ASSESSING CLIMATE CHANGE IMPACTS ON WATER BALANCE IN THE UPPER DANUBE BASIN BASED ON A 23 MEMBER RCM ENSEMBLE

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Abstract

Increasing global temperatures as indicated by climate projections of the Fourth Assessment Report of the IPCC would lead to changes in the hydrological cycle. This would have various impacts on natural and managed aquatic systems such as the transboundary River Danube with its various economic and ecological functions. Against this background adaptation measures have to be developed to fulfil or improve these functions also in the future. Due to the large uncertainties of the future climatic evolution and the complexity of the system there are also large uncertainties in the future water balance of river basins. Hence a “multi-model approach” has to be used to account for the uncertainties that lead to a range of potential future changes. Here the simulation runs of 23 Regional Climate Models from the EU-ENSEMBLES project are used as input of the semi-distributed water balance model “COSERO” running with a monthly time step. This model is calibrated for twelve sub basins of the Upper Danube River up to the gauge Achleiten at the German-Austrian border (76.660 km²). With the results of the water balance simulations it is possible to analyse possible changes of the runoff in the Upper Danube basin up to the end of the 21st century. The bandwith of the results at gauge Achleiten indicates changes in the runoff regime due to a changed snow regime and a reduction of runoff in summer due to an increased evapotranspiration. In this study the impact of climate change on monthly water balance is analysed. Hence no conclusions on high flow situations and only indirect conclusions on low flow situations can be drawn from these results.

Key words climate modelling, changes in hydrological regime, emission scenarios

Introduction

According to the 4th Intergovernmental Panel on Climate Change (IPCC) assessment report on climate change (IPCC 2007) there is a clear evidence for anthropogenically induced climate changes. Among the findings is an observed and projected warming of the climate system. In the Upper Danube basin regional studies (KLIWA 2005, GLOWA Danube 2010) also reveal increasing trends of observed temperatures and changes in seasonality of precipitation in the past. Analysing the projected change in future by regional climate models for the Upper Danube region the median of the projected temperatures of 18 regional climate models show an increase of about 2.5 °C in the near (2021-2050), and 4 °C in the far future (2071-2100) in meteorological summer (June, July, August) and an increase of about 2 °C in the near and 3.5 °C in the far future in meteorological winter (December, January, February) compared with the period 1961 to 1990 (Klein et al. 2011). For precipitation the change signal of the models is less significant than for temperature but the models show a general tendency of a decrease in summer and an increase in winter precipitation (see e.g. Klein et al. 2011). These changes in meteorology will effect water balance in the Upper Danube region. Due to the complex structure and the large elevation gradients of the Alps climate models show particular large differences. Because of these large differences it is important to use a multi-model approach to analyse the impact of climate change in the Upper Danube basin to account for these uncertainties.

For the Upper Danube region these aspects are also addressed by the interdisciplinary research programme “KLIWAS – Impacts of climate change on navigation and waterways – options to adapt” initiated by the Federal Ministry of Transport as well as by the two EU funded projects “AdaptAlp – Adaptation to Climate Change in the Alpine Space” (INTERREG IV) and “ECCONET - Effects of climate change on the inland waterway networks” (EU FP 7). This paper shows preliminary results from these ongoing research projects in the Danube river basin.

In the recently finished project GLOWA-Danube the impact of change in climate, population and land use on the water resources of the German part of the Upper Danube was assessed. The future climate scenarios for the time horizon 2011-2060 are generated from a stochastic climate change scenario generator. Four different trends of temperature and precipitation are considered in the generation of the climate change scenarios. Additionally, the results of the regional dynamic climate models MM5 and REMO driven by the global climate model ECHAM5 and the IPCC emission scenario A1B are used for the analysis. The main results with respect to the water balance show a reduction of the mean annual discharge at gauge Achleiten between 9% and 31% up to the year 2060 and a change in seasonality with the maximum discharges moving from summer to spring.

Statistical methods can be applied on measured data to give an overview of present trends of the hydrological systems, but they are insufficient to perform a long-term prediction of climate change impacts. Hence in this paper a water balance model is applied on a monthly time step to assess impacts of climate change on water balance of the Upper Danube basin using an ensemble of regional climate model projections as input.

