Internationale Kommission für die Hydrologie des Rheingebietes

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Synthesis report

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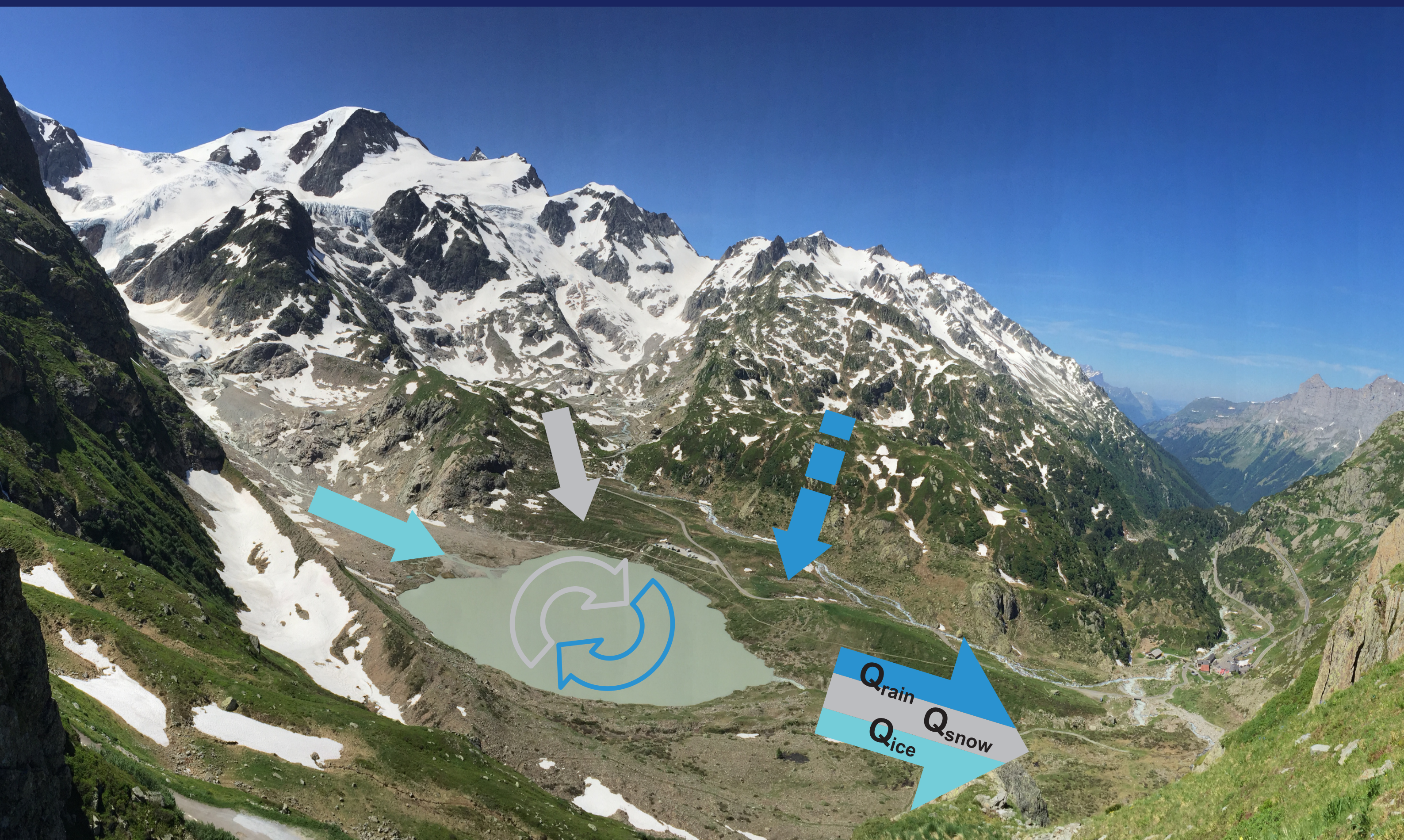

Report No. I-28 of the CHR

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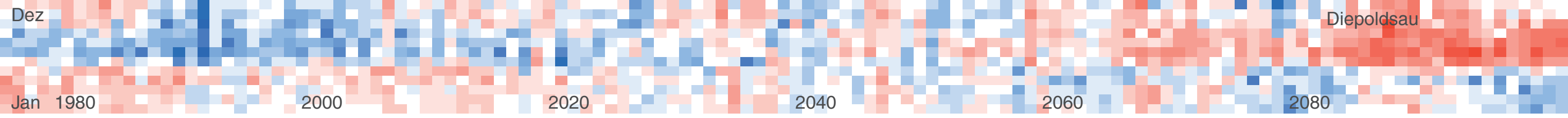

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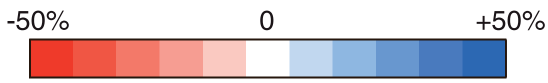
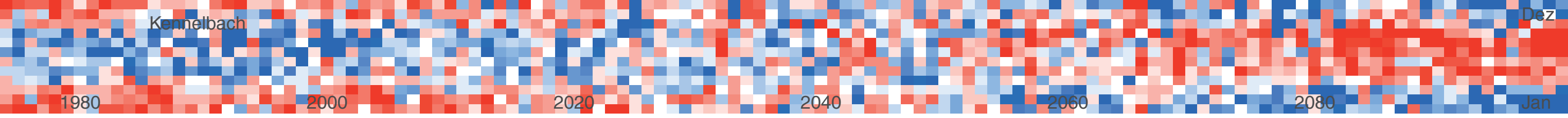
Headers: Anomalies of simulated monthly streamflow from mean monthly flow 1974–2100 (ensemble mean) for selected gauges



Conventions Place names are used in their local versions. German river names are used in maps and figures, but English language text uses Rhine and Moselle.



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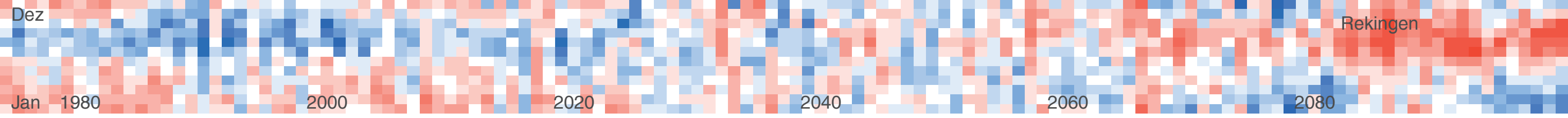
The **HBV-light model** is provided by the University of Zürich (Seibert and Vis, 2012). The **LARSIM models** are maintained by the “LARSIM-developer community” (www.larsim.info). In additon to the software, model files of the LARSIM model were provided: upstream of Basel by the LUBW (Institute for the Environment of the Federal State of Baden-Württemberg) and the agency of the Austrian state of Vorarlberg, for the LARSIM-Rheinmodell downstream of Basel from the Federal Institute of Hydrology (BfG).

External contributions and help by scientists who are not authors of this report, or whose unpublished work cannot be formally referenced, made this work possible. Matthias Huss provided ice thickness datasets that were crucial for model initialisation and calibration. Further observation based datasets were used for the multi-criteria calibration of the model: gridded datasets of snow water equivalent (SWE) time series were provided by the WSL Institute for Snow and Avalanche Research (SLF), MODIS Snow cover products came from MOD10A1 and MYD10A1, Version 6 (Hall and Riggs, 2016) and glacier inventories from Fischer et al. (2014), Maisch et al. (2000), Müller et al. (1976), and Paul et al. (2011). The following colleagues and former students worked on specific aspects of the project: Stefan Fugger was hired to process MODIS data to derive the regional snow line elevations; the Master theses by Judith Meyer, Johanna Geilen, Stefanie Bittner helped various method developments.

In-kind and co-funding contributions are acknowledged from the University of Freiburg, where Jürgen Strub edited every graphic manually and helped with the report’s layout, and from the University of Zürich, where Marc Vis made many changes to the HBV-light model code for the project. The work on the headwater catchments was mainly carried out within the program Hydro-CH2018 (FOEN, 2021) as part of the project ‘Contributions of snow and ice to streamflow of glacierized headwater catchments’ funded by the Swiss Federal Office for the Environment (FOEN).



Preface

The River Rhine originates in the Swiss Alps and flows over a distance of 1,233 km into the North Sea. Its catchment area spans nine countries. Some of the water from the Alps is temporarily stored in alpine reservoirs and flows through large lakes at the edge of the Alps, such as the Lake of Constance and the lakes along the Jura mountains. Below Basel, substantial tributaries join from the upland ranges of Germany and France, such as the Neckar, Main, and Moselle, feeding into the Rhine in the Netherlands. Here, the Rhine branches and, together with the Meuse (Maas), forms a delta.

The Rhine connects important economic regions between the Alps and the North Sea. Around 58 million people live in its basin area. The Rhine's water is used as drinking water, for power generation, for irrigation, for industrial production, and for the transportation of goods. Consequently, it is one of the most intensively-utilized rivers in Europe and one of the busiest waterways in the world. At the same time, it is also an important habitat for wildlife and plants.

The riparian states of the Rhine, via the International Commission for the Hydrology of the Rhine Basin (CHR), jointly develop scientific principles in order to make them available to decision-makers for the sustainable development of the Rhine basin. The Rhine's streamflow stems from rain and, especially in spring and summer, also from snowmelt and glacier ice melt. As a result of global warming, the Alpine glaciers are melting and winter snowpack is progressively declining. What are the consequences of these changes on the streamflow of the Rhine?

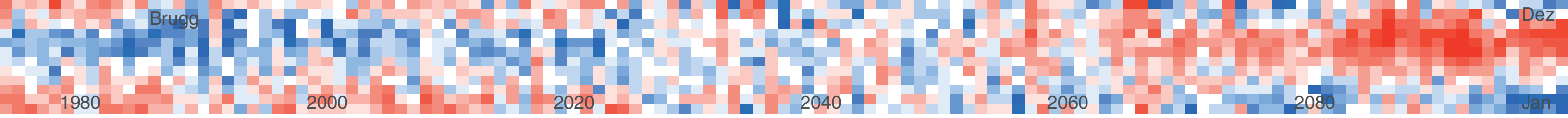
In order to answer this question, the CHR launched the project: "Abflussanteile aus Schnee- und Gletscherschmelze im Rhein und seinen Zuflüssen (ASG)" ("The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change"). It examined how the streamflow components of the Rhine have changed, as well as how they will change in the future, as a result of climate change, retreating glaciers and decreasing snowpacks in the mountains. In the first part of the project, the results of which were published in 2016, the historical changes since 1901 were analyzed. In the second part, which is presented here, the time series of the streamflow components are extended until 2020 and future scenarios are projected.

The results show that major changes in the streamflow of the Rhine are expected to continue and that low flow situations, in particular, will occur more frequently. Therefore, sustainable adaptation to climate change is necessary to secure our activities in the river Rhine and its basin, but also to protect livelihoods in its riparian countries. The hydrological information and knowledge acquired in the project is an important basis for this. However, it is equally important to practice climate protection measures to reduce emissions of greenhouse gases, in order to minimize future changes in the streamflow.

The Commission for the Hydrology of the Rhine Basin would like to thank the scientists involved in the project team of the Universities of Freiburg and Zurich as well as HYDRON GmbH and the steering group accompanying the project for their work.

Dr. Petra Schmocker-Fackel

Federal Office for the Environment, Switzerland, Project Manager



Abstract

The streamflow of the river Rhine and its tributaries consists of rain, snowmelt, and glacier ice melt. These components have already changed in the past decades due to global warming. This project quantified the daily fractions of the rain, snowmelt, and glacier ice melt components for a future climate scenario for all tributaries and along the main river Rhine. An ensemble of projections until 2100 suggests wetter winters and drier summers in the future. Hydrological model simulations with this forcing show that the rain component will dominate the seasonal variability of streamflow in the future more than it has in the past. Snow will melt earlier in winter and spring, resulting in less seasonal water storage in the snowpack. Glacier retreat will continue, and despite different rates of retreat of individual glaciers, the joint ice melt component in the main river Rhine is projected to decrease rapidly and almost disappear by the end of the century. Special stress-test model experiments show that the declining melt components will especially affect low flows downstream. At the end of the century, this means that in hot and dry summers comparable to those in 2003 or 2018 buffering ice melt or low flow augmentation will no longer be available. Overall, according to the simulations, streamflow variability and low flow extremes will increase. Despite the uncertainties reflected in the range of downscaled and bias-corrected climate model data, the projected changes are a clear mandate to reconsider water uses and conservation goals along the river.

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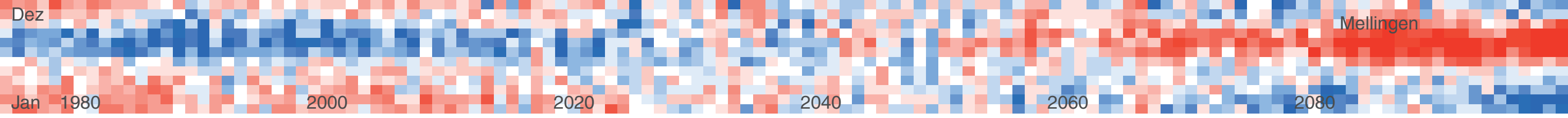


1 Introduction

The river Rhine is one of the largest rivers in Europe. Its water is important for power production, transportation of goods, public water supply, industry, and other water uses. Snow and glacier meltwater feed streamflow in the headwaters and have constituted a characteristic component of the Rhine's streamflow in spring and summer. Rainfall constitutes an important component of the streamflow in the autumn and winter along the course of the entire river, down to the North Sea (Fig. 1). However, progressive global warming has already changed the snow and ice melt components of the Rhine's hydrological regime (Belz et al., 2007; Görgen et al., 2010).

The first phase of the ASG-project "The snow and glacier melt components of streamflow of the river Rhine and its tributaries considering the influence of climate change" (Stahl et al., 2016; 2017) quantified and analyzed the streamflow components from rain, snowmelt, and ice melt from 1901–2006. Model simulations of those components at daily resolution allowed new insights into the roles of snow and ice melt components for low flow events along the river.

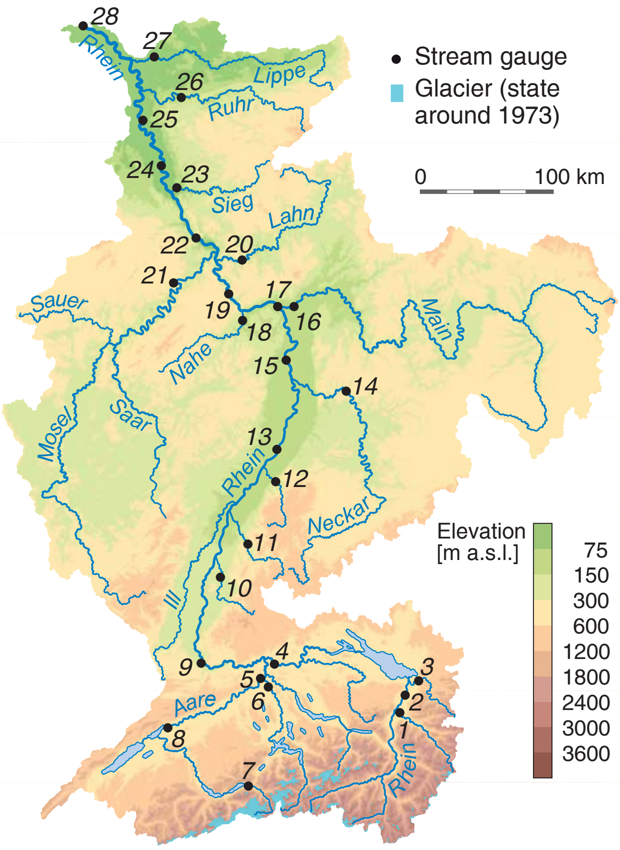


Figure 1: Rhine river basin with important tributaries and gauging stations. Names of stations see Fig. 3.

