

# Impact of climate change on hydrological conditions of Rhine and Upper Danube rivers based on the results of regional climate and hydrological models

Gabriella Szépszó · Imke Lingemann · Bastian Klein · Mária Kovács

Received: 1 August 2012 / Accepted: 3 December 2013 / Published online: 24 December 2013  
© Springer Science+Business Media Dordrecht 2013

**Abstract** The main objective of the Effects of Climate Change On the Inland waterway Networks (ECCONET) EU FP7 project was to assess the effect of climate change on the inland waterway transport network with special emphasis on the Rhine and Upper Danube catchments. The assessment was based on consolidation and analysis of earlier and existing research work as well as application of existing climate change and hydrological modelling tools. A key premise at the planning stage of the project had been that all impact studies conducted within ECCONET should be comparable with each other. This can be guaranteed by the common meteorological and hydrological basis. The climate model simulations, which are the most physics- and process-oriented tools for projecting the future climate evolution, include several uncertainties. In addition, uncertainties exist in the hydrological model simulations. In ECCONET, an effort was made to quantify the uncertainty range by using “representative projections” that represent both the lower and upper signals of hydrological low-flow parameters for 2021–2050 over the Rhine catchment. Their evaluation indicated that the finally chosen two regional climate model simulations could be applied also for the Upper Danube catchments as representative projections. The raw climate model outputs have been corrected to the observation data set through application of the linear scaling and the delta-change method. The first impact studies carried out after validation of the hydrological models resulted in discharge scenarios used as input to the economic models in ECCONET.

**Keywords** Rhine · Danube · Low-flow · Regional climate model · Hydrology · ECCONET

---

G. Szépszó (✉) · M. Kovács  
Hungarian Meteorological Service (OMSZ), Budapest, Hungary  
e-mail: szepszo.g@met.hu

I. Lingemann · B. Klein  
Bundesanstalt für Gewässerkunde (BfG), Koblenz, Germany

## 1 Introduction

The adaptation to the possible climate change impacts is a great challenge not only financially, but also from scientific point of view. To prepare an efficient and determined adaptation strategy, a number of comprehensive and quantified impact studies are needed. However, first of all these investigations require detailed information about the meteorological aspects of the climate change.

The future evolution of the highly nonlinear climate system including atmosphere, hydrosphere, cryosphere, land surface and biosphere can be described by its modelling. Numerical models contain the mathematical equations formed by governing physical processes and solve them by using numerical methods. Atmosphere is the most rapidly changing part of the Earth system, and the further components have different adjustment timescales varying from years to hundreds of thousand years; climate models simulate the asymptotic behaviour of this complex system.

The continuously improving global climate models (GCMs) provide realistic projections for the large-scale climate features; nevertheless, they are insufficient for detailed regional description. Regional climate models (RCMs), focusing not on the whole Earth, but only on a limited area with finer horizontal resolution, ensure dynamic-based tools to interpret and enhance the global results for regional scale (Giorgi and Bates 1989).

In the modelling process, there are several uncertainties, and in climate change projections, the following sources are of key essence:

1. *Internal variability* It is a natural characteristic of the climate system existing also in the absence of any external radiative forcing. The impact of this term can be observed in the changeable trends of shorter time periods (e.g. the temporary cooling in the little ice age or during the shorter period of 1940–1980).
2. *Emission scenario uncertainty* An important element of the climate change is the human activity. In the climate simulations, the socio-economic aspects (population, energy consumption, industrial and agricultural structural changes, etc.) potentially influencing the climate system are taken into account with their carbon dioxide emission and concentration equivalents. The uncertainty is due to the unpredictable future evolution of the anthropogenic factors. In order to assess these uncertainties, several scenarios are constructed for future emission tendencies that include optimistic, pessimistic and medium versions, as well.
3. *Model uncertainty* All global coupled models aim to estimate the response of the climate system to a given forcing; however, they describe the physical processes using various numerical and other approximations (different horizontal and vertical discretization, parameterization schemes, etc.). These uncertainties are inherited in the RCM simulations completed with some additional ones stemming from the differences in the target domain, the spatial resolution, the boundary conditions, etc.

Due to these uncertainties, there is not a single “true” climate model run. In practice, the uncertainties in the climate projections are quantified by the ensemble approach. On climate scale, the multi-model and multi-scenario methods are applied: numerous model simulations are carried out using several GCMs, RCMs and emission scenarios. In the ideal case, this ensemble represents the entire spectrum of the uncertainties and with the assumption that every ensemble member indicates an equally possible future alternative, probabilistic projections can provide a proper view about the future climate change.

Nevertheless, the existing climate change simulations do not span the real uncertainty spectrum due to some limitations. For the 4th assessment report of the Intergovernmental

Panel on Climate Change (2007), a large number of global experiments were accomplished with the today's GCMs using three (A2, A1B and B1) main paths of the SRES emission scenarios (Nakicenovic et al. 2000) prescribing the anthropogenic activity in the twenty-first century. In the last decade, several international projects have been initiated and realized in order to cover the European territory with high-resolution regional climate model experiments. In the Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (PRUDENCE; Christensen 2005) EU FP5<sup>1</sup> project, RCM simulations were conducted on 50-km horizontal resolution focusing on the period of 2071–2100 and using primarily the pessimistic A2 emission scenario as anthropogenic forcing. In the ENSEMBLES EU FP6 project (van der Linden and Mitchell 2009), RCMs were applied on 25-km resolution and forced with the A1B medium emission scenario.

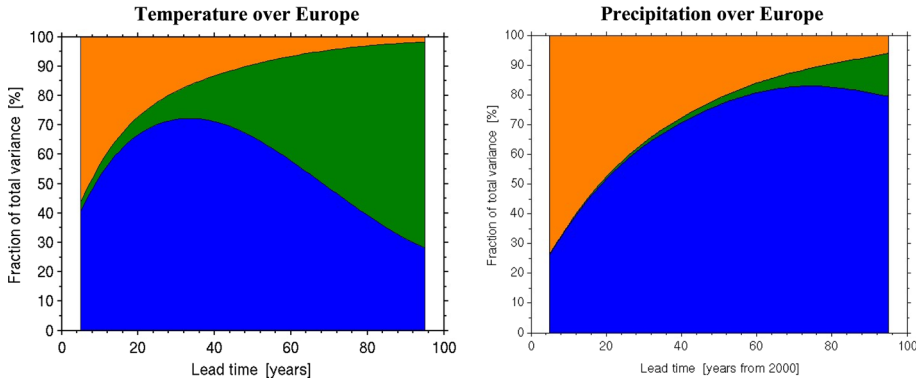
The relative contribution of the three components to the total uncertainty of the climate simulations varies depending on the investigated time period, region and meteorological parameter as indicated by the results of Hawkins and Sutton (2009, 2011) based on 15 different GCMs combined with three different emission scenarios. Concentrating on the temperature change over Europe (left panel of Fig. 1), the relative importance of the natural variability is high at the first decade, but it is reduced in time and almost disappears by the end of the twenty-first century. During the investigated period, the weight of the emission scenario uncertainty increases at the expense of the other two sources. However, it has to be noticed that emission scenario uncertainty becomes important only on multi-decadal timescale, and in the first decades, rather, the model uncertainty is dominant. This is especially valid in the case of precipitation (right panel of Fig. 1), where the importance of the emission scenario choice is almost negligible even at the end of the twenty-first century. The main part of uncertainty is coming from the natural variability in the first decades; afterwards, model uncertainty develops as leading component.

All that means that in the first half of the century, there is larger deviation between the results of two simulations achieved by different GCMs or RCMs, but with the same emission scenario than by the same GCM or RCM with two emission scenarios. The differences in the global and regional models are the most important uncertainty factor at this lead time, and it can be reduced mainly via model development. However, in the case of precipitation, the *unavoidable* natural component has similar magnitude like that of the model uncertainty.

