Generating Rainfall Time-Series of High Temporal Resolution under Future Climate Conditions

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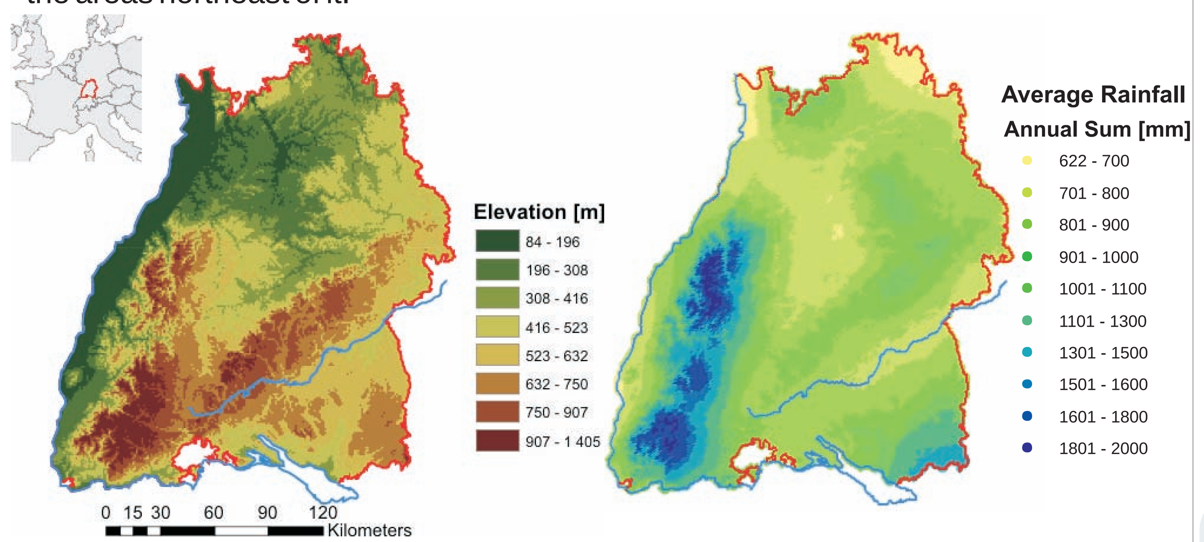
Climatic Conditions in Baden-Württemberg

The Federal State of Baden-Württemberg, which is situated in the South West of Germany, experiences the **temperate climate** conditions of middle Europe. Rainfall is almost **equally distributed over the whole year**. Long dry periods do not occur very frequently. The region receives its moisture mainly from the Atlantic Ocean, most rainfall events are linked to the arrival of warm and cold fronts from the West. In the **summer months** from May to August **convective events** can lead to very heavy rainfall intensities.

Spatial Heterogeneity of Rainfall

The topography of Baden-Württemberg is very heterogeneous. It is divided into many different landscapes e.g. the plains of the Rhine valley in the West and the plateau of the Swabian Alb in the central East. The elevation ranges from less than 100 m in the Northwest to more than 1400 m at the peaks of the Black Forest in the Southwest.

The topographic variability leads to an uneven spatial distribution of rainfall. The **average annual precipitation sum** ranges **from 650 mm to almost 2000 mm**. The mountain ranges of the Black Forest recieve the most precipitation, shielding the areas northeast of it.



Climate Change

In the last few decades, significant changes in the hydrological conditions of Baden-Württemberg have been observed. The **annual rainfall sum has increased** while in the same time, a shift in the annual cycle has occurred. The **increase in precipitation** is most pronounced **during the winter months** while the **summers have become sightly dryer**. But even if it rains less in summer, the **intensities in short time-steps** (up to 1h) have **increased**. When it rains, it rains harder.