The model simulation results for the time period 1901–2006 showed that snowmelt so far has been a considerable component of the total streamflow year-round in the Rhine. Ice melt has played a major role primarily in the Alpine tributaries. Despite a considerable retreat of the glaciers, it was maintained by increased local melt rates over the last century due to warming temperatures. In summer and autumn, the lower reaches of the Rhine benefitted from this. When warm and dry weather led to extreme low flow situations, ice melt provided a substantial fraction of streamflow, accounting for up to one fifth of the simulated monthly flow in the lower Rhine (at Lobith during the historic low flow event of 1947). As a result of glacier retreat, this potential of the ice melt to sustain low flows has already diminished.

Glaciers in the headwaters will continue to retreat and will eventually disappear (e.g. Zekollari et al., 2019). Their meltwater contribution to streamflow will then also diminish. Snowpacks and the amount and timing of the melt component will also change with increasing temperatures (e.g. Vorkauf et al., 2021). Both of these changes may exacerbate low flow situations. A key question is whether projected regional increases in winter precipitation can compensate for the expected changes in melt components in the future. In the second phase of the project, the simulations were extended and the effects of future climatic changes on the streamflow in terms of its components, hydrological regimes, and extremes were investigated (Fig. 2).

Models and tools from the first project phase were used for scenario experiments. The primary objective was to investigate how streamflow in the Rhine will change in response to future climate projections focusing on the roles of the different streamflow components from rain, snowmelt, and ice melt during different seasons and in different sections of the river. As in the first project phase, analyses and considerations targeted the particular relevance of the modeling outcomes for low flow conditions. Some examples of possible changes that are relevant to water use restrictions are presented at the end of the report.

2 Methods

2.1 Modeling streamflow components

Effects of climatic changes can be estimated by forcing hydrological models with future climate model projections (scenarios) (pg. 9). Figure 2 shows how such "climate impact modeling" experiments were implemented within the ASG project to simulate future streamflow components of the river Rhine.

Initially, climate model data were bias-corrected to meteorological data at station-locations. An interpolation across the Rhine basin then created the input for the hydrological models. Important criteria for the project were a realistic representation of the precipitation falling as snow, the initialization of the future scenario simulations with the most realistic glacier extents, and the execution of transient simulations that adapt glacier volume and area over time.

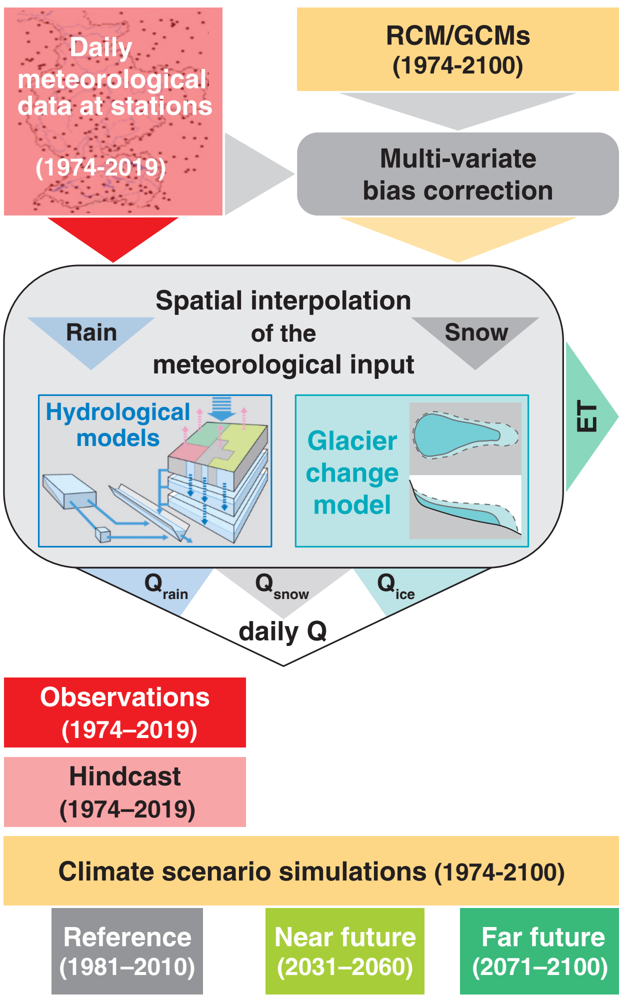


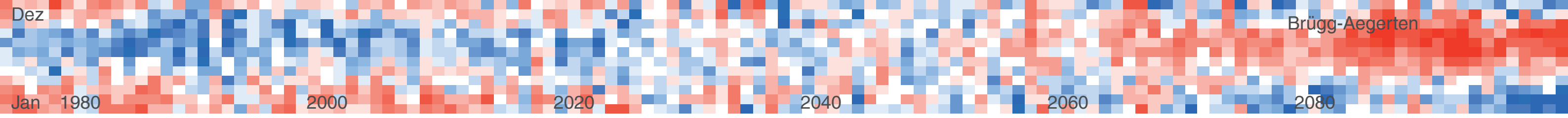
Figure 2: Schematic of the modeling approach.

A prerequisite for such model experiments are well-validated models for historical periods. The ASG project used the models developed and thoroughly tested in the first project phase (Stahl et al., 2017) and supplemented in the Hydro-CH2018 project (Freudiger et al., 2020). The model environment aims specifically at streamflow components from a long-term perspective on the scale of the entire Rhine basin.

The conceptual hydrological HBV-Light model (Seibert and Vis, 2012; Seibert et al., 2018) simulated all glacierized headwater catchments. This semi-distributed conceptual hydrological model includes a snow and glacier routine and also estimates the future glacier changes. The water balance model LARSIM simulated the remaining parts of the Rhine basin with a resolution of 1x1km² upstream of Basel and 5x5km² downstream of Basel. The model also considers reservoir storage in the Alps and in the central European mountain ranges as well as lake regulations based on how they are currently operating.

A mixing tank model-extension developed in the first phase of the ASG-Rhine project tracks the rainfall component of streamflow (Q_{rain}), the snowmelt component of streamflow (Q_{snow}), and the glacier ice melt component of streamflow (Q_{ice}) from their respective runoff generation through runoff concentration in the subcatchments, through lakes and along the tributaries and in the main river (Weiler et al., 2018). This function allows the analysis of the three components throughout the past and into the future.

Model runs driven with historical meteorological observations provided the opportunity to evaluate the models' performance for a "hindcast period". Hindcasts demonstrate models' ability to correctly capture streamflow variability compared to streamflow observations in response to real historical meteorological sequences. Climate scenario driven simulations, however, are only statistical representations of the climate over a longer time period. This report summarizes some important streamflow statistics and streamflow component characteristics and their changes from the transient runs for specific periods: a near-future period and a far-future period, and a reference period in the past for comparison (Figure 2).



2.2 Evaluating hydrological model performance

A good model performance for the past promotes confidence in the simulation results. The HBV model for the glacierized headwaters was calibrated in order to assure that the initial conditions for the future scenario simulations were as realistic as possible. The calibration procedure used daily maps of snowpack and satellite sensed snow cover area, glacier ice volume estimates as well as streamflow time series to calibrate model parameters for best possible performance. The LARSIM models, versions of which are used as operational hydrological models, were not recalibrated for this project.

Model skill varies across the Rhine basin. Four performance measures, comparing modeled streamflow to the gauged observations at different stations, show these differences for part of the hindcast period (Fig. 3). The glacierized headwater catchments were generally simulated best due to the specific calibration. A few large tributary rivers were simulated least well. Examples are the Austrian river Ill at Gisingen or the river Main at Raunheim, both of which are highly regulated, including inter-basin water transfers. Previous studies were able to achieve better simulations for these rivers and for the Rhine below their confluences through the use of water balance correction factors. However, here, such adjustments were not used, as the aim was to study exclusively the hydrological response to glacier retreat and climatic change and to apply as little other adjustments as possible otherwise.

The simulated future hydrology is generally in line with other studies for the Rhine with regard to general trends and uncertainty ranges of future scenario projections. Yet, it provides additional details about the streamflow components to help explain these trends.

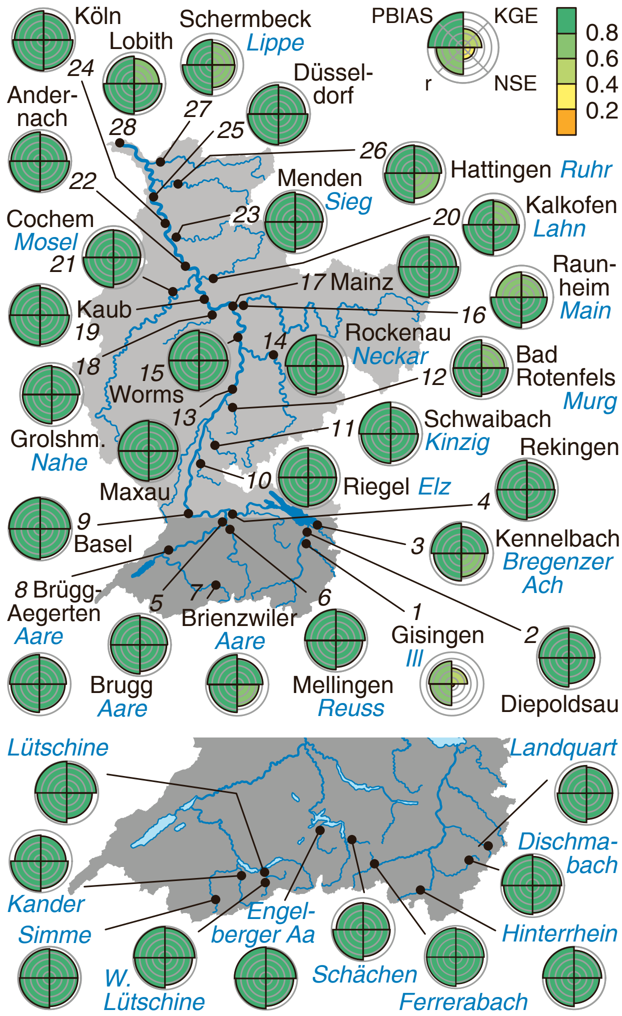
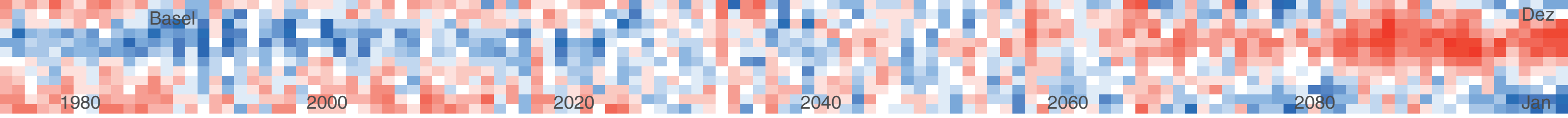


Figure 3: Model performance measures for streamflow in the period 1981–2010 at selected gauges: Kling-Gupta-Model efficiency (KGE) for overall performance, Nash-Sutcliffe efficiency of the logarithm of streamflow (NSE) for low flow representation, correlation coefficient (r) for agreement of relative variations, and a normalized bias measure (PBIAS) for overall deviation.

Measuring model performance and model uncertainty for future projections

Hydrological models can only be validated for the past. When assessing future projections, the fact that conceptualizations of hydrological processes in the models contain empirically derived or calibrated parameterizations, must be taken into account. In this frequently used modeling approach, the assumption is that these will remain constant in the future. Limitations include landcover change, for example: in this study only glacier retreat was taken into account, but not changes in vegetation. Also, storage and outflow rules from lakes and reservoirs, as well as other regulations were kept constant in addition to the general model parameters. The uncertainty stemming from the model parameterization was studied as part of the headwater model calibration and regionalization of model parameters to ungauged catchments (Freudiger et al. 2020; Van Tiel et al., 2022), e.g. to assess glacier melt-out dates (see pg. 13) among other aspects. Large uncertainty, however, also propagates from the climate models into the hydrological models (see box on pg. 12).



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).

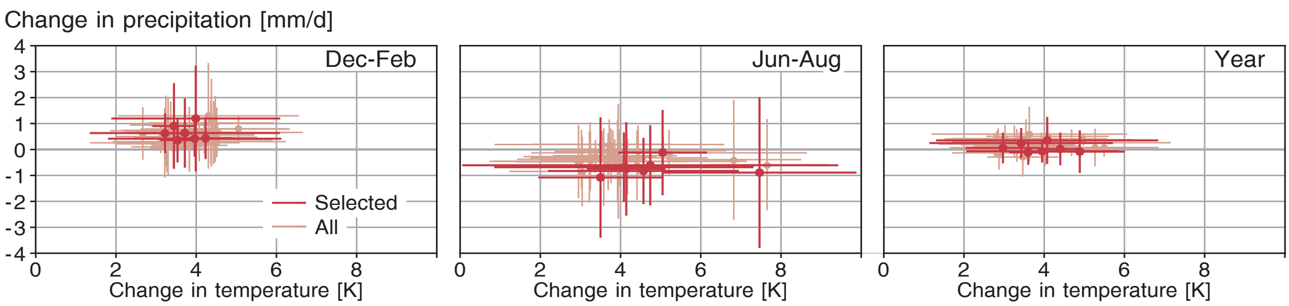
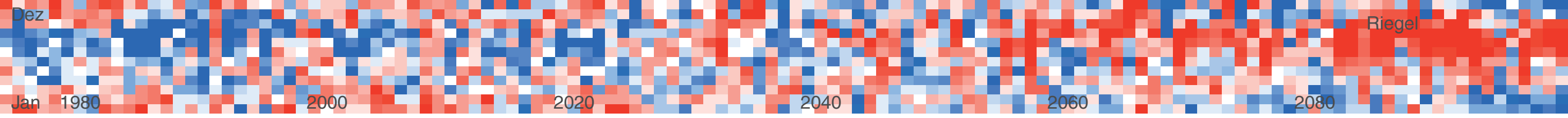


Figure 4: Climatic change over 100 years in the selected ASG project ensemble against all available EURO-CORDEX data at the time of the analysis: mean and range of model combinations for the Rhine basin (2070–2099 vs 1970–1999).



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.