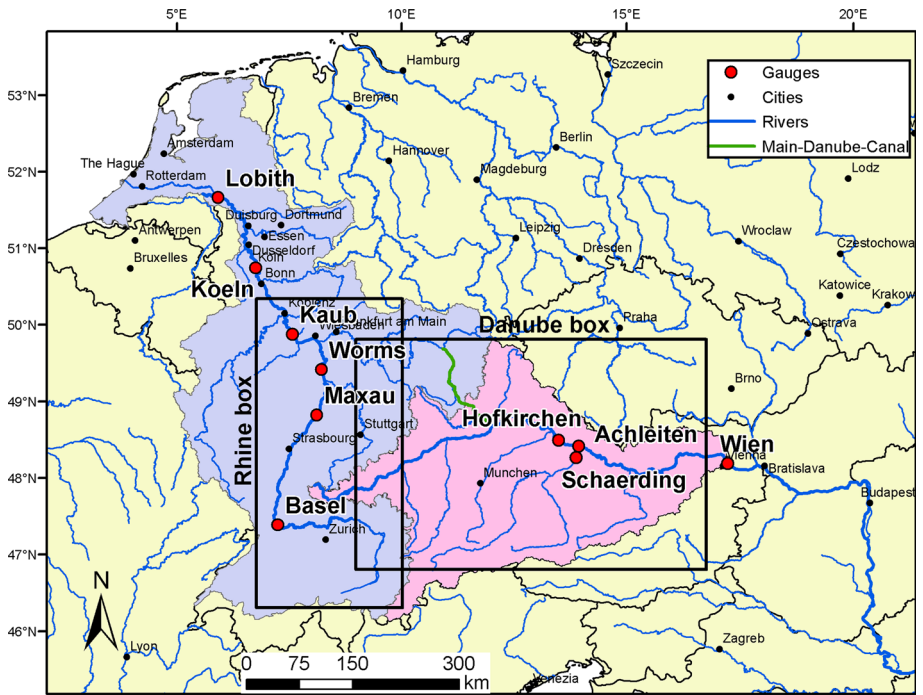
The climate simulation uncertainties have further influence on the impact studies, as well. Therefore, it is indispensable to consider and account for these uncertainties and more importantly quantify them for the users and end-users. The ECCONET EU FP7 project was dedicated to assess the climate change effects on the inland waterway transport network for the Rhine and Upper Danube catchments based on earlier research and application of existing climate change and hydrological assessment tools. (The scope of the studies is shown in Fig. 2 for both catchments.) At planning the investigations in the project, two key points of view were followed: (1) to use the same meteorological and hydrological basis for the impact studies and (2) to take the climate simulation uncertainties into account in the impact studies in a representative way.

The time horizon of ECCONET was basically 2021–2050, and the investigation of the inland waterway transport network requires hydrological studies, strongly based on precipitation-related variables. In agreement with the conclusions of Fig. 1, for this period, the

<sup>1</sup> EU FP5: Fifth Framework Programme of the European Union.



**Fig. 1** The fraction of total variance [%] in decadal predictions explained by the three (orange internal variability, green emission scenario, blue model) components of total uncertainty for decadal mean temperature (left) and precipitation (right) over Europe. Source: Hawkins and Sutton 2009, 2011



**Fig. 2** The chosen domain for the Rivers Rhine and Upper Danube superimposed on the Rhine River catchment (blue) and the Upper Danube River catchment up to the gauge Vienna (pink). The coordinates of the Rhine and Danube boxes are as follows: 46.5°–50.5°N; 7°–10°E and 47°–50°N; 9°–16°E, respectively

emission scenario choice does not play role for construction of the aforementioned common and representative meteorological basis, and consequently, only one (A1B) emission scenario was investigated in the framework of the project.

Ideally, the whole ensemble of available projections should be considered in the impact models in order to evaluate possible changes and adaptation options. However, in ECCONET, it was not feasible to consider the full ensemble of climate projections in the complete model chain of impact models due to the large amount of data and calculation times needed. Therefore, an effort was made to address not the entire spectrum, but only the boundaries of the remaining uncertainty by determining *representative projections* or *extreme model chains* for the Rhine and Upper Danube catchments. These extreme model chains attempt to represent both the lower and upper signals of hydrological parameters for the time horizon of 2021–2050. The method had been developed in the KLIWAS programme (Auswirkungen des Klimawandels auf Wasserstraßen und Schifffahrt 2009), where the whole spectrum of model uncertainty (including the uncertainties associated with the different GCMs and RCMs) was taken into account by an ensemble of RCM simulations based on various RCMs with different resolution and utilizing hydrological impact models. The raw climate model outputs, before using them as inputs for the hydrological impact model, were bias-corrected to the observation data set for the past, and the same correction was applied also for the future. Then, a methodology was generated in order to select the representative projections from the ensemble of hydrological model outputs, and two extreme model chains were chosen that describe the range of possible discharges of the Rhine in the future. This was done to transfer these boundaries to the Danube simulations, where model output is limited due to the temporal resolution.

The present article provides a general assessment of the climate change and its impacts on the hydrological conditions of the Rhine and Upper Danube rivers based on the investigations motivated by the ECCONET project. An ensemble of 20 run-off projections was available from the hydrological model simulations, for the Rivers Rhine and Upper Danube (see Sect. 3). As meteorological input, bias-corrected RCM outputs were used (see Sect. 2.4). Using these run-off time series, the climate projections generating the lower and upper boundaries of hydrological parameters were selected as representative projections, and the method is introduced in Sect. 2.1. (It has to be remarked that in the framework of ECCONET, a more simple selection method was used for the Upper Danube.) The chosen RCM results served as input for the following economic models in the model chain of ECCONET; therefore, their thorough meteorological analysis is conducted in Sects. 2.2–2.4: besides the validation and projection assessments, some insights are also presented into the main characteristics of climate model simulations over the target regions through a comparative analysis of the raw and bias-corrected climate model outputs. Special emphasis is put on quantifying the uncertainties before the hydrological modelling procedure. The resulting discharge scenarios are evaluated to describe changes in the hydrological system due to an expected climate change.

## 2 Climate modelling background of the ECCONET studies

### 2.1 Methodology for model selection

The ECCONET project was focussing on establishing policy guidelines and development plans for inland water transportation to react to changes in water regimes and on time due to the dependencies of water levels on navigation. The model selection must correspond to the aim of the investigation, and the selected projections should cover the range of the possible effects due to climate change.

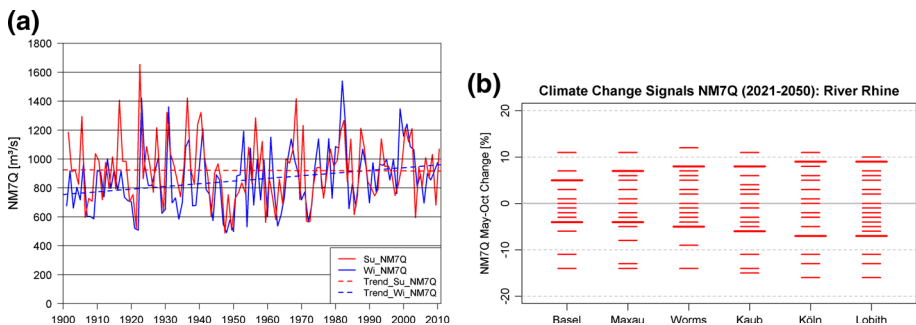
### 2.1.1 Model selection on a hydrological basis for the River Rhine

In the KLIWAS programme and the Rheinblick2050 project (Görgen et al. 2010), a methodology was generated to select the representative projections based on an ensemble of hydrological model output. The results will be utilized to provide an overview on climate model projections generating extreme flow conditions that mainly affect inland waterway transport for the Rhine. The extreme low-flow conditions as determined by a hydrological impact model are characterized by different indicators like the parameter “lowest seven-day mean discharge” (referred to as NM7Q hereafter) or the 90th per cent quantile (Q90). Figure 3b is a demonstrative example with focus on hydrological summer NM7Q (lowest value between 1 May and 31 October) at selected gauging stations on the River Rhine.

The graph of Fig. 3b is based on a climate projection ensemble consisting of 20 members for the time horizon of 2021–2050. All members are bias-corrected (Lenderink et al. 2007) and taken as input for the hydrological model HBV134 (Görgen et al. 2010; te Linde et al. 2008). The “representative projections” are selected on the outer rim of the main cluster, the “scenario horizon” of results as indicated by the fat lines in Fig. 3b. The main cluster of projections is identified through cluster analysis (Görgen et al. 2010; Nilson and Krahe 2012). Scenario horizons are zones in the ensemble of discharge projections which are consistently simulated by most of the ensemble members and cover all ensemble members whose results are within a higher probability density. Clear outliers are omitted.

Figure 3a is for knowledge of the variability of the existing hydrological system, the importance of NM7Q of half-years and the persistent change of weight between winter and summer occurrences. It is shown there has been a trend in recent years toward increasingly lower water depths during hydrological summer at station Kaub. (Kaub is situated at the Middle Rhine and can be seen as the most critical shallow water at the River Rhine for navigation between Rotterdam and Basel.) Thus, in order to describe a range of possible extreme low-flow conditions for the River Rhine, for the hydrological summer NM7Q at Kaub, the following regional climate model projections as representative projections have been chosen in KLIWAS (using KLIWAS nomenclature, for more details, see Table 1) for 2021–2050:

- Dry: A1B\_HADCM3Q0\_HADRM3Q0\_25;
- Wet: A1B\_BCM\_RCA\_25.



