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Evaluation of two precipitation data sets for the Rhine River using streamflow simulations

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Abstract. This paper presents an extended version of a widely used precipitation data set and evaluates it along with a recently released precipitation data set, using streamflow simulations. First, the existing precipitation data set issued by the Commission for the Hydrology of the Rhine basin (CHR), originally covering the period 1961–1995, was extended until 2008 using a number of additional precipitation data sets. Next, the extended version of the CHR, together with E-OBS Version 4 (ECA & D gridded data set) were evaluated for their performance in the Rhine basin for extreme events. Finally, the two aforementioned precipitation data sets and a meteorological reanalysis data set were used to force a hydrological model, evaluating the influence of different precipitation forcings on the annual mean and extreme discharges compared to observational discharges for the period from 1990 until 2008. The extended version of CHR showed good agreement in terms of mean annual cycle, extreme discharge (both high and low flows), and spatial distribution of correlations with observed discharge. E-OBS performed well with respect to extreme discharge. However, its performance of the mean annual cycle in winter was rather poor and remarkably well in the summer. Also, CHR08 outperformed E-OBS in terms of temporal correlations in most of the analyzed sub-catchment means. The length extension for the CHR and the even longer length of E-OBS permit the assessment of extreme discharge and precipitation values with lower uncertainty for longer return periods. This assessment classifies both of the presented precipitation data sets as possible reference data sets for future studies in hydrological applications.

1 Introduction

Precipitation forcings of streamflow simulations have a considerable influence on model performance, irrespective of the type of the model structure (Te Linde et al., 2008). In this section, we illustrate the importance of extended and well-defined precipitation data sets referring to studies concerned with hydrological responses to projected climate changes through precipitation data sets of different origin, for the Rhine basin. Direct Global Climate Models (GCMs) outputs are considered unsuitable to feed into hydrological models owing to their coarse spatial resolution and systematic bias (Leander and Buishand, 2007). However, downscaling with Regional Climate Models (RCMs) introduces an inherent source of uncertainty originating from their inability to simulate present day climate conditions accurately (Christensen et al., 2008). In addition, the estimation of flood quantiles suffers from the limited length of the RCM simulations (Leander and Buishand, 2007).

Alternatively, the direct approach uses bias-corrected climate model output as forcing of the hydrological model. However, climate model outputs can show considerable bias, i.e. when they do not adequately represent observed variability in the variables of interest (Diaz-Nieto and Wilby, 2005; Hay et al., 2000; Lenderink et al., 2007). Daily observations between 1961 and 1995 of the International Commission for the Hydrology of the Rhine basin (CHR) are often used to evaluate and correct biases in climate model projections. Over the years, the CHR data set is accepted as a high quality precipitation and temperature data set. Hurkmans et al. (2010) studied the impact of climate change for the Rhine taking into account climate scenarios with relatively high spatial resolution in order to better represent extremes using a Land Surface Model (LSM). Shabalova et al. (2003) studied changes in the discharge of the Rhine by the end of

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the 21st century using integrations of the Hadley Centre regional climate model HadRM2 and the RhineFlow model. Both studies used the CHR data set as observational reference to correct the climate model bias on a daily basis for each of the 134 sub-catchments of the Rhine. Implementing a bias correction method proposed by Leander (2009), Terink et al. (2010) used the CHR precipitation and temperature to correct European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis data, ERA15. The bias correction led to satisfactory results and precipitation and temperature errors decreased signicantly, although, a few episodes remained for which the correction of precipitation was less sufficient. Te Linde et al. (2010) used the operational version of the HBV model (Bergström and Forsman, 1973; Lindström et al., 1997) (calibrated only with the CHR data set) to examine the effectiveness of flood management measures for the river Rhine assuming an extreme climate scenario for the year 2050.

A large statistical uncertainty arises from quantifying the return levels of extreme discharges in the order of 1000 years and longer from a data record of limited length. For this, an extreme value distribution is fitted to annual maximum discharge values and extrapolated to the return period of interest. Sources of uncertainty in these procedures come from the strong extrapolation of short-term observational/climate output data and by neglecting changes in the river basin. To overcome some of these problems, Leander and Buishand (2007) used a stochastic weather generator to resample long daily sequences of area precipitation and station temperature to simulate extreme flows for the Meuse River. A number of studies used the CHR precipitation data set in a stochastic weather generator to create long simultaneous records of daily rainfall and temperature over the Rhine basin (De Wit et al., 2007; Beersma, 2002; Beersma et al., 2001; Brandsma and Buishand, 1999). The weather generator is then coupled with hydrological and hydraulic models, which transform the generated records into discharge series. Eberle et al. (2002) took a 1000-year simulation with the rainfall generator using the CHR data set as input for the HBV-96 model for the river Moselle, the largest tributary of the Rhine basin. Uncertainty was introduced in the procedure by the relatively short length of the observed precipitation record (35 years) and by the limited period with data available for the calibration of the HBV-96 model in the Rhine basin.

Thus, for all the aforementioned reasons, it appears that there is a need for extensive and long duration forcing data sets – based either on gauges or using the growing availability of radar and satellite-based high-resolution data sets – to improve physical descriptions and refining grid size. The purpose of this paper is threefold. The first is to present an extended version of the widely used CHR precipitation data set, referred to as CHR08. The existing CHR precipitation data (currently covering the period 1961–1995) is extended until 2008 using three different data sets of observed precipitation, including both rain-gauge and radar-based desegregation data. The second goal is to asses the effect of the length extension of the CHR08 gridded precipitation data set, in comparison with the original CHR on the extreme values of discharge and precipitation in the Rhine river. To provide additional reference, the Version 4 of the E-OBS gridded precipitation and temperature data set derived from the European Climate Assessment & Data set (ECA & D) (Haylock et al., 2008; Van den Besselaar et al., 2011) is also analysed. The E-OBS data set is even longer than CHR08; 1950–2009. The extension of the CHR and the use of E-OBS reduce the large uncertainties in the estimation of the 10-day maximum precipitation and the extreme discharges at long return intervals. The third goal is to evaluate these data sets in terms of their ability to generate realistic Rhine discharges. For this, we force the HBV-96 with these two extended precipitation data sets. We hereby follow earlier approaches analysing the impact of changed precipitation regimes on the Rhine discharges (Lenderink et al., 2007; Shabalova et al., 2003). The ERA-Interim re-analysis data set from ECMWF (labeled ERA-Int; Simmons et al., 2007) is also used for further reference. The simulated discharges are evaluated in terms of mean annual cycle and high and low flow for the two gauging stations in the main river (Lobith and Basel) and two gauging stations (Cochem and Raunheim) of important tributaries (Moselle and Main) of the Rhine River. Spatial variability of the correlation between observed and simulated discharge is analyzed using a larger number of discharge stations spread across the basin. The manuscript of this paper is structured as follows. In Sect. 2, the precipitation data sets used for the extension of the CHR are presented, along with E-OBS and ERA-Int data sets. The methodology that was followed to extend the CHR data set is also explained in this section. Also, a short description of the hydrological model HBV-96 and the set-up used in this study are described. In Sect. 3, the analyses of the modeled discharges are presented and discussed. Conclusions are formulated in Sect. 4.