Method

In the recent years, global and regional climate models have improved significantly in terms of resolution, process incorporation and parameterisation. As a consequence the models are an increasingly better representation of reality. But in face of the large uncertainties in climate modelling there is no and there will never be a single “true” climate model run. Different but equally inevitable sources of uncertainty are e.g. internal variability due to the deterministic-chaotic behaviour of the climate system, the emission scenario uncertainty and model uncertainty due to the simplification and incomplete knowledge of the system. For a more detailed overview of the different sources of uncertainty in climate modelling see Hawkins & Sutton (2009, 2010) and an evaluation of the uncertainties in hydrological modelling see Krahe et al. (2009).

Because of these large uncertainties an ensemble must be used ideally by coupling all available global climate models, various regionalisation models, and different hydrological models. Also bias-correction methods need to be applied to account for systematic errors (Mudelsee et al. 2010).

Here the current best established regional climate multi-model ensemble from the EU-ENSEMBLES (2009) project are used for the assessment of the impact of climate change on the water balance. Altogether 23 regional climate simulations are used. The climate model chain consists of several combinations of 7 global climate models (GCM) and 12 regional climate models (RCM) all driven by the same IPCC emission scenario A1B. Within the KLIWAS research programme (Nilson et al. 2010) several other model chains will be analysed in the Upper Danube basin in future. Fig. 1 shows the selected model chains of the KLIWAS framework.

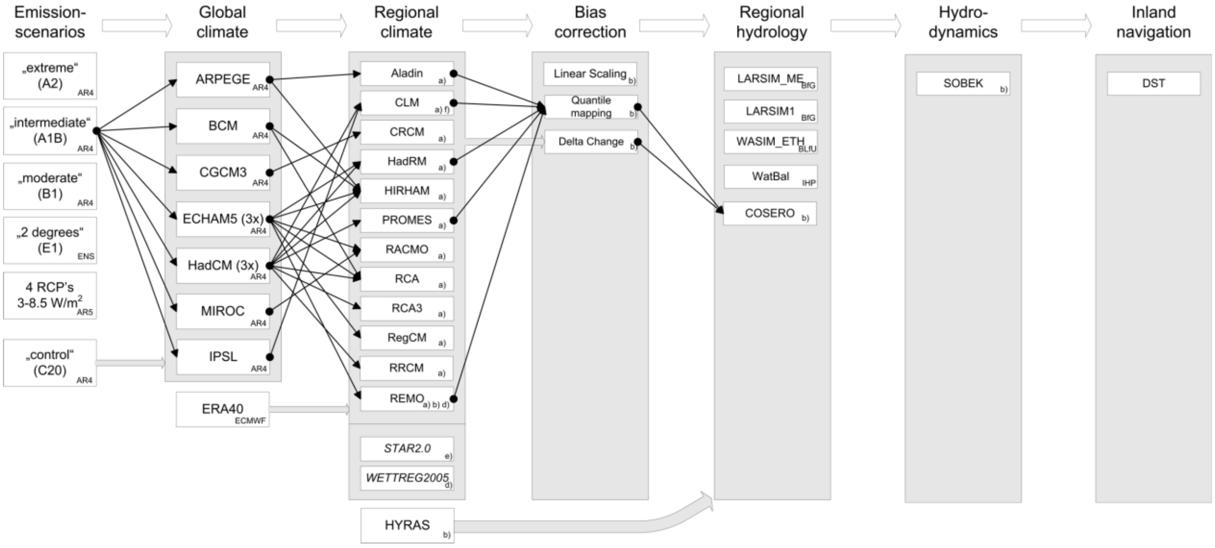

Fig. 1: Model chains considered in this paper from the database of the multi-model approach in KLIWAS project 4.01 Hydrology and Inland Navigation. Sources: (a) EU-ENSEMBLES, (b) BMVBS-KLIWAS, (c) KHR-Rheinblick2050, (d) REMO_UBA, (e) PIK-STAR, (f) BMBF-CLM, (g) CMIP3/IPCC_AR4, (h) CMIP5/IPCC_AR5 (changed after Nilson et al. 2010).

Within such a modelling or processing chain each step is associated with specific uncertainties. The process of accumulation of uncertainty with each step in the model chain throughout the process of climate change analysis and impact assessment has been described as the "uncertainty cascade" (Schneider 1983) and "uncertainty explosion" (Henderson-Sellers 1993). Hence, the ensemble of simulations at each processing step shows a bandwidth of respective results.