**Fig. 3** **a** Time series (solid) and linear trends (dashed) at the gauge station Kaub for NM7Q during both hydrological summer (May through October; red) and hydrological winter (April through November; blue). **b** Change of lowest seven-day mean discharge (NM7Q) at major gauging stations along the River Rhine for the time horizons 2021–2050. Fat lines indicate representative projections (source: Görgen et al. 2010)

**Table 1** Main characteristics of the chosen RCM experiments: the driving GCM, the horizontal resolution, the applied emission scenario and the acronym

RCM	Driving GCM	Resolution	Scenario	Acronym
HadRM3Q0	HadCM3Q0	25 km	A1B	HadCM3Q0_HadRM3Q0
RCA	BCM	25 km	A1B	BCM_RCA

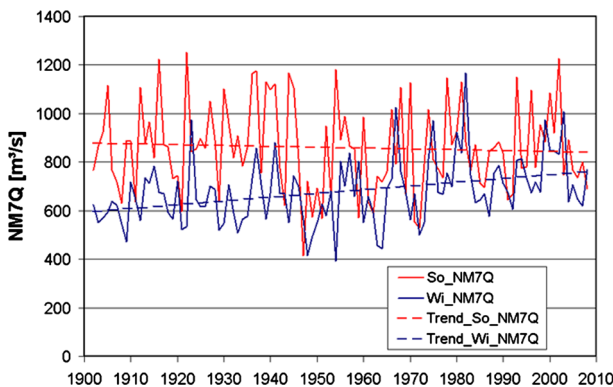
The two simulations of the representative projections (also referred to as extreme model chain) represent the lower and upper boundaries of low flows for time horizon of 2021–2050.

2.1.2 Evaluation of the selected scenarios for the Danube basin

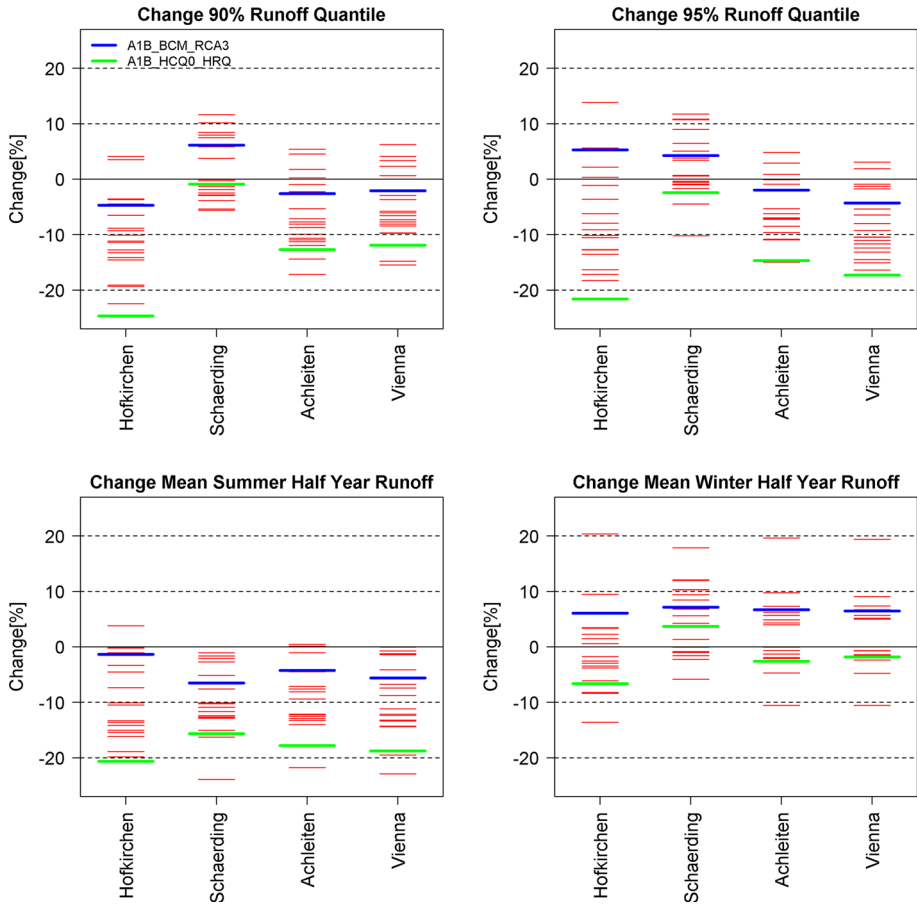
In the Danube basin, a water balance model working on a monthly timestep was applied to assess the potential impact of climate change on hydrology (Kling et al. 2012). The method of model selection by the indicator NM7Q chosen at the River Rhine cannot be transferred consistently to the Danube. Hence, low-flow indicators based on monthly run-off values, e.g. 90th quantile for monthly values, have to be evaluated instead of the NM7Q. The correlation of low-flow indicators and navigation relevant parameters is very strong and is described in Nilson et al. (2012).

Figure 4 shows the observed NM7Q for both hydrological summer and winter from 1900 to present for the gauging station of Achleiten on the Austrian side of the German–Austrian border. The contribution of the catchment discharge until Achleiten is dominating discharge behaviours for the Middle Danube and all its bottlenecks. This figure indicates that the Upper Danube has low-flow conditions mostly during hydrological winter (November through April) rather than hydrological summer (May through October). Regarding the trend of summer and winter series in the past, it could be possible that the annual low-flow events will occur more often in summer in future. As a conclusion, summer and winter low-flow indicators have to be considered in the scenario evaluation.

To evaluate the selected representative projections of the River Rhine for the River Danube, the projected relative changes of the 90th quantile and 95th quantile of the 30-year flow duration curves of the mean monthly values as well as the mean summer and winter



**Fig. 4** Time series (solid) and linear trends (dashed) for the Upper Danube at gauging station Achleiten of the lowest seven-day mean discharge (NM7Q) during hydrological summer (red) and hydrological winter (blue) from 1900 to present



**Fig. 5** Changes of the 90th quantile (*top left*) and 95th quantile (*top right*) of the 30-year flow duration curves of the mean monthly as well as mean hydrological summer (*bottom left*) half-year and winter half-year (*bottom right*) run-off according to an ensemble of 20 discharge projections. Values are expressed as per cent change in the period 2021–2050 compared to 1961–1990. Representative members selected for further impact analysis are marked

half-year run-off of the period 2021–2050 with reference to the control period 1961–1990 are used. In Fig. 5, the relative changes of the 20 run-off projections are shown as lines for four selected gauges (see Fig. 2). The selected scenarios are marked in blue and green. Evaluating the four indicators, it is obvious that these two projections could also be used as representative projections at the River Danube.

## 2.2 Validation results

As described in the former subsection, extreme model chains have been determined for both the Rhine and Upper Danube catchments which might describe “low” and “high” scenarios for low-flow situations in the near-future. The results of the two selected RCMs (Table 1) are validated against observational data set in order to assess their performance over the target regions of ECCONET. The evaluation is achieved for the GCM-driven regional climate model simulations, because the future hydrological impact investigations

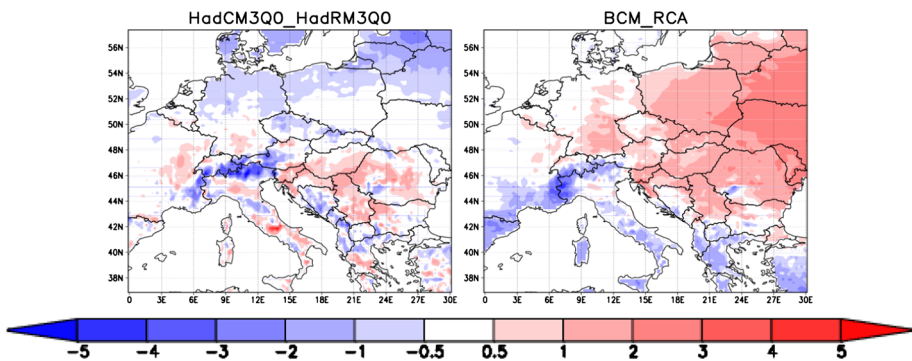


are based on these results. Therefore, this validation provides information about the consequences of the nonlinear interaction between the RCMs and GCMs. The reference data set for the normal period 1961–1990 is served by version 3 of the E-OBS database (Haylock et al. 2008). The evaluation is concentrating on 2-m mean temperature and precipitation amount on annual, seasonal and monthly basis. The mean characteristics are calculated for the two regions of the ECCONET interest: the Upper and Middle Rhine and the Upper Danube catchments (see Fig. 2).

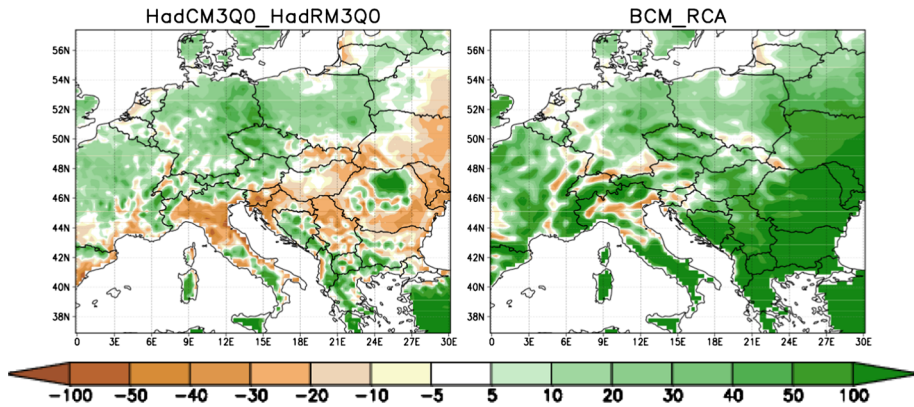
The regional climate model simulations indicate different temperature characteristics over Europe; however, the underestimation over the regions with complex topography, especially over the Alps, is a common feature and exists in each experiment (Fig. 6). The RCA simulation indicates larger positive bias (reaching 3 °C) in annual temperature than the HadRM3Q0 simulation. The investigated RCMs are capable of reproducing the intra-annual temperature cycle over the Rhine and Upper Danube regions, generally with a slight overestimation in winter and underestimation in summer. The monthly mean errors mostly do not exceed 1.5 °C, though there are some exceptions (e.g. the temperature overestimation in HadRM3Q0 reaches 2.4 °C in summer months; not presented).