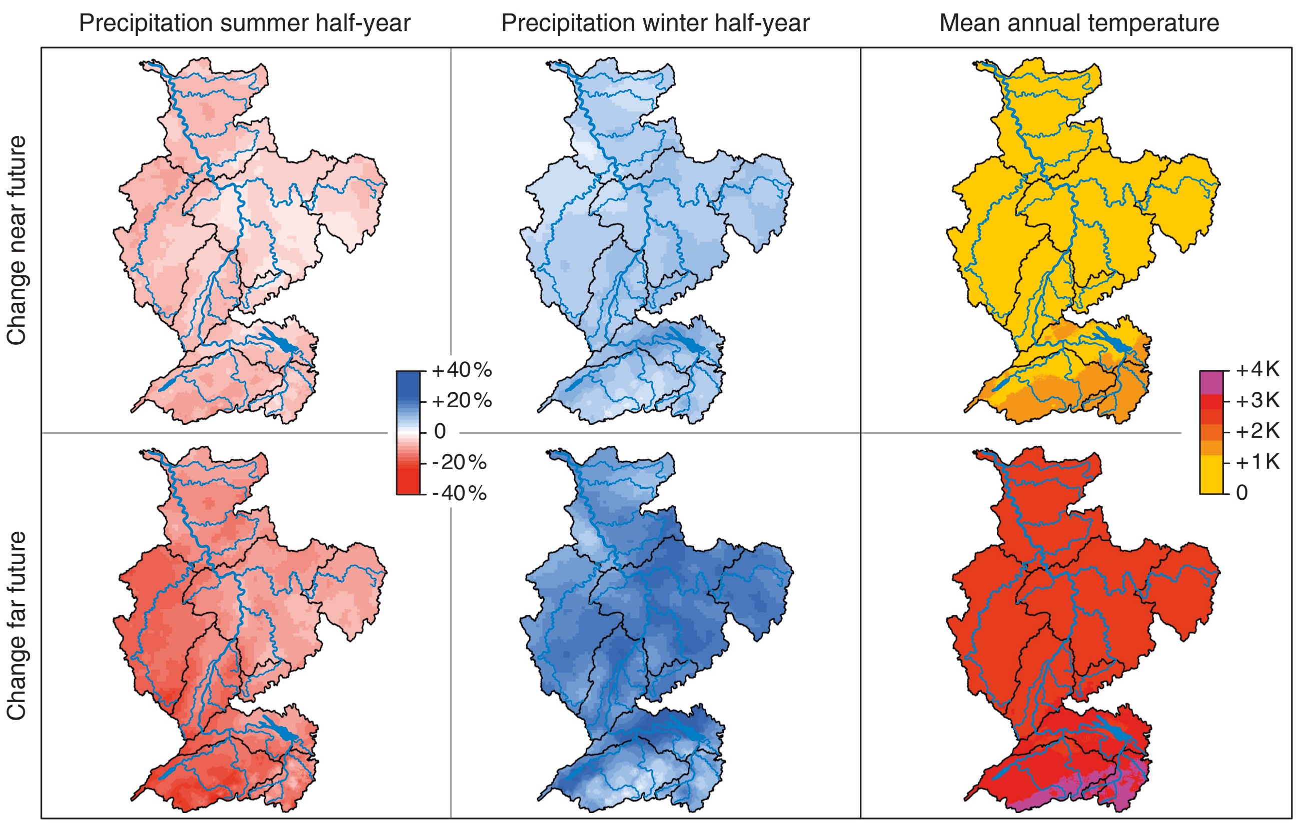
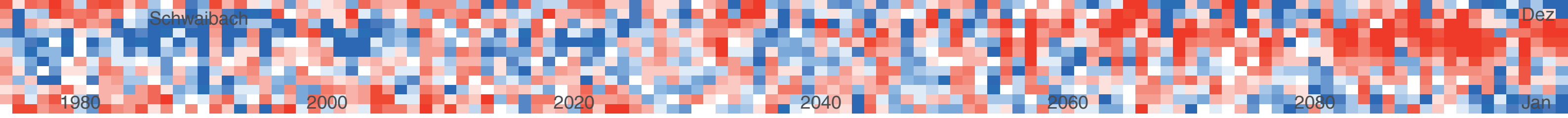


Figure 5: Climatic changes for the ASG ensemble means, i.e. the average change of the bias corrected, spatially interpolated GCM-RCM ensemble members (RCP8.5 scenario). Shown are average changes of the near future (2031–2060) and far future (2071–2100) relative to the reference period (1981–2010). Black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



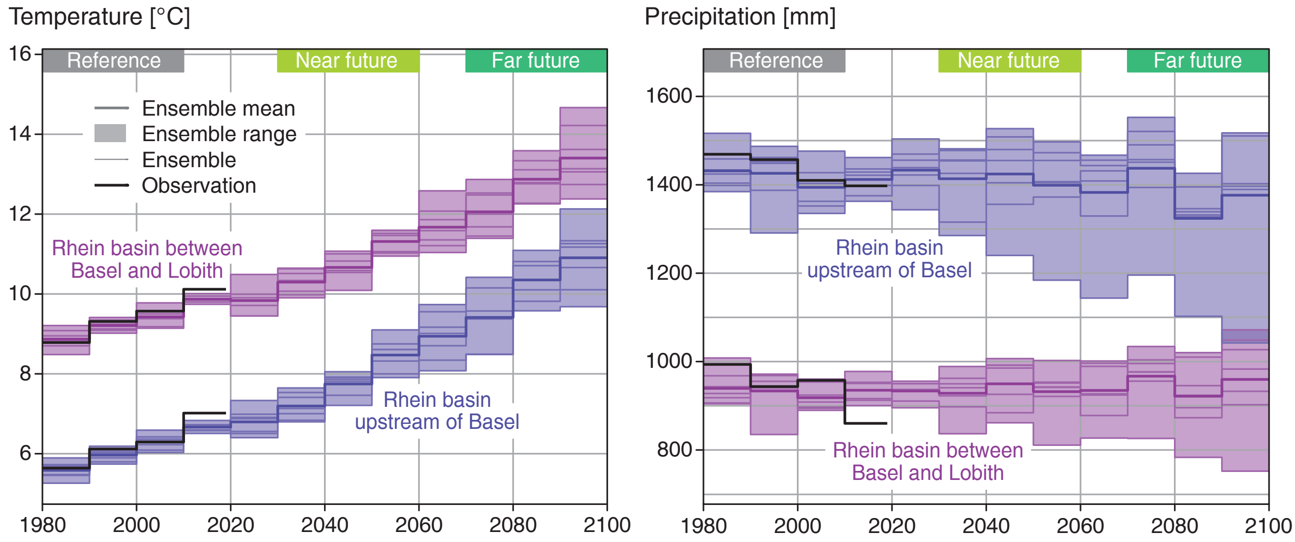


Figure 6: Time series of ten-year averages of mean annual temperature (left) and annual precipitation sum (right) of the ensemble mean (thick line) and the seven ensemble members (thin lines); black lines show the observed climate data until 2019. Shown are grid data averaged in space for the Rhine basin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

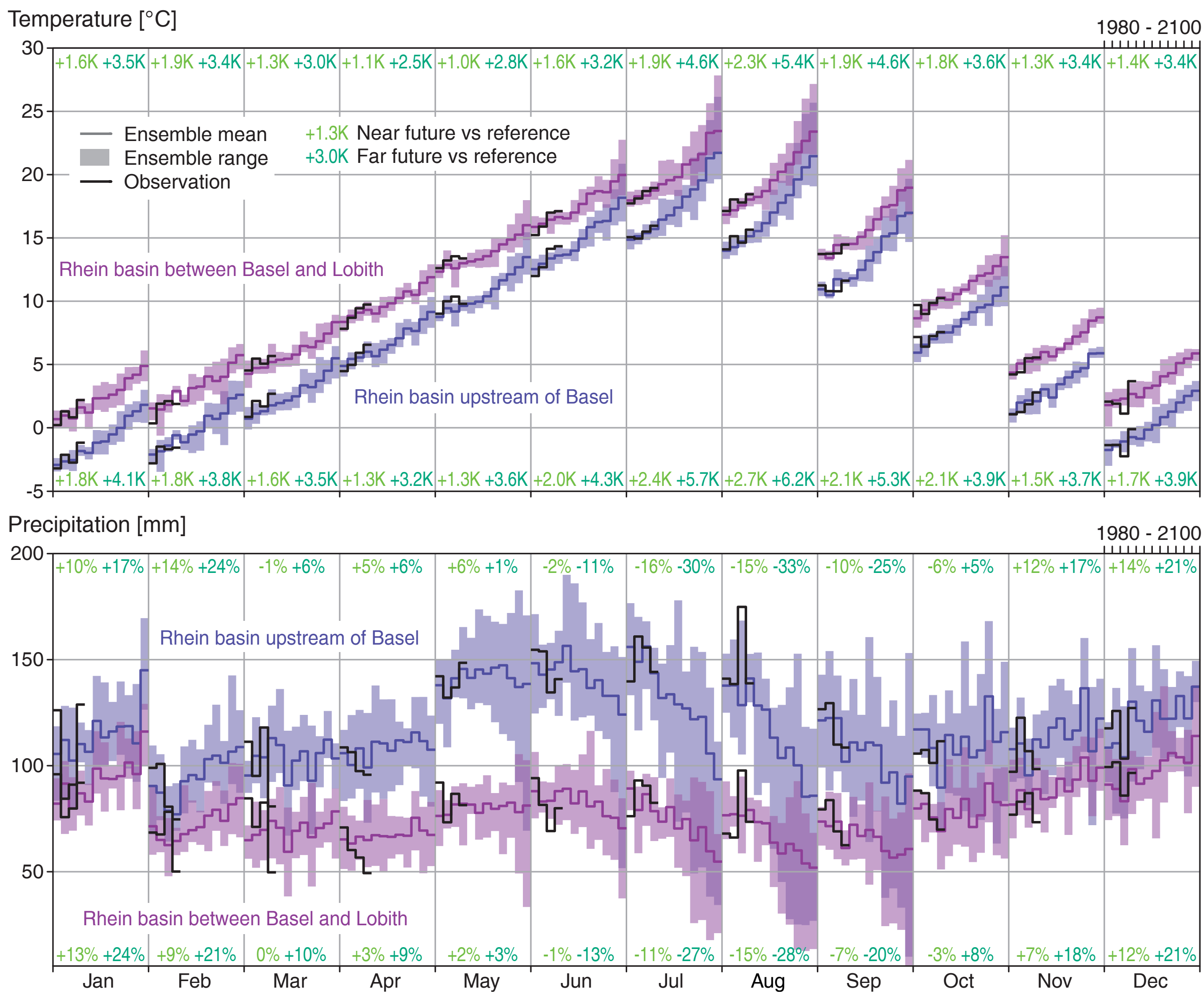
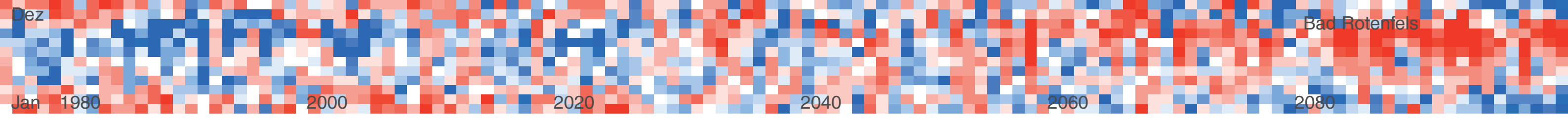
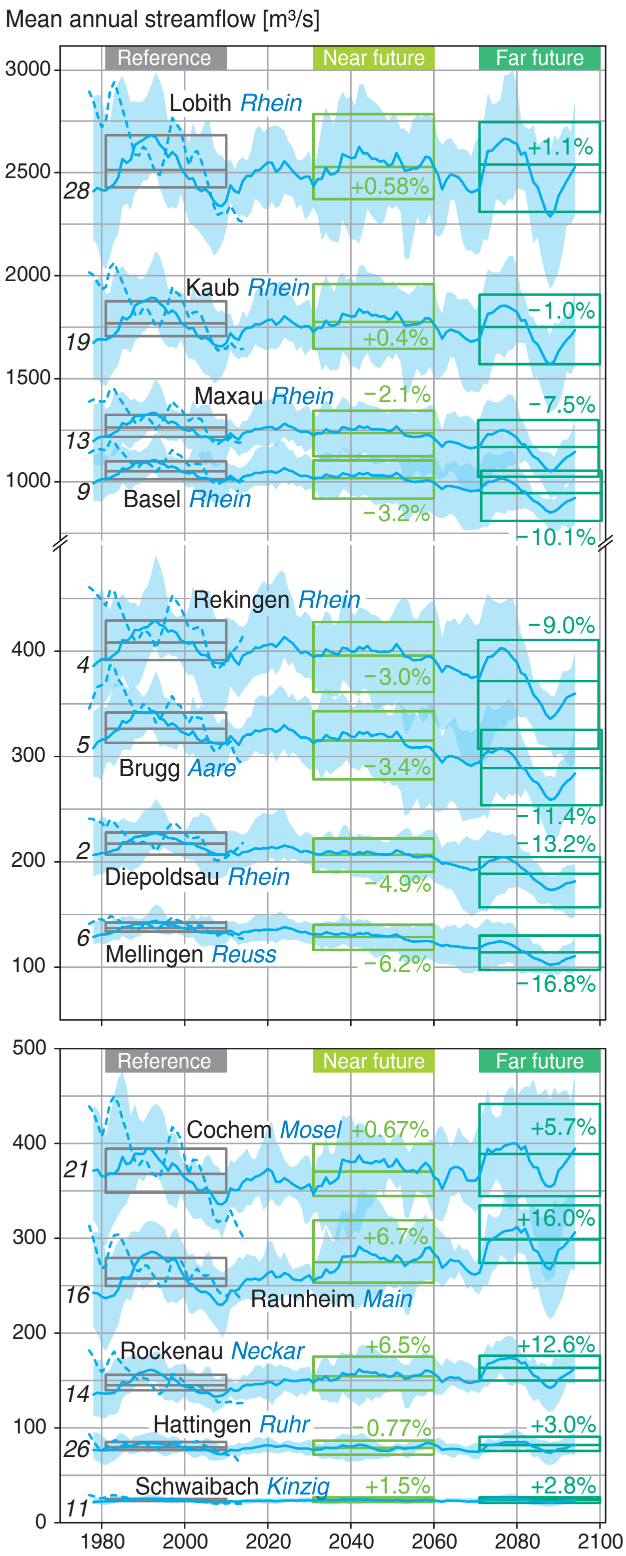


Figure 7: Time series 1981–2100 for each month in each compartment: 10-year averages of mean monthly temperature (upper) and precipitation sum (lower), averaged in space for the Rhine basin upstream of the gauge Basel and for the Rhine basin between gauges Basel and Lobith; black lines show the observed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



4 Future evolution of streamflow

4.1 Mean annual streamflow



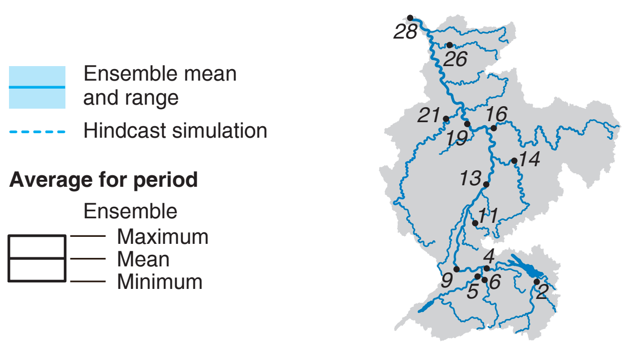
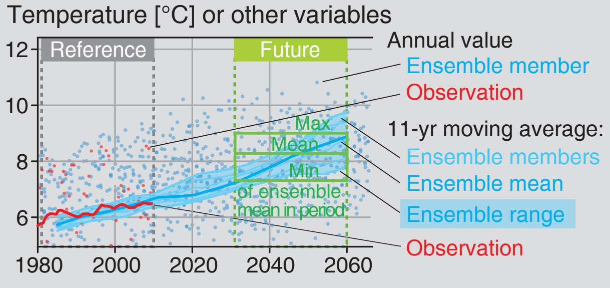


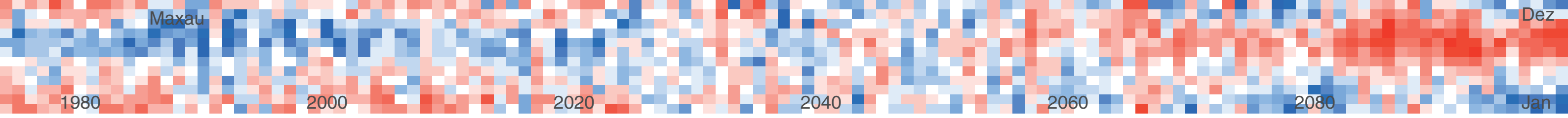
Figure 8: 11-year moving averages of hindcast and climate scenario simulations of mean annual streamflow including mean changes for future periods at different gauges in the main river and in selected tributaries.