2 Methodology

2.1 Description of precipitation data sets

2.1.1 CHR08

The CHR08 precipitation data set covers the period of 1961 until 2008 and is based on the extension of the well-known and validated CHR daily precipitation set covering the period of 1961–1995 (Sprokkereef, 2001). The CHR data set was prepared in conjunction with the set-up of the daily HBV-96 model for the Rhine basin and is therefore adapted to the HBV-96 model structure. For the extension of CHR, the Rhine basin was separate into three major sub-basins; Lower Rhine, Western Rhine and Upper Rhine (see Fig. 1). For each sub-basin, gridded data sets of daily precipitation were used.

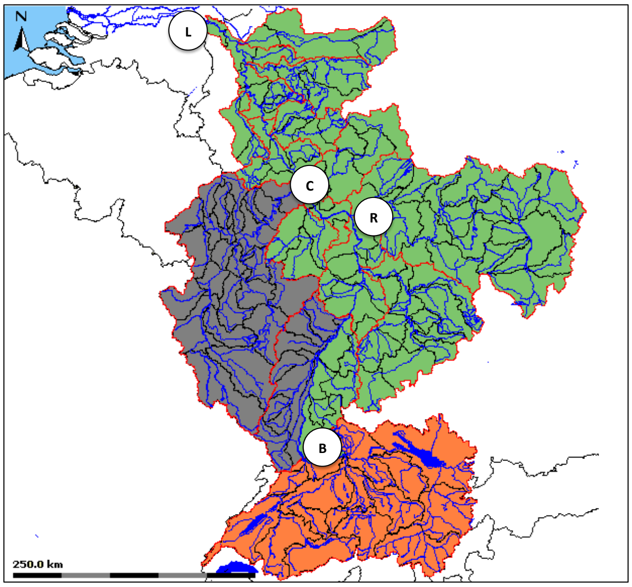

Fig. 1. The Rhine basin, the 134 sub-catchments and the three major sub-basins (Lower: upper right panel, Western: left panel, Upper: lower panel). The labels indicate the discharge observations presented in the results section, L: Lobith, C: Cochem, R: Raunheim, B: Basel.

In Fig. 2, an overview of the construction of the CHR08 data set for each sub-basin is presented and described below:

- Lower sub-basin: the data for this sub-basin are compiled from the original daily CHR data set as background for the period of 1961–1990 and completed by the $1\times1\,\mathrm{km}^2$ REGNIE (Regionalisierte Niederschlagshöhen) data set provided by the German Weather Service (Deutscher Wetterdienst-DWD).

- Western sub-basin: the daily gridded precipitation data for the Western sub-basin, which covers areas in France, Luxembourg and Belgium, were obtained from the University of Trier, for the period 1961 until 1998 (White, 2001). Note that the same data from 1961 until 1995 were used in the construction of CHR. For the period 1999 until 2008, a gridded REGNIE emulation data set derived by Weerts et al. (2008) is used. Weerts et al. (2008) developed and tested an approach to emulate daily precipitation grids for the river Rhine for operational low flow forecasting (forecasting system operated by the Bundesanstalt für Gewässerkunde – BfG) and flood forecasting (forecasting system operated by the Waterdienst). This approach interpolates daily precipitation anomalies (based on all operational available precipitation data and monthly mean background grids based on REGNIE data for Germany, ETH data for Alpine region and University of Trier data for France/Luxembourg/Belgium) to the same grid as the background grid. Multiplying the background grid and the interpolated anomaly fields yields the daily precipitation fields for the different parts of the river Rhine and can be combined to a precipitation grid for the whole of the basin (see also Terink et al., 2010).

- Upper sub-basin: a gridded data set from ETH (Eidgenössiche Technische Hochschule, Zürich) covers the period of 1970 until 2000 and is based on observations from high-resolution networks of the Alpine countries. The daily precipitation fields were produced with an advanced distance-weighting scheme commonly adopted for the analysis of precipitation on a global scale (Frei and Schär, 1998). This gridded analysis is based on 6700 daily precipitation series with spatial resolution of 25 km encompassing just the Alpine countries. Data for the period of 2001 until 2008, were derived from the REGNIE emulation approach developed by Weerts et al. (2008) and described above.

A comparison between the annual mean and extreme discharges of CHR08 and CHR for the Lower (REGNIE), Western and Upper sub-basins showed that for the first two basins there were no distinct differences. For the Upper sub-basin, it was found that the precipitation data set from ETH generates more accurate discharge values than the CHR data set. In particular, the maximum discharge in the mean annual cycle (typically during spring) generated by the CHR data set is much larger than the corresponding maximum of the ETH discharges.

2.1.2 E-OBS

A new version of gridded precipitation data set recently became available from the ENSEMBLES project and ECA & D (Haylock et al., 2008; Van den Besselaar et al., 2011, E-OBS Version 4). It was constructed for validation of RCMs and for climate change studies. The spatial resolution of this data set is 0.25° by 0.25° on a regular latitude-longitude grid. The long-term mean and standard deviation of this data set correspond well with popular reanalysis data, although in areas with a relatively high station density the gridded data is closer to the independent station data than the reanalysis products. Also a very good agreement exists with daily weather charts for selected storm events. Haylock et al. (2008) argue that there are several similar gridded daily data sets available for Europe, none of which can compare to E-OBS in terms of the length of record (today 1950–2010), spatial resolution, the incorporation of daily uncertainty estimates and the quality of the interpolation method. For our study, a simple area weighted averaging was applied to interpolate the gridded E-OBS daily data set into the 134 sub-catchments of the Rhine basin. The number of underlying stations for E-OBS data set is much smaller than REGNIE. However, E-OBS is regularly updated, classifying it as one of the most up to date meteorological data sets.

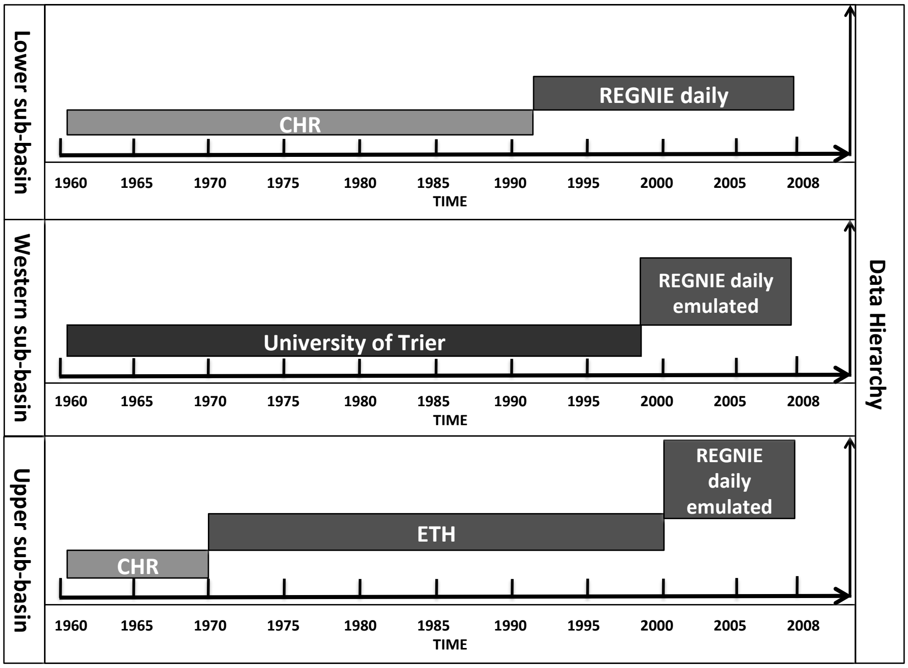

Fig. 2. Schematic representation of the data sets used to construct CHR08 for each of the major sub-basins.

