Socioeconomic Pathway*; Scenarios of a possible socioeconomic development

RCP = *Representative Concentration Pathway*; related radiative forcings [W/m²] via GHG-concentrations in the atmosphere



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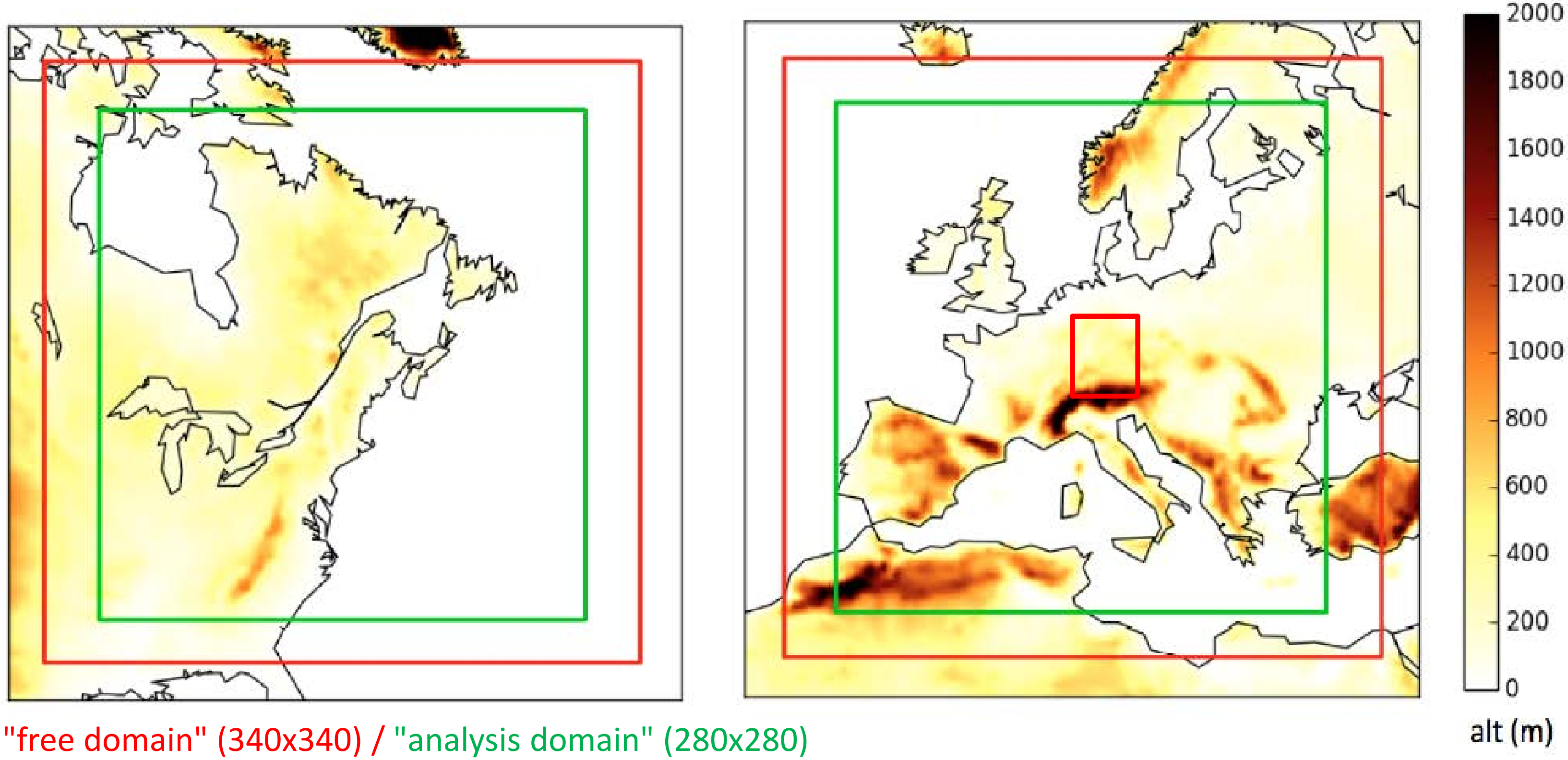
ClimEx

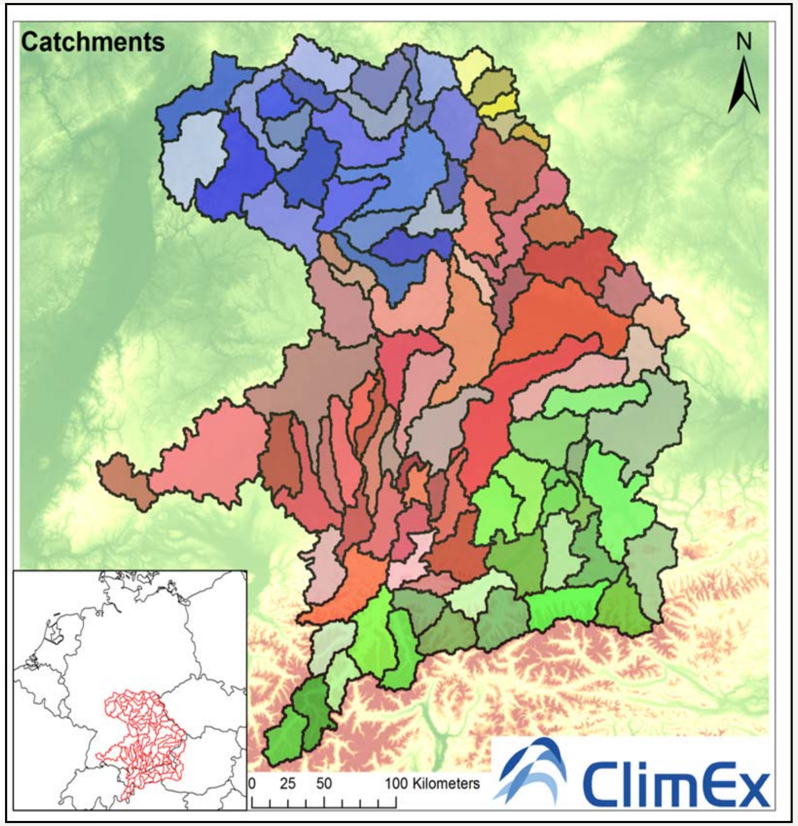
ClimEx – Research questions

- How does climate change contribute to higher intensities and frequencies of hydro-meteorological extreme events?
- How can we distinguish between the effects of natural variability and a "clear" climate change signal?
- What are feasible and effective adaptation options to reduce risk on regional and cross-sectoral scales?