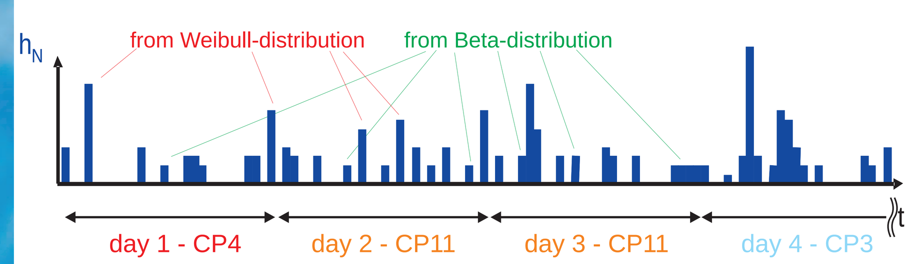
NiedSim-Klima Time-Series Generator

The NiedSim-Klima generator was developed to deliver **rainfall time-series under future climatic conditions** which are comparable to observed rainfall time-series. The **generated time-series represent point values** with a **temporal resolution of 1h**. They can be **disaggregated to 5min values**. There are **two generation periods**: a **control-period from 1961-1990** and a **future period from 2021 to 2050** according to the **IPCC A1B CO_2 emission scenario**.

Generation Principle

1. **Monte-Carlo simulation** fo an initial 1h-rainfall time-series
 The **initial time-series** has a **correct distribution** of 1h-precipitation values, but the **sequence of values** is **arbitrary**.
2. **Optimisation of the sequence** by a simulated annealing algorithm
3. Possibility of **disaggregation to 5min values** by simulated annealing

Initial Time-Series



For each 1h-value:
Draw random number! - rainfall (yes-no)"
If yes:
Draw random number! - for intensity

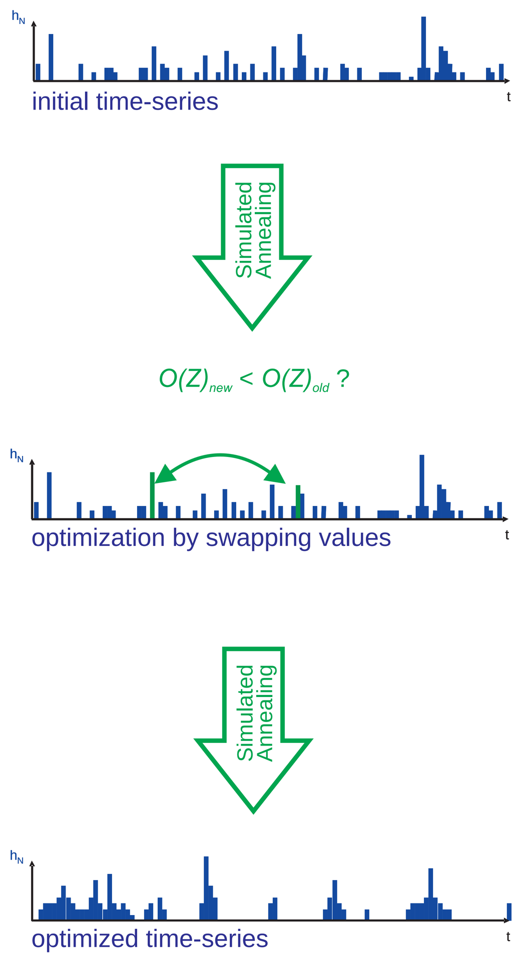
Parameters for initial time-series

$P_0(CP,T)$	Probability for rainfall intensity > 0.0 mm/h
$P_1(CP,T)$	Probability for rainfall intensity > 1.0 mm/h
α_β, β_β	Parameters of Beta-distribution for intensities between 0 and 1 mm/h
λ, κ	Parameters of Weibull-distribution for intensities > 1 mm/h

depending on:
- **CP** atmospheric circulation pattern of day
- T_{avg} average temperature of day

supported by:

Optimisation of the Sequence in the Time-Series



The **parameters** describing the **statistical characteristic** of the initial time-series are calculated. They are **compared with target values** of these parameters at the simulation location by the following objective function:

$$O(Z) = \sum_{i=1}^{k} w_i \left(\rho_{i,work}(Z) - \rho_{i,target}(Z) \right)^2 \rightarrow \min$$

If **$O(Z) = 0$** the synthetic **time-series Z perfectly fulfills** the **target values** ρ_{target} of the k statistical parameters.

