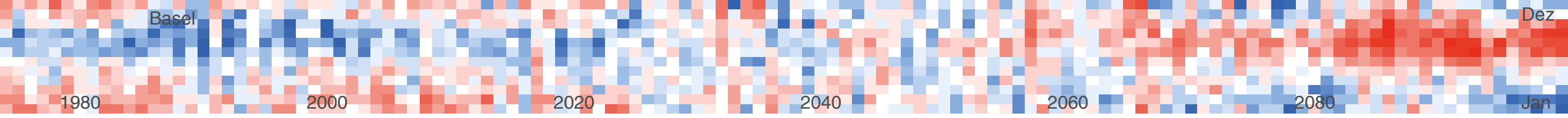


2.3 Climate model scenario

The ASG project ensemble of climate model runs was selected from the EURO-CORDEX climate scenario modeling experiment (www.cordex.org). In CORDEX Global Climate Models (GCMs) are downscaled with Regional Climate Models (RCMs) to obtain higher resolution fields of meteorological variables, e.g. at 0.11° (~12.5 km horizontal resolution) in a coordinated effort. CORDEX climate model output, e.g. temperature, precipitation, etc. of future scenarios (until 2100) and control runs (until 2005) from a variety of GCM-RCM combinations is freely available for download.

The ASG project considered climate model runs of one 'Representative Pathway' (RCP), the RCP8.5 scenario, thus targeting a worst-case change under the assumption of late measures for CO_2 reduction (e.g. Van Vuuren et al., 2011). The project used a selection of seven GCM-RCM combinations for the RCP8.5 scenario to create an ensemble of transient climate variables to drive the hydrological model simulations (Table 1).

Table 1: Selected GCM-RCM combinations.

Global climate model	**Regional climate model**
CCCma-CanESM2	CLMcom-CCLM4-8-17
ICHEC-EC-EARTH	CLMcom-CCLM4-8-17
ICHEC-EC-EARTH	SMHI-RCA4
IPSL-IPSL-CM5A-MR	SMHI-RCA4
MIROC-MIROC5	CLMcom-CCLM4-8-17
MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17
MPI-M-MPI-ESM-LR	SMHI-RCA4

The selection of these seven combinations (five GCMs, two RCMs) was based on available high resolution RCM model outputs and several project specific criteria. The selection used spans a major part of the range covered by currently existing climate simulations of RCP8.5 (Fig. 4). Other initiatives have used other selections that partly overlap with the project's, e.g. the national climate scenarios and impact assessments for Switzerland (see FOEN, 2021), or the KLIWA cooperation for southern Germany (e.g. Zier et al., 2021), or Nilson et al. (2021) who selected 16 combinations for a climate impact assessment of all major German Rivers (incl. the Rhine).

Bias correction

The use of climate model data to force hydrological models requires a so-called 'bias correction'. This procedure removes offsets in climate variable values that result from climate models' focus on energy balance rather than on water balance and of a less detailed consideration of the land surface than is required for for hydrological simulations or other impact models.

Several univariate and multivariate bias correction methods were tested in the ASG project. To select a bias correction method for the project, the remaining bias and the consistency of the climate change signal from the corrected and uncorrected GCM-RCM outputs were evaluated based on 24 derived climate indices. The chosen bias correction method simultaneously corrected the meteorological input variables for the hydrological models. This multivariate transformation is based on a quantile mapping and was introduced by Cannon (2018). For example, the approach guaranteed the best possible representation of precipitation falling as snow and is therefore important for the representation of snow cover and the subsequent modeling of the snow and ice melt contributions to streamflow (Meyer et al., 2019).

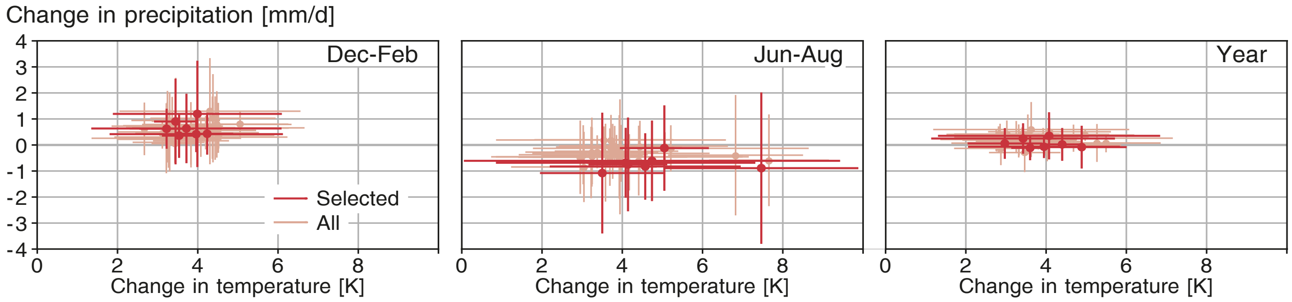
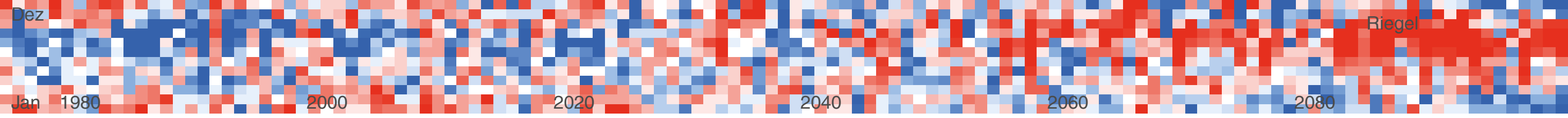