2.1.3 ERA-Interim

The ERA-Int reanalysis data set consists of atmosphere and surface analyses for the period from 1989 (recently since 1979) to present based on the ECMWF Integrated Forecast System (IFS) model. In the reanalysis various types of observations including satellite and ground based measurements are assimilated (Simmons et al., 2007). ERA-Int relies on a data assimilation system which uses observations within the windows of 15:00 UTC to 03:00 UTC and 03:00 UTC to 15:00 UTC (in the next day) to initialize forecast simulations starting at 00:00 UTC and 12:00 UTC, respectively. Daily precipitation data for period of 1989–2007 were derived from ERA-Int reanalysis using a combination of 3 hourly forecast intervals discarding the first nine hours to avoid spin-up biases in the reanalysis data. The data were projected on a grid of 0.5° × 0.5° from the original Gaussian reduced grid (T255 reduced Gaussian grid of about 0.7° × 0.7°). For small catchments (smaller than the grid-size of the input precipitation data) data were bi-linearly interpolated. Balsamo et al. (2010) report on systematic biases in ERA-Int precipitation data, and use GPCP precipitation data to correct for these biases. These corrected precipitation fields were not used in the present study.

2.2 Hydrological application with HBV-96: description of the hydrological model and its forcing

The HBV-96 hydrological model (Bergström and Forsman, 1973; Bergström, 1976; Lindström et al., 1997) is a semi-distributed conceptual hydrological model originally developed at the Swedish Meteorological and Hydrological Institute (SHMI) in the 1970s. The HBV-96 precipitation-runoff model of the Rhine river basin has been successfully used, for instance, to estimate extreme runoff from catchments or to quantify the impacts of predicted climate changes (Berglöv et al., 2009). HBV-96 describes the most important runoff generating processes. The model consists of subroutines for snow accumulation and melt, a soil moisture accounting procedure, routines for runoff generation and a simple routing procedure. A complete description of the HBV-96 calculation scheme and model structure for the Rhine basin can be found in Eberle et al. (2005) and Sprokkereef (2001). The forcings of the model can consist of either observations or climate model outputs of precipitation and temperature and estimates of potential evaporation for daily or shorter time steps. The spatial model structure for the river Rhine is based on the boundaries of 134 sub-catchments determined by the working group Geographic Information System of the CHR (Mülders et al., 1999). This subdivision has been employed in several earlier studies (Eberle et al., 2002, 2005). For the Rhine basin, HBV-96 has been calibrated and validated with daily temperature, potential evapotranspiration and precipitation from the CHR, covering the period 1961–1995 (Mülders et al., 1999; Eberle et al., 2002, 2005). Weirs and structures are not represented in HBV-96, which may affect model performance in the Cochem and Raunheim catchments. The set-up of the HBV-96 model for the present study is described as follows. Three different precipitation and one temperature data set were used to force the HBV-96 model.

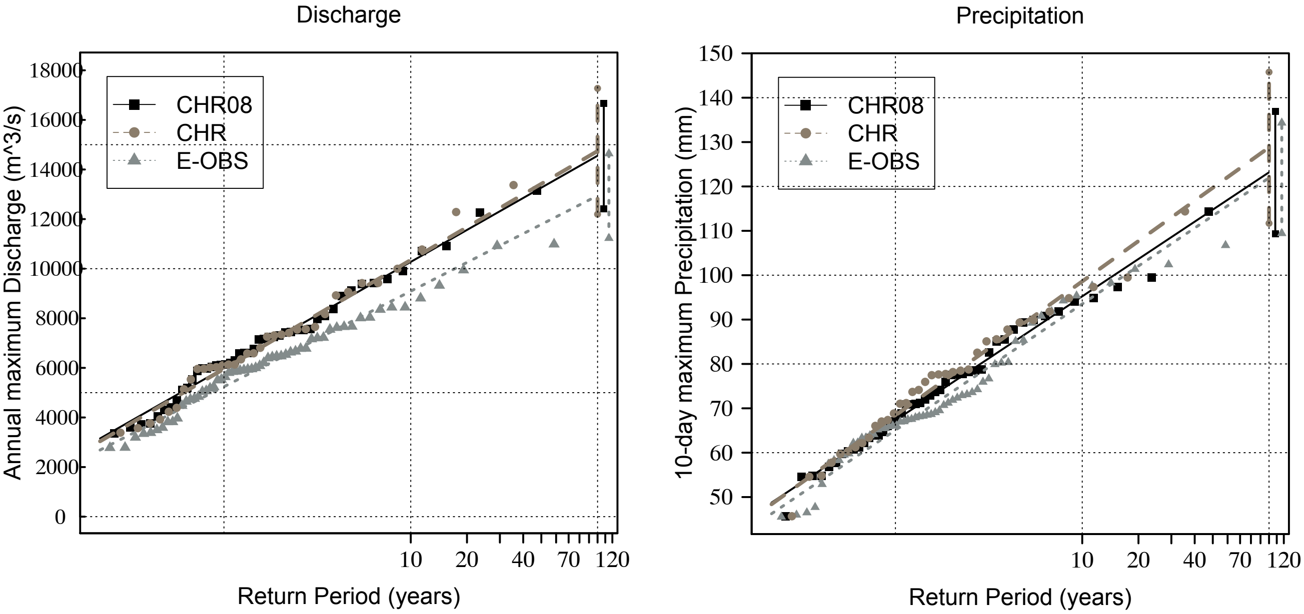

Fig. 3. Gumbel plots of (left panel) annual maximum discharge and (right panel) 10-day precipitation maximum for CHR, CHR08 and E-OBS at Lobith, with the Gumbel fits and the 95 % confidence intervals.

The precipitation data sets are: CHR08 (Extended version of CHR), E-OBS (Version 4) and ERA-Int reanalysis data.

Temperature forcing in all simulations was derived from E-OBS Version 4 gridded data. Analysis of hydrological model results generated with E-OBS temperature data correspond very well with results using interpolated ERA-Int temperature fields, and the selection of the temperature data does not affect our results. HBV-96 model also uses a potential evapotranspiration that is derived from a reference value with a fixed annual cycle. In this study, mean monthly values of potential evapotranspiration were derived from the Penman-Wendling approach based on daily sunshine duration and temperature (Eberle et al., 2005). For this, climatological station data of air temperature and sunshine duration have been obtained from the CHR and the German Meteorological Service (DWD). Height corrections and areal weighting factors were assigned to each station (Eberle et al., 2005). The mean monthly potential evapotranspiration is then transformed into a daily time series by assuming a 5 % increase of the potential evapotranspiration per one degree of temperature anomaly. In order to improve the discharge performance at Lobith, all the empirical correction factors that were applied to the input potential evapotranspiration, precipitation and peak discharge values were calibrated only for the CHR data set precipitation and temperature data sets for the period of 1961–1995.

At this point we would like to note that further calibration of the HBV-96 model with the CHR08 and E-OBS data sets did not take place. Recalibration per precipitation data set may affect the differences between the generated discharge results, thereby possibly hiding relevant differences in the features of these precipitation data sets. It is also worth noting that a similar strategy concerning the recalibration of the HBV-96 model was followed by Te Linde et al. (2010) and Leander (2009).