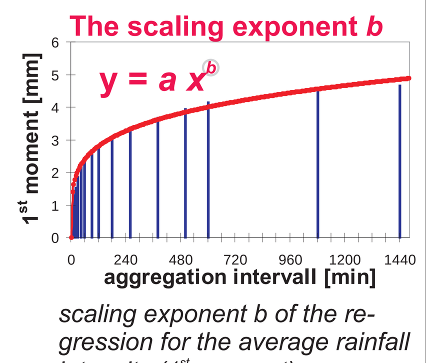
The **objective function** is **minimized** by continuously **swapping 1h rainfall values.** The optimisation algorithm is **Simulated Annealing:**

- A swap of two values is tested.
- If the swap improves the time-series ($O(Z)$ is decreasing) the swap is kept, the time-series is altered.
- If a swap worsens the time-series ($O(Z)$ is increasing) the swap is kept with a certain probability P_{accept}. This is necessary to avoid that the optimisation gets stuck in a local minimum.
- The probability of accepting such a "bad" swap decreases during the optimization
- The optimisation is terminated when the ratio of accepting a tested swap is lower than a defined termination limit.

Parameters for optimization of sequence

$P_{24h}(CP,T)$	Probability for day with rainfall > 0.0 mm/24h
$q_{month}(CP,T)$	Fraction of yearly rainfall sum in actual month
a_{gum}, β_{gum}	Parameters of Gumbel distribution for max. 24h-rainfall-sum in year
$\rho_{a,l}$	Autocorrelation on different aggregations a (5min to 24h) and different lags l (1 to 6 time-steps)
b_m	Exponent of polynomial regression function between aggregations from 5min to 24h for m = 1[st] to 3[rd] moment

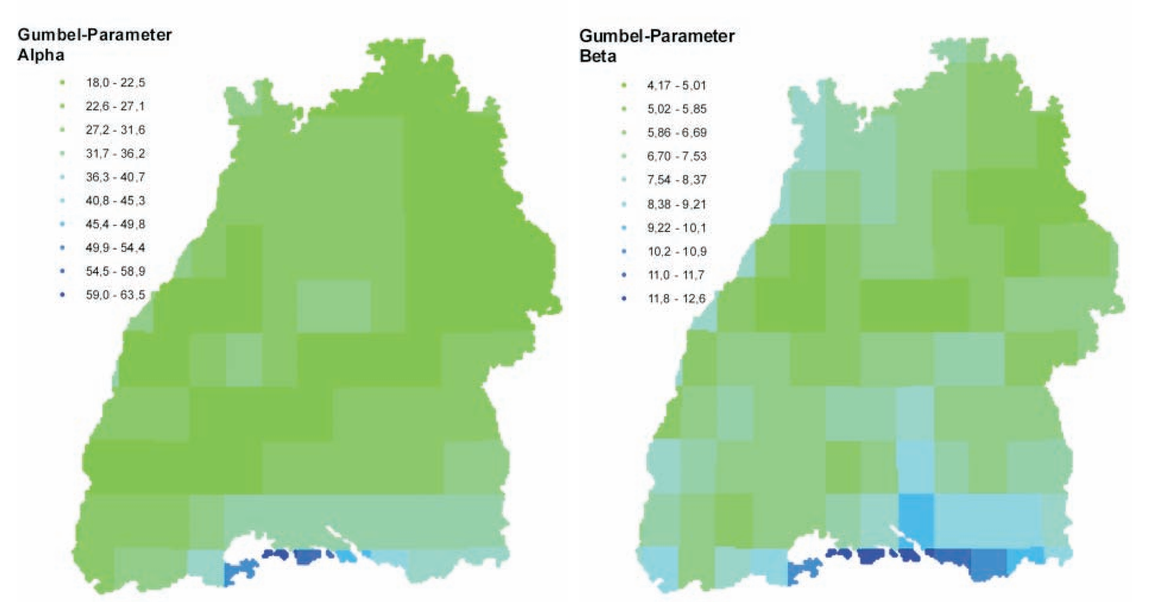
depending on:
- **CP** atmospheric circulation pattern of day
- T_{avg} average temperature of day



scaling exponent b of the regression for the average rainfall intensity (1[st] moment)

Regionalisation of the Parameters

All necessary simulation parameters come from a **database in 1x1 km raster**. The parameters are regionalised on this raster. For any simulation, the **parameters at the respective grid point** are read out.