The evaluated RCMs generate precipitation overestimation over major part of the continent, both annually and almost every season with the exception of summer. In summer, one of the RCMs underestimates the past precipitation amount over the southern and south-eastern parts of Europe, while in the results of the other RCM, the overestimation is still typical (see Fig. 7). The summer results of HadCM3Q0 indicate an “intermediate” zone over Central Europe, which separates the areas characterized by overestimation in the north and the regions of underestimation in the south (in agreement with other RCM results in former studies; Jacob et al. 2007; Szépszó and Horányi 2008). The positive errors have the largest magnitude over the high mountains like the Alps; however, some underestimation can also be concluded.

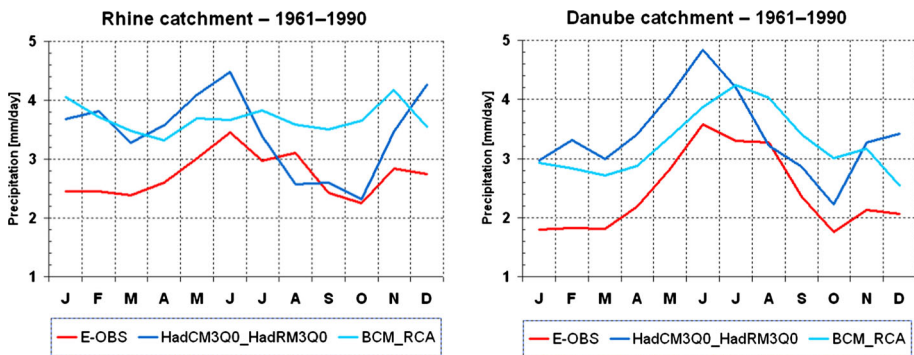
Concentrating on the two regions of interest (Fig. 8), the main characteristics of the (observed) precipitation climatology are similar for the two catchments: the seasonal precipitation cycle has primary and secondary maxima in summer (in June and August, respectively), while the lowest amounts were recorded in October, January, February and March in the normal period. Nevertheless, the precipitation climatology over the Rhine catchment is more “balanced” than over the Danube region, i.e. the difference between the summer maximum and winter minimum is lower than for the Danube. The BCM-driven RCA was not able to reproduce this feature of the Rhine precipitation climatology, and it



**Fig. 6** Annual mean temperature difference [°C] between the results of two RCMs and E-OBS reference data set for 1961–1990



**Fig. 7** Summer mean precipitation difference [%] between the results of two RCMs and E-OBS reference data set for 1961–1990



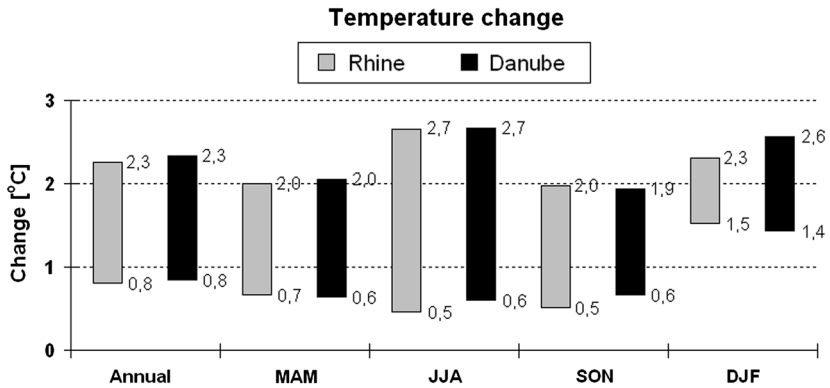
**Fig. 8** Monthly mean precipitation values [mm/day] over the Rhine catchment (*left*) and Danube catchment (*right*) based on the results of two RCMs (*blue curves*) and E-OBS reference data set (*red*) for 1961–1990

generates almost a flat annual distribution. The situation is fairly better for Upper Danube catchment: apart from the general overestimation, RCMs reasonably represent the key properties of seasonal precipitation distribution. All that considered, it can be pinpointed that the precipitation simulations are mainly hampered by overestimation for both regions, with larger relative errors for the Upper Danube catchment for every month.

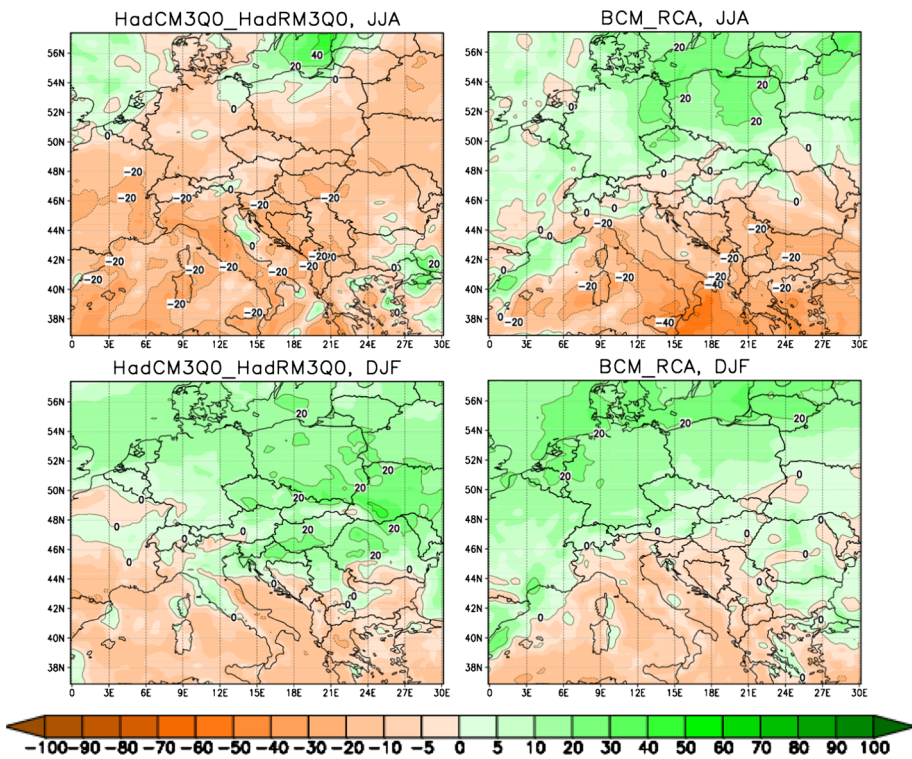
### 2.3 Projection results

The direction of the future temperature tendency is clear for every season and every part of Europe: increase is projected by each regional climate model simulation. According to the investigated RCM results, the warming will reach 0.5 °C and the highest increase is foreseen in summer for both study regions (Fig. 9); however, it does not exceed 3 °C for 2021–2050. The departure between the low and high temperature signals is the largest in summer, approximately 2 °C. There is no significant difference between the ranges for the two catchments, apart from the broader interval over the Upper Danube in winter.

The regional precipitation changes (Fig. 10) are not as evident as the temperature tendencies. Based on the results of HadRM3Q0 providing lower boundary of the low-flow



**Fig. 9** Annual and seasonal mean temperature change [°C] over the Rhine catchment (grey) and Danube catchment (black) based on the results of two RCMs for 2021–2050 with respect to 1961–1990



**Fig. 10** Summer (top) and winter (bottom) mean precipitation change [%] based on the results of two RCMs for 2021–2050 with respect to 1961–1990

signal over both catchment areas for the near-future, a summer precipitation decrease is projected over most Europe. In case of RCA simulation producing higher boundary of the low-flow signal for 2021–2050, the future tendencies of northern and southern regions are different: over South and South-eastern Europe a reduction, while over North and North-

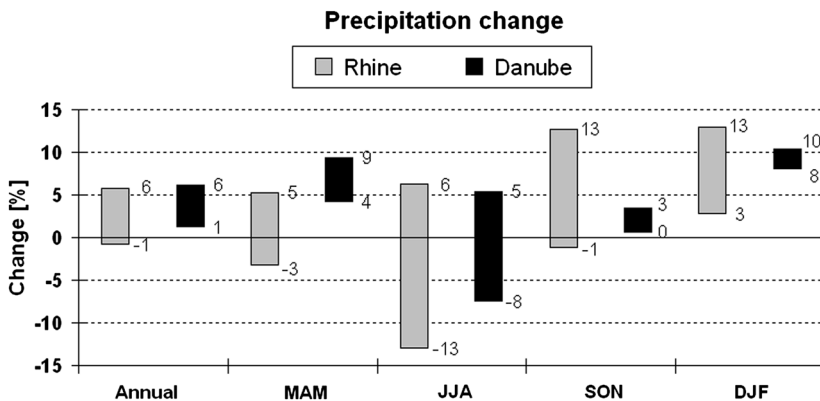
eastern Europe an increase can be foreseen. This feature can be noticed in other season, just the isoline of no-change is moving by seasons.