3 Analysis of the results

3.1 Impact of the extension on estimates of extreme discharge

The construction and design of flood defense infrastructures is based on estimates of the magnitude of a discharge event of a given probability. Usually the return time of these events (e.g. 1250 yr as for the Rhine basin in the Netherlands) is much longer than the available data record length (approximately 100 yr; Deshotels and Fitzgerald, 2001). Extreme value theory is used to extrapolate the available observations to longer return times (Coles, 2001). Here, we present the calculated annual maximum discharge and the fitted peak levels with a return time up to 1/100 yr using the CHR data set for the period 1961–1995 (35 yr), the CHR08 for the period 1961–2008 (47 yr) and the E-OBS for the period 1950–2008 (58 yr). Figure 3 (left panel) shows the results for Lobith, the entrance point of the Rhine into the Netherlands (see Fig. 1).

The extreme discharge levels with long return times are estimated from the data using a Gumbel fit. As expected a wide uncertainty range is present for longer return periods due to the statistical uncertainty of the extrapolation. For a 100 yr return period, the fit using the CHR08 data

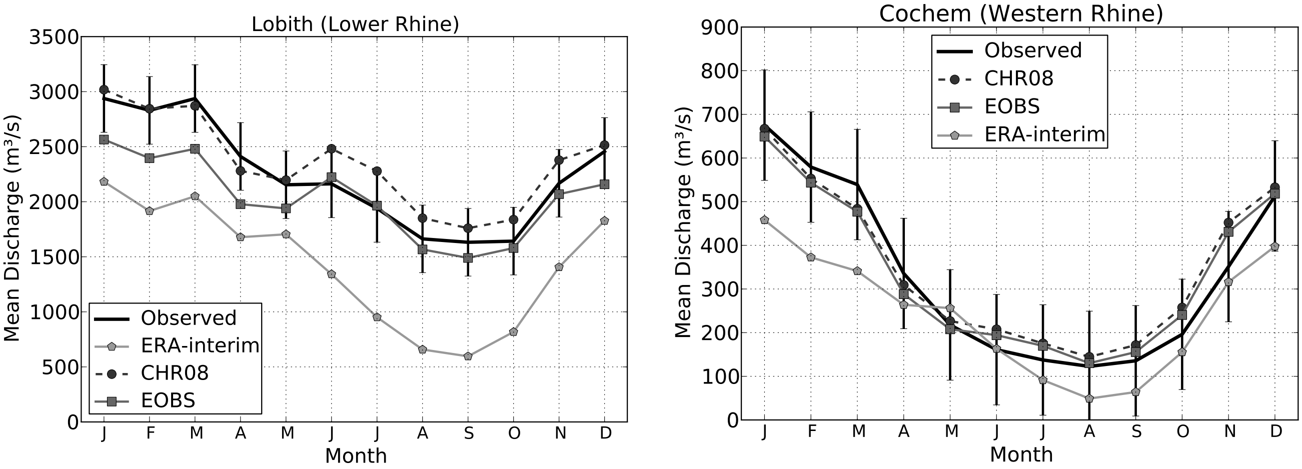

Fig. 4. Mean annual cycle of observed and modeled discharges at Lobith (left panel) and Cochem (right panel) for the period 1990–2008. Also shown are the 95 % confidence intervals from the interannual variability of the observed discharges.

set yields a similar estimate as CHR, but for E-OBS the 1/100 yr return level is significantly lower. The 95 % confidence interval from CHR08 simulations spans a range between $12\,420\,\mathrm{m^3\,s^{-1}}$ and $16\,669\,\mathrm{m^3\,s^{-1}}$. For the CHR data set, the 100 yr return period with the 95 % confidence interval range from $12\,195\,\mathrm{m^3\,s^{-1}}$ to $17\,273\,\mathrm{m^3\,s^{-1}}$ and for E-OBS between $11\,229\,\mathrm{m^3\,s^{-1}}$ and $14\,642\,\mathrm{m^3\,s^{-1}}$. The data set extension from CHR to CHR08 of 12 yrs (34 %) leads to a reduction in the discharge uncertainty of $829\,\mathrm{m^3\,s^{-1}}$, which is only approximately 5 % of the central estimate for both return intervals. E-OBS produces a reduction in the discharge uncertainty of approximately 8 % due to the longer data record.

Figure 3 (right panel), shows Gumbel plots for the annual maximum 10-day precipitation sum averaged over the catchment area upstream of Lobith. For the 1/100 yr return period the fit of the CHR08 and E-OBS data sets yield a significantly lower estimate than the corresponding fit of CHR data set. The relative reduction of the uncertainty range of the CHR08 is approximately 4 % and for E-OBS 6 %. It is pointed out that the CHR and CHR08 give similar peak discharges with similar 10-day precipitation sums. E-OBS gives slightly lower precipitation amounts, which are leading to lower discharges, especially for return periods of 100 yr. Differences and similarities in the several discharge results points at the non-linear process transferring precipitation peaks into discharge maxima.

3.2 Annual cycles of mean discharge

In this sub-section, the mean annual cycle of observed and simulated discharge at selected sub-catchments is presented, starting from the northwest Lobith (Lower sub-basin) and moving towards the south through Cochem (Western sub-basin), Raunheim (Main) and eventually Basel (Upper sub-basin, Fig. 1). Figure 4 (left panel) shows the mean annual cycle of discharge at Lobith for observed and modeled discharges, simulated with the CHR08, E-OBS and ERA-Int precipitation datasets used as forcings. Also shown is the 95 % percentile uncertainty range of the observed discharges derived from the interannual variability.

Hydrological simulations produced with the CHR08 data set have a good agreement with observed discharges, particularly for mid November to May. In the summer season (May until December) a persistent positive bias of approx. $200\,\mathrm{m^3\,s^{-1}}$ ($\sim 0.1\,\mathrm{mm\,day^{-1}}$) exists. For June and July, CHR08 exceeds the 95 % confidence interval of the observed discharges. For the rest of the summer months, the bias remains within the uncertainty limits of the observed discharges. E-OBS generally gives lower values, which leads to poor skill in winter (systematically lower than the 95 % uncertainty range). However, E-OBS has an excellent agreement with observations during summer. ERA-Int gives persistently low discharge volumes, especially in the summer months. The low discharges of ERA-Int are likely due to the underestimation of ERA-Int daily precipitation (Balsamo et al., 2010). ERA-Int presents smaller precipitation means especially from May until December. This is consistent with results from Szczypta et al. (2011), who compared ERA-Int precipitation data with the SAFRAN atmospheric analysis system and found an average 27 % low bias of ERA-Int over France.

For the catchment of Cochem (located in the Western subbasin see Fig. 1), CHR08 and E-OBS give very similar results throughout the year (Fig. 4, right panel). They both tend to underestimate discharge during the period from January until April and overestimate in June until November. ERA-Int gives consistently low discharge values, with the winter estimation out of the 95 % intervals.