Parameters of the Gumbel-Distribution describing the annual 24h-maximum rainfall according to the Regional Climate Model REMO as an example of the regionalization

Data Sources for Generation Parameters

- ***$P_0(CP,T)$, $P_1(CP,T)$, $P_{24h}(CP,T)$, a_β, β_β, λ, κ, $\rho_{a,l}$***
derived from 1h-time-series from several hundred rainfall stations
- ***CP, T***
derived from Global Circulation Model ECHAM5
- ***a_{gum}, β_{gum}***
derived from Regional Climate Models REMO, RACMO
- ***b***
extrapolation of observed trend in 1h-time-series from rain gauge records

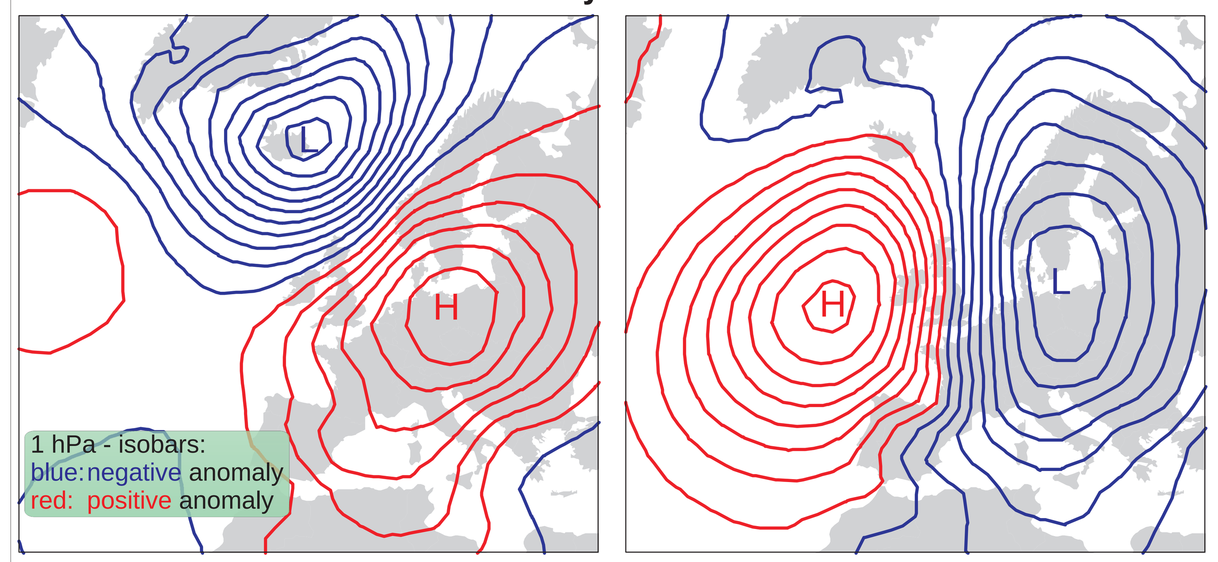
objective function O(Z) is time-dependent!

Climate trend signal in time-series generation

Climate Change Signals in NiedSim-Klima

Atmospheric Circulation Patterns CP

The CP classification used in NiedSim-Klima is defined by a **Fuzzy Rule based classification system** on **sea level pressure (SLP) anomalies** over Europe and the Northern Atlantic Ocean. **CP-definition** was done for a **calibration** period from 1991 to 2003 with **NCEP-NCAR reanalysis** data.



average SLP anomalies of all days classified CP 3 - dry conditions

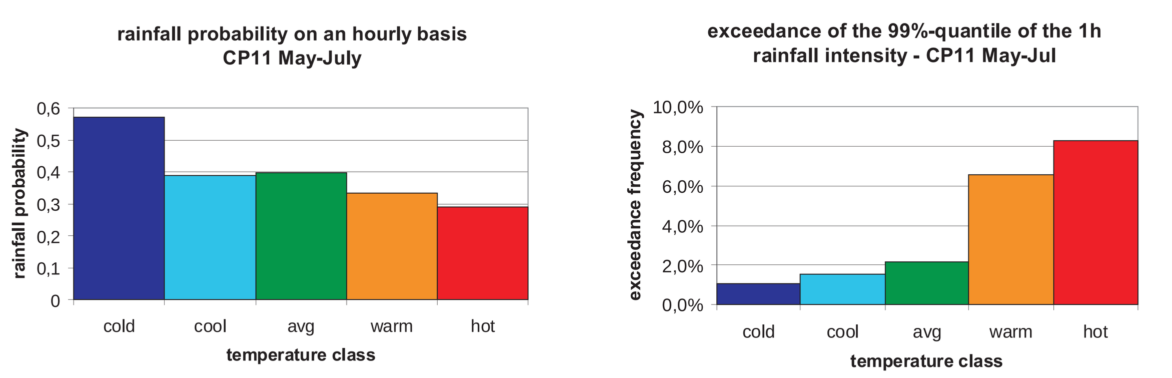
average SLP anomalies of all days classified CP11 - wet conditions, high potential for extreme rainfall intensities