Figure 11 shows the seasonal precipitation change based on the two selected RCMs describing the low and high boundaries of the low-flow signals over the two catchment areas. The correlation between future change of the two parameters (precipitation and NM7Q, respectively, 90th and 95th quantiles) is not clear, e.g. precipitation decrease is not necessarily linked with low flows in every season. For the River Rhine, the “dry” (“wet”) scenario is mostly dry (wet) in terms of precipitation change for the near-future time horizon, apart from autumn. While the correlation in winter is positive between the two parameters, a general increase (between 3 and 13 %) is noted in both simulations. Precipitation enhancement is indicated by both simulations over the Upper Danube catchment for every season, with the exception of summer, when 8 % reduction is projected by the dry scenario.

## 2.4 Post-processing: bias correction

Although RCMs and GCMs driving RCMs are the current state-of-the-art models to simulate the highly complex climate system, it is well known that these models suffer from imperfections. These imperfections are largely related to incomplete knowledge of certain processes (in the atmosphere, ocean, etc.) and limitations of the spatial and temporal resolution because of available computational resources. As a consequence, model simulations do not reproduce the observed climatology exactly (as demonstrated in validation). Being coupled to hydrological models to determine the future change in various discharge characteristics of the Rhine and Danube, climatic biases are undesired. With a large bias in precipitation, the hydrological model might give a wrong sensitivity to future climate change (especially in the case of nonlinear response), or a correct snow accumulation and melt particularly depend on the proper reproduction of the air temperature. These shortcomings are caused partly by the RCM and partly by the driving GCM. The individual bias of the RCMs can be tested by forcing them with observation-based re-analysis fields (e.g. Arnold et al. 2009); however, in the GCM-driven simulation, the errors of the RCM and GCM cannot be clearly distinguished.

In this study (and in ECCONET), we focus on the overall bias of the different GCM–RCM combinations. Climate models are capable of describing the dynamics of physical processes



**Fig. 11** Annual and seasonal mean precipitation change [%] over the Rhine catchment (*grey*) and Upper Danube catchment (*black*) based on the results of two RCMs for 2021–2050 with respect to 1961–1990

governing the climate system and simulating the response of the system for a hypothetical anthropogenic forcing (quantified by future greenhouse gas emission). To exploit this knowledge in climate impact research, several bias correction methods have been developed.

For the RCM results selected for the Rhine catchment, the *linear scaling method* was applied. Linear scaling manipulates climate model data with the assumption that the bias of a variable is originated from its shifted mean value, whereas its daily distribution is correct or at least of a realistic shape/characteristic. In case of the present model chain, the biases of monthly long-term means are aimed to fit within a reference period. In ECCONET, the E-OBS observation data set is used as reference for the bias correction for 1961–1990. Linear scaling method is applied like in Lenderink et al. (2007) to the simulated daily precipitation amount, daily mean, minimum and maximum temperature for the control period (i.e. 1961–2000) and 2001–2050:

$$\begin{aligned} T_c(t) &= T_r(t) + (\overline{T_{obs}} - \overline{T_{ref,r}}), \\ P_c(t) &= P_r(t) \times (\overline{P_{obs}} / \overline{P_{ref,r}}), \end{aligned}$$

where  $T(t)$  and  $P(t)$  indicate daily temperature and precipitation, the indices of  $c$ ,  $r$ ,  $obs$ ,  $ref$  represent the corrected and raw RCM results, the observations and the raw RCM results for the reference period, respectively, and the overbar represents long-term monthly means over the reference period. The correction factors are calculated on monthly intervals and not on a basis of 10-day intervals like in Lenderink et al. (2007). The modification of the approach and its results for the River Rhine is described in Görden et al. (2010).

For the RCM results selected for the Upper Danube catchment, the *delta-change method* was utilized for bias correction on a monthly scale. The delta-change approach was applied before the results of climate models were published and assumptions of a temperature increase were added to the historical measured temperature records. Since climate model results are available, the delta change is calculated from these results for temperature, precipitation and other variables.

$$\begin{aligned} T_c(t) &= T_{obs}(t) + (\overline{T_r} - \overline{T_{ref,r}}), \\ P_c(t) &= P_{obs}(t) \times (\overline{P_r} / \overline{P_{ref,r}}), \end{aligned}$$

where  $T(t)$  and  $P(t)$  indicate monthly mean temperature and precipitation, the indices of  $c$ ,  $r$ ,  $obs$ ,  $ref$  represent the corrected and raw RCM results, the observations and the raw RCM results for the reference period, respectively, and the overbar represents long-term monthly mean over the reference period. The method and its application in the Danube catchment are described in Kling et al. (2012). Lenderink et al. (2007) state that the excessive hydrological feedback found in the control simulation is carried over to the future climate.

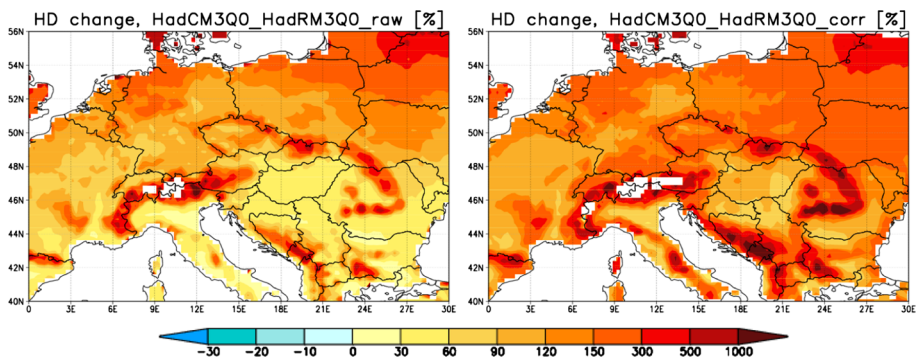
As mentioned, the main target of the linear scaling correction as well as delta-change approach is RCM mean value, i.e. the methods adjust the long-term mean of time series, but it does not necessarily improve other statistical properties (e.g. distribution function) of the simulation results. Concerning the future change, even though these methods do not transform the linear signal (e.g. mean temperature change), they might seriously affect the tendency of nonlinear variables (threshold-related extreme indices, for instance). In this section, the impact of the linear scaling correction method on the climate change signal is briefly demonstrated for two threshold-dependent extreme indices (see Table 2). The uncertainty due to the delta-change bias correction method is not examined here, because it was analysed in Kling et al. (2012) in detail.

**Table 2** Definition of the investigated extreme indices

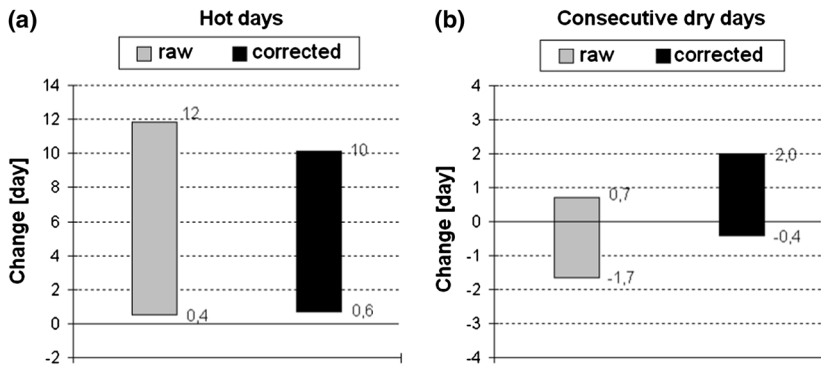
Index	Name	Definition
HD	Annual number of hot days	When daily maximum temperature exceeds 25 °C
CDD	Annual maximum length of dry periods	When daily precipitation does not exceed 1 mm

In the case of temperature-related hot days, the linear scaling method has impact mainly on the magnitude of the change (with stronger *relative* signal in the corrected version), but it does not modify the key spatial features (Fig. 12). Based on the raw and bias-corrected results of HadRM3Q0 (projecting low climate change signal in terms of low-flow parameters), near-future increase is expected in both versions, with the modest relative values over South and South-east, the highest ones in the mountains and over Northern Europe (due to the low frequency of hot days at that places in the control period). Similar overall future intensification is resulted also by the RCM providing high low-flow signal. Focusing on the investigated Rhine catchment (Fig. 13a), the raw results of the two RCMs providing low and high low-flow signals in the near-future period indicate somewhat larger uncertainty than the bias-corrected data: the expected growth does not exceed 10 days in the last case, while the minimum increase is around zero in the raw RCM results.