Figure 4: Climatic change over 100 years in the selected ASG project ensemble against all available EURO-CORDEX data at the time of the analysis: mean and range of model combinations for the Rhine basin (2070–2099 vs 1970–1999).



3 Future climate in the Rhine basin

The bias corrected climate simulations of the ASG project ensemble represent a future climate with warmer temperatures in the entire Rhine basin (Fig. 5). Warming is stronger in the winter half year than in the summer half year. The alpine areas of the southern part of the Rhine basin are projected to warm more than the downstream regions in the northern part of the basin.

The scenario presents a climate with drier summers and wetter winters. The drying is somewhat stronger in the western part of the basin and the winter wetting is less pronounced in the Alps than on the Swiss plateau and up- and lowland regions north of Switzerland. But these spatial patterns are weak. All changes become more pronounced in the far future.

Transient time series of the climate variables are displayed in Fig. 6 and Fig. 7. The seven ensemble members agree on the direction of change but show differences in the rate of warming. These differences become larger in the second half of the 21st century and the ensemble range widens. This range of future trajectories of the ensemble members is commonly considered an important aspect of the uncertainty of future climate impact modeling. The climate model simulations represent observed changes during the reference period 1981–2010 well. However, in the decade 2010–2020 observations appear to already have exceeded the temperatures of the RCP8.5 scenario forcing. The dry spring months in the Rhine basin downstream of Basel in the 2010s also appear to be outside the range of the RCP8.5 forcing.

Monthly time series provide more detailed seasonal information. It is notable that temperatures from February to June late in the century are often similar to those one month later in 1981 at the beginning of the time period, e.g. May in 2100 may be like June nowadays (Fig. 7). Precipitation change uncertainty is larger in the Rhine basin upstream of Basel in particular in the summer months with their decreasing trends.