The simulated changes in annual streamflow (Fig. 8) show some long-term modes of variability. Overall, the decreasing streamflow in the alpine tributaries (e.g. Reuss, Aare, Rhine at Diepoldsau, Rekingen, and Basel) reflects the changes in precipitation. The northern tributaries (e.g. Neckar, Main, Moselle) reflect the increasing precipitation of the climate scenario. In the main river Rhine, changes in the ensemble mean of streamflow appear to balance out (Rhine at Maxau, Kaub, and Lobith). The lower end of the range of the ensemble, however, suggests a decreasing future mean flow.

The pattern of wet and dry periods in the climate model reference period clearly differs from the real temporal sequence in the hindcast. This is to be expected because climate models only provide a possible representation of the given years. Where hydrological processes have a multi-year memory, for example, due to catchment storage changes, including glacier changes, differences in the hydrological simulations are also to be expected.

Visualizing uncertainty from the climate ensemble





4.2 The ice melt component Q_{ice}

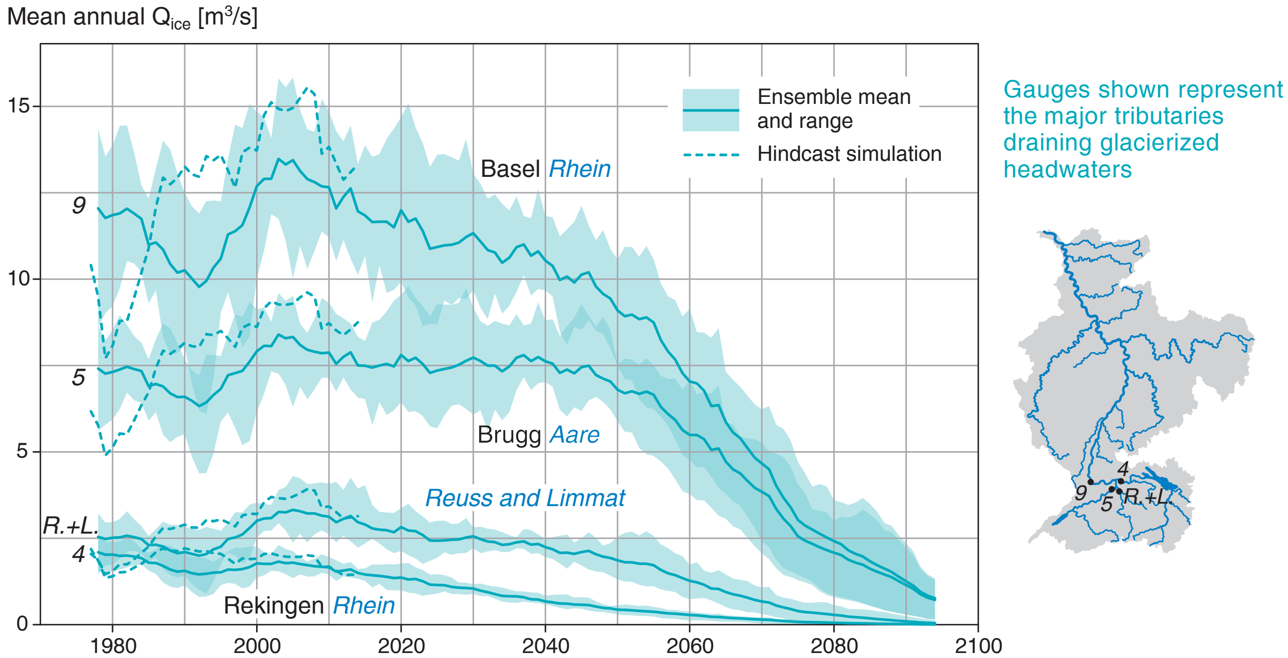


Figure 9: 11-year moving averages of hindcast and climate scenario simulations of mean annual Q_{ice} at different tributaries.

Q_{ice} from the glacierized headwaters will decrease (Fig. 9). For the Rhine and the tributaries Reuss and Limmat (R.+L.) this simulated decline already started at the end of the reference period. A consistent Q_{ice} contribution until 2040 is simulated for the Aare river. The headwaters of the Aare river have the largest glaciers and will continue to contribute Q_{ice} longer than other tributaries. Overall, results show that Q_{ice} in the Rhine at Basel has passed its peak - also known as "glacier peak water". The scenario reference period has a relatively cold period in the 1990s, while in reality the late 1970s–early1980s were cool and generated low Q_{ice} in the beginning of the hindcast period.

Results explained

The glaciers have already retreated and, according to the simulations, until 2050 they will loose about half of their volume and area (Fig. 10). The models were calibrated to observation-based ice volume estimates. The corresponding glacier area is slightly overestimated but shows the retreat, with a spread in the ensemble. At the scale of individual headwater catchments this uncertainty is also notable in the variation of the year of glacier disappearance. Larger glaciers melt out at a later date, but their disappearance varies by up to 20 years depending on the ensemble member. This also leads to a difference in the Q_{ice} estimates.

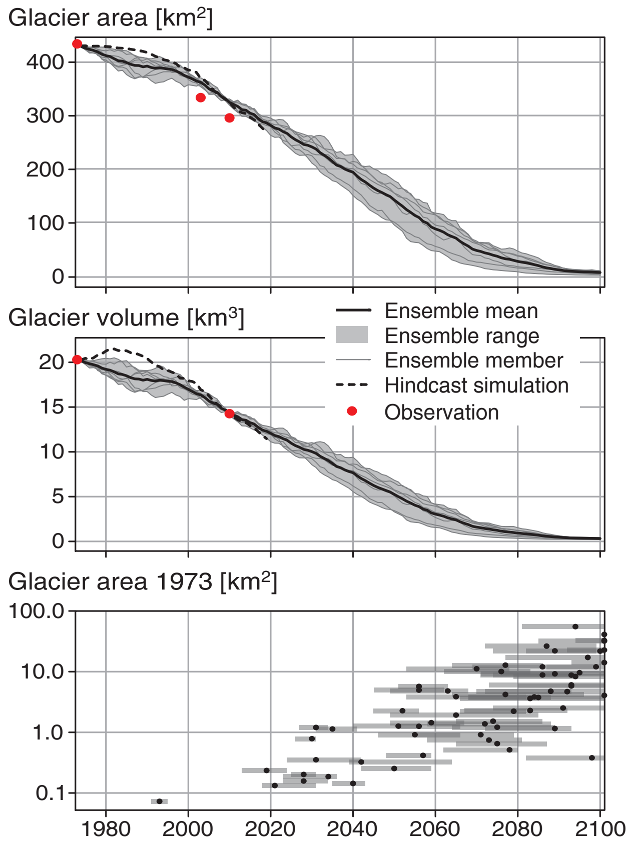
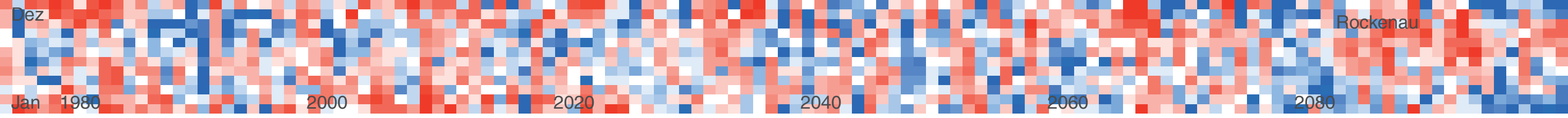


Figure 10: Modeled glacier change in the headwater catchments: total glacier area (upper) and total glacier volume of all catchments of the Rhine Basin (middle). Year of glacier disappearance in individual headwater catchments sorted by their initial glacier area in 1973 (lower).



4.3 The snowmelt component Q_{snow}

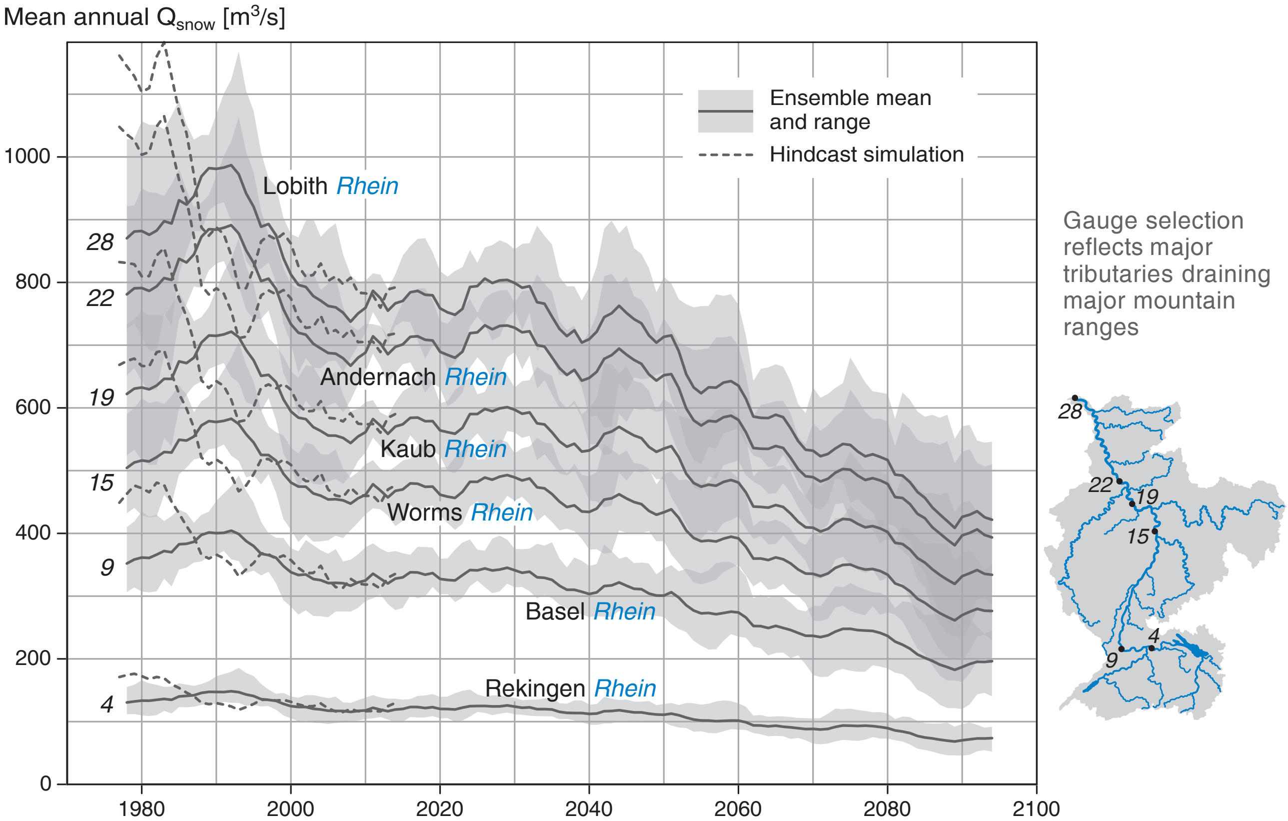


Figure 11: 11-year moving averages of hindcast and climate scenario simulations of mean annual Q_{snow} at different gauges.

Results explained

Q_{snow} will decrease in all tributaries and in the main river Rhine (Fig. 11). At Lobith, the simulated Q_{snow} decreases from 800–900 m³/s to about half by 2100. A decrease was already simulated during the reference period. This decrease is followed by only a small additional change until about 2030, followed by an increased decline. At the beginning of the simulation period, about half of Q_{snow} comes from the central European uplands north of Basel. While the absolute changes are large, various regions will continue to contribute Q_{snow} in the future. As a result of higher winter temperatures, less snowpack will be available to generate meltwater (Fig. 12). Areas with seasaonal snowpacks will decrease in the Alps. Snowfall will still occur in the central European upland regions ("Mittelgebirge") but towards the end of the century there will be no substantial accumulation of snow anymore in those regions.

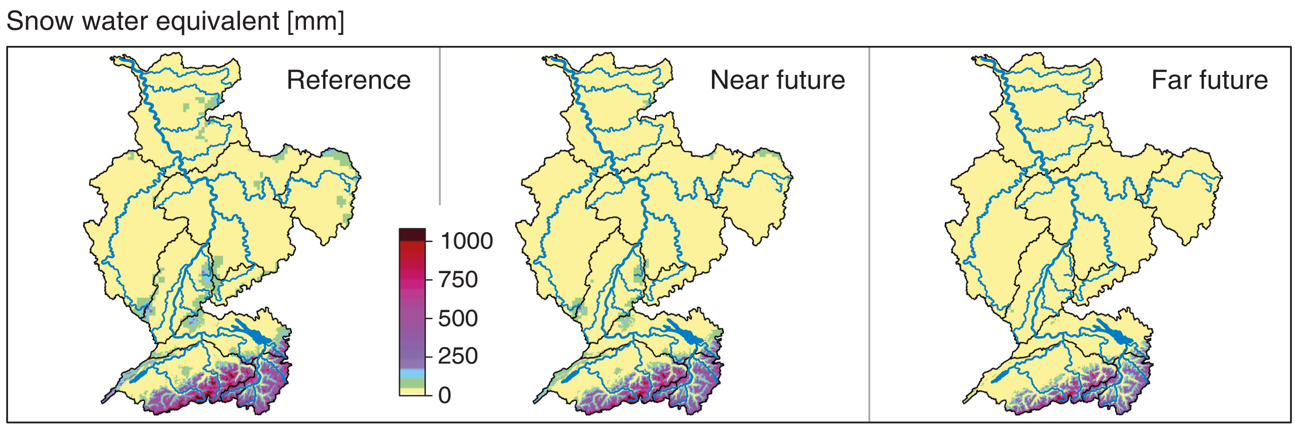


Figure 12: Ensemble mean of the maximum monthly snow water equivalent (SWE in mm) in the reference period, near future, and far future. Values can be seen as a proxy for annual meltwater generation potential. Black lines: as Fig. 5.