The ClimEx-Project – Case studies



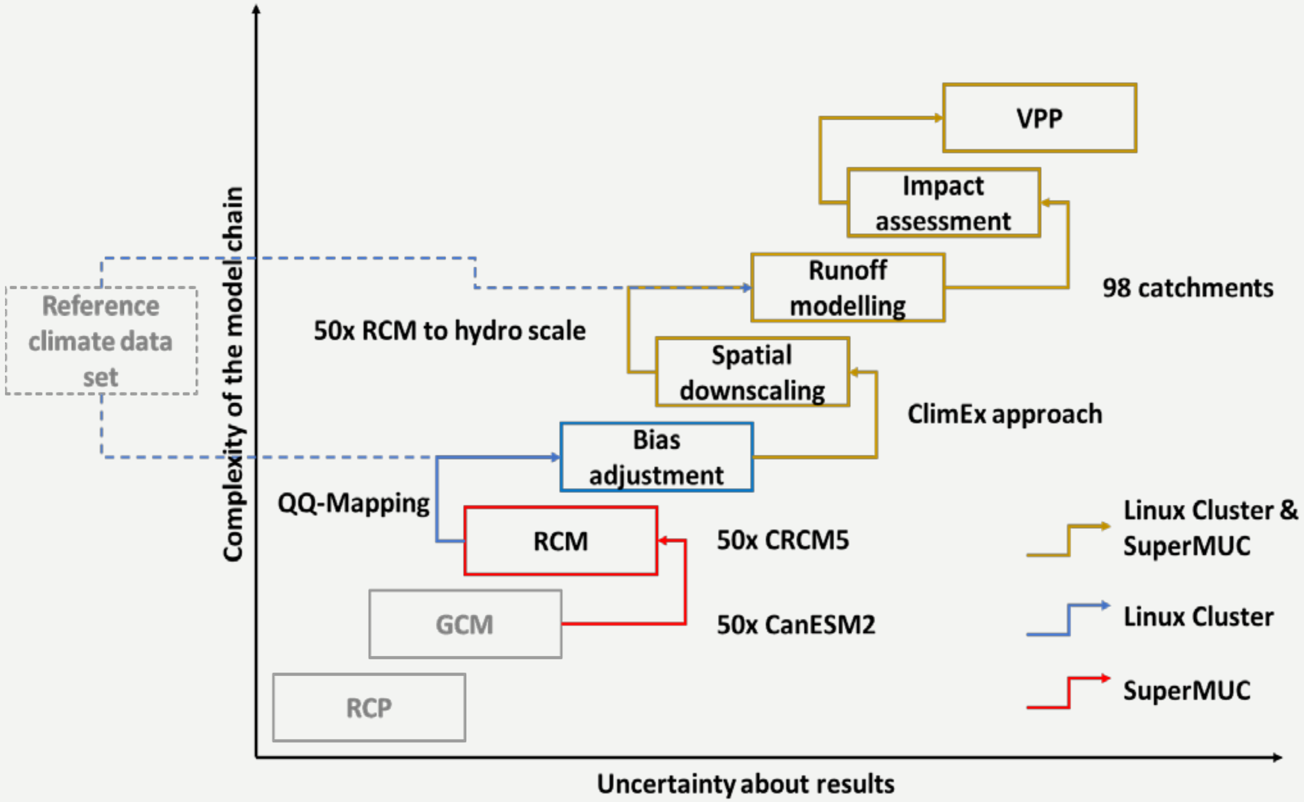
"free domain" (340x340) / "analysis domain" (280x280)



Scope: Assess the dynamics of climate change related extreme events in Europe and (hydrological) Bavaria

Goal: a) Improve process understanding of non-linear hydro-meteorological extreme events
b) Provide management options for stakeholders and decision makers to reduce related risks

The ClimEx-Project - Methodology



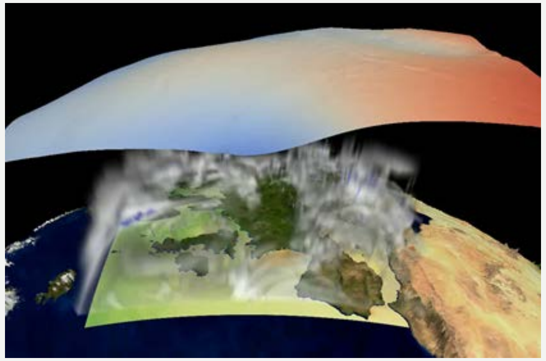
Method: Novel process chain from regional climate model ensemble (LMU, Ouranos) to process-based impact models (LMU, INRS, ETS) and practical evaluation of results (LfU, DEH), utilizing massive HPC and Big Data (LRZ)

→ Special (50 model members, i.e. 50 possible climate pathways (1950-2099)

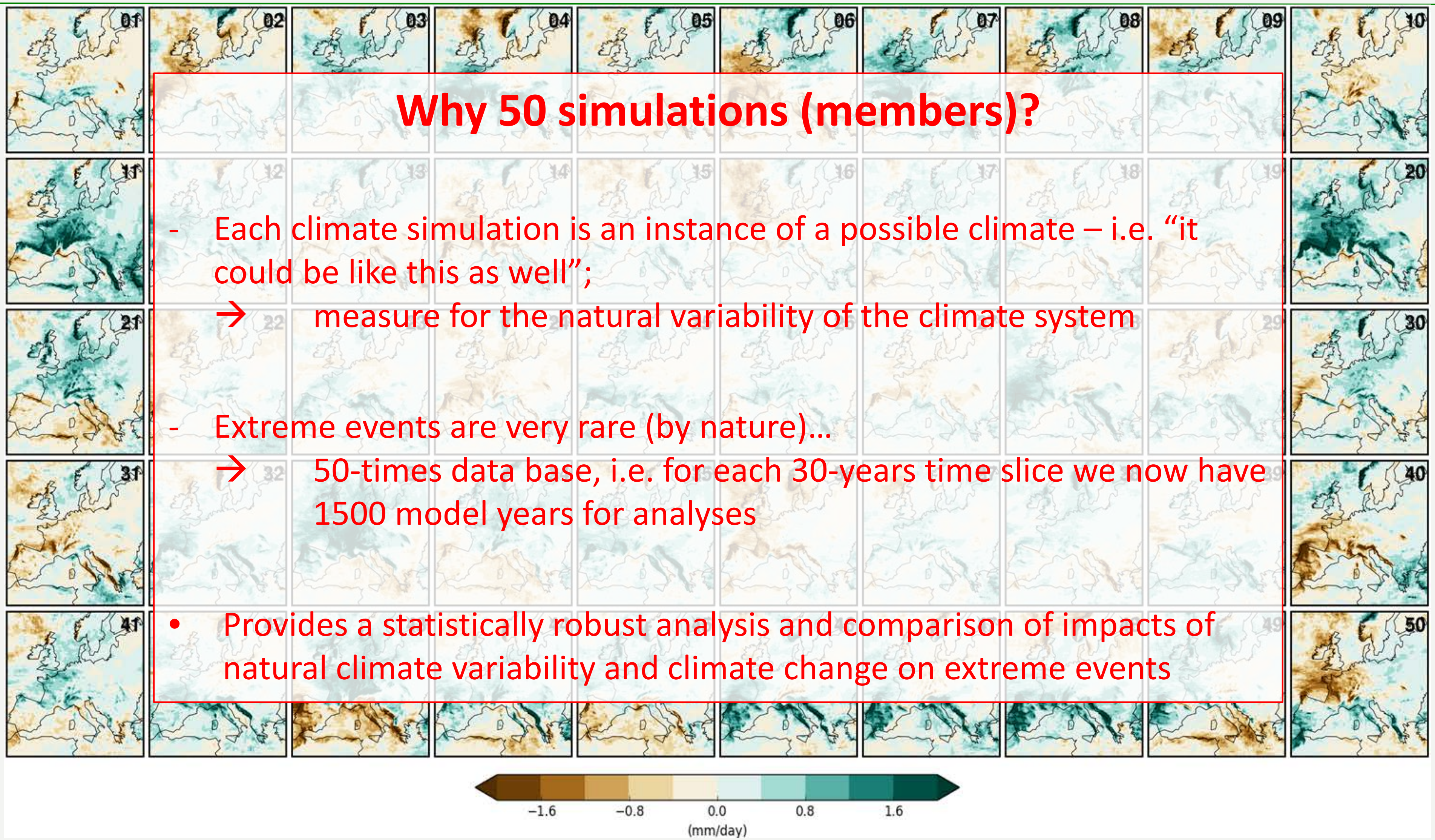
→ 7500 model years (+ 700 model years of counterfactual world)