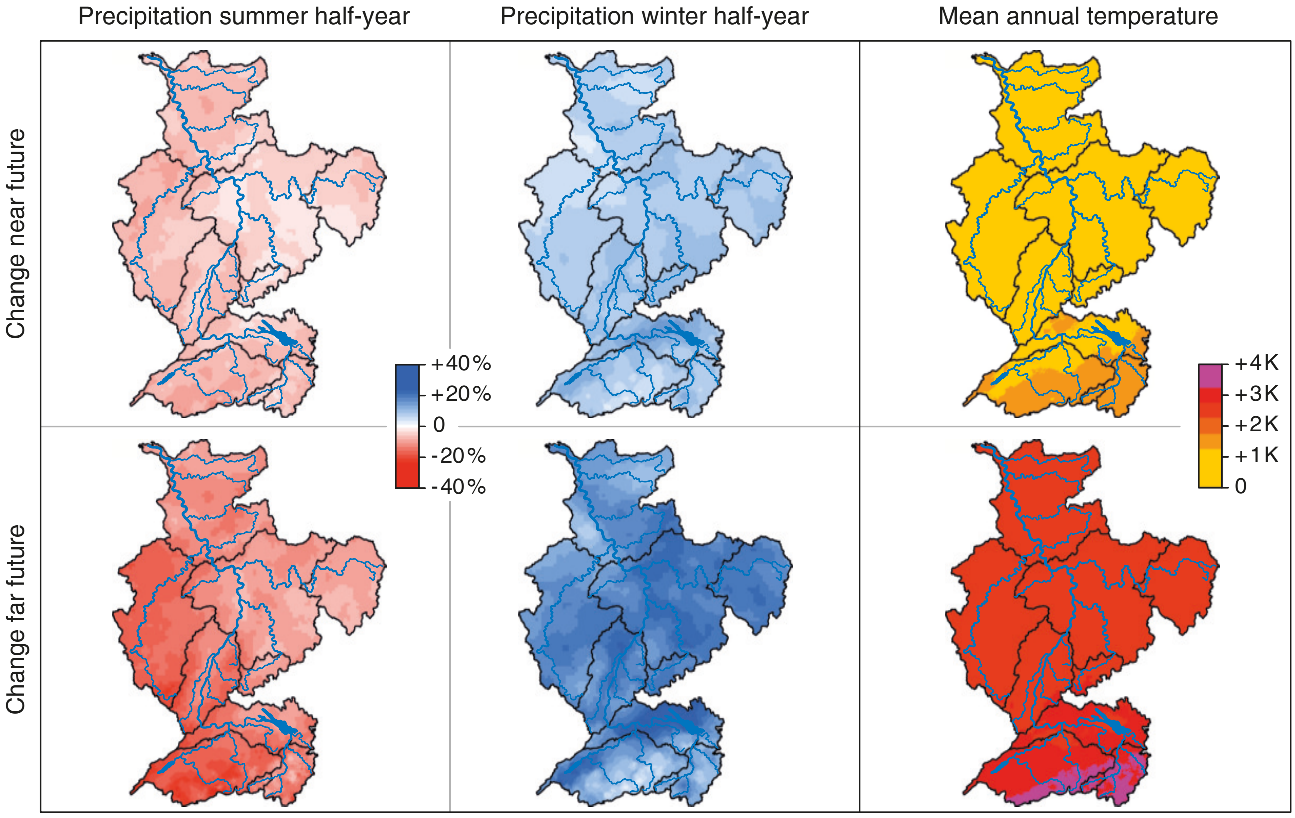
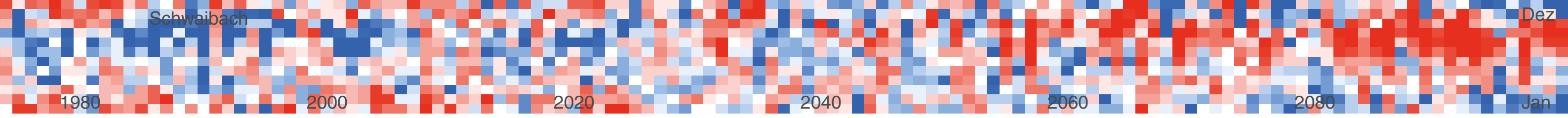


Figure 5: Climatic changes for the ASG ensemble means, i.e. the average change of the bias corrected, spatially interpolated GCM-RCM ensemble members (RCP8.5 scenario). Shown are average changes of the near future (2031–2060) and far future (2071–2100) relative to the reference period (1981–2010). Black lines: Rhine basin and sub basins.



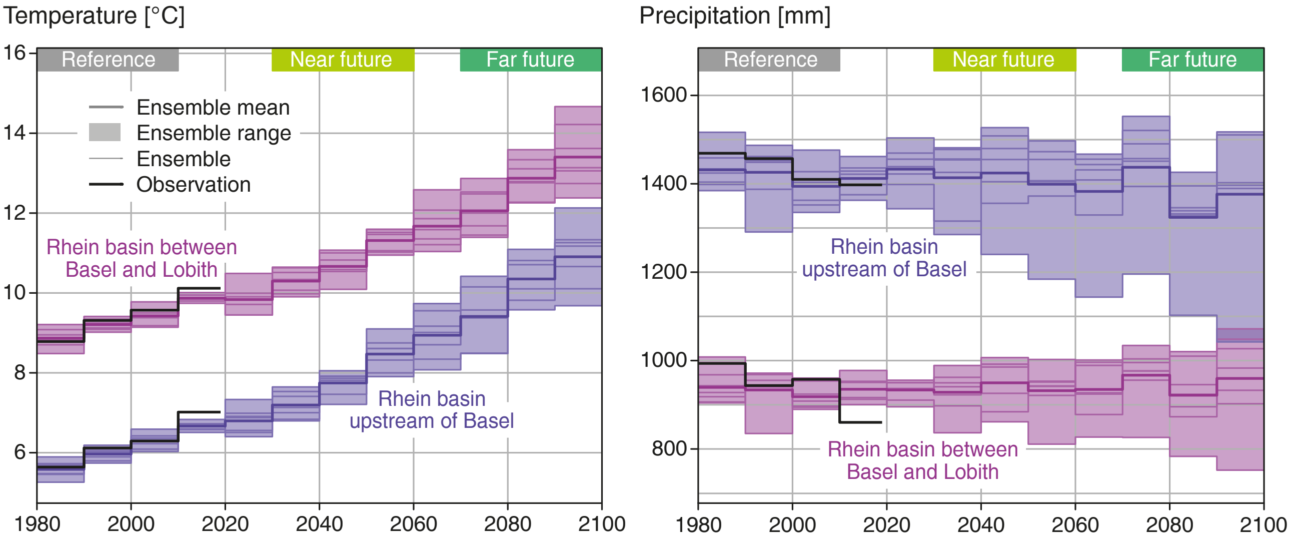


Figure 6: Time series of ten-year averages of mean annual temperature (left) and annual precipitation sum (right) of the ensemble mean (thick line) and the seven ensemble members (thin lines); black lines show the observed climate data until 2019. Shown are grid data averaged in space for the Rhine basin upstream and downstream of the gauge Basel.