4.4 The rain component Q_{rain}

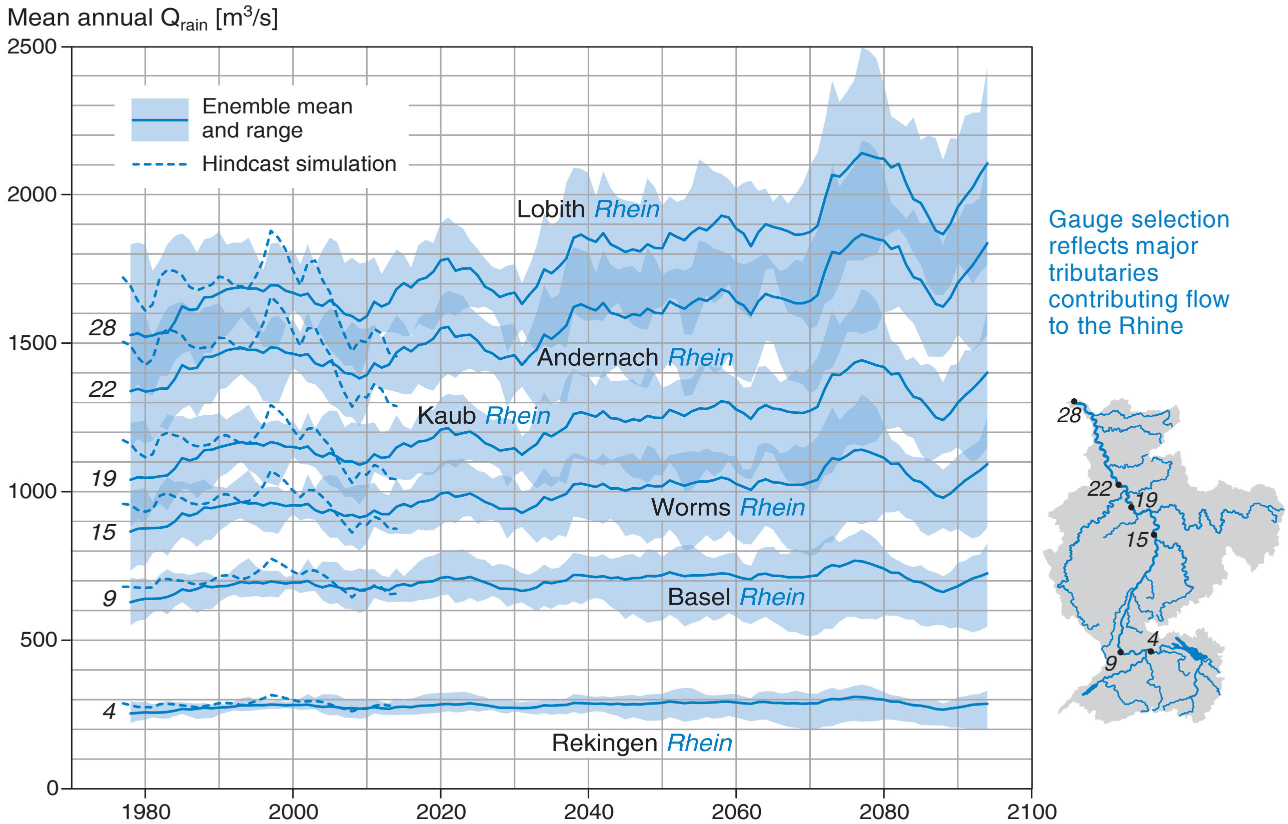


Figure 13: 11-year moving averages of hindcast and climate scenario simulations of mean annual Q_{rain} at different gauges.

Results explained

Q_{rain} will increase in a warmer future (Fig. 13), in contrast to the melt components. This increase becomes stronger later in the century and larger in the downstream reaches. In the Rhine at Basel and Rekingen, changes in Q_{rain} are small with a decrease in the lower ensemble range. Maps of precipitation changes (Fig. 14) show the reason. The climate scenario simulations project different changes in the Rhine basin at the annual scale. In large parts of the Rhine basin upstream of Basel the annual precipitation sum decreases, because the decrease in summer is not compensated by the increasing precipitation in winter. Downstream of Basel the annual precipitation increases as winter precipitation is projected to increase more than summer precipitation decreases.

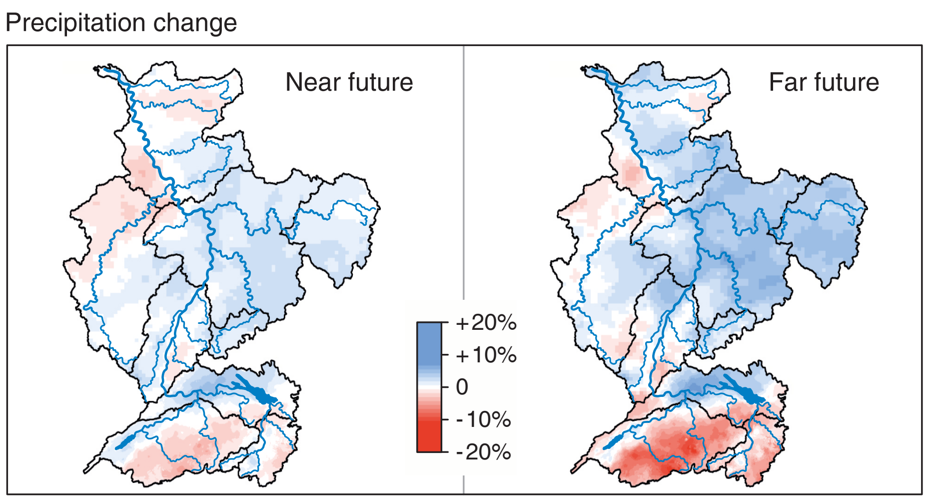


Figure 14: Projected changes in mean annual precipitation in the Rhine basin: ensemble mean changes in the near future (left) and far future (right) relative to the reference period.
Black lines: Rhine basin and sub basins.

5 Changing seasonality of streamflow and its components

The hydrological regime changes along the river Rhine, i.e. the seasonal variation of streamflow (Fig. 15). From the headwaters to the mouth, the regime, changes from a glacier and snowmelt dominated regime with a maximum in late spring and summer (Weisse Lütschine below) to a complex regime with two maxima (Rhine at Maxau) to a rainfall dominated regime in the downstream regions with a maximum in winter (Rhine at Lobith). These contrasting regimes will gradually change in the future (Fig. 15) with the spring-summer maxima in the simulations decreasing and pluvial winter maxima increasing. Downstream low flows decrease and their timing shifts to earlier in the autumn.

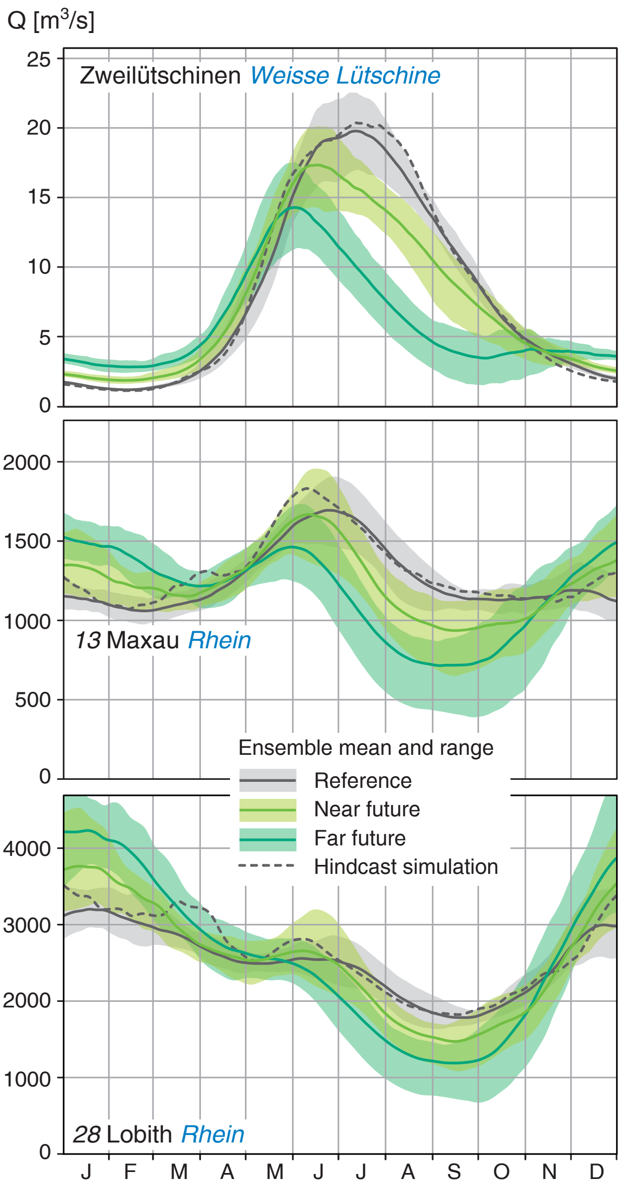


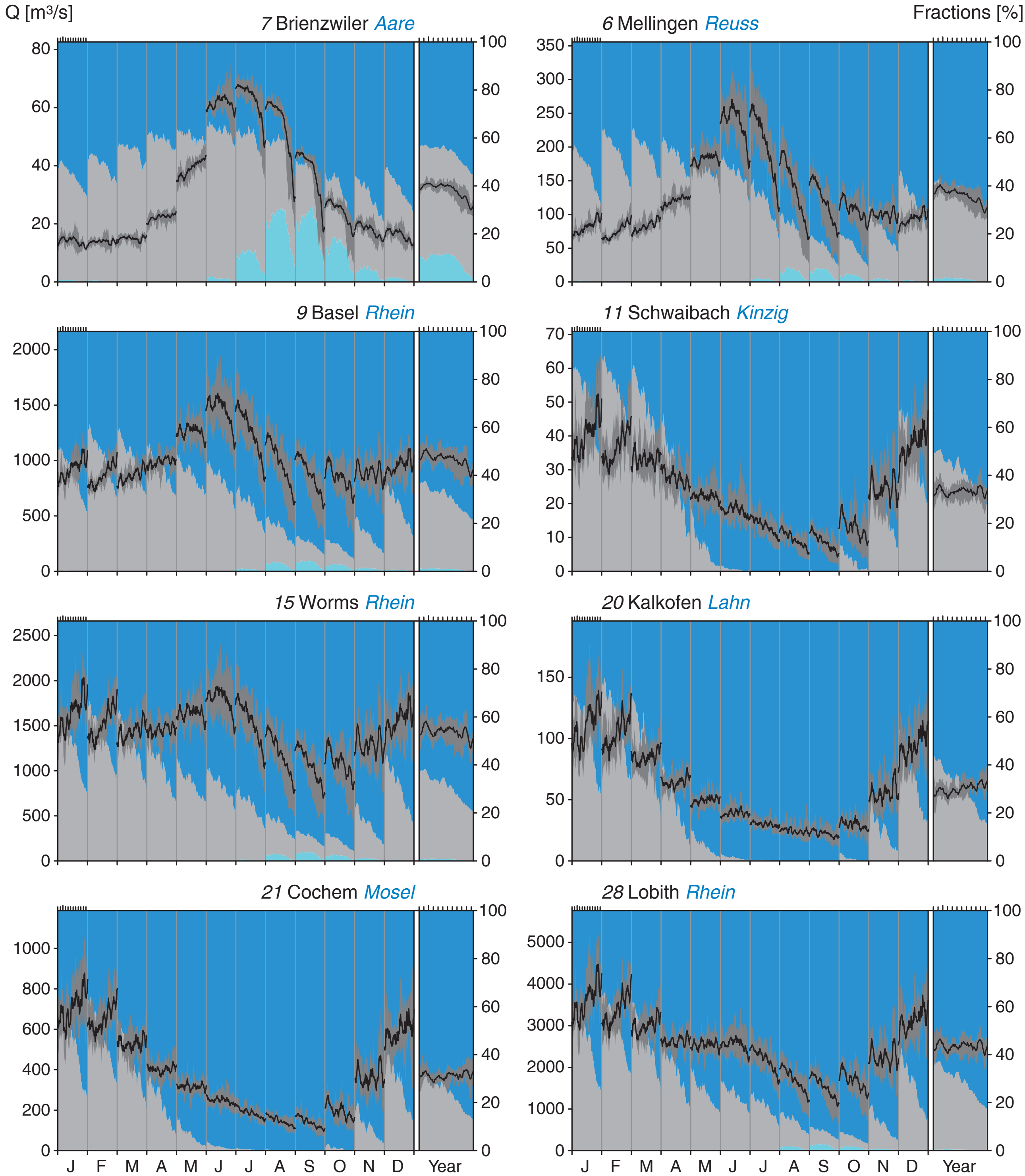
Figure 15: Changing streamflow regimes over time for three gauges in the upstream, midstream and downstream section: 30-day moving average of simulated mean daily streamflow. Location of gauge see Fig.16

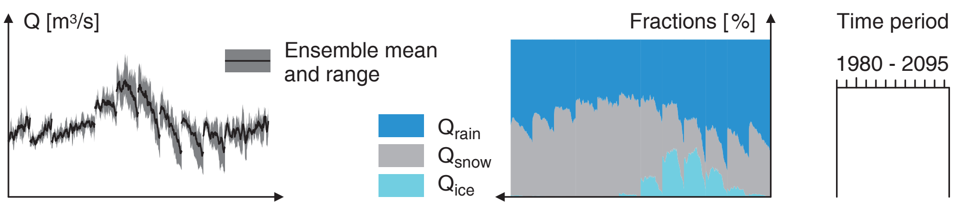
The simulations show different magnitudes of streamflow changes in different seasons at different gauges. Figure 16 on the next page combines a view of regimes (seasonality) with the changes into the future. Overall, decreasing trends dominate the simulated streamflow changes for the summer months at all gauges. The alpine tributaries' snow and ice melt-dominated regimes (e.g., Aare and Reuss) show the largest changes from May to October, in the season with the highest streamflow. Streamflow decreases from July to September are most notable. Downstream most winter months show increasing streamflow trends.

The components help explain and quantify these changes. The Aare at Brienzwiler for example collects the tributaries from the largest glacierized area in the Rhine basin. Therefore its streamflow contains the largest contribution of Q_{ice} of all gauges presented here. This streamflow component will start to decline strongly in the near future with a mostly local and seasonally relevant effect.

A main component of streamflow affecting a great part of the river network is Q_{snow}. Its future decline has considerable effects from the headwaters to the downstream reaches. As the generated runoff component passes through the modeled hydrological system its effect on total streamflow will be delayed. Snow dominated regimes such as for the Rhine at Basel show strong declining trends in early summer, i.e during and after the time of snowmelt. In Basel, streamflow decreases are simulated from June onwards.

The Rhine tributaries originating from the central European uplands in Germany and France (e.g. Kinzig and Moselle) do not show strong streamflow changes. Although the relative fraction of Q_{snow} also declines considerably, it appears to be mostly compensated by Q_{rain} in winter. For the Rhine in summary, while Q_{snow} and Q_{ice} decline, their net effect on total streamflow (see Fig. 8, pg. 12) is smaller further downstream, due to an increase in Q_{rain} there.





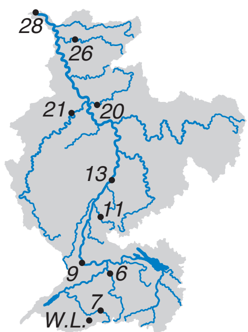


Figure 16: Time series of modeled streamflow and the percentages of its components Q_{rain}, Q_{snow}, and Q_{ice} for each month and year (11-year moving averages from 1980–2095). The component fractions (right axis) represent ensemble means.

6 Changing year-to-year variability of streamflow components

Streamflow components vary from year to year. A comparison of their mean and variability allows a quantification of how much they change in the future compared to the reference period and whether this change is statistically significant (Fig. 17).

In the Alpine tributaries (examples Aare, Reuss, and Alpenrhein), the changes in mean Q_{rain} are small positive and negative. Mean Q_{snow} decreases by up to 14% in the near future and up to 36% in the far future projections (significant for the entire ensemble). Q_{ice} decreases by over 80% in the far future with greatly reduced variability. The changes in the near future differ, with a slight increase of Q_{ice} in the Aare but strong decreases in Reuss and Rhein at Diepoldsau (significant).

The streamflow components of the tributaries from the central European uplands (e.g., the Moselle and the Main) show considerable increases in mean Q_{rain} of up to 50%, with more extreme values, and decreases in mean Q_{snow} of up to 50%, with less extreme values. These changes are significant for about half the ensemble members for the near future, and for all members for the far future.

For the main river Rhine, this same pattern intensifies from Basel downstream, also with significant results for half, or for all, ensemble members respectively, in the near and far future.