HPC & (really) Big Data…

- ~ 100 MCPU-h, 500 Tbyte (*2 Backup); Data Science Storage (DSS)
- 1 year of computation on SuperMUC; 1.25 GWh of electricity…



Results – Natural variability (of precipitation)



Why 50 simulations (members)?

- Each climate simulation is an instance of a possible climate – i.e. "it could be like this as well";
  → measure for the natural variability of the climate system
- Extreme events are very rare (by nature)…
  → 50-times data base, i.e. for each 30-years time slice we now have 1500 model years for analyses

• Provides a statistically robust analysis and comparison of impacts of natural climate variability and climate change on extreme events

50 possible future changes for PRC (in %) between 2020-2039 and 2000-2019 over Europe from CanESM2-CRCM5 at a 12-km resolution

(Leduc et al., 2019, *JAMC*)

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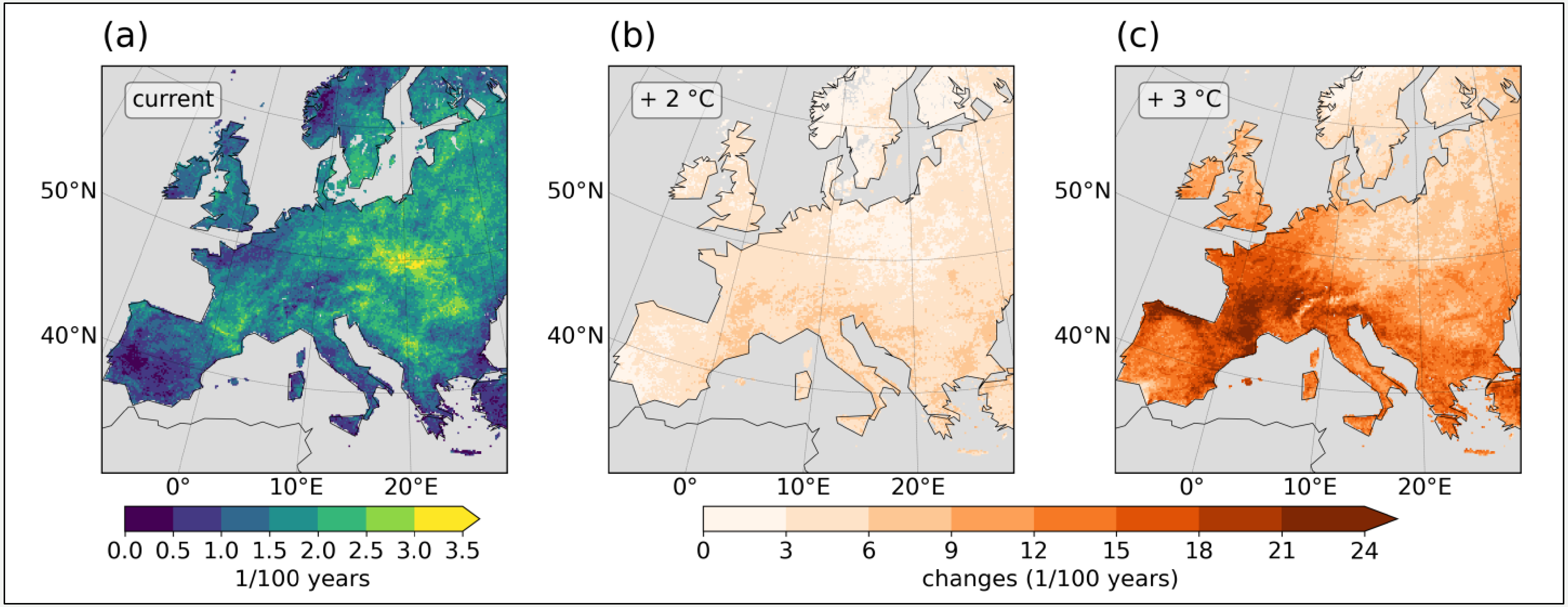
Hydrometeorological Extremes (in Europe and Bavaria)

- Droughts and Heat -

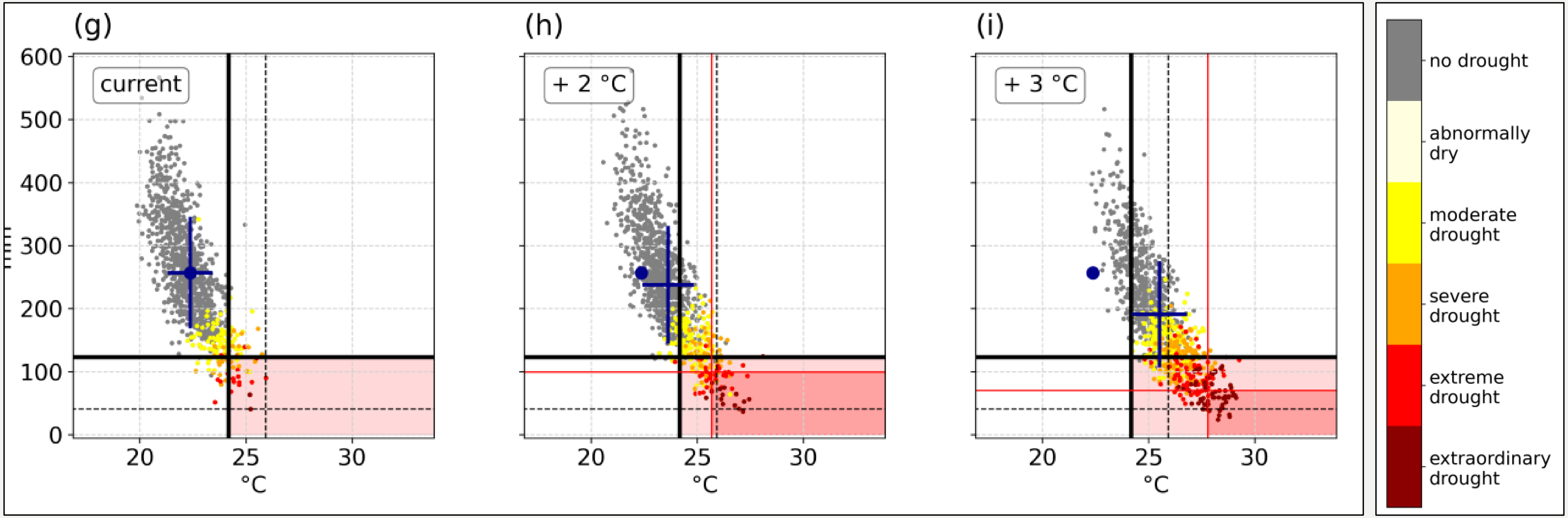
ClimEx – Compound Drought and Heat Extremes