study area

The study area (Fig. 2) is the Upper Danube basin up to the German-Austrian border at the gauge Achleiten, which covers an area of 76 660 km². It is shared by the four countries, Germany, Austria, Switzerland and Italy. The elevation ranges from an altitude of 287 m a.s.l. (gauge Achleiten) up to a maximum of 4049 m a.s.l. (Piz Bernina). These large differences in altitude lead to strong meteorological gradients in annual precipitation sums ranging from 500 mm to over 2000 mm. The mean annual discharge at the outlet Achleiten is 1420 m³/s. The largest tributary is the River Inn with a catchment area of 26 000 km² which has on average a greater discharge than the receiving Danube River. The mean discharge of the Inn river is 740 m³/s (gauge Passau-Ingling). Other important tributaries are the Alpine rivers Iller (2152 km²), Lech (3926 km²) and Isar (8370 km²) and the northern tributaries of the Danube draining the low mountain range are Altmühl (3258 km²), Naab (5512 km²) and Regen (2876 km²). For the analysis of the water balance the Upper Danube is divided in 12 subbasins with catchment sizes ranging from 2157 km² (Catchment Nr. 8 Kajetansbruecke located at the Upper Inn) to 9193 km² (Catchment Nr. 11 Schaerding located at the Lower Inn).

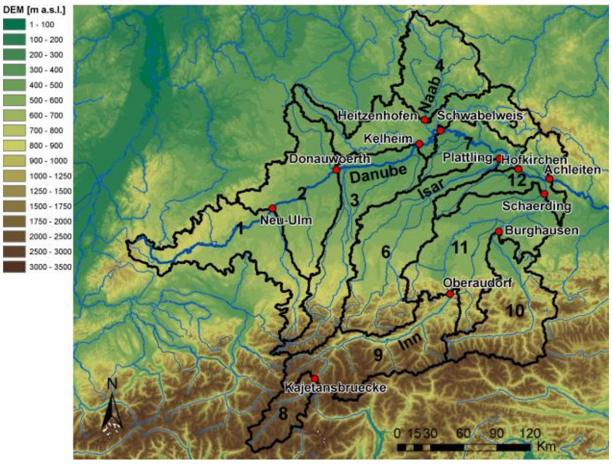

Fig. 2: Catchment of the Upper Danube River and subcatchments considered in the water balance simulation

The flow regime at the gauge Hofkirchen (see Fig. 3) after the inflow of the Alpine river Isar in the Danube shows a complex broad-peaked runoff regime from an overlapping of precipitation and snowmelt influence. After the classification of Pardé (1964) it is a pluvio-nival regime. After the confluence of the River Inn the flow regime of the Danube River at the gauge Achleiten shows a pronounced, single-peak mountain snow regime (glacial-nival). The early summer maximum slowly reduces in time as a result of an superposition of high-mountain glacial melt and summer storm water. The analysis of the runoff regime of different time periods in Fig. 3 reveals that the discharge regime has changed in the past. It shows a decrease of monthly discharge in summer and an increase in winter at both gauges within the observed time. This change is caused by the construction of the large Alpine reservoirs, but some part of this change could also be an indicator for a change towards a more rainfall dominated regime over time.

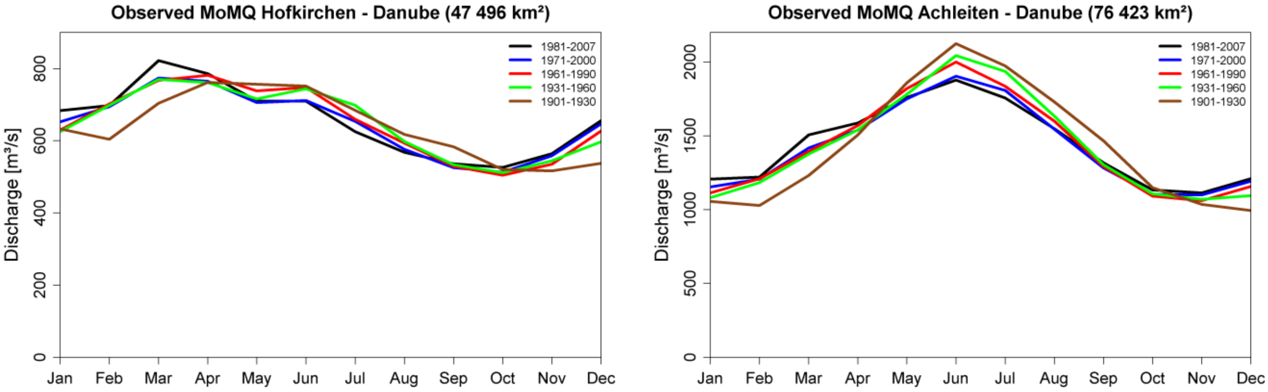

Fig. 3: Observed long-term mean monthly discharges at the gauges Hofkirchen and Achleiten for different time periods

WATER BALANCE MODEL COSERO

The hydrological simulations are carried out with the water balance model COSERO (**Co**ntinuous **se**mi-distributed **r**un**o**ff model) (Kling 2006). It is a continuous, semi-distributed deterministic precipitation-runoff model. The considered processes within the model are accumulation and melting of snow, actual evapotranspiration and a separation of runoff in different flow components (surface flow, inter flow and base flow). Melt of glaciers is considered within the model via a negative mass balance approach. A reservoir module is also implemented in the model. The temporal resolution is one month.