For Raunheim (Fig. 5, left panel), the discharge from the three simulations display pronounced differences with the observations, but the size of the catchment (and the

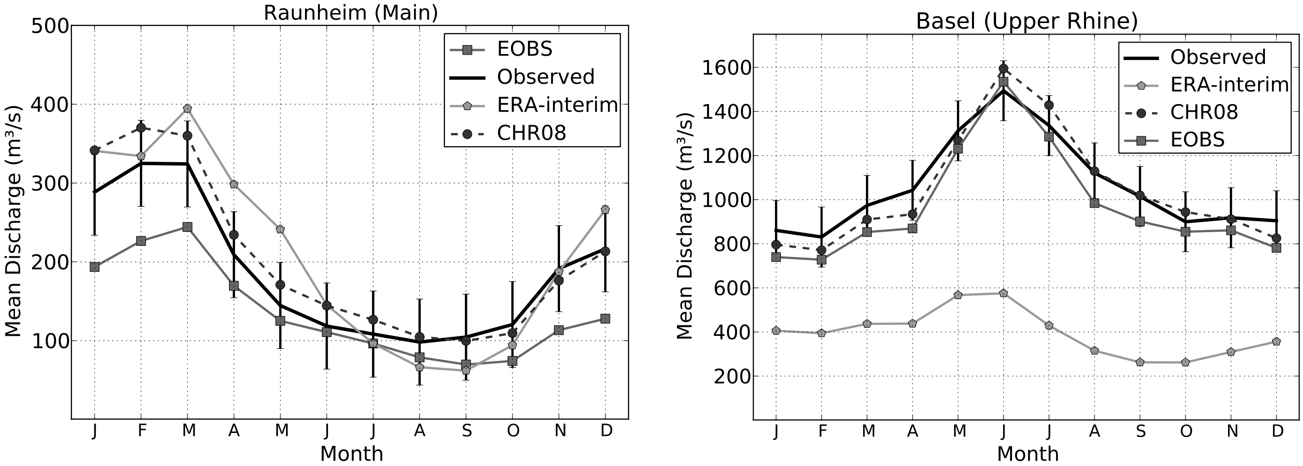

Fig. 5. Mean annual cycle of observed and modeled discharges at Raunheim (left panel) and Basel (right panel) for the period 1990–2008. Also shown are the 95 % confidence intervals from the interannual variability of the observed discharges.

mean discharge) is notably smaller than for the earlier examples. E-OBS shows the largest negative bias during winter, while ERA-Int performs much better in this catchment than in the earlier examples. CHR08 overestimates the winter discharges but from August the performance improves significantly.

At Basel (Fig. 5, right panel) discharge generated in Switzerland is measured, allowing assessment of the effect of Alpine snowmelt on the Rhine water balance. In this subcatchment, CHR08 has a small bias from January until August, with the remaining months having negligible bias. E-OBS is close to CHR08, but has a lower discharge than observed for all of the months but it captures the annual peak of the discharges. ERA-Int has the largest bias of all three simulated discharges, with remarkably low flows. Although the differences and skill have a strong spatial variability, CHR08 is in general outperforming the other driving data sets in all seasons except summer. E-OBS is performing better in the summer, especially for Basel and consequently Lobith. The observed discharge in Cochem and Raunheim could be affected by weirs and structures of the Rhine in these areas which are not taken into account by HBV-96. Summertime bias may be related to the problems of the evapotranspiration treatment in HBV-96.

In Table 1, the correlation coefficients (R^2), the root mean square error (RMSE) and the Nash-Sutcliffe modeling efficiencies (Nr) of modeled daily discharge driven with CHR08, E-OBS and ERA-Int for the period of 1990–2008 are shown for 14 sub-catchments. CHR08 is performing better in almost all the sub-catchments for all statistics. The only subcatchment where CHR08 and E-OBS give a poor correspondence with observations is Erft. This is in agreement with Eberle et al. (2002) who used HBV-96 with a stochastic weather generator to estimate extreme discharges. This poor performance may be due to the fact that the discharge dynamics of the river Erft are dominated by technical measures related to brown coal mining.

3.3 Annual winter maximum and summer minimum discharges

In this section the annual winter maximum and summer minimum discharge is analyzed for the sub catchments of Lobith, Cochem, Raunheim and Basel. In Fig. 6, the modeled winter maximum and summer minimum discharges are compared with observed maxima and minima at Lobith. Both in summer and winter, the CHR08 extreme discharges have a fair agreement with the observed values for small return periods (<5 yr) but overestimate the annual maximum discharge of less frequent events in winter. In the summer, CHR08 performs better than E-OBS and ERA-Int in large return periods. E-OBS agrees well with observed winter maximum for the 10-year return period and underestimates the summer discharges of large return periods. ERA-Int gives a large underestimation of both maximum and minimum values.

In Cochem (Fig. 7) the CHR08 and E-OBS forcings produce an excellent agreement with the observed discharges for the winter extremes but give an underestimation in the summer extremes with large return periods. ERA-Int results in a large underestimation of the extremes for all return periods. In the summer minimum discharges, E-OBS gives the best estimation for return periods smaller than 5 years. CHR08 overestimates the summer minimum discharges for almost all the return periods and ERA-Int has gives a large underestimation for all the return periods.

For Raunheim (Fig. 8), ERA-Int has good agreement with the observed discharges during nearly the entire winter and presents the smallest bias from the other two forcings. E-OBS and CHR08 maximum values have a large bias after return period of 5 years. In the summer discharge, CHR08 gives the best estimation for return period larger than two years, with E-OBS underestimating the minimum values for return periods smaller than 10 years. All the data sets tend to underestimate the summer discharges of small return periods. CHR08 and E-OBS tend to underestimate the winter

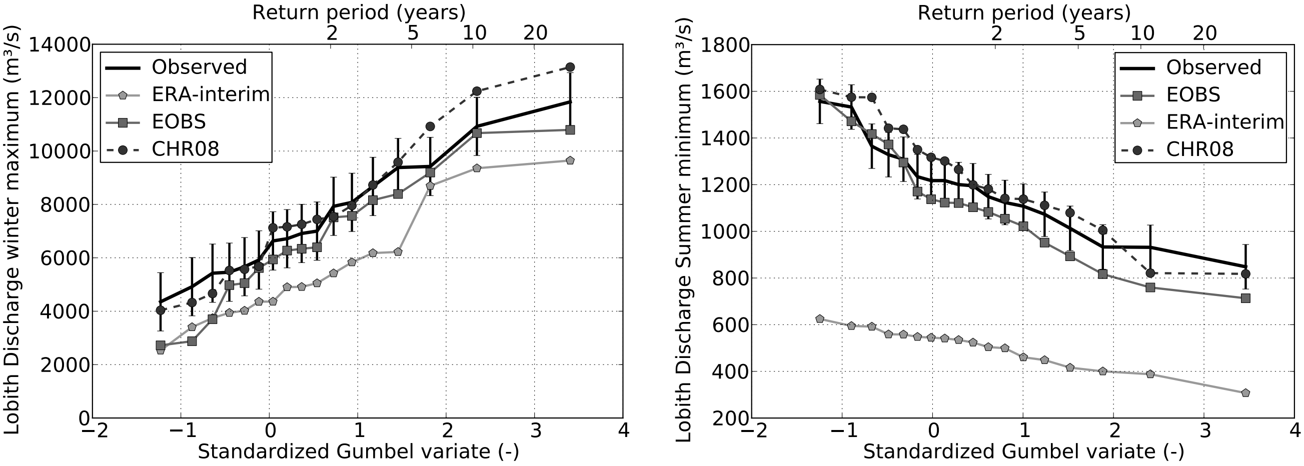

Fig. 6. Gumbel plot for CHR08, E-OBS, ERA-Int and observed winter maximum (left panel) and summer minimum (right panel) discharges and the 95 % confidence interval for the observed discharges at Lobith for the period 1990–2008.