CDHE frequency for three global warming levels (absolute values for present climate (a) and changes under GWL2 (b) and GWL3 (c)). Events are defined as local exceedance of the current (2001–2020) 95th percentile of temperature and (negative) precipitation

(Böhnisch, Felsche, Mittermeier, Poschlod & Ludwig, 2023, *Earth's Future*, submitted)

ClimEx – Compound Drought and Heat Extremes



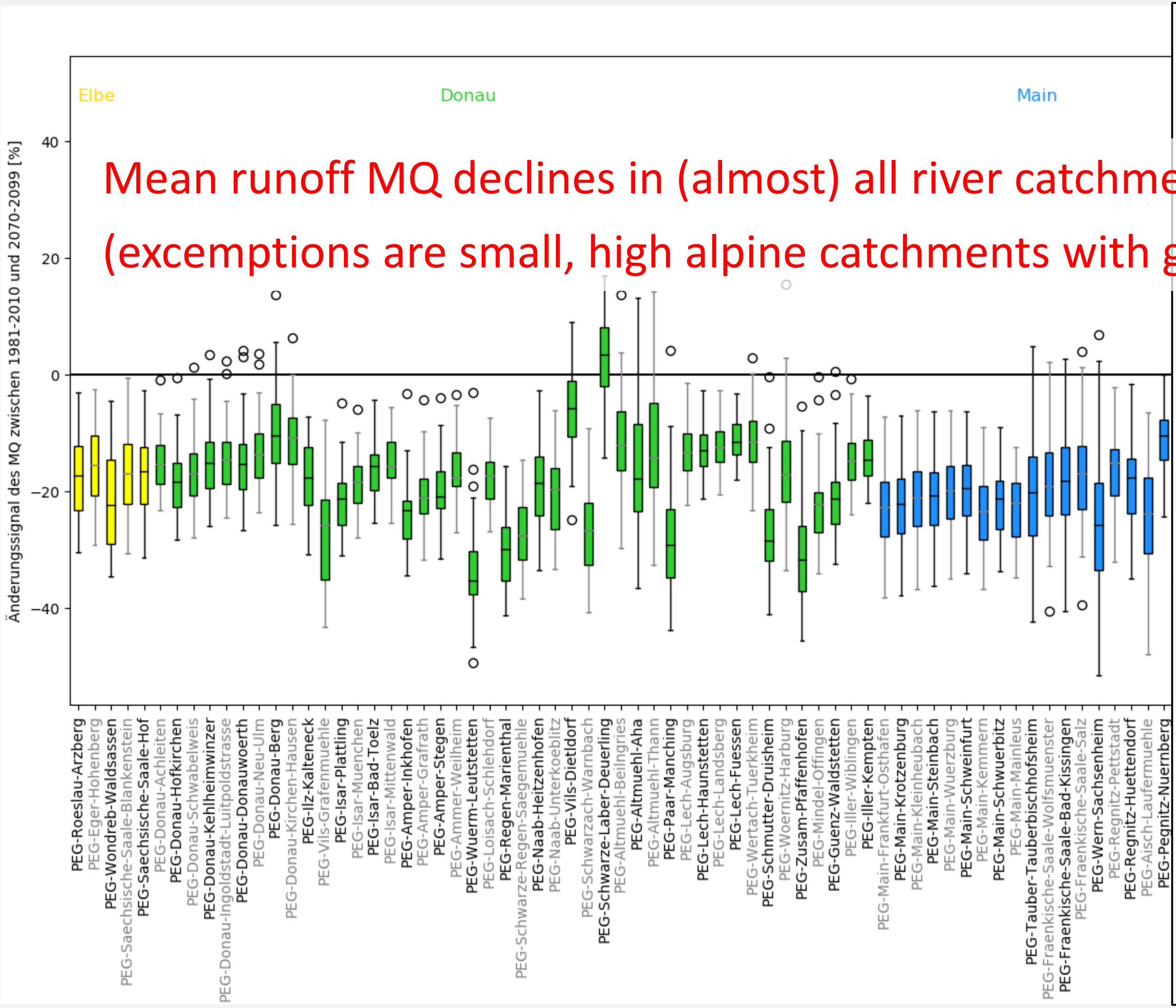
(g)–(i) scatterplots of summer precipitation against summer temperature for an exemplary region. Thick (thin) black lines show the present 5th and 95th percentiles (min and max) for precipitation and temperature, respectively. Red lines mark the 5th and 95th percentiles for GWL2 and GWL3. Light red background highlights current CDHE summers; strong red background CDHE summers for GWL2 and GWL3

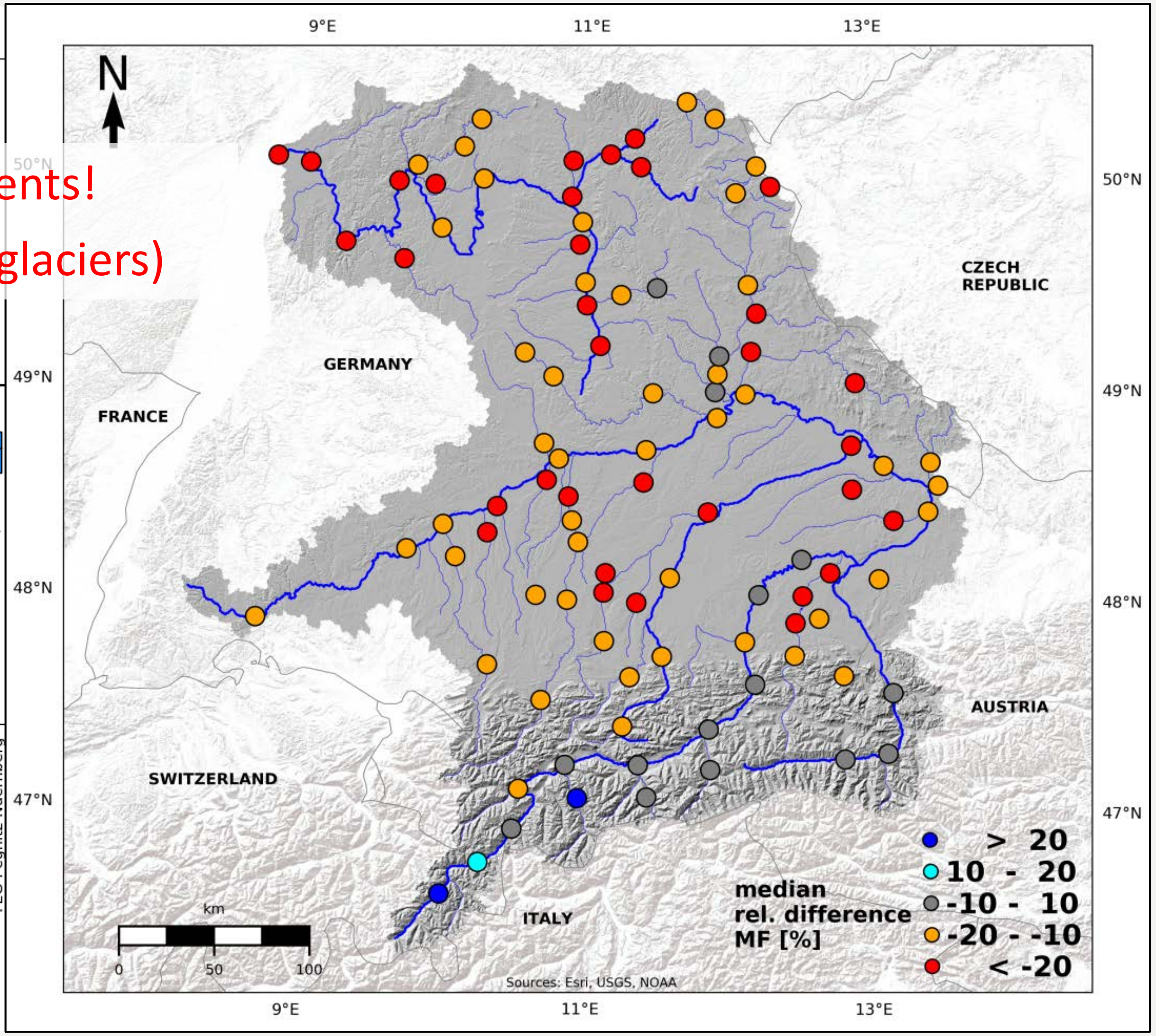
(Böhnisch, Felsche, Mittermeier, Poschlod & Ludwig, 2023, *Earth‘s Future*, submitted)

