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Validation of two precipitation data sets for the Rhine River

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Abstract

This paper evaluates a number of recently constructed or extended precipitation data sets used for hydrological applications and climate change studies in the Rhine basin. Firstly, 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. The length extension permits the assessment of extreme discharge and precipitation values with lower uncertainty than the original version. Secondly, the E-OBS Version 4 (ECA&D gridded data set) was evaluated for its performance in the Rhine basin for extreme events. The two ex-
- tended 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, but its performance of the mean annual cycle was rather poor in winter and remarkably well in the summer.

1 Introduction

The Rhine river crosses a number of countries and it is used for multiple purposes.
 Deviations in the water balance of the Rhine river, in particular in extreme events, could directly affect the safety of the natural habitat of the surrounding sub-basins. Floods are observed more frequently than droughts and usually have larger impacts on public awareness and safety. Alertness for drought events (like 2003, 2006 and 2007) is rising, as they also lead to severe problems in riparian countries. For instance,
 the warmest Central European summer in recent history (2003) has seen economic losses of about 12 billion Euros (Munich Re, 2004). Insight into these changes are of





major importance for planning and mitigation measures on a nationwide, regional and local scale.

Due to the vulnerability of the Rhine basin to both floods and droughts, many climate change impact assessments have been carried out using climate change scenarios of greenhouse gas emissions. For the Western-European area climate scenarios fore-see an increase in both the frequency and intensity of extreme precipitation events, including an increase in the precipitation rate of the 10-day accumulated winter precipitation of about 10 % per degree global temperature rise (Van den Hurk et al., 2006). The discharge regime of the Rhine will be affected by these changes. Related studies have been carried out to quantify the impact of climate change on the water balance

- and extreme value distribution, both in the Rhine River and elsewhere (Görgen et al., 2010; Milly et al., 2005; Kwadijk, 1993; De Wit et al., 2007; Buishand and Lenderink, 2004; Van Pelt et al., 2009). For instance, Middelkoop et al. (2001) used a set of models with doubled CO_2 concentrations to assess the impact of climate change on
- ¹⁵ hydrological regimes and subsequently the water resources management in the Rhine basin. All models indicate similar trends: higher winter discharge as a result of intensified snow-melt and increased winter precipitation, lower summer discharge caused by reduced snow storage and increased evapotranspiration. Variability between these results persists due to inherent uncertainty in the projections caused by natural variability, different spatial and temporal scales and different modeling approaches of hydrological
- ²⁰ different spatial and temporal scales and different modeling approaches of hydrological processes.

The majority of studies concerned with hydrological responses to projected climate changes usually evaluate representative climate change signals from Global Climate Models (GCMs) or Regional Climate Models (RCMs), introducing the climate outputs

intact in hydrological models. The use of raw output from GCMs or RCMs as hydrological forcing can hamper the resulting river streamflow. Direct GCM output is considered unsuitable to feed into hydrological models owing to their coarse spatial resolution and systematic bias (Leander and Buishand, 2007). Downscaling with 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).

Transferring the signal of climate change from climate models to hydrological models is not a straightforward process as meteorological variables from climate models are often subject to systematic errors (Graham et al., 2007). Lenderink et al. (2007) and Te Linde et al. (2010) used different scenarios of future meteorological conditions as input to a hydrological model of the Rhine river basin. They compared different approaches to impose the climate model output on the hydrological model. In
the so-called delta approach, climate projections are constructed by applying simple

- model-derived corrections to observed temperature and precipitation time series. The main disadvantage of the delta approach is that the extremes resulting from this approach are derived from present climate observations that have been either enhanced or dampened according to the delta factors (Graham et al., 2007). Alternatively, a
- direct approach uses bias-corrected climate model output as forcing of the hydrological model. This has the potential advantage of taking into account changes in the temporal and spatial divergence of climate variables, which may affect the characteristics of the hydrological variables. However, these potential advantages may turn into disadvantages if the quality of the climate model output shows considerable bias, i.e.
- ²⁰ when it does not adequately represent observed variability in the variables of interest (Diaz-Nieto and Wilby, 2005; Hay et al., 2000; Lenderink et al., 2007).

For applications of the direct approach, 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

²⁵ 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), the Variable Infiltration Capacity (VIC) model. Shabalova et al. (2003) studied changes in the discharge of the Rhine





by the end of 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

- ⁵ by Leander (2009) for the Meuse river, 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. A large statistical
- ¹⁰ 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 arise 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 CHR data set as input for the HBV-96 model (Bergström and Forsman, 1973; Lindström et al.,
- 1997) 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.