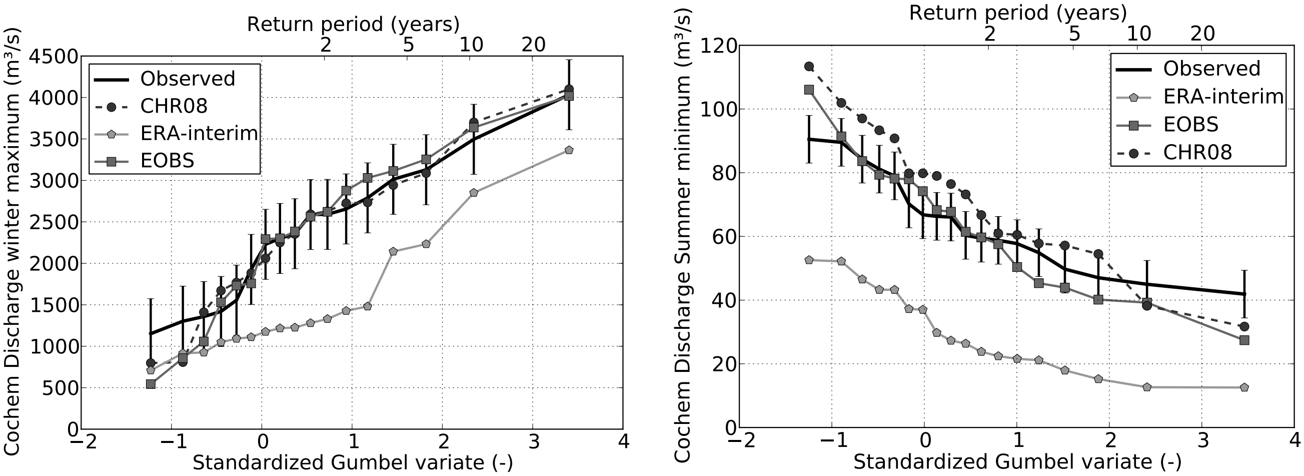

Fig. 7. Gumbel plot for CHR08, E-OBS, ERA-Int and observed winter maximum (left panel) and summer minimum (right panel) discharges and the 95 % confidence interval for the observed discharges at Cochem for the period 1990–2008.

maximum discharges for Basel (Fig. 9) during the entire period. For the summer minimum discharges, CHR08 and E-OBS give a very good estimation for all the return periods with E-OBS performing slightly better than CHR08 except at extremes with return periods of 2 years. ERA-Int gives an underestimation for both winter and summer discharges.

4 Discussion and conclusions

In this study, two new precipitation data sets are presented and their performance to produce annual discharges and hydrological extremes is evaluated. First, the CHR data set was extended until 2008 using three other data sets covering the larger catchments of the basin for the more recent episode. Note that the use of different data sources over time may introduce inhomogeneities, in particular for the Swiss part of the basin. However, the impact of these inhomogeneities on extreme river flows at Lobith is considered to be small, because these are mainly due to large-scale multi-day rainfall events downstream of Switzerland (Buishand, A. personal information). Secondly, we investigated the effect of the length extension of the CHR, together with the E-OBS gridded precipitation data set in comparison with the original length of the CHR, on extreme discharges and precipitation values for the Rhine basin by extrapolating the available records to a 1/100 years return period. The length extension of CHR data set is considered to be a valuable contribution to flood defense and climate change studies. Thirdly, the CHR08 and E-OBS data sets were used to force the HBV-96 hydrological model, simulating daily discharges for the entire length of the sets. The reanalysis precipitation data set ERA-Int was also used as input in the hydrological model and compared with observed discharges for the period 1990 until 2008. We assessed the performance of the precipitation data set

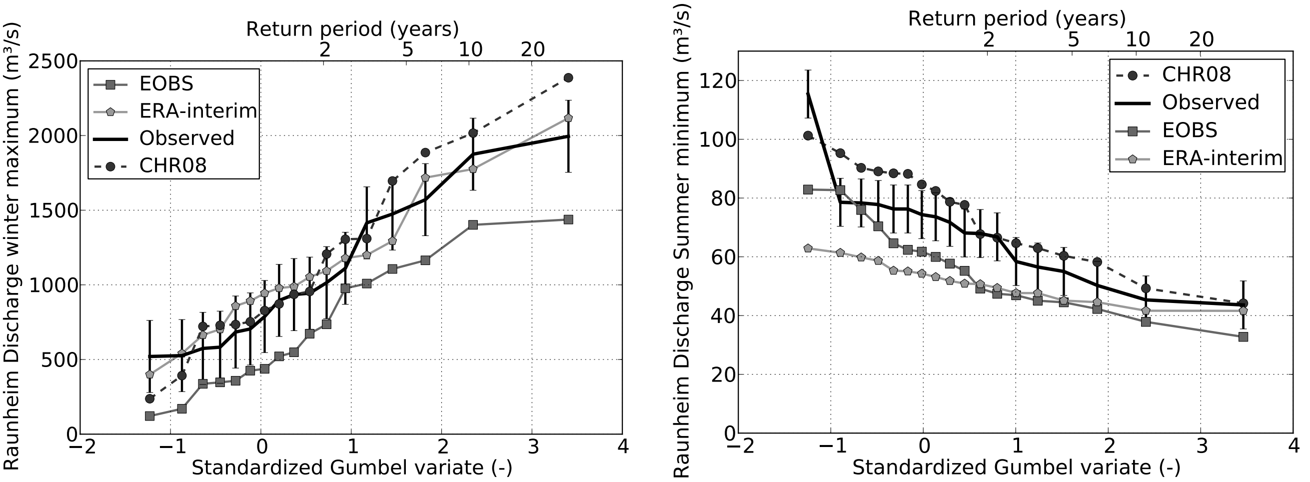

Fig. 8. Gumbel plot for CHR08, E-OBS, ERA-Int and observed winter maximum (left panel) and summer minimum (right panel) discharges and the 95 % confidence interval for the observed discharges at Raunheim for the period 1990–2008.