ClimEx – Changes in annual mean flow in Bavaria (MQ)

Mean runoff MQ declines in (almost) all river catchments!

(excemptions are small, high alpine catchments with glaciers)





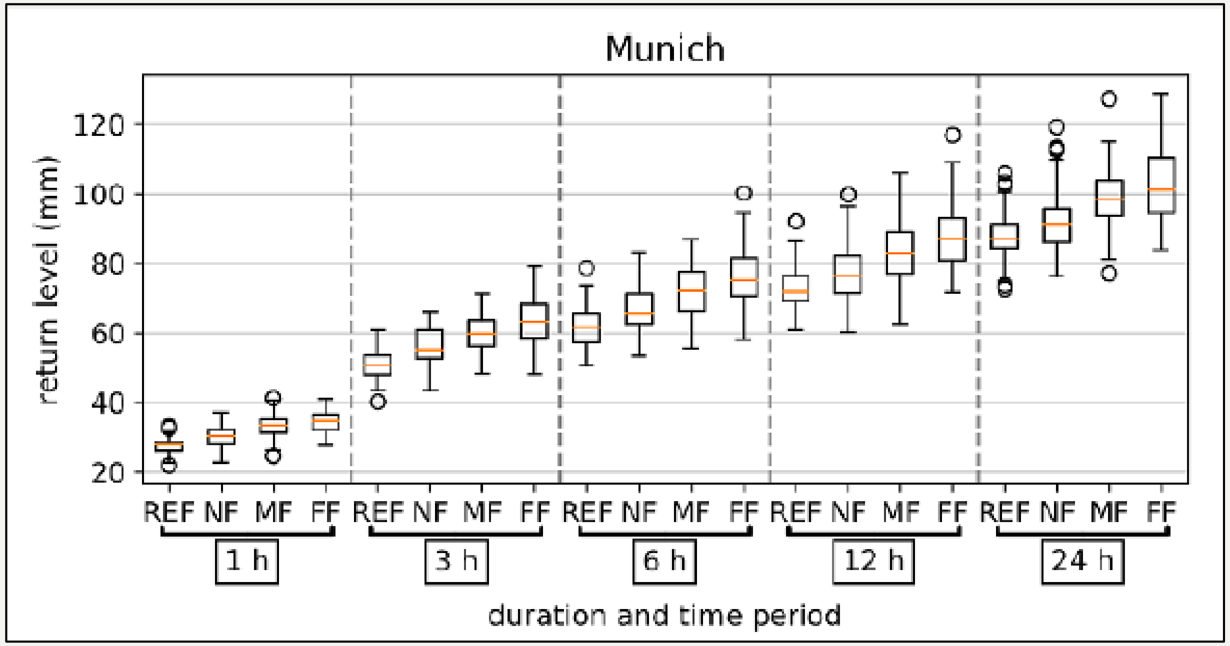
(Willkofer, Ludwig et al., in prep.)

ClimEx

Hydrometeorological Extremes (in Europe and Bavaria)