The subcatchments in Fig. 2 are further subdivided in height zones to improve the snow modelling. Altogether 45 hydrological response units (12 regions and 5 classes of elevation) are used for the water balance modelling.

As meteorological input for the calibration and validation of the water balance model the HISTALP database (of precipitation, temperature and sunshine duration (Böhm et al. 2009) are used within this study. 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 14 most important reservoirs (capacity > 20 mio m³) are considered. The control rules of these reservoirs are available from the project GLOWA Danube (2006). The historic simulation of COSERO considers the reservoir capacities from the year of their completion. Fig. 4 shows exemplarily for the Inn catchment that the real reservoir capacity is almost completely implemented in COSERO.

With such a tool the effect of the reservoirs on the water balance can be analysed. Fig. 5 shows simulation results with and without reservoirs. It can be seen that parts of the snow melt is stored in the reservoirs in late spring/summer for a later electricity production in winter time. This leads to an equalisation of the annual cycle in glacial-nival regimes.

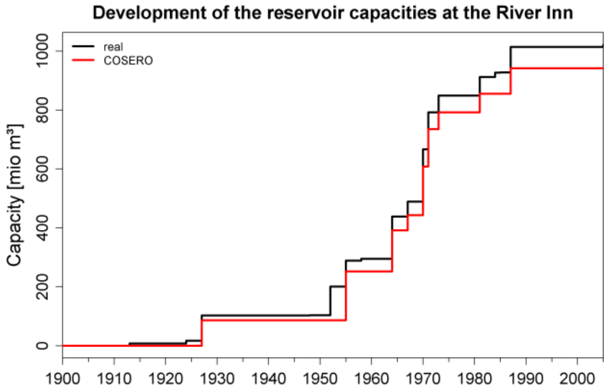

Fig. 4: Temporal development of the cumulated reservoir capacity in the Inn catchment (various data sources) and the capacity considered in COSERO

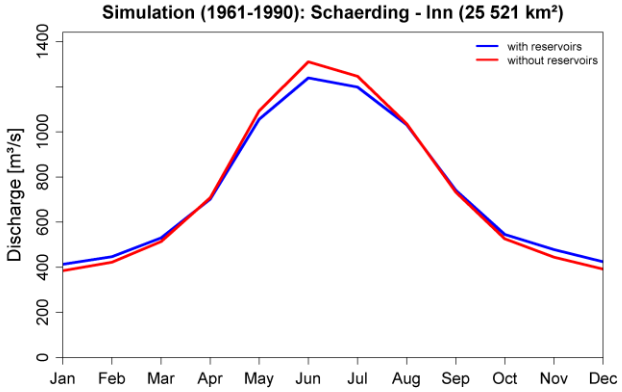

Fig. 5: Simulated long-term mean monthly discharges of the Inn catchment with and without the influence of reservoirs

Fig. 6 shows the comparison of simulated and observed long-term mean monthly discharge and the distribution of the individual monthly values as box-whisker-plots of the period 1961 – 1990 of the two gauges Hofkirchen and Achleiten. A good agreement between the simulation of the model and the observation can be seen there.