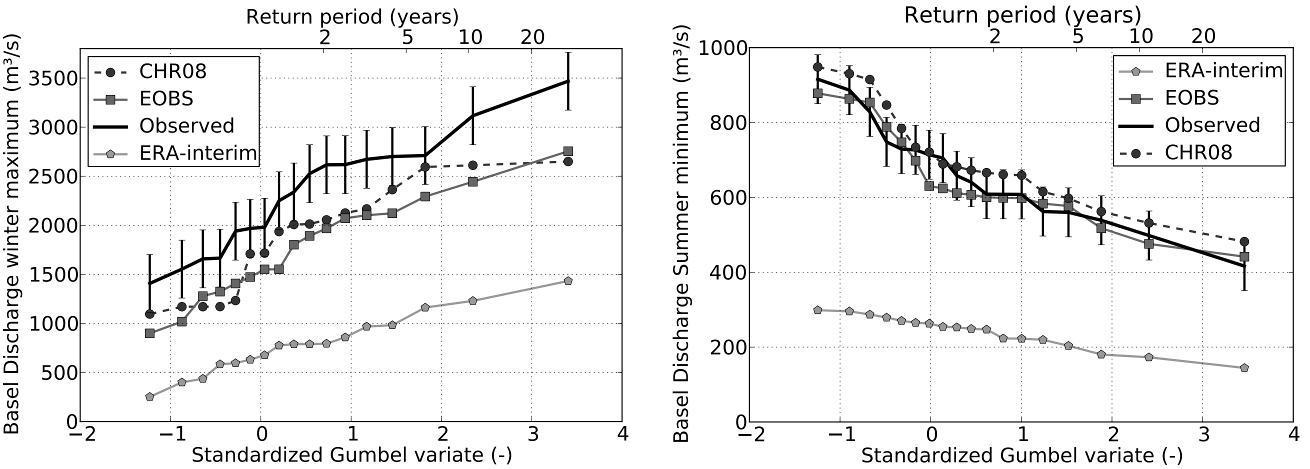

Fig. 9. Gumbel plot for CHR08, E-OBS, ERA-Int and observed winter maximum (left panel) and summer minimum (right panel) discharges and the 95 % confidence interval for the observed discharges at Basel for the period 1990–2008.

in hydrological applications by evaluating the annual mean, winter maximum and summer minimum; and at last by comparing statistics of daily steps for a range of sub-catchments.

As mentioned in the Methodology section, we did not choose to recalibrate the HBV-96 model for the Rhine, but instead used the daily model as is. In the present study, the goal of the intercomparison of CHR08 and E-OBS is only to find out if the extended data set of E-OBS (which is considerably longer) is a valid candidate (next to CHR08) for bias correction of climate model outputs as there is a need for extended data sets of high quality. In the intercomparison, as discussed below and shown in the results section, our decision not to recalibrate the model could hide relevant differences in the features of the precipitation data sets, and could lead to underperformance of the data sets not used in the calibration. However, given the fact that one of the features of the E-OBS and CHR08 precipitation datasets is similar (Fig. 3, right panel), we expected at least similar behaviour in the winter period. The differences presented and discussed below concerning the hydrological results should all be viewed in the light of this limitation. Certainly, the ideal way to compare these datasets would be to recalibrate the HBV-96 model with all three data sets and compare the resulting hydrographs. However, such recalibration will hide biases present in all the data sets. In the extreme case, it would be possible to obtain identical results after recalibration for the three precipitation data sets (Melching, 1995).

The simulated annual maximum discharges of the CHR08 (1961–2008) and E-OBS (1950–2008) data set were extended into long return levels and were compared with the corresponding annual maximum of the original CHR (1961–1995). For the CHR08, the 95 % confidence interval of simulated discharge is reduced by approximately 5 % and the corresponding interval of the 10-day annual precipitation sum by 4 %.

Table 1. Statistics of daily discharges for the period of 1990–2008, for 14 sub-catchments of the Rhine. Locations are roughly ordered from Lobith to the upstream catchment of Basel. Shown are square correlation coefficient (R^2), Root Mean Square Error (RMSE) and Nash-Sutcliffe modeling efficiency (Nr).

Scores	R^2			RMSE ($m^3 s^{-1}$)			Nr		
Data sets	CHR08	E-OBS	ERA-Int	CHR08	E-OBS	ERA-Int	CHR08	E-OBS	ERA-Int
Basin (km^2)									
Lobith (160 800)	0.89	0.86	0.17	422	482	1463	0.87	0.83	−0.54
Lippe (4880)	0.84	0.75	0.08	17	30	47	0.81	0.74	−0.31
Ruhr (4500)	0.83	0.80	0.06	36	54	96	0.82	0.61	−0.20
Erft (1880)	0.12	0.21	0.03	3	7	12	−0.31	−6.21	−22.35
Wupper (838)	0.69	0.53	0.02	8	14	17	0.66	0.10	−0.40
Sieg (2880)	0.81	0.67	0.06	30	56	72	0.80	0.30	−0.15
Mid. Rhine (679)	0.91	0.86	0.16	358	484	1419	0.89	0.81	0.89
Lahn (6000)	0.83	0.77	0.16	25	32	61	0.80	0.67	−0.19
Moselle (27 088)	0.86	0.85	0.21	142	153	358	0.85	0.83	0.08
Main (27 142)	0.85	0.78	0.12	77	106	229	0.82	0.67	−0.54
Nahe (4060)	0.72	0.72	0.12	28	29	53	0.72	0.69	−0.02
Neckar (14 000)	0.71	0.68	0.08	79	79	158	0.62	0.62	−0.51
Maxau (50 196)	0.87	0.89	0.12	197	182	876	0.85	0.57	−1.92
Basel (35 897)	0.86	0.79	0.14	173	227	784	0.85	0.74	−2.03
Mean	0.77	0.72	0.11	114	138	403	0.72	0.16	−2.12

Although E-OBS decreased the uncertainty of the 95 % confidence interval by 8 % and 10 day annual precipitation sum with 6 %, the annual maximum discharge of the 1/100 years return period is much lower than the corresponding one of CHR, CHR08 and observed. The length extension permitted the assessment of extreme events with lower uncertainty than the original version.

CHR08 performed well in most of the sub-catchments for the mean annual cycle (especially in winter) and for extreme events with small return periods. E-OBS, on the other hand, performed better in the summer means and in extreme events of large return periods for both winter and summer discharges. ERA-Int underestimated the discharges in almost all the sub-catchments and all the extreme events for both winter and summer. The reanalysis data give a lower precipitation rate for the Rhine basin, which leads to the production of lower flows.

Concerning R^2, RMSE and Nr for a number of smaller sub-basins, CHR08 outperformed E-OBS and ERA-Int in almost every catchment, proving that the good performance of the CHR08 is present in the entire basin of the Rhine River.

The hydrological application of the CHR08 and E-OBS precipitation data set showed that both of them could produce accurate representations of observed discharge for the Rhine basin. E-OBS performed relatively well in spite of the fact that the calibration of the HBV-96 model was applied with the CHR precipitation and temperature data, and despite the lower station density of the underlying observations. Both data sets have the ability to generate valid flows and extreme hydrological events for the entire Rhine basin. Due to the fact that it is quite difficult and time consuming to get longer time series for a river basin that covers several countries, the contribution of E-OBS is significant. Its length permits more accurate correction of climate model projections with lower uncertainties in the long return levels. Both CHR08 and E-OBS are candidates for the new precipitation and temperature data set to update the Generator of Rainfall and Discharge Extremes (GRADE) (De Wit et al., 2007) for the Rhine basin. For future hydrological studies, were E-OBS is used for bias correction of climate model output, the HBV-96 model needs to be recalibrated with the E-OBS data set. The CHR08 data set, as described here, is already being used in recently started research project called Knowledge for Climate Research related to climate change in the Rhine basins. Details can be found in http://knowledgeforclimate.climateresearchnetherlands.nl/

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References

Balsamo, G., Boussetta, S., Lopez, P., and Ferranti, L.: Evaluation of ERA Interim and ERA-Interim-GPCP-rescaled precipitation over the USA, ERA report series, 5, 10 pp., ECMWF, Reading, available at: http://www.ecmwf.int/publications/library/do/references/list/782009, 2010

Beersma, J. J.: Rainfall generator for the Rhine Basin; Description of 1000-year simulations, KNMI-publication, 186-V, 18 pp., 2002.