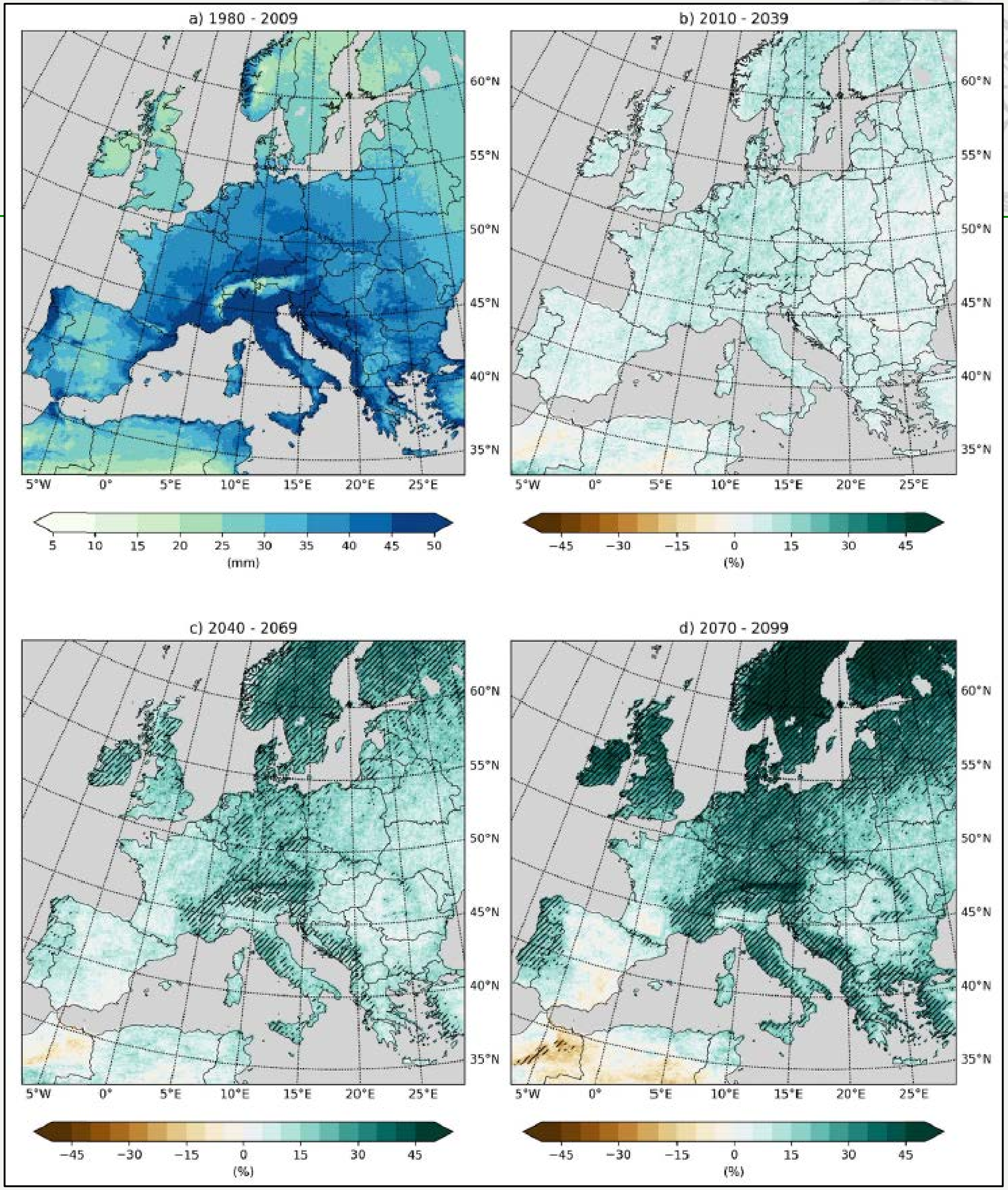
- Extreme Precipitation and Floods -

Heavy precipitation (10-year return)



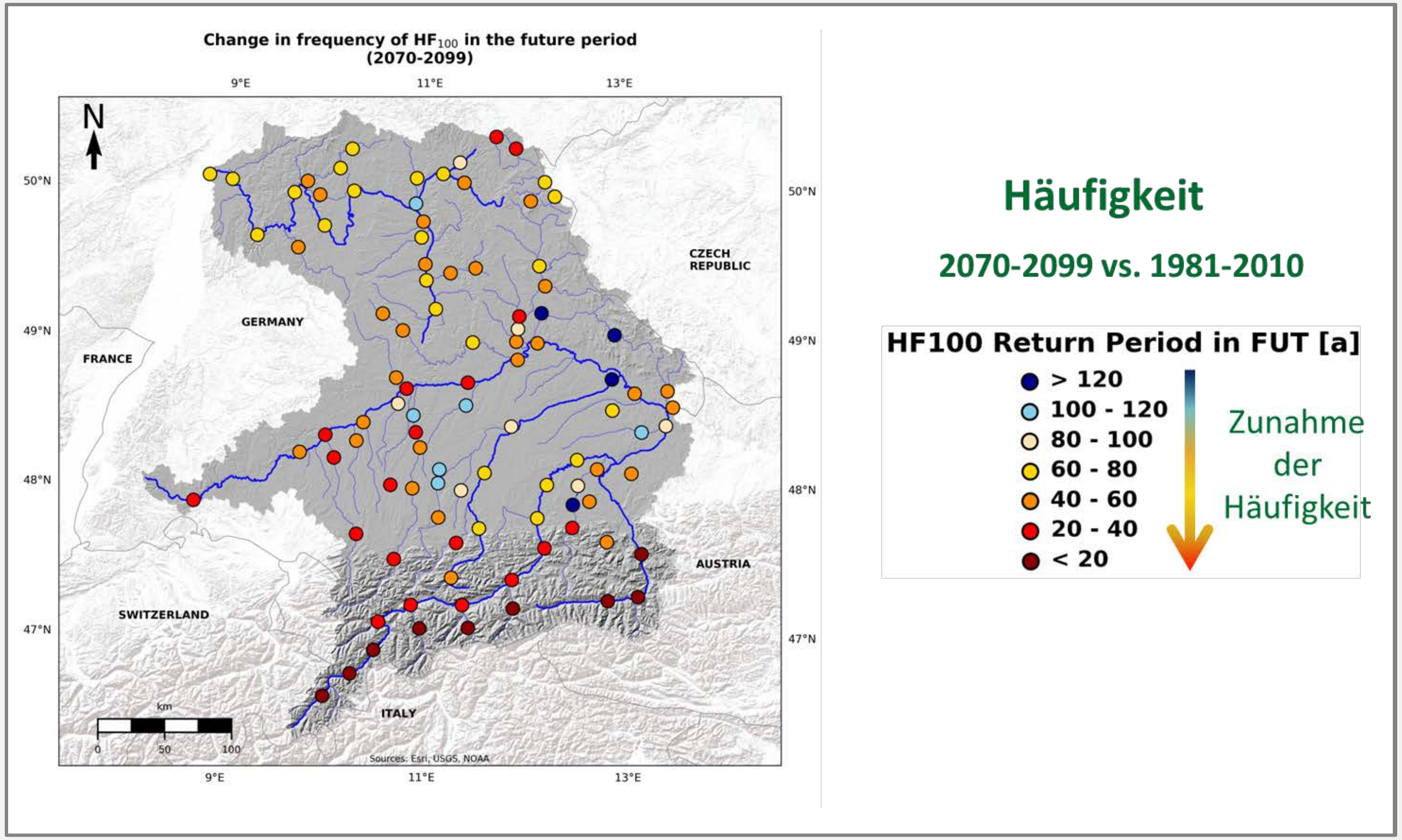
- into the future, the 10-year extreme precipitation increases for any temporal level (1h, 3h, 6h, 12h and 24h)
- similar behaviour visible for most European cities

(Poschlod & Ludwig, ERL, 2021)