There are **12 CP classes** that were **subdivided into 5 temperature classes** reaching from "cold" (with the coldest 20% of all days) to" hot" (hottest 20%). The temperature data was **deseasonalized** before the classification. It came from 205 measurement stations in Baden-Württemberg.

The CP dependent simulation parameters $P_0(CP,T)$, $P_1(CP,T)$ and $P_{24h}(CP,T)$ were estimated with this data.

In the NiedSim-Klima generator the classification system is applied to sea level pressure and air temperature fields from the Global Circulation Model **ECHAM5** to determine the **CP** and **temperature class** of each day in the climate prediction **for 2021 to 2050.**

Temperature Sensitivity of CPs



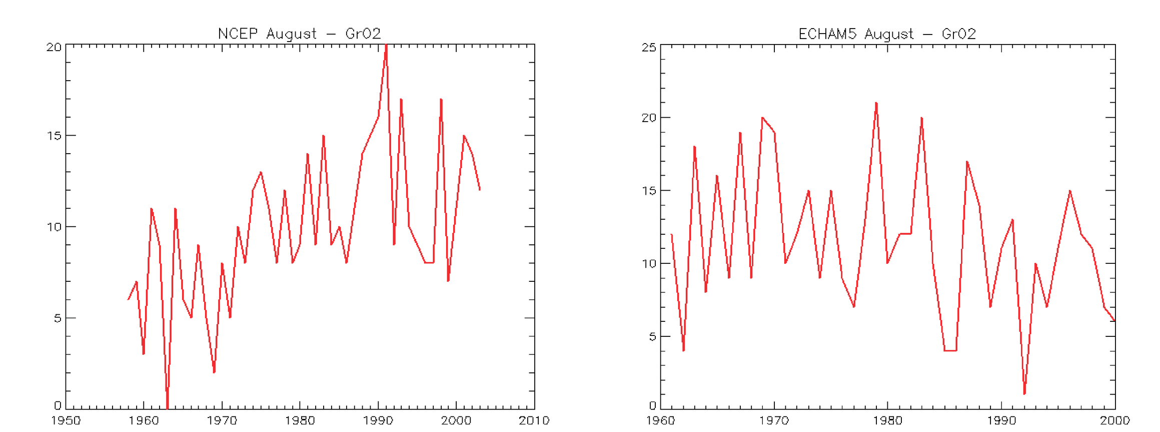
Especially wet CPs show a clear temperature sensitivity in summer months:

- With **increasing temperature**, the **probability of rainfal**l (on hourly time-steps) **drops**
- At the same time, the **probability of heavy rainfall intensities is increasing**. The probability of exceeding the 99% quantile during CP11 on a hot day is more than 8 times higher than on a cold day.

If the temperature is increasing with climate change, this will lead to shorter but more intensive rainfall events in summer.

Time Trends in CP-Sequence

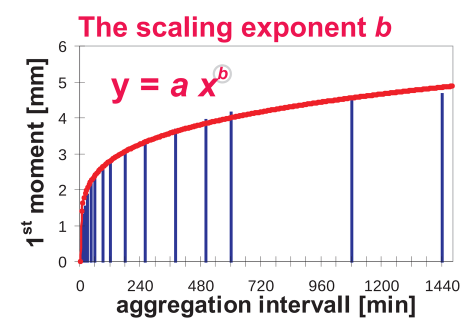
When the CP and temperature classification is applied to the whole time period of the NCEP/NCAR reanalysis from 1958 to 2007, clear time trends show up. In **sommer months**, the **frequency of dry CPs is increasing**. At the same time, the high temperature classes (potentially leading to extreme rainfall) occur more often.