The bias correction does not have an obvious impact on the climate change signal in case of the extreme indices related to precipitation or its absence. The future change in the maximum number of consecutive dry days indicates large spatial variability that was mainly not affected by correction (not shown). Comparing the corrected RCM data with the raw ones for the Rhine catchment (Fig. 13b), it has to be noted that the post-processed data do not keep necessarily the orientation of the signal: the small negative change below 2 days is almost disappeared (being close to zero) and the similarly low positive change amplified after applying the method. Although the selection process was based on the NM7Q parameter, this outcome allows the conclusion that the procedure would lead to different representative projections if it was based on raw or corrected RCM results. In our case, the latter one was applied, because the hydrological impact models apply bias-corrected data as input. Nevertheless, for the near-future, no change or a slight (2-day) increase of the index can be envisaged over the region based on the corrected model results providing low and high signals.



**Fig. 12** Change of hot days [%] based on the raw (*left*) and bias-corrected (*right*) RCM results for 2021–2050 with respect to 1961–1990



**Fig. 13** Change of **a** hot days and **b** maximum length of dry periods [day] based on the raw (grey) and bias-corrected (black) RCM results providing low and high NM7Q signals over the Rhine catchment for 2021–2050 with respect to 1961–1990

### 3 Hydrological investigations

#### 3.1 Applied hydrological models

The results of the HBV were already used for the selection of the climatological model in Sect. 2.1 and are once more described in the following section. The HBV (Hydrologiska Byråns Vattenbalansavdelning) model used for the River Rhine is a semi-distributed conceptual hydrological model for continuous calculation of run-off, and it was originally developed at the Swedish Meteorological and Hydrological Institute in the 1970s (Bergström 1976; Bergström and Forsman 1973). In the 1990s, major changes in the model structure were made as published by Lindström et al. (1997).

The main components of HBV describe the snow accumulation and melt, the soil moisture processes, the run-off generation and a simple routing method. The spatial discretization is defined by sub-basins which can be further divided into zones of different elevation and land cover (forest, non-forest, lake and glacier). Meanwhile, manifold operational or scientific applications of HBV exist (e.g. in short-range forecasts, climate impact modelling) which are reported from more than 50 countries around the world. The model structure of HBV is described in Görgen et al. (2010) in detail.

The advantage of HBV is that it can be set up with a relative low number of parameters, and it gives a good performance and can be handled easily, which is important, when modelling such a big catchment as the Rhine River basin. As with any model, there are also limitations. These are described and quantified in detail using an inter-model comparison, and an evaluation of some limitations in the specific context of this study is given in Görgen et al. 2010.

The HBV model adopted for the case of the international catchment of the Rhine River is set up in a cooperation between the institutes of RWS-WD (Rijkswaterstaat Waterdienst, Lelystad) and BfG. This version (called HBV134 hereafter) has a daily timestep and covers the catchment upstream of gauge Lobith at the German–Dutch border. HBV134 is calibrated using the CHR\_OBS data, which is a combined raster data set from different national products (Eberle et al. 2005). The calibration of model parameters was achieved on the basis of expert knowledge (Eberle et al. 2005). Several refinements are made in successive studies. Model parameters can be considered to be optimized over the period of

1961–1995, e.g. the parameter “*etf*” defined for each sub-basin affects daily potential evapotranspiration and introduces a relation between air temperature and calibration results.

The hydrological simulations for the Danube are carried out with the water balance model, Continuous semi-distributed run-off model (COSERO; Kling et al. 2006). The considered processes in the model are accumulation and melting of snow, actual evapotranspiration and a separation of run-off in different flow components (surface flow, inter flow and base flow). Melt of glaciers is described in the model via a negative mass balance approach, and a reservoir module is also implemented. The temporal resolution is 1 month. The concept is similar to the HBV model (Bergström 1995). The model structure of COSERO is described in Kling et al. (2006) in detail. The 16 sub-catchments are further subdivided in height zones to improve the snow modelling. Altogether 61 hydrological response units are used for the water balance modelling.

As meteorological input for the calibration and validation of the water balance model, the Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region (HISTALP) database (precipitation, temperature and sunshine duration; Auer et al. 2007; Böhm et al. 2009) is used. To incorporate the detailed spatial distribution of precipitation additionally, detailed maps from the spatial long-term distribution of annual precipitation are used (Petrovic et al. 2006, Kling et al. 2005).

Reservoirs have an important impact on the water balance in the Danube. In the model, the 13 most important reservoirs (capacity > 20 mio m<sup>3</sup>) are considered. The control rules of these reservoirs are available from the project GLOWA Danube (2010). The historical simulation of COSERO considers the reservoir capacities from the year of their completion. As calibration period, 1961–1990 was chosen.

### 3.2 Future scenarios for the River Rhine and River Danube and validation of the model selection

For completion of the ECCONET “workflow” and a navigation-orientated evaluation of the Rhine–Danube river system, three exemplary gauges are evaluated in this article: Kaub, Hofkirchen, and Achleiten. As mentioned, Kaub is situated at the Middle Rhine and can be seen as the most critical shallow water at the River Rhine for navigation between Rotterdam and Basel. Hofkirchen is described as representing the shallow water situated between the Isar confluence and the Inn confluence at the Upper Danube. Achleiten is situated downstream the confluence of River Inn and River Danube, where the discharge regime changes significantly but providing major parts of the water which is relevant for shallow waters downstream in Wildungsmauer (Austria) and Nagymaros (Hungary). These shallow waters are dominating loading capacities of long distant navigation at the Danube.

The evaluation at the River Rhine is based on a 20-member ensemble, which is the basis of the Rheinblick2050 Project (Görgen et al. 2010), too. The ensemble evaluated for the Danube has 20 members from the ENSEMBLES project (Kling et al. 2012). The selection of representative members can be done based on the overall changes in the hydrological regime which can be expected in the near-future as described in detail in Sect. 2.1. Validation takes place on main gauges and the most important tributaries at the River Rhine and the Upper Danube. However, only the validation for the above-mentioned gauges is shown here. As validation of the selected Rhine scenarios for the representativeness at the River Danube, an additional figure is shown.

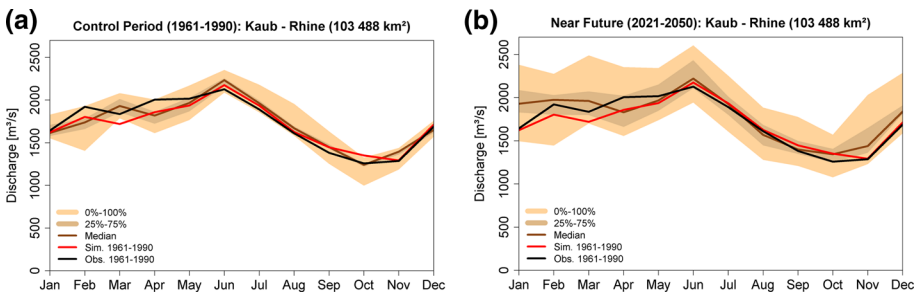
The validation on a basis of monthly long-term means is demonstrated over the River Rhine in Fig. 14a, whereas the black line is indicating the mean monthly discharges



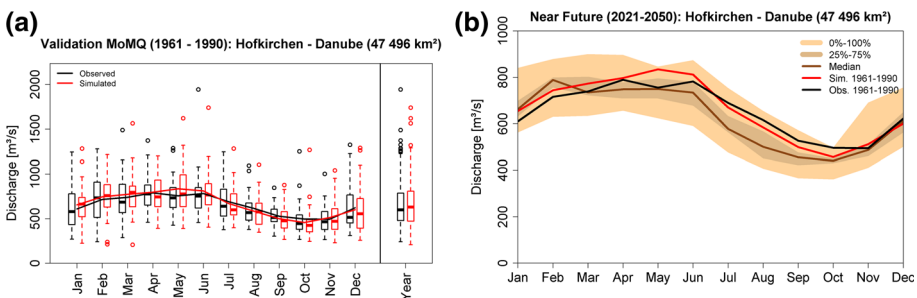
measured at Kaub, the red line is the simulated equivalent of the period 1961–1990. The simulations fit in most months quite well. Only from February until April, within the main snow melt season, a deviation can be seen. Due to the meteorological pre-processing of climate model results, also the comparison of the hydrological response of these results is shown in Fig. 14a for this period. Here, the 25–75 % quantiles and also the 100 % range of all applied climate models can be seen for the Rhine catchment. Also the reference runs show the highest inhomogeneity within the snow melt months, but the range of the hydrological response lies in maximum between  $-200$  and  $200 \text{ m}^3/\text{s}$  and can be seen as quite narrow.