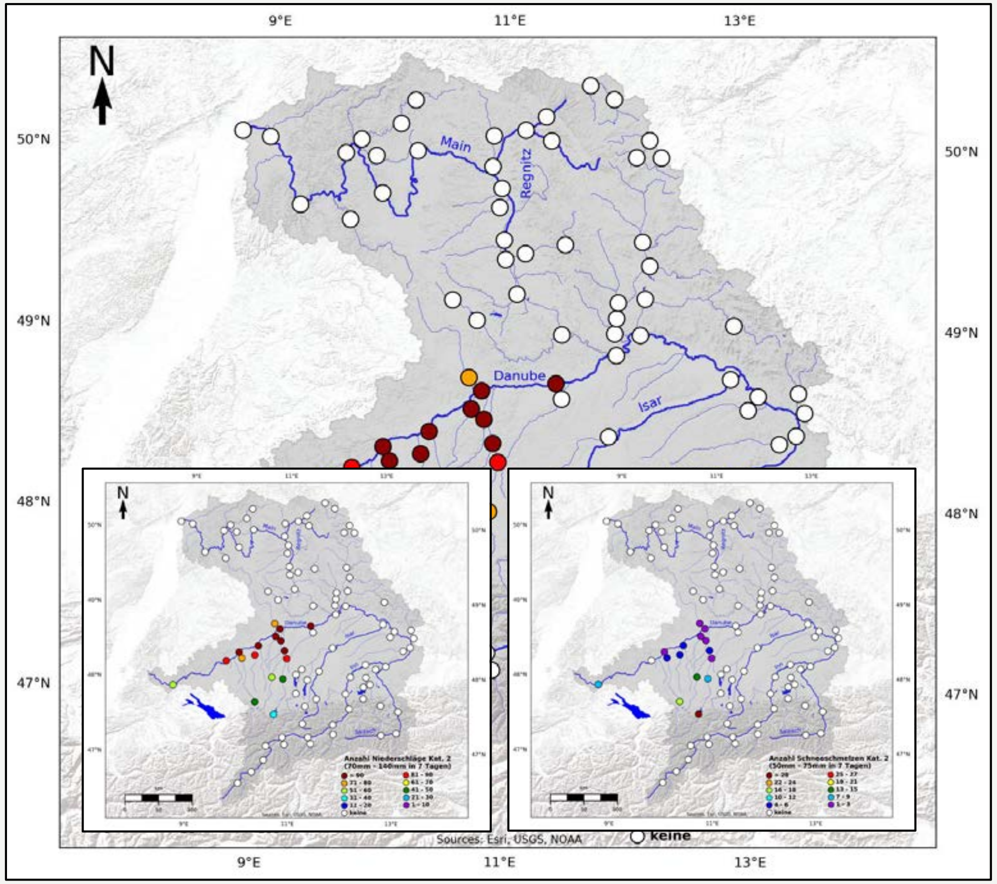
Results – Will extreme flows/floods (e.g. HQ100) be more severe?

Changes in Frequency and Intensity of HQ100 in Bavarian river basins



(Willkofer et al., in prep.)

Determining regional sources and drivers for extreme floods (Ex. gauge Ingolstadt)



(Poschlod et al., in prep.)

Contents

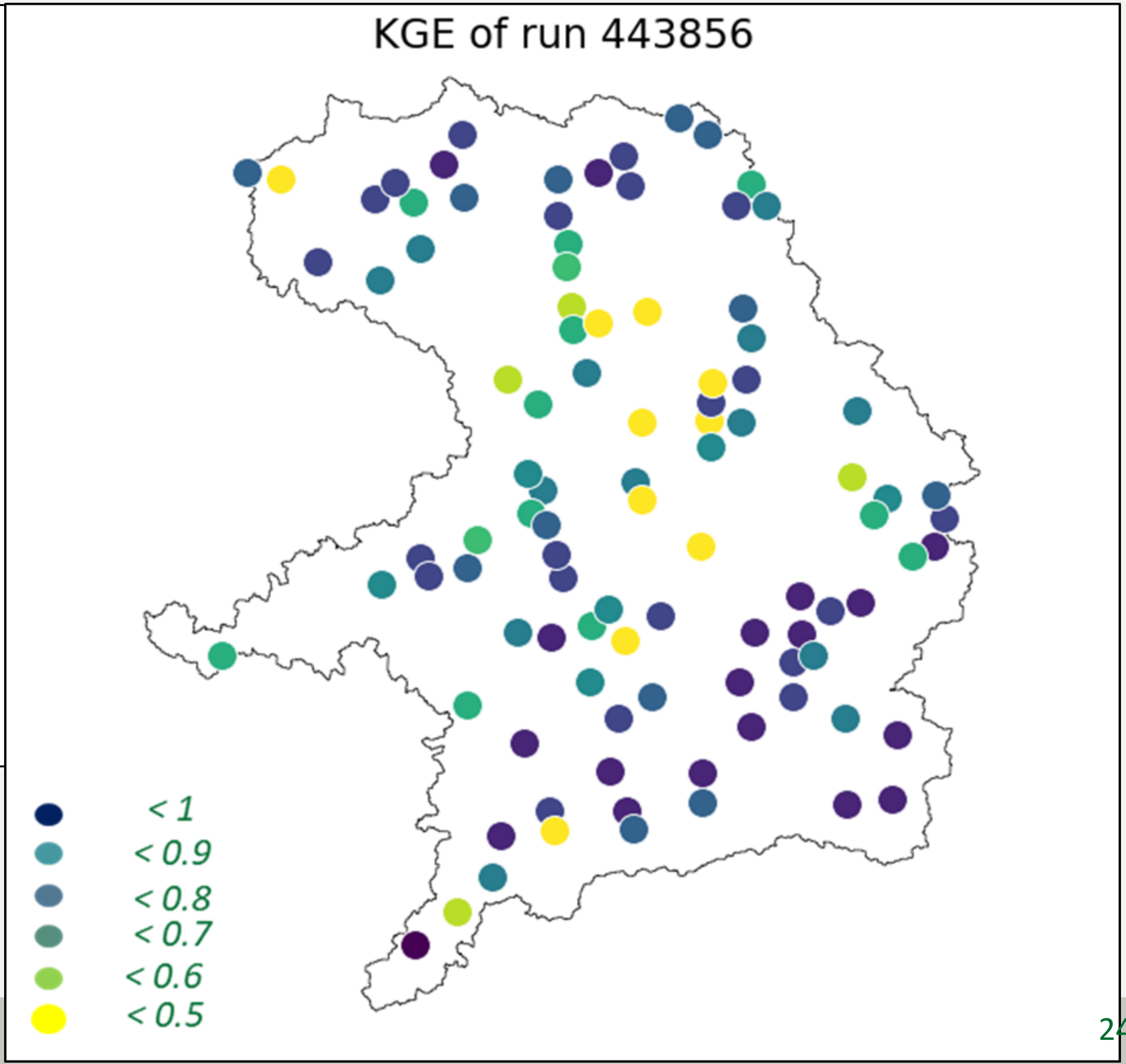
Results - Runoff Modeling (using LSTM-CNN)