The HBV-96 model is used extensively as hydrological modeling tool in the Rhine basin. Te Linde et al. (2008) compared the performance in simulated discharges from HBV-96 and VIC when forced with three different atmospheric data sets: the re-analysis data ERA15, CHR and the Climate Research Unit (CRU) historical data set. Overall,

- ⁵ HBV-96 performed better than VIC, especially in simulating extreme events. However, there is still room for identifying different runoff response mechanisms and to characterize the key state variables during calibration for both types of models. A relevant conclusion for the present study is that the forcing data sets have a considerable influence on model performance, irrespective of the type of the model structure.
- ¹⁰ Thus, for all the abovementioned 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 space high-resolution data sets to improve physical descriptions and refining grid size. This data set should provide both accurate annual means and extreme peaks in the discharge behavior.
- ¹⁵ The purpose of this paper is to evaluate two newly developed precipitation data sets, both candidates to serve as reference for downscaled climate model output or weather generator applications. This assessment helps to decrease the large uncertainties in the estimation of extreme discharges at long return intervals. The data sets under consideration are a new extended version of the CHR precipitation data set for the
- Rhine, and 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). 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.
- Both data sets are used as forcing for HBV-96 set up for the Rhine basin and compared to similar simulations using another ECMWF re-analysis data set ERA-Interim (labeled ERA-Int; Simmons et al., 2007) as precipitation forcing. 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 selection of these gauging stations (i.e. catchments) is consistence with relevant studies on the assessment of the impact of climate change on the Rhine River.

The manuscript of this paper is structured as follows. In Sect. 2, a short description of the hydrological model HBV-96 and 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. In Sect. 3,

¹⁰ the analyses of the modeled discharges are presented and discussed. Conclusions are formulated in Sect. 4.

2 Methodology

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

- ¹⁵ The HBV-96 hydrological model (Bergström and Forsman, 1973; Bergström, 1976; Lindström et al., 1997) is a semi-distributed conceptual hydrological model for continuous calculation of runoff that has been originally developed at the Swedish Meteorological and Hydrological Institute (SHMI) in the 1970s. The HBV-96 precipitation-runoff model of the Rhine river basis has been successfully used, for instance, to estimate ex-
- treme 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 struc-
- ture 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. 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 transformed into a daily time series by assuming a 5% increase of the potential evapotranspiration per one degree of temperature anomaly. Empirical correction factors
- are applied to input potential evapotranspiration, precipitation and peak discharge values, in order to improve the discharge performance at Lobith. These correction factors were calibrated for the CHR data set only. Eberle et al. (2002) point at the systematic underestimation of the annual maximum discharges for most sub-basins of the Rhine.

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). A fully description on the sub-establishments distribution and further routines.
- 2002, 2005). A fully description on the sub-catchments distribution and further routines in the HBV-96 can be found in Sprokkereef (2001). Wires and structures are not represented in HBV-96, which may affect model performance in the Cochem and Raunheim catchments.

In this study, three different precipitation and one temperature data set are used to ²⁵ force the HBV-96 model. The precipitation data sets are:

- CHR08 (Extended version of CHR).
- E-OBS (Version 4).
- 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.

5 2.2 Description of precipitation data sets

2.2.1 CHR08

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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). This dataset 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. Precipitation data for the German part of the Rhine river basin (Fig. 1) was generated using a combination of grid based daily data and hourly station values. For the Moselle river, precipitation data were used from the University of Trier.

- ¹⁵ The CHR08 precipitation data set presented in this paper is compiled from the original daily CHR data set as background, completed by the 1×1 km² REGNIE (Regionalisierte Niederschlagshöhen) data set provided by the German Weather Service (DWD), precipitation data for the Moselle provided by the University of Trier, and a gridded data set from ETH (Eidgenössiche Technische Hochschule, Zürich) for the Swiss basin.
- These additional regional precipitation data sets were used to extend or replace the CHR background data, in order to make full use of the enhanced quality of them. Three major basins are discerned: Germany, Switzerland/Alps, and the river Moselle (see Fig. 1). For each basin, gridded data sets of daily precipitation were used. In Fig. 2, an overview of the construction of the CHR08 data set for each basin is presented.