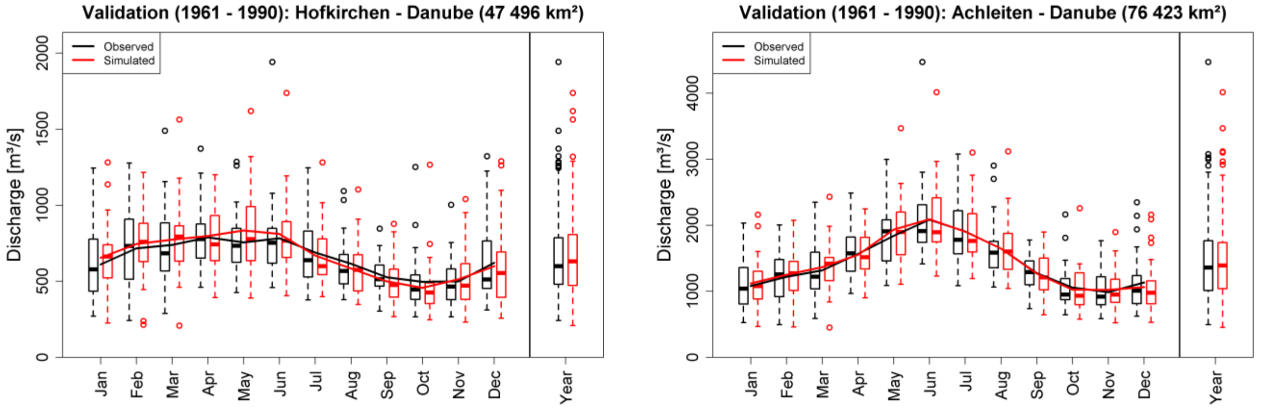

Fig. 6: Comparison between the simulated and observed long-term (1961-1990) monthly mean discharge and the distribution of the simulated and observed monthly values within the different months of the gauges Hofkirchen and Achleiten

Climate change projections as basis for hydrological simulations in the Upper Danube Basin

The downscaling techniques and the driving global climate models presented in Fig. 1 are state-of-the-art - since 2005 (regarded as "current" here). It cannot be expected that these models reproduce observed data exactly because they represent simplifications of the real system. Simulations of the climate of the 20th century show that all regional climate models have limitations in reproducing the present climate (commonly denoted as 'bias') which differ by region, season and meteorological variable. Fig. 7 and Fig. 8 show this differences of the long-term (1961-1990) mean monthly precipitation sums and temperature between the observations and the 23 different regional climate model runs considered here.

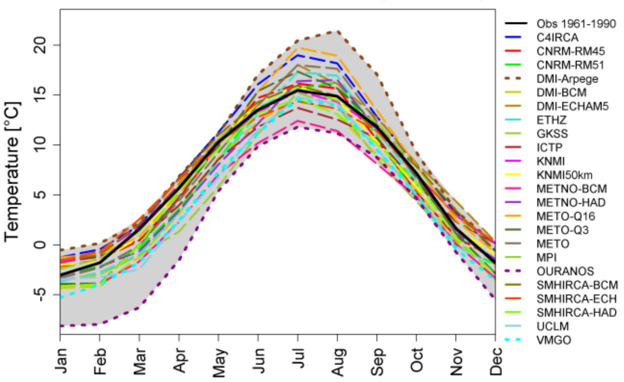

Fig. 7: Long-term (1961-1990) mean monthly temperature for the whole catchment upstream of gauge Achleiten derived from 23 different regional climate model runs (data source ENSEMBLES 2009)

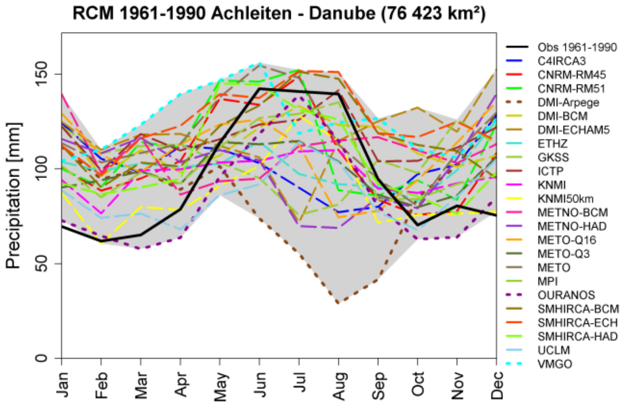

Fig. 8: Long-term (1961-1990) mean monthly precipitation sums for the whole catchment upstream of gauge Achleiten derived from 23 different regional climate model runs (data source ENSEMBLES 2009)

These biases are so large, that a directly use of simulated data as input to hydrological models becomes unreasonable. The nonlinearity of hydrological model equations would lead to implausible responses. Hence, a bias-correction has to be applied.

Statistical bias correction fits model output to the observation data of the same period. Some regional climate simulations have biases which are beyond plausibility, as the spatial and seasonal distribution of the simulated meteorological variables are completely different than the distribution of the observed data. Here after a detailed analysis three models (OURANOS, VMGO, DMI-Arpege) marked with dotted lines in Fig. 7 and Fig. 8 are not considered in further analysis.