When evaluating the near-future, the range of uncertainty grows especially in winter time. Most of the hydrological signals of the different meteorological forcings are showing increasing discharges between November and March. The rest of the year, no changes are obvious when we compare the simulated reference of 1961–1990 with the mean of the hydrological response ensemble.

The validation of monthly mean discharge values within the reference period of 1961–1990 is shown over the River Danube in Fig. 15a. As described before, the COSERO simulation follows the delta-change approach. Using the delta-change approach, the projected changes of the regional climate projections in the future are added to the observations. Thus, in the control period 1961–1990, the simulations of the different RCMs are identical with the simulation using observed values. Instead, the monthly means of discharges from measured records are compared with the simulated monthly discharges



**Fig. 14** Quartiles of the long-term monthly mean discharge ensemble (based on a 20-member model chain) [ $\text{m}^3/\text{s}$ ] **a** for the control period (1961–1990) and **b** for the near-future (2021–2050) compared with the observed and simulated mean values of the period 1961–1990 at the gauge Kaub/Rhine



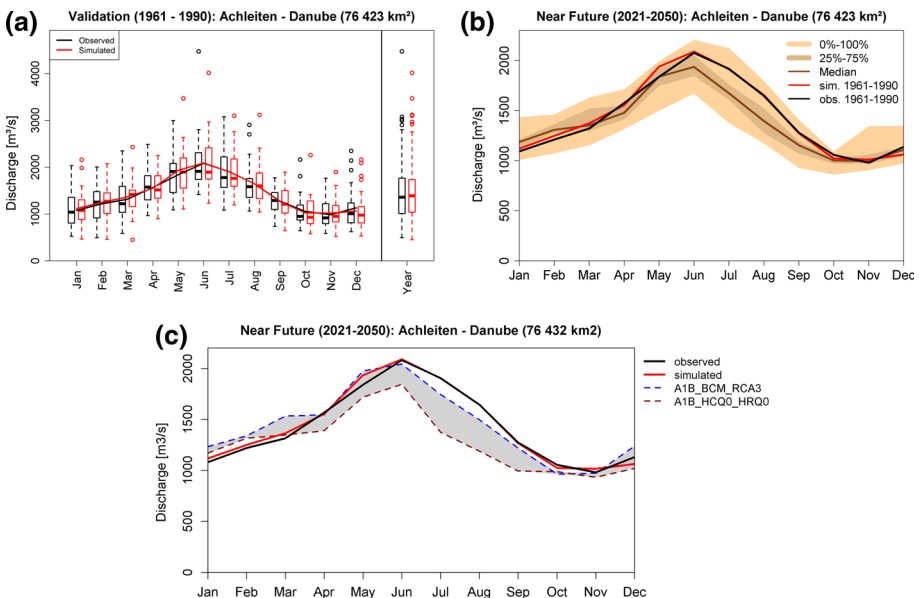
**Fig. 15** Quartiles of the long-term monthly mean discharge ensemble (based on a 20-member model chain) [ $\text{m}^3/\text{s}$ ] **a** for the control period (1961–1990) and **b** for the near-future (2021–2050) compared with the observed and simulated mean values of the period 1961–1990 at the gauge Hofkirchen/Danube

basing on the meteorological input of HISTALP of the reference period. The similarity of long-term mean of simulated monthly discharges and measured monthly discharges is impressively high.

After modifying the meteorological input with climate change deltas from the climate model results collected within the ENSEMBLES project, a certain span of possible hydrological response can be expected. Figure 15b shows the 100 % spread and also the 25–75 % quantiles of the hydrological responses. In comparison with the measured reference from 1961 to 1990, the summer discharges come into focus, which show a slight reduction. During the rest of the year, the observed and the simulated references lie within the 25–75 % quantiles.

Former studies showed irregularities of representative members along the river. At the River Rhine, they were not always the same when evaluating the ensemble results of climate impact. Also different hydrological variables (e.g. NM7Q and the mean annual discharge, MQ) need different representative members. Thus, as described before, the relevant indicator (here focus on low-flow NM7Q) and the critical location (gauge Kaub at the River Rhine) have to be defined before the selection.

The selected scenarios at the River Rhine have been evaluated at the River Danube at different locations and for different parameters. The results have shown that these scenarios could be used for the Danube, too. As an additional evaluation step, the changes in the run-off regime of the selected future projections assumed to be the dry and the wet scenarios by evaluating NM7Q at River Rhine are shown in Fig. 16c and could be compared with the projected changes of the complete ensemble at this gauge in Fig. 16b. In particular, when comparing the uncertainty band represented by the two selected scenarios with the 25–75 % quantiles of the whole ensemble, it can be seen that these two scenarios



**Fig. 16** Quartiles of the long-term monthly mean discharge ensemble [m<sup>3</sup>/s] **a** for the control period (1961–1990), **b** for the near-future (2021–2050) based on a 20-member model chain; and **c** for the near-future (2021–2050) with the selected projections compared with the observed and simulated mean values of the period 1961–1990 at the gauge Achleiten/Danube

provide a good representation of the total uncertainty without consideration of the extreme outliers.

#### 4 Summary, conclusions

In this article, the impacts of climate change on hydrological conditions of River Rhine and River Upper Danube were introduced based on the results of regional climate and hydrological models. Special attention was dedicated to quantify the uncertainties of these scenarios in a simple and effective way. These efforts were motivated by the ECCONET EU FP7 project initiated to determine the climate change impacts on the inland waterway transportation network with the main focus on these two rivers. Nevertheless, the method applied in ECCONET and the approach presented in the paper are not completely the same due to some practical issues (time constraint, data availability for further studies, etc.) to be often faced with the international projects.

The twenty-first century climate change for Europe is described by a number of regional climate model experiments characterized by a range of uncertainties. However, these uncertainties are not restricted on the RCM results: they have consequences on the further studies using the meteorological data and naturally not only climate modelling possesses them, but also hydrological, economical and other impact modelling. Essential objective of ECCONET was to consider these uncertainties in the impact investigations. The time horizon of the project was 2021–2050, until when the emission scenario choice has no relevance, instead the model differences are the leading factor in the total uncertainty. The meteorological basis forming input for the ECCONET impact studies was selected along with the extreme model chains for the Rhine as determined in KLIWAS programme through hydrological modelling that utilized an ensemble of bias-corrected RCM data as input. These representative projections describe the lower and upper boundaries of climate change effects based on the analysis of the lowest seven-day mean discharge (NM7Q) for the near-future. The extreme model chains selected for the River Rhine are evaluated for Upper Danube catchment. (Instead of employing the same thorough method for the River Danube, a simple correlation analysis technique was used in ECCONET).

The validation gave an insight into the performance of the selected RCMs over Europe in general, and over the Upper and Middle Rhine catchment and Upper Danube catchment in particular, using the E-OBS normal period 1961–1990 as a reference data set. To represent the processes playing role in precipitation formation is a challenging area of the model developments even today, and they are described by climate models in different way. The uncertainty due to the various methods applied by climate models together with the high temporal and spatial variability has particularly large effect on the quality of precipitation simulations.

To avoid the impact of the systematic errors, the ECCONET studies are based on bias-corrected instead of raw meteorological data. This is especially desired, since the climatic time series are coupled with hydrological impact models of the Rhine and Danube to determine the future change in various discharge characteristics, and the large biases often make unreasonable to apply the raw simulated data as for hydrological models. In ECCONET, the focus was on eliminating the overall bias of the different GCM-RCM combinations using the linear scaling method for the River Rhine and the delta-change approach for the River Danube. The bias correction was accomplished for the 2-m temperature and precipitation, in the case of linear scaling also on daily scale.

The post-processed RCM data serve as input for the hydrological modelling. For the River Rhine, the HBV model is used which describes the processes of snow accumulation, snow melt, soil moisture and run-off with daily time step. For the Upper Danube catchment, the COSERO model is employed which has monthly temporal resolution. In the first hydrological studies, the results obtained by using the whole (20-member) RCM ensembles are assessed for three gauges, Kaub at the Middle Rhine, Hofkirchen and Achleiten at the Danube. For the latter point, the results of the representative projections (the extreme model chains) are evaluated and compared with the results of the “grand” ensemble, as well.

The main conclusions of the investigations are summarized below:

- The validation of the selected RCMs indicated that while the temperature simulations of the RCMs are reasonable with lower errors, the RCMs have several deficiencies in representing the details of the precipitation climatology. Over the Upper Danube catchment, the simulation results were characterized by overestimation, whereas for Rhine, one of the RCMs was not capable of reproducing the seasonal cycle.
- Over the two areas of our interest, a general temperature increase can be envisaged for 2021–2050 based on the results of the representative projections, which is accompanied by intensification of the upper temperature extreme indices like hot days. The linear scaling applied for bias correction over the River Rhine affects only the magnitude of the change of hot day occurrences: the relative climate change signals are stronger based on the corrected data than on the original ones.
- The precipitation tendencies are not so evident. For the River Rhine, one of the representative scenarios projects some decline, while the other one renders an increase in the near-future, apart from winter. Over the Upper Danube catchment, the wet and dry scenarios often provide same precipitation change: increase in every season apart from summer. The linear scaling can modify the orientation of the slight changes in the case of the precipitation-related indices, like maximum number of consecutive dry days. This outcome allows the conclusion that the procedure would result in different representative projections if it was based on raw or corrected RCM data.
- The results of the run-off projections indicate an increasing discharge for the River Rhine between November and March and no clear tendency of change in the rest of the year. Considering low-flow parameters, such as the lowest seven-day discharge in summer, there is also no clear tendency of change for the period 2021–2050 at the River Rhine. Over the Upper Danube catchment, most model simulations tend to the minor reduction in summer and autumn months. Focusing on the selected two representative projections, it can be concluded that they follow the same tendency.