Absolute frequency (in days) in August of all CPs leading to dry, anticyclonic conditions according to NCEP/NCAR (1958 - 2004) and the control run of ECHAM5 (1961 - 2000)

While **ECHAM5 captures the increase in temperature quite well**, it **is not able to model the changes in the CP-sequence correctly**. Instead of the observed increase in the number of days with dry high-pressure CPs during the second half of the 20th century, a decrease is predicted.

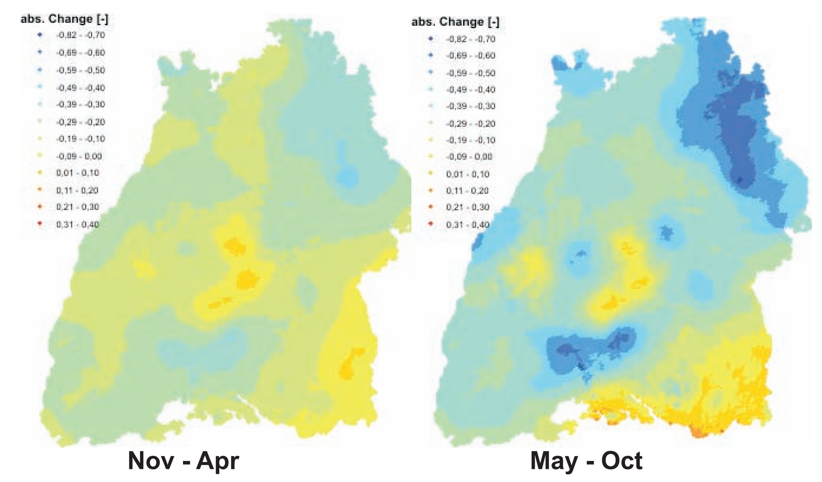
Trend signal in the scaling parameter *b*



scaling exponent b of the regression for the average rainfall intensity (1[st] moment)

The **scaling exponent *b***, for the 1[st] statistical moment describes the **shape of a regression** function between **the mean of the rainfall sum on different aggregation intervals** from **5min to 24h**.

For observed rainfall time-series b_1 is always between 0 and 1. If b_1 is 1, the average rainfall sum was a linear function of the aggregation interval which means the average intensity was constant, independent of the aggregation interval. If b_1 is 0, the regression function was a horizontal line. The whole daily rainfall would always fall in one 5min-event. The **lower b_1**, the **more important high rainfall intensities on short time-intervals** become.