In this study the "delta-change" approach (Fowler et al. 2007) is applied to the meteorological variables temperature and precipitation of all regional climate model runs in order to overcome the bias. By applying the delta change method the monthly change signals between the period 1961-1990 and respectively 2021-2050 and 2071-2100 are calculated for each hydrological response unit. These change signals are attached to the original timeseries from 1961-1990. Using this method the time series in the future have the same sequence of wet and dry periods as well as warm and cold periods as in the observed time series from 1961-1990. But these climate conditions can change in future as well. Hence, for five selected RCM models the statistical bias correction method "quantile mapping" (Piani et al. 2010) has been applied to assess the uncertainties of the different correction methods.

impact of climate change on the water balance Resulting from Discharge Projections

The output of the resulting hydrological multi-model ensemble is analysed for the periods 2021-2050 and 2071-2100. The analysis of climate change impacts on water balance is focused on long-term means of monthly discharges for the gauges Hofkirchen and Achleiten.

Additionally the projected change of long-term means of annual runoff as well as mean runoff in hydrological summer half year (defined as period 1.5.-31.10.) and hydrological winter half year (1.11. – 30.04.) are analysed for all gauges in the study area. As described above three regional climate models are not considered because of large biases. Furthermore, not all regional climate simulations are available up to the year 2100. Hence for the analysis of the near future (2021-2050) 20 runoff projections and for the far future (2071-2100) 15 runoff projections are available. For brevity only the results from the delta change approach are presented here because the results from the five projections bias-corrected with quantile mapping do not differ significantly from the delta-change approach in long-term mean monthly values.

The different runoff projections represent the bandwith of possible results. Fig. 9 shows the comparison between observed (1961-1990) and projected long-term mean monthly discharges at the two gauges Hofkirchen and Achleiten for the near and the far future. The bandwidth of the results is represented by the min, max, 25% quartile, 75% quartile, and median of the ensemble for each month. For the near future (2021-2050) the results at both gauges show a tendency to a moderate decrease of summer runoff and an increase of winter runoff. The seasonality changes with the maximum occurring earlier in the year. The uncertainty band 25%-75% representing 50% of the projections is relatively narrow at both gauges.

For the far future (2071-2100) this uncertainty band increases. Nevertheless all projections show a significant reduction of summer runoff and the change in seasonality is more pronounced at both gauges. During the summer months (June – September) the observation is outside of the uncertainty band of the ensemble. This means that even the most optimistic model shows a decrease in summer runoff. Concentrating on the median of the projections the projected reduction of mean monthly summer runoff in the far future is about 200 m³/s at the gauge Hofkirchen and respectively 500 m³/s at gauge Achleiten by comparing with the simulated values from 1961-1990. The reduction of summer runoff is a consequence of the increased actual evapotranspiration due to higher temperatures. The changes in seasonality are caused by a temperature influenced change in snow accumulation and snowmelt. These processes are affecting the snow regime.