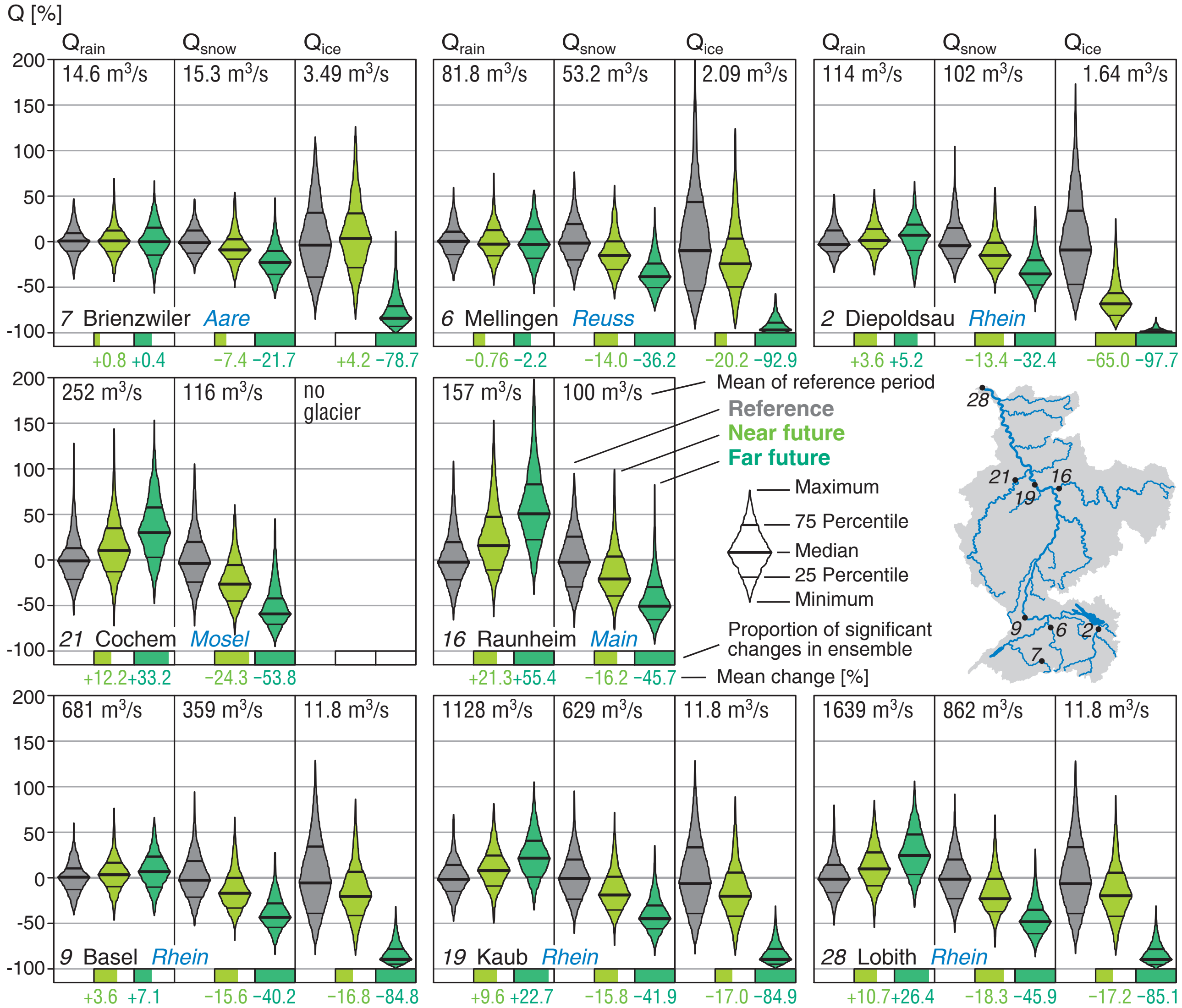


Figure 17: Distributions of annual mean streamflow components of seven ensemble members for 30-year periods (7*30 values per boxplot) at selected gauging stations. Numbers are in relative changes in % from the mean of the reference period.

7 Low flows and high flows

7.1 Evolution in the future

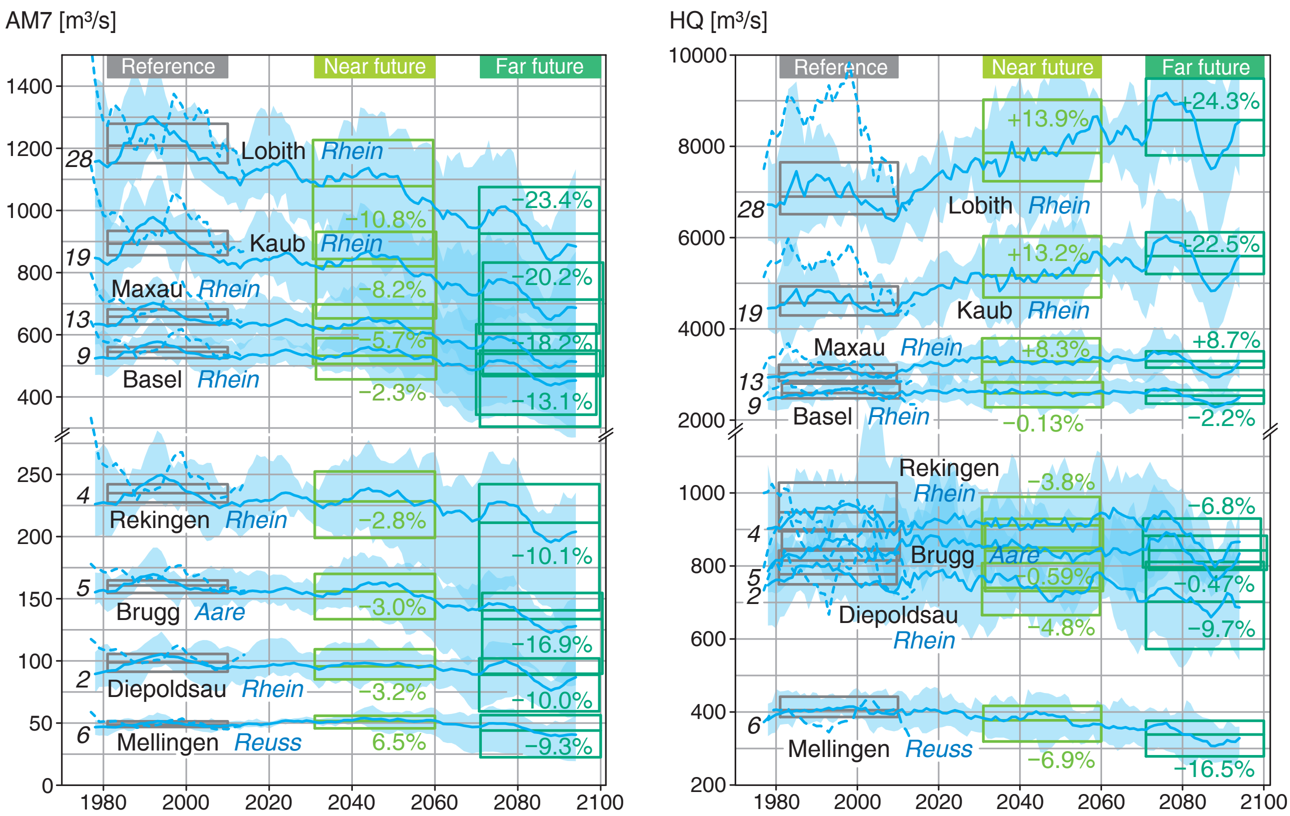
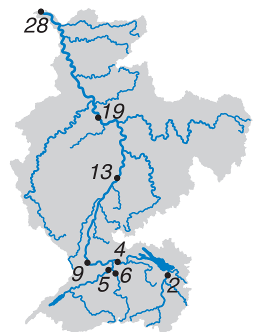


Figure 18: Time series of modeled high flows (annual 1-day maxima, HQ) and low flows (annual 7-day-minima, AM7) at gauging stations in the Rhine basin (11-year moving averages).



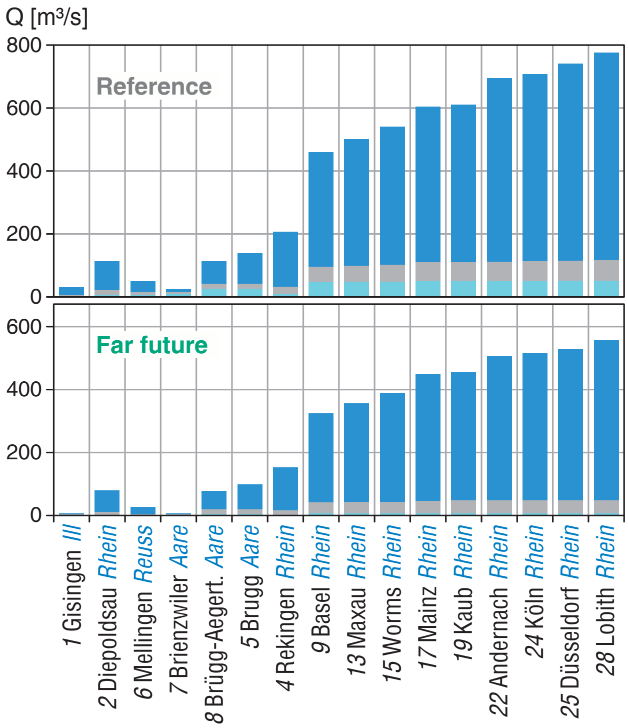
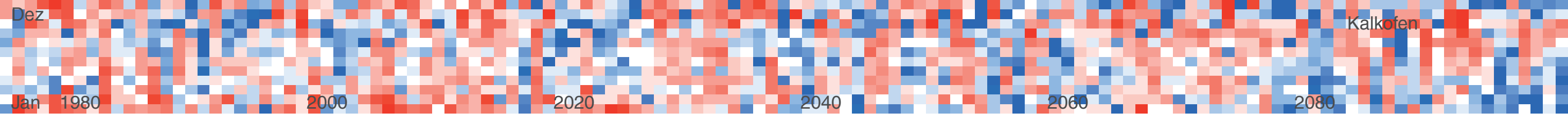


Figure 19: Ensemble mean modeled annual summer low flows (April–Oct) and corresponding streamflow components along the Rhine.

Annual high flows (HQ) show a somewhat similar future trend to the development of mean flows (pg. 12). For the Rhine upstream of Basel high flows decrease (Reuss) or remain rather constant (Aare, Alpenrhein), downstream of Basel they increase (Maxau to Lobith) (Fig. 18). Annual low flows decrease. The uncertainty from the climate ensemble range is large, but the simulations suggest that the decrease downstream might be stronger. The AM7 values that were averaged originate from different seasons (pg. 21).

The decreasing annual summer low flows along the Rhine from the gauge Brienzwiler to Lobith are impacted by their streamflow components (Fig. 19). With a contribution of around 30 m³/s, the Q_{ice} still played a major role in the reference period. In future, this component will no longer exist to augment summer low flow. In addition, future summer low flows will also be characterized by lower Q_{rain} and Q_{snow} than in the reference period.



7.2 Variability and seasonality

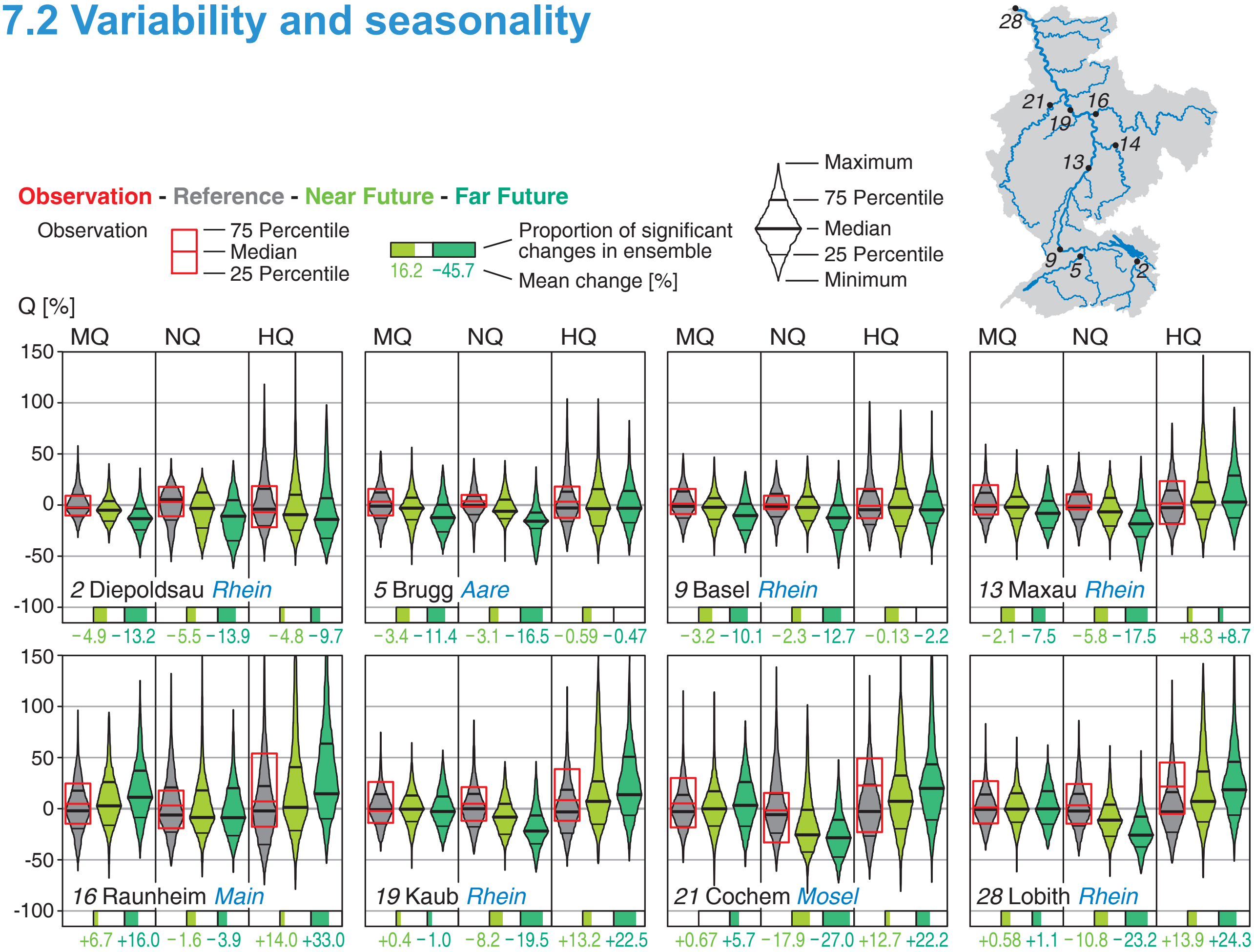


Figure 20: Distributions of annual mean (MQ), annual minima (NQ), and annual maxima (HQ) of observed streamflow and streamflow modeled by the ensemble members for 30-year periods (7*30 values per boxplot) at selected gauging stations.

The distributions of streamflow characteristics such as mean flows (MQ), high flows (HQ) and low flows (NQ) are important for hydrological planning. The variation of these characteristics in observed (gauged) streamflow agree with the simulations for the reference period, showing that the models simulate observed mean and variance well for most gauges and characteristics. For the tributaries Moselle and Main there are model deviations in the extremes (see model evaluation, pg. 8) that also affect HQ in the Rhine at Lobith.

Based on the simulation results, the box-percentile-plots allow comparing future changes of these streamflow characteristics relative to their mean of the reference period (Fig. 20). The future changes in the mean MQ are only significant at three of the gauges shown. The MQ decreases for the Rhine at Diepoldsau and increases for the Main at Raunheim, as well as for the Moselle at Cochem. Most gauges show this pattern of change.

The changes in NQ are clearer. With only two exceptions, all of the selected gauges show a significantly lower NQ for the near future period. The variance of the NQ changes for the tributaries from the Alps and from the central European uplands. For the far future, the NQ for most gauges along the Rhine will decrease significantly, between 10% and 25%. Some smaller tributaries even show a decrease in the NQ, of up to 50 %.