Static variables: watershed
watershed size, slope, height

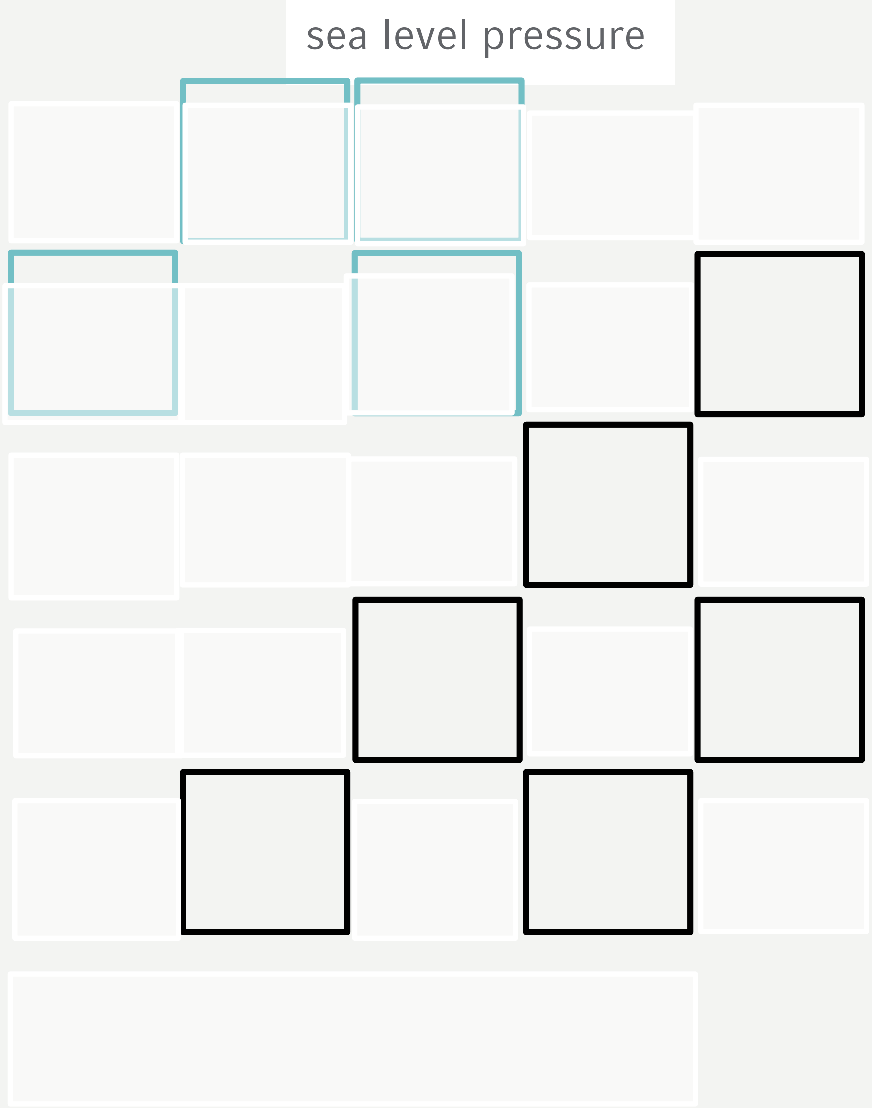
Dynamic variables:
precipitation,
temperature, rel.
humidity,
precipitation based
indices …

LSTM → runoff

Window size: up to 365 days



Results - Weather Circulation Type Patterns



- 29 circulation types over Europe called „Großwetterlagen“ by Hess & Brezowsky
- One of the most established classification schemes in Europe (manual/subjective)
- Studies on the relationship between atmospheric circulation and extreme events (dynamic driver)

☐ Favoring conditions for heat and drought in Central Europe

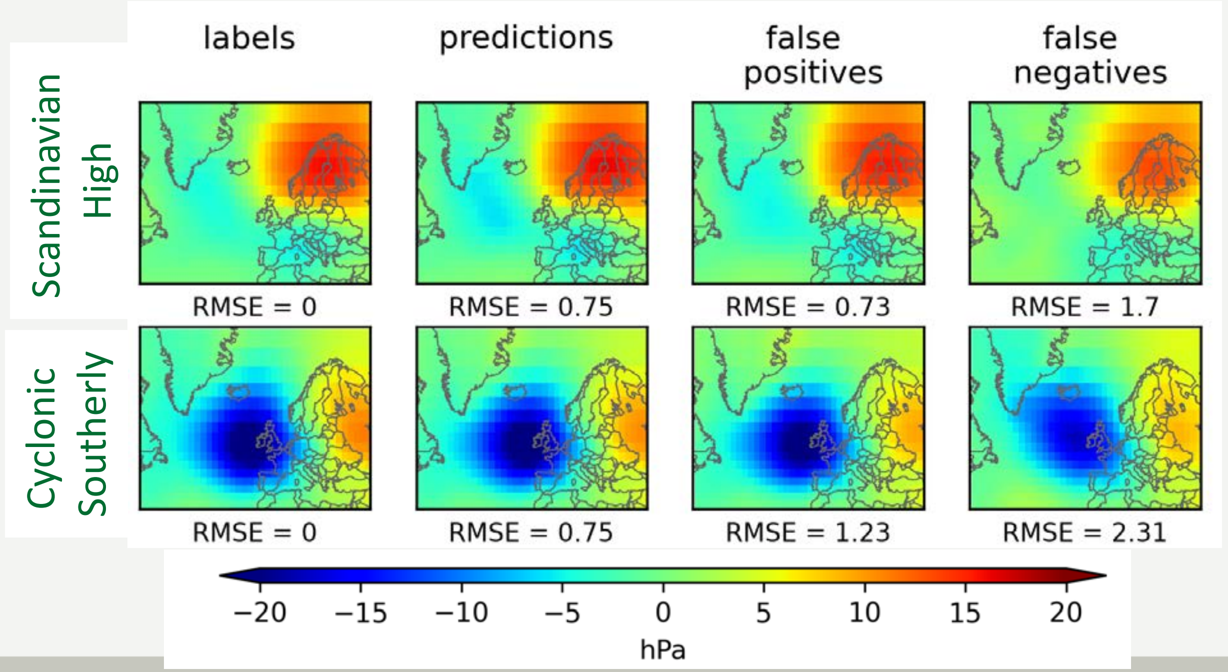
☐ Conditions associated with winter floods in Germany

Automatization required for application to climate models

Results - Weather Circulation Type Patterns

- Overall accuracy: **41 %**
- Subjectiveness of the original classification → Many misclassifications of our network seem to be synoptically correct
- Previous methods for automatization: 35 % (Krüger 2002), 39 % (James 2006)
- Advantages of our automatization: open-source, low computational cost → application to SMILEs

Signature plots showing synoptic characteristics of a specific class in contrast to other classes



→ unquantified human level error

Mittermeier, et al. (2022), *ERL*

Results - Weather Circulation Types

Analysis of the SMHI-LENS (CMIP6) using the
EC-Earth 3.0 model with 50 members

Shared Socioeconomic Pathway SSP37.0

20 of 29 classes show significant

frequency changes despite high

internal variability

Westerly a	south-west c	no category a	Northerly c	Easterly a	south-east c
Westerly c	north-west a	no category c	north-east a	Easterly c	Southerly a
south-west a	north-west c	Northerly a	north-east c	south-east a	Southerly c

Mittermeier, et al. (2022), *ERL*

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Looking into the future…

- using data from a sensitive climate model under an extreme climate change scenario shows for Bavaria:
  - very strong increase in temperature, particularly in summer → increased risk for heat waves
  - strong increase in winter precipitation → floods
  - strong decrease in summer precipitation → droughts
  - reduced mean annual flow / strong increase in flood risk

→ *strong implications for multiple economic and societal domains (agriculture, forestry, water, health…)*

→ *an urgent need for international and interdisciplinary collaboration to build adaptation strategies for climate resilient regions (especially in the absence of a globally effective climate mitigation …)*

Conclusions

- Next generation in big data applications for climate impact studies:

  → “large convection permitting climate model ensemble”
  → meteorological forcing in very high spatio-temporal resolution (1-3h, downscaled to hydrological model grid)

- Process-based and ML-based hydrological modeling tools as a test environment for the efficacy and efficiency of (nature-based) adaptation solutions to mitigate hydrometeorological extremes ((flash) floods, droughts)

- Scenario-tool to assess land-cover change and water management

→ Big(ger) data!

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