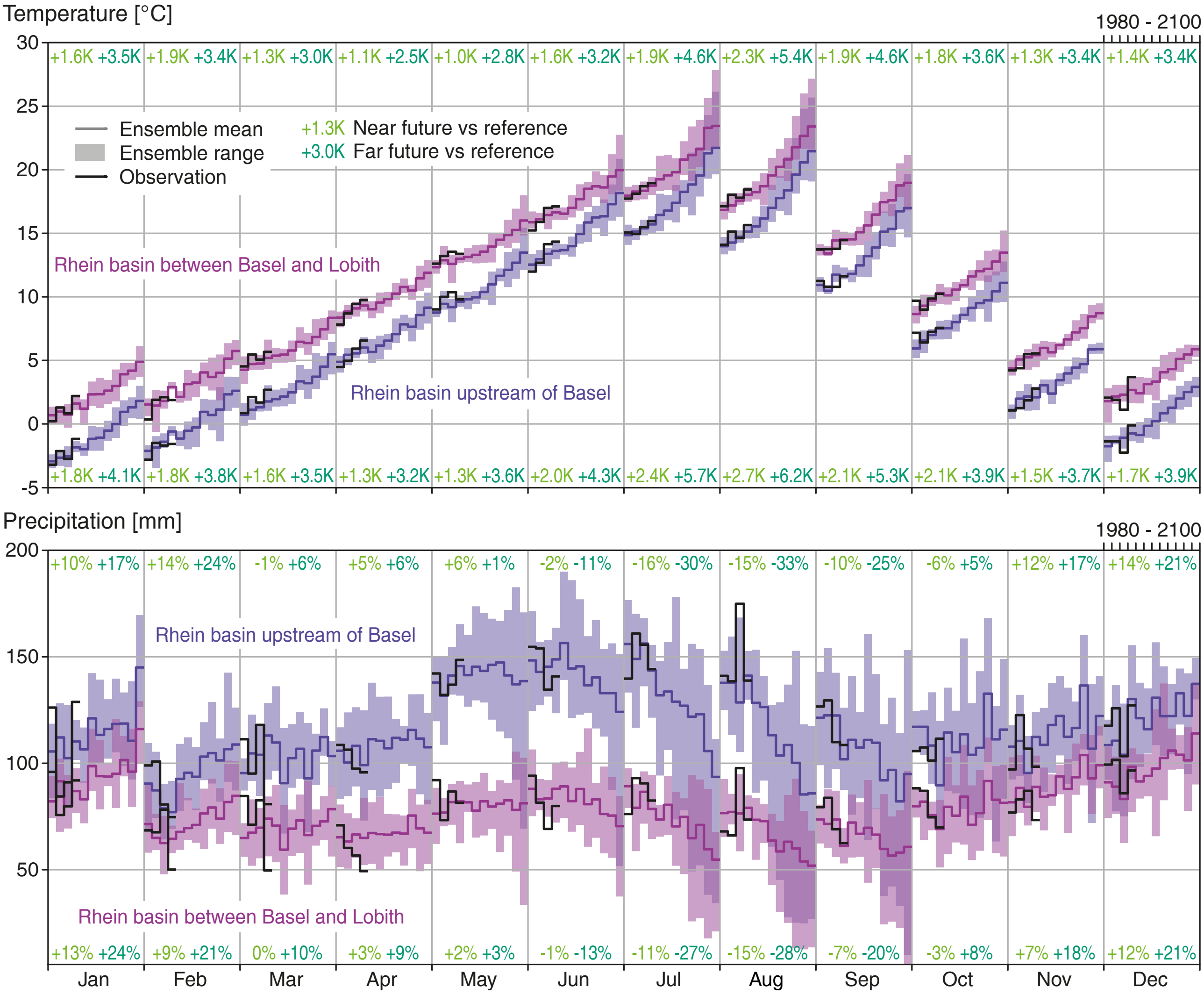


Figure 7: Time series 1981–2100 for each month in each compartment: 10-year averages of mean monthly temperature (upper) and precipitation sum (lower), averaged in space for the Rhine basin upstream of the gauge Basel and for the Rhine basin between gauges Basel and Lobith; black lines show the observed climate data until 2019.