The simulated changes in annual maxima (HQ) are most evident in the Rhine basin downstream of Basel. The gauges of the main river and the tributaries show significant increases of the mean and variance of HQ for the near future as well as for the far future. These changes can be substantial with HQ increases ranging from 10% to 33%. No substantial change in HQ was simulated for any of the gauges upstream of Basel. In the case of significant changes, such as for the Rhine at Diepoldsau, the annual high flows and their variance decrease. Some of these changes can be explained by the changes in seasonality (see next page).

The timing of annual high and low flows (Fig. 21) is relevant for seasonal water uses and for the estimation of potential hazards from extreme events.

The seasonal occurrence of NQ will change most markedly at the gauges of the Aare at Brugg and the Rhine at Basel, Maxau and Kaub. This change is related to the changes in the hydrological regimes (pg. 16/17). The simulations indicate a shift in the timing of winter low flows at these gauges to early winter in the near future and even to late autumn in the far future. The probability of low flow occurrence in the summer, a time of year when, historically, low flows have not occurred, will increase. In the high alpine catchments the seasonality will not change notably. Downstream from Basel the simulation shows that low flows will occur a month earlier in the near future. While NQ may still occasionally occur in the winter months, the low flow season in the autumn will be more predominant than during the reference period.

The average seasonality of the HQ from December to March will remain relatively stable for all gauges downstream of Basel, including the tributaries. For the gauges on the main river Rhine (e.g. at Maxau), however, the occurrences will be more concentrated in the earlier winter .

For the gauges upstream of Basel the seasonality of HQ is projected to change considerably. In the higher Alpine catchments, the HQ occurrence will shift from summer to spring. The gauges at Basel or Brugg, where high flows are generated by rainfall and snowmelt, show the most pronounced changes in seasonality. The typical summer high flows in the reference period will be replaced by spring and early winter high flows in the far future.

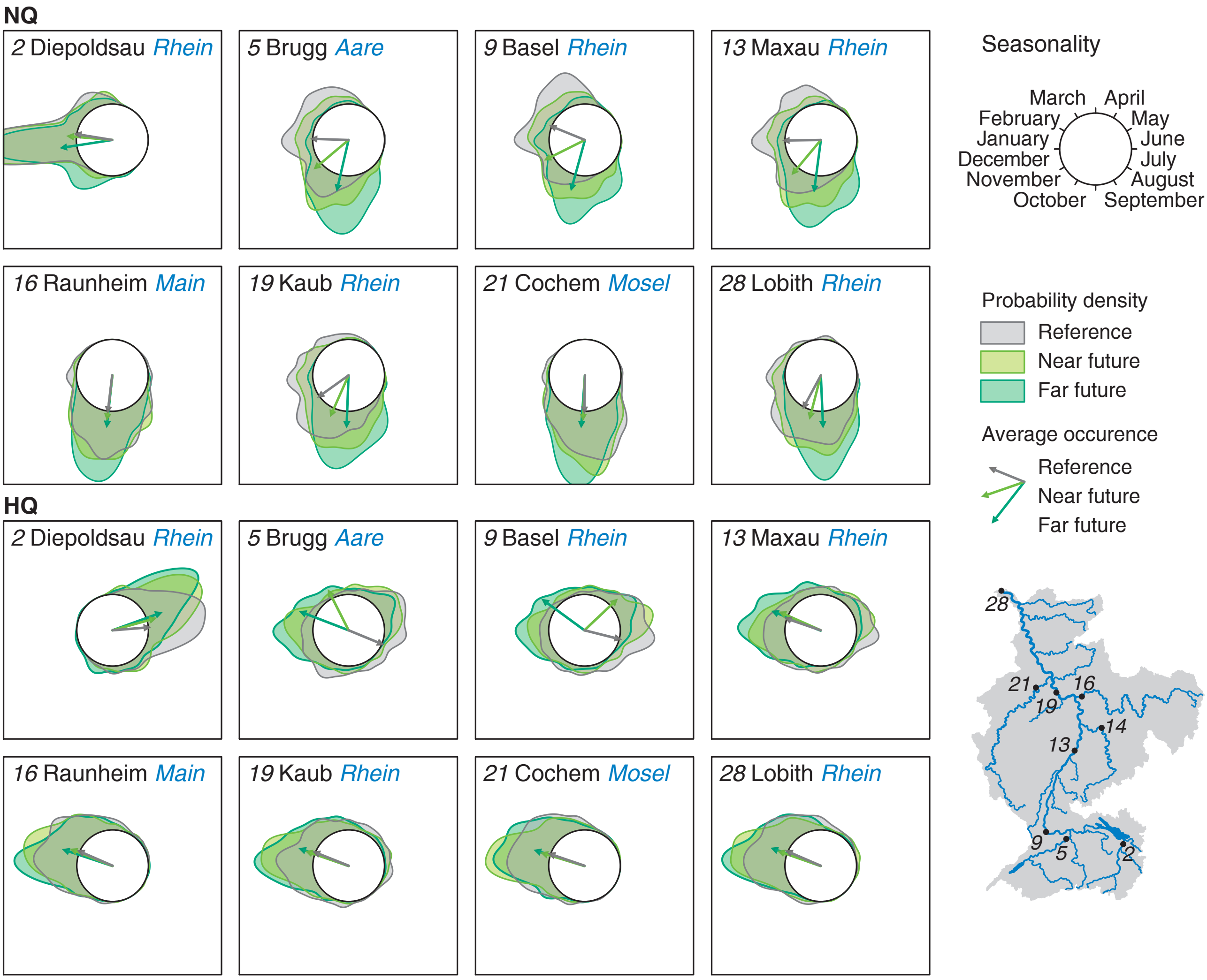


Figure 21: Circle plots of selected gauging stations show the seasonal occurrences of the annual streamflow minima (NQ) and maxima (HQ) as probability density distributions wrapped around the reference circle.

7.3 Extreme low flow events in a model stress test

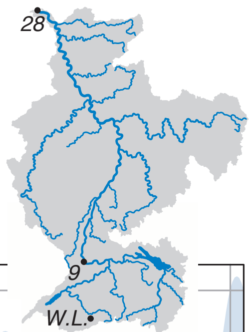
Since the 1970s severe low flow events occurred in the river Rhine from Basel to the Netherlands (Fig. 22). The event of 1976 was caused by a long dry period in western Europe, 2003 stood out by a particularly hot and dry summer season and 2018 had characteristics of both previous events. Distinctive for all events were severe water use restrictions.

The ASG models allowed for the development of "stress tests" that placed these known events into the future to answer the question:

Will low flows be more severe if a similar meteorological situation as in 1976/2003/2018 will occur again, now, in the near future or far future, i.e. at a time when glaciers will have strongly retreated in the model world?

These stress tests were simulated by placing the observed meteorological input of these extraordinary years again in the simulated years, i.e. they use the initial conditions of

- 2018: "now",
- 2031: "near future",
- 2071: "far future".



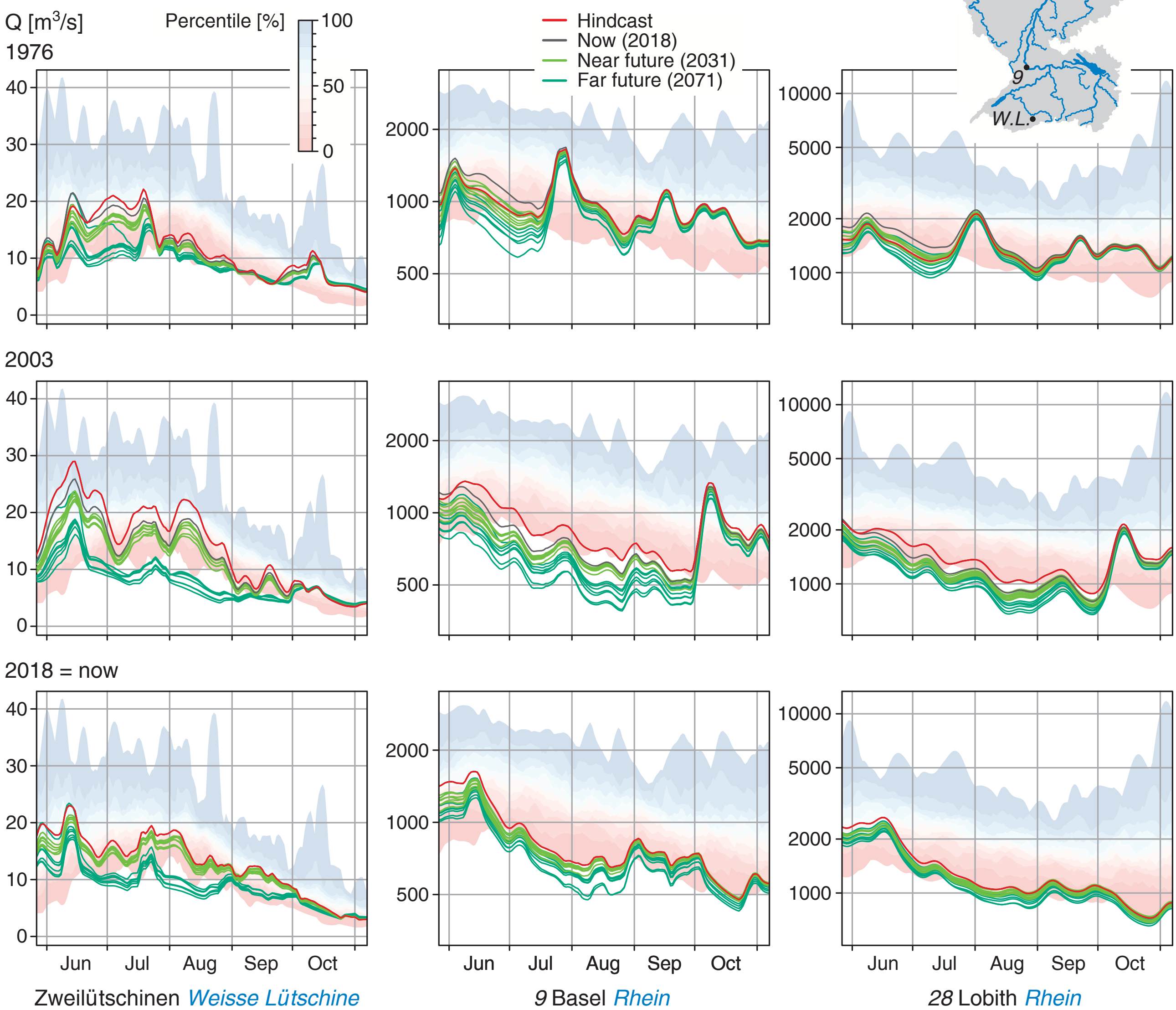


Figure 22: Daily streamflow (7-day moving average) from June–October of the past low flow years and results of future stress tests (7 ensemble members) for three exemplary gauges (columns) Note the logarithmic y-axis scaling for Basel and Lobith. Background coloring shows the simulated streamflow percentiles for the period 1974–2019.

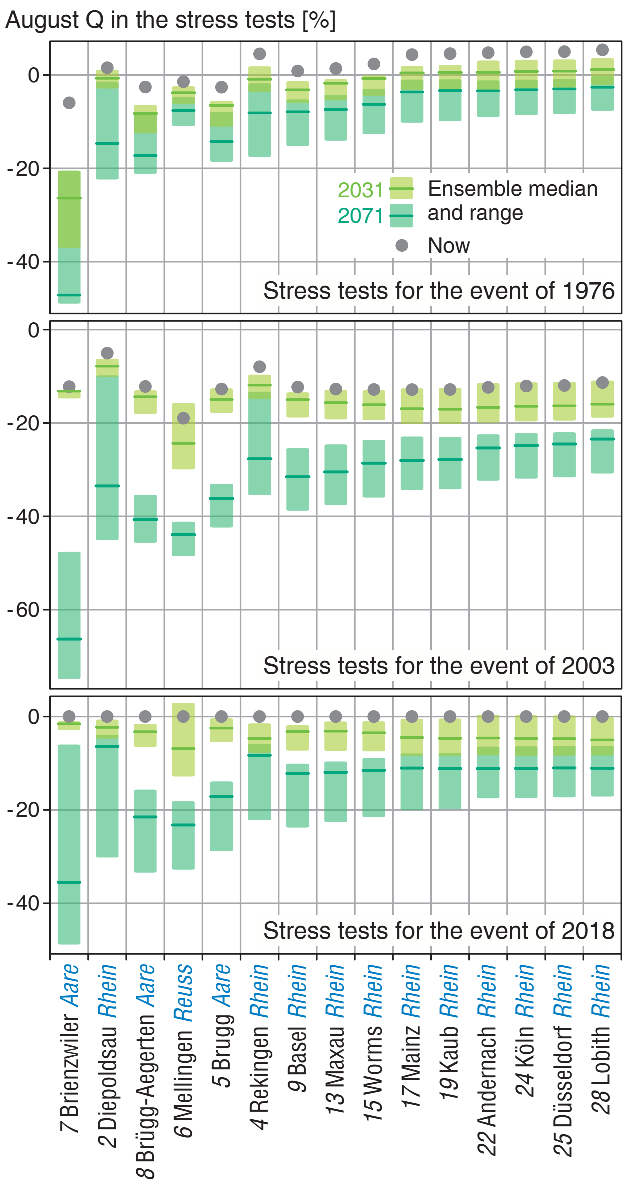


Figure 23: Change in August streamflow for the stress tests for gauging stations along the Rhine. Changes are relative to the mean at each station in the reference period.

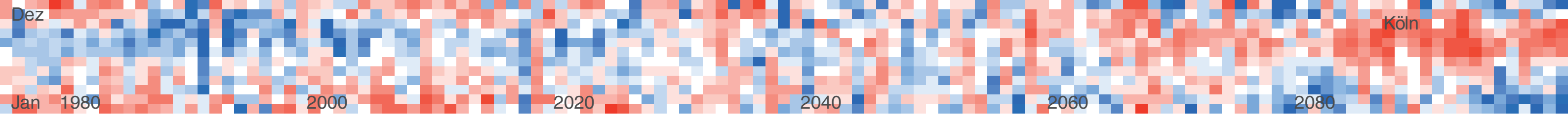
The results of these stress tests can be compared to the hindcast simulation and the simulated percentiles in the past (Fig. 22). The results show that the well-known low flow situations would become even more extreme if they recurred in the future. For the 2003 and 2018 meteorological drought stress, summer streamflows in the simulations would be so low that they would be out of the range of observed low flows of 1974–2019. This extreme response occurs especially in August and September, when the glacier ice melt component will be diminished in the future. The absolute effect of reduced flow is larger in the Alpine headwaters (e.g. Weisse Lütschine). Here the glacier ice melt makes up a major proportion of the streamflow. However, because of an increased sensitivity to extended dry weather periods, low flows become more extreme further downstream.

The simulated effects of the meteorological drought stress of the years 1976, 2003, and 2018 differs along the Rhine (Fig. 23). The largest relative changes in August streamflow occur in the Alpine tributaries and upstream reaches of the Rhine with reductions of over 30% simulated for the far future, for the stresses of 2003 and 2018. The range of changes in August streamflow for the near and far future is caused by the different initial conditions and the state of glacier retreat as a response to the different climate model scenarios. The uncertainty from the glacier melt-out dates (pg. 13) amplifies the ensemble spread in the far future.