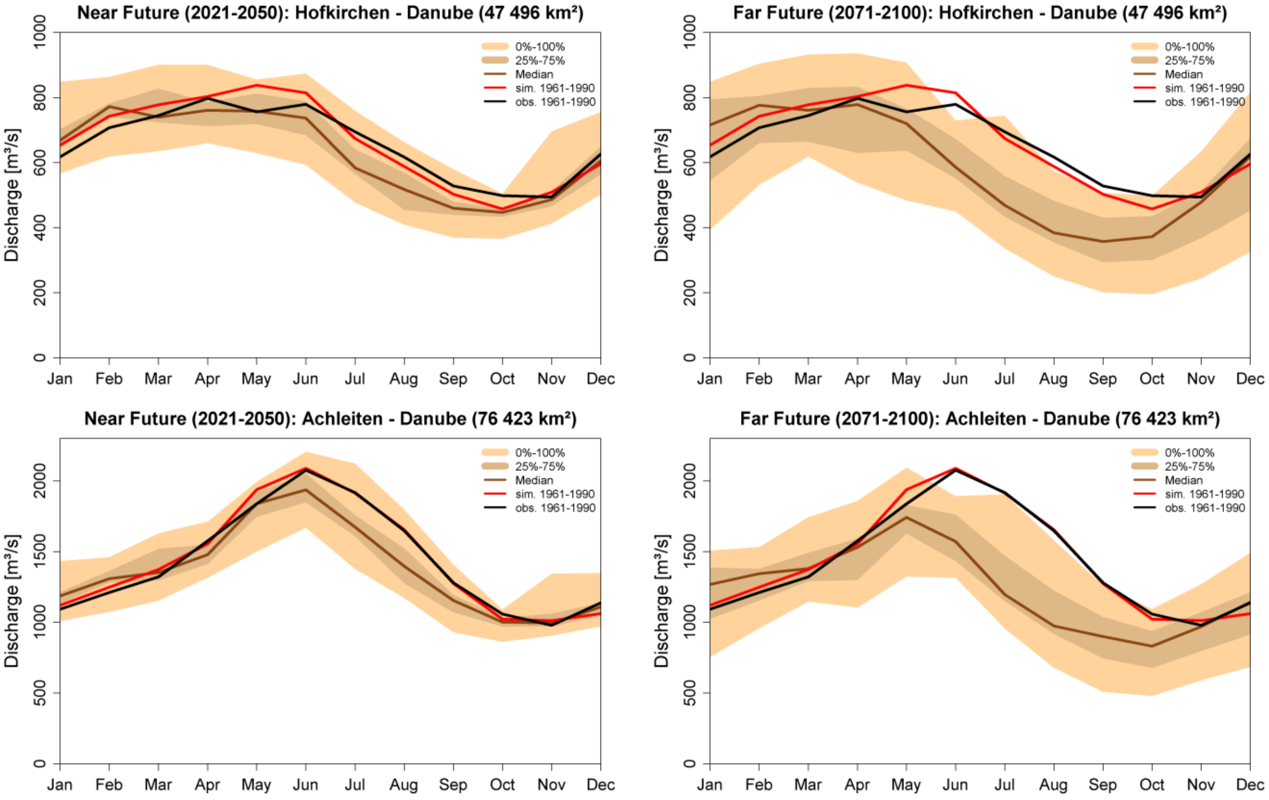

Fig. 9: Quartiles of the simulated long-term monthly mean discharge ensemble of the near (2021-2050) and far future compared with the observed and simulated values of the period (1961-1990) for the gauges Hofkirchen and Achleiten

Fig. 10 shows the changes of mean annual discharge in future for all model subbasins and all runoff projections in comparison with the control period 1961-1990. For the near future (2021-2050) the projected changes are between +10% and -20% except for the gauge Heitzenhofen which shows changes between +20% and -10%. For the far future (2071-2100) for nearly all gauges and all projections the mean annual runoff decreases between -50% and 0%. At the gauge Heitzenhofen no clear tendency with changes between -35% and + 20% can be identified. The discharges at the gauge Heitzenhofen shows a different regime than the other gauges because the river Naab originates North of the Danube in low mountain range and is influenced mostly by precipitation.

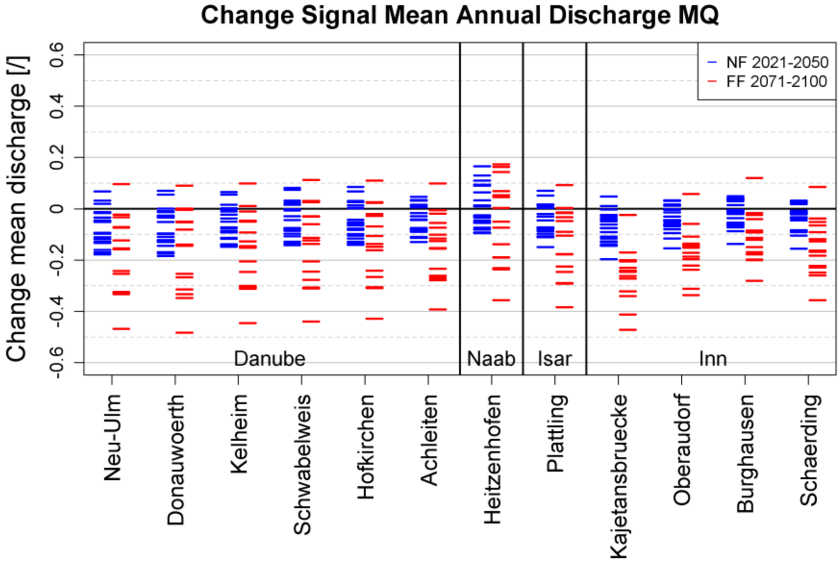

Fig. 10 Projected relative changes for the mean annual discharge MQ with reference to the control period 1961 – 1990. Each blue or red line segment represents a single climate projection. 21 for the near (2021-2050) and 16 for the far future (2071-2100).

Analysing these changes separately for hydrological summer half year (01.05.-31.10.) and hydrological winter half year (01.11.-30.04.) the picture is divided (see Fig. 11 and Fig. 12). In summer for all gauges except Heitzenhofen and almost all projections the mean discharge show a clear tendency to decrease between -25% and 0% for the near future and -55% and 0% for the far future.