Beersma, J. J., Buishand, T. A., and Wójcik, R.: Rainfall generator for the Rhine basin: multi-site simulation of daily weather variables by nearest-neighbour resampling, Tech. Rep. I-20, CHR-Report, 2001.

Berglöv, G., German, J., Gustavsson, H., Harbman, U., and Johansson, B.: Improvement HBV model Rhine in FEWS, Final Report, Tech. rep., SMHI Hydrology, 2009.

Bergström, S.: Development and application of a conceptual runoff model for Scandinavian catchments, Ph.D. thesis, Department of Water Resources Engineering, University of Lund, Lund, Sweden, 1976.

Bergström, S. and Forsman, A.: Development of a conceptual deterministic rainfall-runoff model, Nord. Hydrol., 4, 147–170, 1973.

Brandsma, T. and Buishand, T. A.: Rainfall generator for the Rhine basin: multi-site generation of weather variables by nearest-neighbour resampling, KNMI-publicatie, 186-II, 58 pp., 1999.

Christensen, J. H., Boberg, F., Christensen, O. B., and Lucas Picher, P.: On the need for bias correction of regional climate change projections of temperature and precipitation, Geophys. Res. Lett., 35, L20709, doi:10.1029/2008GL035694, 2008.

Coles, S.: An Introduction to statistical modeling of extreme values, Springer, 2001.

De Wit, M. J. M., Van den Hurk, B., Warmerdam, P. M. M., Torfs, P. J. J. F., Rouling, E., and Van Deursen, W. P. A.: Impact of climate change on low-flows in the river Meuse, Climate Change, 82, 351–372, doi:10.1007/s10584-006-9195-2, 2007.

Deshotels, B. and Fitzgerald, M.: Designing for extreme temperatures, Chance, 14, 2001.

Diaz-Nieto, J. and Wilby, R. L.: A comparison of statistical downscaling and climate change factor methods: impacts on low flows in the river Thames, UK, Climate Change, 69, 245–268, 2005.

Eberle, M., Buiteveld, H., Beersma, J., Krahe, P., and Wilke, K.: Estimation of extreme floods in the river Rhine basin by combining precipitation-runoff modelling and a rainfall generator, in: Proceedings International Conference on Flood Estimation, Berne, CHR report II-17, International Commission for the Hydrology of the Rhine basin (CHR), lelystad, The Netherlands, 2002.

Eberle, M., Buiteveld, H., Krahe, P., and Wilke, K.: Hydrological Modelling in the River Rhine Basin, Part III: Daily HBV model for the Rhine basin, Report 1451, Bundesanstalt für Gewässerkunde (BFG), Koblenz, Germany, 2005.

Frei, C. and Schär, C.: A precipitation climatology of the Alps from high-resolution rain-gauge observations, Int. J. Climatol., 18, 873–900, 1998.

Hay, L., Wilby, R. L., and Leavesley, G. H.: A comparison of delta change and downscaled GCM scenarios for three mountainous basins in United States, J. Am. Water Res. Assoc., 362, 387–397, 2000.

Haylock, M. R., Hofstra, N., Klein Tank, A. M. G, Klok, E. J., Jones, P. D., and New, M.: A European daily high resolution gridded data set of surface temperature and precipitation for 1950–2006, J. Geophys. Res., 113, D20119, doi:10.1029/2008JD010201, 2008.

Hurkmans, R., Terink, W., Uijlenhoet, R., Torfs, P., Jacob, D., Troch, P. A.: Changes in Streamflow Dynamics in the Rhine Basin under Three High-Resolution Regional Climate Scenarios. J. Climate, 23, 679–699, doi:10.1175/2009JCLI3066.1, 2010

Leander, R.: Simulations of precipitation and discharge extremes of the river Meuse in the current and future climate, Ph.D. thesis, University of Utrecht, Utrecht, The Netherlands, 2009.

Leander, R. and Buishand, T. A.: Resampling of regional climate model output for the simulation of extreme river flows, J. Hydrol., 332, 487–496, 2007.

Lenderink, G., Buishand, A., and van Deursen, W.: Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach, Hydrol. Earth Syst. Sci., 11, 1145–1159, doi:10.5194/hess-11-1145-2007, 2007.

Lindström, G., Johansson, B., Persson, M., Gardelin, M., and Bergström, S.: Development and test of the distributed HBV 96 hydrological model, J. Hydrol., 201, 272–288, 1997.

Melching, C. S.: Chapter 3: Reliability Estimation, Computer Models of Watershed Hydrology, Water Resources Publications, 1995.

Mülders, R., Parmet, B., and Wilke, K.: Hydrological Modelling in the river Rhine basin, final report, Report 1215, Bundesanstalt für Gewässerkunde (BFG), Koblenz, Germany, 1999.

Shabalova, M. V., Van Deursen, W. P. A., and Buishand, T. A.: Assessing future discharge of the river Rhine using regional climate model integrations and a hydrological model, Clim. Res., 23, 233–246, 2003.

Simmons, A., Uppala, S., Dee, D., and Kobayashi, S.: ERA-I: New ECMWF reanalysis products from 1989 onwards, Newsletter 110, ECMWF, 2007.

Sprokkereef, E.: Eine hydrologische Datenbank fur das Rheingebiet, Technical report, RIZA, 2001.

Szczypta, C., Calvet, J.-C., Albergel, C., Balsamo, G., Boussetta, S., Carrer, D., Lafont, S., and Meurey, C.: Verification of the new ECMWF ERA-Interim reanalysis over France, Hydrol. Earth Syst. Sci., 15, 647–666, doi:10.5194/hess-15-647-2011, 2011.

Te Linde, A. H., Aerts, J. C. J. H., Hurkmans, R. T. W. L., and Eberle, M.: Comparing model performance of two rainfall-runoff models in the Rhine basin using different atmospheric forcing data sets, Hydrol. Earth Syst. Sci., 12, 943–957, doi:10.5194/hess-12-943-2008, 2008.

Te Linde, A. H., Aerts, J. C. J. H., and Kwadijk, J. C. J.: Effectiveness of flood management strategies on peak discharges in the Rhine basin, J. Flood Risk Manage., 3, 248–269, doi:10.1111/j.1753-318X.2010.01076.x, 2010.

Terink, W., Hurkmans, R. T. W. L., Torfs, P. J. J. F., and Uijlenhoet, R.: Evaluation of a bias correction method applied to downscaled precipitation and temperature reanalysis data for the Rhine basin, Hydrol. Earth Syst. Sci., 14, 687–703, doi:10.5194/hess-14-687-2010, 2010.

Van den Besselaar, E. J. M., Haylock, M. R., Van der Schrier, G., and Klein Tank, A. M. G.: A European daily high-resolution observational gridded data set of sea level pressure, J. Geophys. Res., 116, D11110, doi:10.1029/2010JD015468, 2011.

Weerts, A. H., Meißner, D., and Rademacher, S.: Input Data

Rainfall-Runoff Model Operational Systems FEWS-NL and FEWS-DE, Tech. rep., Deltares, 2008.

White, W.: Spatio-Temporal Structure of Precipitation in the Moselle Basin with Particular Regard to Flood Events, Ph.D. thesis, University of Trier, 2001.