The relative changes in August streamflow differ among the three stress test scenarios. Placing the meteorological stress year into another position in time may cause different initial conditions than in the real past. In the case of the stress year of 1976 such an effect caused a small positive change in streamflow when placed in the 'now' and 'near future' position due to larger early-winter snowpacks (Fig. 23). Overall, however changes are negative and they are largest for the stress years of 2003, for which decreases in August streamflow of 30–60% were simulated under far future conditions. The stress of 2018 resulted in streamflow reductions of 10–20% that of 1976 in smaller changes. The results can be attributed to the differences in the glacier melt component during the original low flow years, which was highest in 2003, followed by 2018 (Table 2). In 2003 in particular, a strong heat wave caused a large amount of ice melt.

Table 2: Streamflow fraction of Q_{ice} for the day when it was largest in the hindcast simulation of the specific low flow year and the corresponding values in the stress tests.

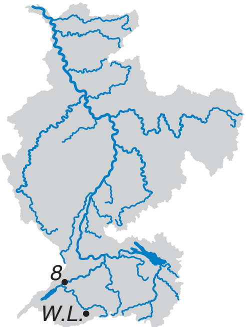
		Date	Q_{ice} [%] Hind-cast	stress tests Now (2018)	Near future	Far future
1976	W. Lütschine	Oct-10	39.4	29.6	26.7	3.2
	Basel	Jul-18	5.6	2.0	1.8	0.2
	Lobith	Aug-9	3.2	1.6	1.5	0.2
2003	W. Lütschine	Aug-13	63.7	60.5	58.7	17.6
	Basel	Aug-27	18.6	17.5	14.5	2.2
	Lobith	Aug-28	12.1	11.0	9.2	1.1
2018	W. Lütschine	Sep-21	47.8	-	42.0	6.4
	Basel	Aug-28	10.9	-	9.1	1.2
	Lobith	Sep-3	6.4	-	5.5	0.6



8 Future changes affecting water use: examples along the Rhine

In water management practice, streamflow indices and low flow thresholds are applied for many different purposes. Such thresholds might be reached either more frequently, or less frequently, in the future. The following examples used the simulation results to illustrate possible changes in some thresholds along the Rhine.

A defined minimum flow serves to protect the river ecology, such as certain fish habitats (see photos). In Switzerland and Austria, the low flow index Q_{95}, here referred to as Q347, is the basis for this. According to the Swiss Water Protection Act, Q347 is the flow that is reached or exceeded 95% of the time, corresponding to 347 days in an average year. It is derived from a ten year reference period. Other countries often use longer reference periods.



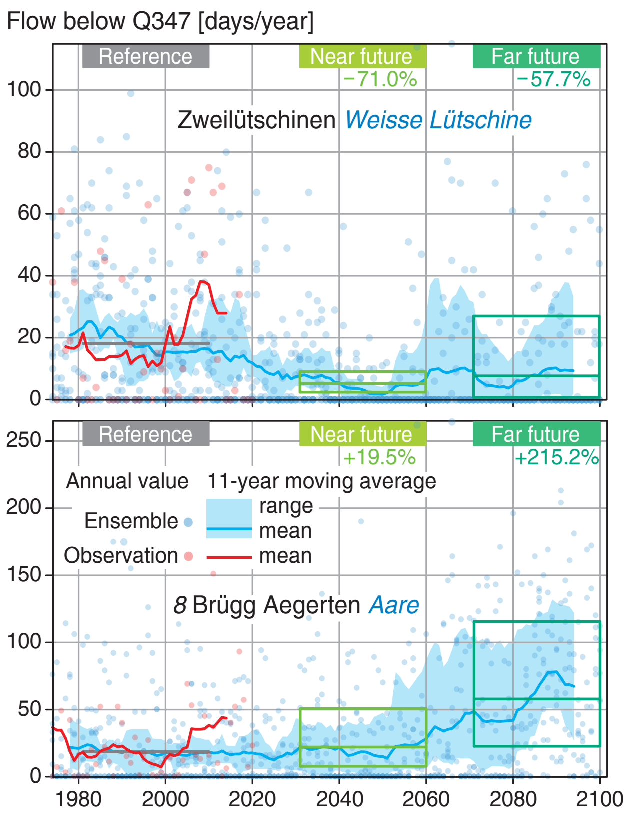
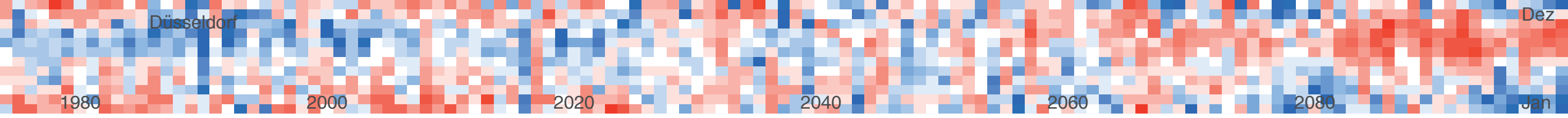


Figure 24: Past and future duration of streamflow below Q347 of the reference period (1981–2010) for the glacierized headwater catchment (upper) and at the station Brügg-Aegerten (lower).

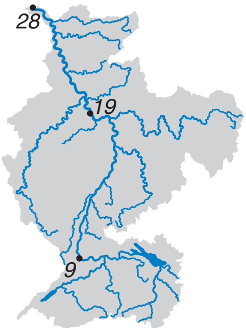
Valley of the river Kander with riparian woodland and typical mountain channel sediment dynamics (photo: Markus Weiler).

Two exemplary catchments (Fig. 24) show different changes in the number of days per year with streamflow below the Q347 threshold from the 30-year long reference period in the ASG project ($Q347_{ref}$). In the Weisse Lütschine glacierized headwater catchment, where low flow conditions occur during winter, the times with flow below $Q347_{ref}$ will decrease. Further downstream in the Aare catchment, where low flow occurs in late summer and autumn, the duration of such a condition will increase by only 10% in the near future. However, in the far future, an extreme increase of >200% was simulated. In some catchments between 1500 and 2000 m a.s.l. the low flow occurrence will shift from a winter to a late summer or autumn low flow regime, which may be ecologically relevant (pg. 21; FOEN, 2021; Muelchi et al., 2021).

Lake run brown trout (Seeforelle) in the stream Urbachwasser (photo: Matthias Meyer, 2014).



At the ‘Märkt Weir’ near the city of Basel, most of the Upper Rhine’s streamflow is diverted to the Grand Canal d‘Alsace in France, where it is used for hydro power production, as cooling water and for navigation. Run-of-the-river hydroelectricity produced at the Kembs power plant is shared by France and Switzerland. Based on the current thresholds for residual flow regulation for the „Altrhein“ and the capacity of the power plant, the annual amount of water potentially available for power generation can be derived from the future flow simulations (Fig. 25): These suggest only a slight decrease in hydropower potential in the near future but a more notable decrease of about 10% based on the ensemble mean for the far future.



Long periods with impaired navigation and freight traffic prevailed e.g., during the low flow year 2018 (BfG, 2019). Such situations can have far-reaching implications on other sectors. The gauge at Kaub is used to indicate critical situations for sections of the middle reaches of the Rhine and defines an important flow and water level threshold. An intensification of extremes (p. 19 ff.) will lead to longer periods with limitations (Fig. 25). Based on the currently applicable thresholds, restrictions to navigation could prevail, on average, for more than two months per year at the end of the century.

Navigation on the river Rhine near Oberwesel during the low flow situation in November 2015 (photo: Jörg Belz).

Flow at the gauging station in Lobith is one of the key indicators for national drought monitoring and the early warning system in the Netherlands. Below a certain streamflow, normal conditions change to a warning “niveau 1” and a task force will become active. Currently, this threshold is between 1000 and 1400 m³/s, depending on the season (WMCN, 2021). The project’s simulations suggest that much longer periods with flow below this threshold are to be expected in the future (Fig. 25).

Weir Märkt at the hydro power plant Kembs (photo: Thomas Berwing; ©: https://creativecommons.org/licenses/by-sa/4.0/).

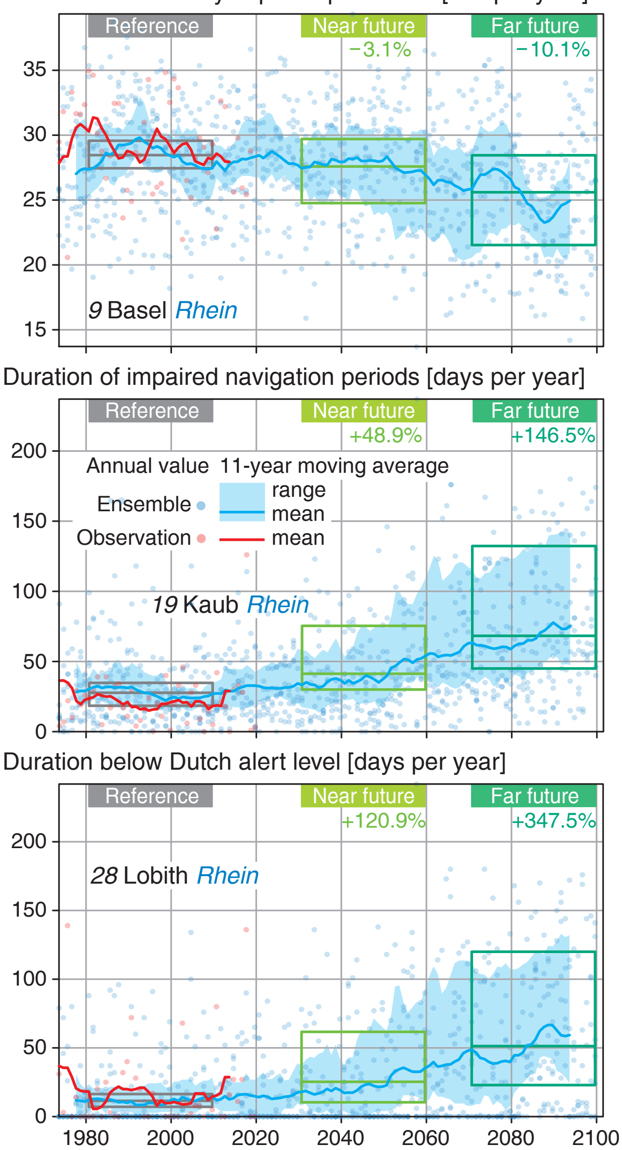
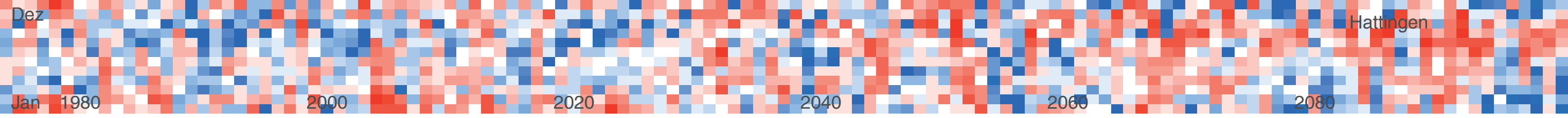


Figure 25: Available water at the gauge Basel for hydropower production at Kembs (upper), duration of impaired navigation periods at Kaub (middle) and duration of periods with flow at Lobith below the Dutch drought Level 1 (lower).



9 Concluding remarks

In the second phase of the ASG-Rhine project daily fractions of the rain, snowmelt, and glacier ice melt components of streamflow were quantified for a future climate scenario until 2100. A warmer climate with more variable precipitation will exert strong hydrological changes in the Rhine basin. Model-chains for such climate change impact studies combine many datasets, models and tools and inevitably make assumptions about the systems modeled. Not all of the resulting uncertainties could be addressed in detail here, but despite the limitation to the RCP8.5 scenario and one hydrological model, the ensemble simulation yielded a considerable range of uncertainty. However important changes stand out clearly amidst the range of uncertainty. The modeled changes in streamflow and its components are clear enough to suggest that implications for various water uses are to be expected.

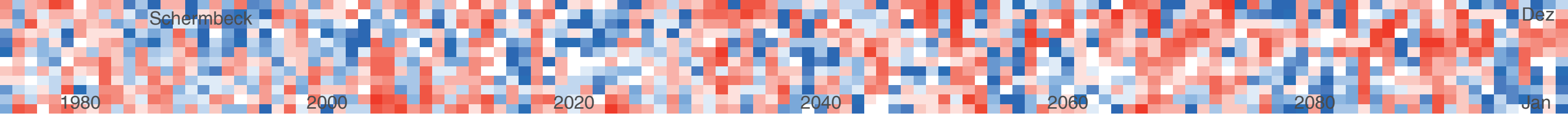
The already-reduced fraction of ice melt in streamflow will rapidly become even smaller. This change varies in the Rhine's alpine tributaries. For the river Aare a relatively constant glacier ice melt component is expected until about 2040. Other tributaries' ice melt components have already been declining and will continue to do so. Ice melt, which has sustained recent extreme low flow situations, e.g., with up to a tenth of the flow at Basel, will soon become negligible in the downstream reaches.

The snowmelt component is the one that will have the largest effect on streamflow. It accounts for a large fraction of the streamflow along the entire Rhine. A projected increase in winter precipitation is unlikely to compensate for the expected future reduction of the spring-summer snowmelt component in the Rhine upstream of Basel. Downstream, where the rainfall component increases more, some compensation is projected for the annual streamflow, despite seasonally increased variability. Snowmelt changes will affect the seasonality most clearly and will no longer provide a considerable contribution even to those low flow events that occur in early summer. Given the importance of the snowmelt component, consistent long-term snow monitoring remains crucial. Models need to be corroborated for their correct snow processes. Whether artificial reservoirs could partially compensate for the loss of natural seasonal storage, remains the subject of future studies.

The rain component is a very important factor in determining the quantity and the short-term variability of streamflow, where seasonal and long-term buffers from snowmelt and ice melt are reduced. Climate models are not specialized in simulating individual extreme events in the future, and the hydrological models that were used were not optimized or tested for the simulation of flood waves, for example. Nevertheless, all projections downstream of Basel show an increase in the annual high flows (daily resolution) in the future. The forcing precipitation changes, however, vary strongly in the different climate model runs for the same RCP8.5 scenario, which is, then, also reflected in the uncertainty of the projected hydrology. Considering other RCPs that are more optimistic about reduction of greenhouse gas emissions, would expand that range of uncertainty even more.

A particular focus was the research into low flow situations. For a clearer picture of potential changes, stress tests were simulated in addition to the climate scenario. The meteorology of known low flow years with warm and dry weather acted as 'stress' and results showed that it will have an enhanced impact in the future, even at higher elevations, due to the reduced and missing snow and ice components.

Low flows will become more extreme, in particular downstream of Basel. The implications for water usage restrictions, assuming currently applicable thresholds, would be considerable. For example, periods with impaired navigation in relevant sections of the middle Rhine would get much longer and drought warning levels in the Netherlands would be reached more often. Plans of the various water use sectors need to take such changes into account in the future. The effects of climate change on the streamflow of the river Rhine and its tributaries are already being felt today and the project results suggest that they will continue to intensify in the future. Water body protection and water usage planning must face up to the challenge of new hydrological conditions and water availability. Climate protection through greenhouse gas emission reductions, as well as the adaptation of water management and water use, are essential to limit the environmental and social impacts of these projected future changes.



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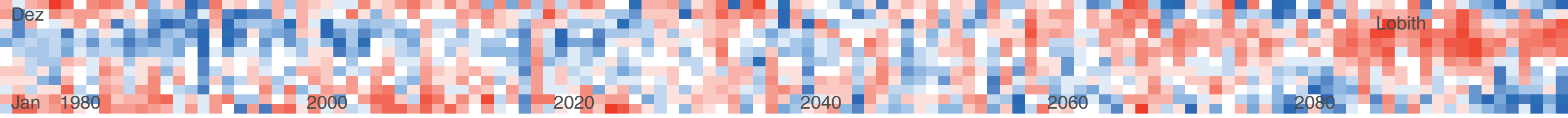

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