In hydrological winter half year for the gauges located at the Danube no clear tendency can be identified and for the gauges in the Inn subbasin a clear tendency to an increase of runoff can be identified for the near and the far future. This increase in the high Alpine region is caused by the projected precipitation increase in winter time and changes in snow accumulation.

These are changes in mean annual and seasonal discharge values. Therefore, no conclusions can be drawn on future low flow and high flow situation at the Danube.

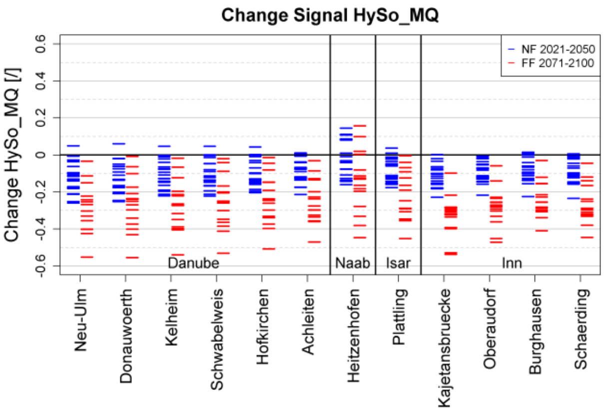

Fig. 11: Projected relative changes for the mean discharge HySo_MQ in the summer half year

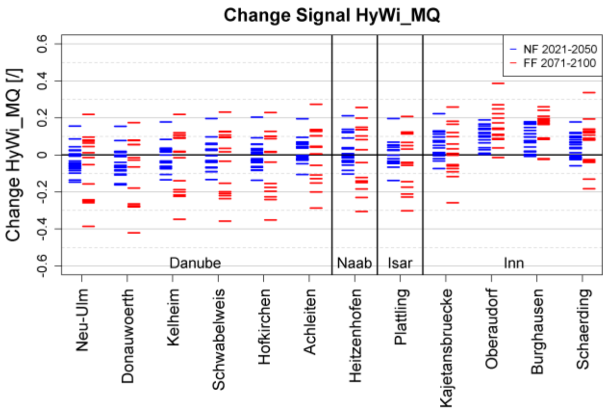

Fig. 12: Projected relative changes for the mean discharge HyWi_MQ in the winter half year

conclusions

Impact modelling with RCM-data allows the quantification of possible climate change effects on water balance. It is possible to capture uncertainties in the model chain, e.g. by applying a multi-model ensemble and taking as much information as possible into account. This approach of the study is in high agreement with the IPCC –Assessment Report 4, Working Group II on Adaptation (2007), who stated that different scenarios and local scales need to be incorporated in impact studies. The removal of systematic errors of regional dynamical models is a necessary step and the verification of impact models and climate model outputs increases the reliability of results. The historic simulation of runoff using the water balance model COSERO shows a good representation of the observed runoff for different periods. Hence it is a suitable tool for the analysis of climate change impacts on the water balance. The runoff simulations of the future driven by 20 regional climate simulations show a large bandwith even though they are basing all on the same IPCC emission scenario A1B. Nevertheless general tendencies can be identified from the simulations. The results show a shift away from a snow influenced to a rainfall dominated discharge regime. Most projections agree on a reduction in summer discharges which is more pronounced in the far future (2071-2100). The former summer maximum shifts to the spring. These changes are caused by the increased actual evapotranspiration in summer due to higher temperatures, changes in precipitation seasonality and a reduced snow accumulation. These general tendencies are in agreement with other climate change studies in the Upper Danube such as GLOWA-Danube (2010). Again by interpreting these results it has to be stated that all simulations are based on one emission scenario (A1B) for the future. The real emissions in future and as a consequence the change in temperature, precipitation and water balance can differ from this scenario.

It must be noted that from the results of this study no direct conclusions can be drawn on the low flow situation on the Danube because only monthly values have been analysed. In the Danube region low flow situations mostly occurs in winter time (see e.g. Klein et al. 2011) for which the monthly values show no clear change tendencies. In future in the context of the research program KLIWAS this aspect will be analysed in detail using daily time step simulations from the hydrological model LARSIM_ME which is currently under development.

Acknowledgements The results shown here are part of the research programme KLIWAS financed by the Federal Ministry of Transport, and the projects AdaptAlp (INTERREG IV) and ECCONET (EU FP 7) funded by the European Union. This study carried out by Pöyry Energy GmbH in order of the Federal Institute of Hydrology (BfG) is based on the study

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