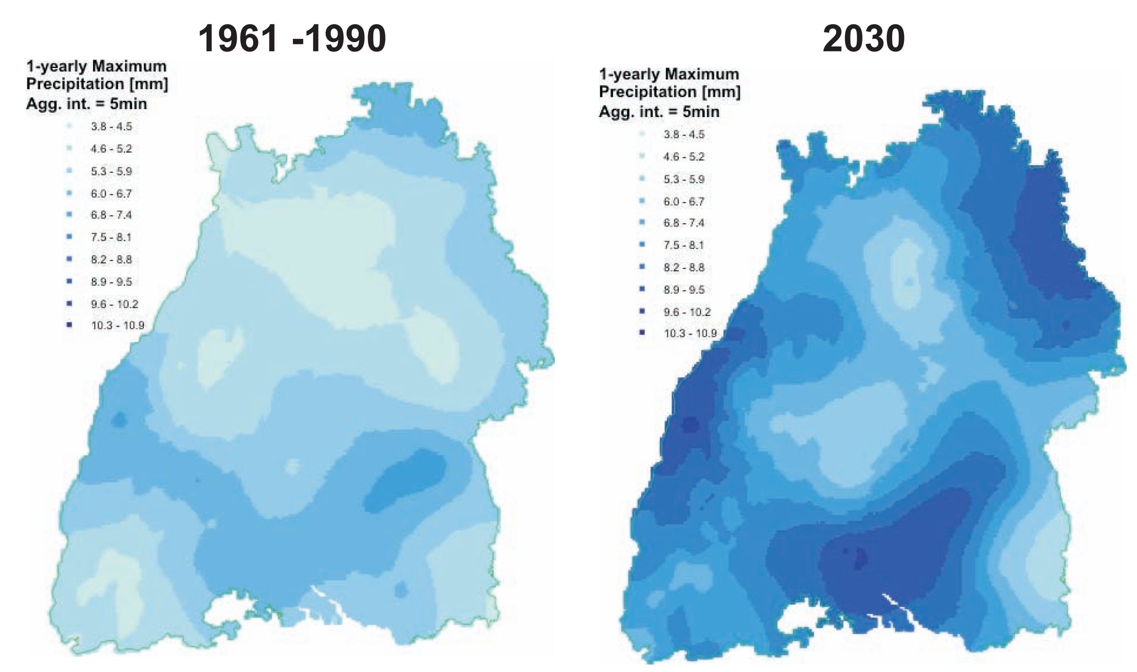


Change in the scaling exponent b (1958-1980 to 1981-2003) for the 1[st] statisical moment

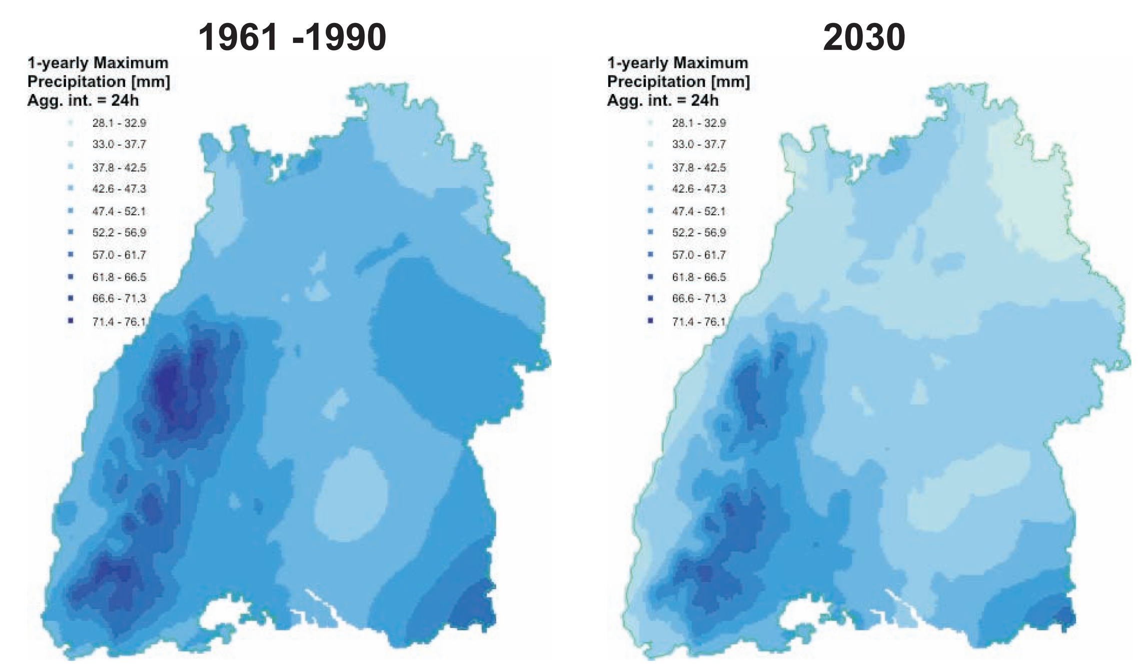
The maps show the absolute **change in the scaling exponent *b***, between the two time-periods for calculation from 1958 to 1980 and 1981 to 2003. Data was derived from 291 rainfall measurement stations and kriged over the whole study area. **Blue to yellow** indicate a **decrease**, **orange to red** an **increase**. The scale exponent decreased almost everywhere - in summer, the changes are very significant. Thus **climate change affects the scaling** of rainfall and shifts the average towards high intensities in short time-intervals.

Analysis of Simulated Time-Series

The following maps show the first results from NiedSim-Klima time-series generation. They were **derived from simulated 5min rainfall time-series at 63 equally distributed locations**. They present the **average annual maximum precipitation** in a 30 year time-series. The results were regionalised using external drift kriging (with the square root of the elevation as drift). The **left column** shows the simulation for the **control period from 1961 to 1990**. The **right column** shows results of a the simulation under the **predicted climatic conditions of 2030**.



Average annual maximum 5min precipitation derived from simulated 30 year time-series.



Average annual maximum of the 24h precipitation derived from simulated 30 year time-series.