Some further general conclusions are as follows:

- To account for the uncertainties existing in every step of the climate change impact studies and provide a range of possible futures, an ensemble, as generated via a multi-model approach using different GCMs and RCMs, different impact (e.g. hydrological) models, should be used. However, it is important to note that reality may actually lie outside this range, and ECCONET does not aim to quantify the complete uncertainty range. (In practice, this would not possible due to the partial representation of the individual uncertainties by the large international projects.)
- ECCONET is specifically based on existing application tools of former climate change and hydrological research works. The collection of data from numerous projects in

several study areas is possible to set side by side, but a variety of approaches due to different targets make difficult to compare their results. Usually the projects are in different stages and potential assumptions sometimes obvious and reliable for one study area turn out to be unlikely for the other.

- The spatial heterogeneity of climate model results, hydrological systems and economical interests make the individual analysis of each model system obviously necessary. The comparison of different hydrological model systems must be validated on the basis of one study area, before they can be compared at different study areas.

**Acknowledgments** The authors would like to express their special thanks for *Tanya Prozny* for her invaluable work in the construction of model selection method. Grateful thanks are given to the reviewers for the revision work contributed significantly to the improvement of the manuscript. The regional climate model data used in this work were funded by the EU FP6 Integrated Project ENSEMBLES (contract number GOCE–CT–2003–505539). We acknowledge the E-OBS data set from the EU-FP6 project ENSEMBLES (<http://ensembles-eu.metoffice.com>) and the data providers in the ECA&D project (<http://eca.knmi.nl>). Special thank is going to the modelling groups of the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model data set. Support of this data set is provided by the Office of Science, US Department of Energy. The work is supported by the ECCONET EU-FP7 project (contract number 233886; <http://www.econet.eu>).

## References

- Arnold J, Pall P, Bosshard T, Kotlarski S, Schär C (2009) Detailed study of heavy precipitation events in the Alpine region using ERA40 driven RCMs. ENSEMBLES Deliv D5(32):49
- Auer I, Böhm R, Jurkovic A, Lipa W, Orlik A, Potzmann R, Schöner W, Ungersböck M, Matulla C, Briffa K, Jones PD, Efthymiadis D, Brunetti M, Nanni T, Maugeri M, Mercalli L, Mestre O, Moisselin J-M, Begert M, Müller-Westermeier G, Kveton V, Bochnicek O, Stastny P, Lapin M, Szalai S, Szentimrey T, Cegnar T, Dolinar M, Gajic-Capka M, Zaninovic K, Majstorovic Z, Nieplova E (2007) HISTALP—Historical instrumental climatological surface time series of the greater Alpine region 1760–2003. *Int J Climatol* 27:17–46
- Bergström S (1976) Development and application of a conceptual runoff model for Scandinavian catchments. SMHI Reports RHO, No. 7, Norrköping
- Bergström S (1995) The HBV model. In: Singh VP (Ed) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, CO, USA, ISBN 0-918334-91-8
- Bergström S, Forsman A (1973) Development of a conceptual deterministic rainfall-runoff model. *Nord Hydrol* 4(3):147–170
- Böhm R, Auer I, Schöner W, Ganekind M, Gruber Ch, Jurkovic A, Orlik A, Ungerböck M (2009) Eine neue Webseite mit instrumentellen Qualitäts-Klimadaten für den Großraum Alpen zurück bis 1760. In: Wiener Mitteilungen Band 216, Hochwässer: Bemessung, Risikoanalyse und Vorhersage, 7–20
- Christensen JH (2005) Prediction of regional scenarios and uncertainties for defining European climate change risks and effects. Final Report. Danish Meteorological Institute, Copenhagen, p 269
- Eberle M, Buitefeld H, Wilke K, Krahe P (2005) Hydrological modelling in the river Rhine basin, Part III—Daily HBV model for the Rhine Basin. BfG-Berichte, BfG-1451. Federal Institute of Hydrology, Koblenz
- Giorgi F, Bates G (1989) The climatological skill of a regional model over COMPLEX terrain. *Mon Weather Rev* 117:2325–2347
- GLOWA-Danube-Project (2010) Global Change Atlas. Einzugsgebiet Obere Donau, LMU München (Hrsg.), München
- Görgen K, Beersma J, Brahmeh G, Buiteveld H, Carambia M, de Keizer O, Krahe P, Nilson E, Lammersen R, Perrin C, Volken D (2010) Assessment of climate change impacts on discharge in the Rhine River Basin: Results of the RheinBlick2050 Project. CHR report, 1–23, p 229, Lelystad, ISBN 978-90-70980-35-1
- Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. *B Am Meteorol Soc* 90:1095–1107

- Hawkins E, Sutton R (2011) The potential to narrow uncertainty in projections of regional precipitation change. *Clim Dyn* 37:407–418
- Haylock MR, Hofstra N, Klein Tank AMG, Klok EJ, Jones PD, New M (2008) A European daily high-resolution gridded dataset of surface temperature and precipitation. *J Geophys Res*. doi:[10.1029/2008JD10201](https://doi.org/10.1029/2008JD10201)
- IPCC (2007) Fourth assessment report: climate change 2007. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *The physical science basis. Contribution of Working Group I of the fourth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge, United Kingdom and New York, USA, p 996
- Jacob D, Bärring L, Christensen OB, Christensen JH, Hagemann S, Hirschi M, Kjellström E, Lenderink G, Rockel B, Schär C, Seneviratne SI, Somot S, van Ulden A, Van den Hurk B (2007) An inter-comparison of regional climate models for Europe: design of the experiments and model performance. *Climatic Change* 81:31–52
- Kling H, Nachtnebel HP, Fürst J (2005) Mean annual areal precipitation using water balance data. In *Hydrological Atlas of Austria, BMLFUW* (ed), 2nd edition, map sheet 2.3, Vienna, ISBN 3-85437-250-7
- Kling H, Fürst J, Nachtnebel HP (2006) Seasonal, spatially distributed modelling of accumulation and melting of snow for computing runoff in a long-term, large-basin water balance model. *Hydrol Process* 20:2141–2156
- Kling H, Fuchs M, Paulin M (2012) Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. *J Hydrol* 424–425:264–277
- KLIWAS (2009): Impacts of climate change on waterways and navigation in Germany. Federal Ministry of Transport, Building and Urban Development. In: *Proceedings of the first status conference*, Bonn
- Lenderink G, Buishand TA, Van Deursen W (2007) Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. *Hydrol Earth Syst Sci* 11:1145–1159
- Lindström G, Johansson B, Persson M, Gardelin M, Bergström S (1997) Development and test of the distributed HBV-96 hydrological model. *J Hydrol* 201:272–288
- Nakicenovic N et al (2000) Special report on emissions scenarios: a Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
- Nilson E, Krahe P (2012) Zum Transfer der Unsicherheiten von Abfluss-Projektionen des 21. Jahrhunderts in den politisch-administrativen Raum (in German). In: Weiler, M. (Ed.): *Wasser ohne Grenzen. Forum Für Hydrologie und Wasserbewirtschaftung, Beiträge zum Tag der Hydrologie am 22./23. März 2012 an der Albert-Ludwigs-Universität Freiburg*, Heft 31.12, S.:287–292
- Nilson E, Lingemann I, Klein B, Krahe P (2012) Impact of hydrological change on navigation. Deliverable 1.4 of the ECCONET project. Available at: [http://www.econet.eu/deliverables/ECCONET\\_D1.4\\_final.pdf](http://www.econet.eu/deliverables/ECCONET_D1.4_final.pdf)
- Petrovic P, Nachtnebel HP, Zimmermann L, Kling H, Kovács P, Brilly M (2006) Basin-wide water balance in the Danube river basin. *The Danube and its basin—hydrological monograph follow-up Volume VIII, IHP UNESCO*, p 161
- Szépszó G, Horányi A (2008) Transient simulation of the REMO regional climate model and its evaluation over Hungary. *Időjárás* 112:203–231
- te Linde AH, Aerts JCJH, Hurkmans RTWL, Eberle M (2008) Comparing model performance of two rainfall–runoff models in the Rhine catchment using different atmospheric forcing data sets. *Hydrol Earth Syst Sci* 12:943–957
- van der Linden P, Mitchell JFB (2009) *ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project*. Met Office Hadley Centre, Exeter