For the German sub-basins, the original CHR data are used for the period 1961–1990, and for the period from 1991 until 2008 daily sub-basin averaged precipitation





are created from the REGNIE daily gridded data of the German Meteorological service (Deutscher Wetterdienst-DWD). The REGNIE grid has a spatial resolution of $1 \times 1 \text{ km}^2$. A short description on the CHR and REGNIE data sets can be found in Terink et al. (2010).

- The daily gridded precipitation data for the River Moselle, 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 REG-NIE 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 mean monthly mean background
- ¹⁵ grids based on REGNIE data for Germany, ETH data for Switzerland 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.
- The data for the Swiss/Alpine basin cover the period 1970 until 2000. This data set 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 encompasses just the Alpine countries. A comparison between the
- annual mean and extreme discharges of CHR08 and CHR for the German (REGNIE), Moselle and Swiss basins showed that for the first two basins there were no distinct differences. For the Swiss 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. Data for the period of 2001 until 2008, were derived from the REGNIE emulation approach developed by Weerts et al. (2008) and described above.

5 2.2.2 E-OBS

A new version of gridded precipitation data set recently became available from the ENSEMBLES project and ECA&D (E-OBS Version 4, Haylock et al., 2008; Van den Besselaar et al., 2011, in press). 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 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 un-

- certainty 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 restruc-
- 20 E-OBS data set is much smaller than REGNIE. However, E-OBS is regularly restruct tured, classifying it as one of the most up to date meteorological data sets.

2.2.3 ERA-Interim

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The ERA-Int reanalysis data set consists of atmosphere and surface analyses for the period from 1989 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 bilinearly 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.

3 Analysis of the results

3.1 Impact of the extension on estimates of extreme discharge

The construction and design of flood defenses infrastructures is based on estimates of the chance of exceeding a discharge event of a given probability. Usually the return time of these events (e.g. 1250 years as for the Rhine basin in the Netherlands) is much longer than the available data record length (approximately 100 years; 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 year using the CHR data set for the period 1961–1995 (35 years), the CHR08 for the period 1961– 2008 (47 years) and the E-OBS for the period 1950–2008 (58 years). Figure 3 (above), shows the results for Lobith, the entrance point of the Rhine into the Netherlands (see Fig. 1).
- ²⁵ 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-year return period, the fit using the CHR08 data set yields a similar estimate as CHR, but for E-OBS the 1/100 year return level is significantly lower. The 95% confidence interval from CHR08 simulations spans a range between 12420 m^3 and 16669 m^3 . For the CHR data set, the 100 year return period with the 95% confidence interval range from

⁵ CHR data set, the 100 year return period with the 95% confidence interval range from 12195 m³ to 17273 m³ and for E-OBS between 11229 m³ and 14642 m³. The data set extension from CHR to CHR08 of 12 years (34%) leads to a reduction in the discharge uncertainty of 829 m³, 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 (below), shows Gumbel plots for the annual maximum 10-day precipitation sum averaged over the catchment area upstream of Lobith. For the 1/100 year 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 discharges with different 10-day precipitation sums,

while CHR08 and E-OBS give different discharges with similar 10-day precipitation sums. The differences in the 10-day precipitation sums between CHR and CHR08 could be due to the extension of 12 years. Differences and similarities in the several
²⁰ discharge results may be related to the fact that HBV-96 has not been recalibrated for the different precipitation data sets.

3.2 Annual cycles of mean discharge

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In this sub-section, the mean annual cycle of observed and simulated discharge at selected sub-catchments is presented, starting from the northwest Lobith and moving towards the south through Cochem (Moselle), Raunheim (Main) and eventually Basel (Switzerland) (Fig. 1). Figure 4a 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 and the 95% percentile of the observed





discharges derived from the interannual variability.

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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. $200 \text{ m}^3/\text{s}$ (~0.1 mm/day)

- ⁵ exists. For June and July, CHR08 is higher than 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 Moselle basin – see Fig. 1), CHR08 and E-OBS give very similar results throughout the year (Fig. 4b). 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. 5a), the discharge from the three simulations display pronounced differences with the observations, but the size of the catchment (and the 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. 5b) 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 remarkable 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 wires 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 catchments. CHR08 is performing better in almost all the sub-catchments for all statistics. The only sub-catchment 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.

20 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 years) but overestimates 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





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15 discharges of small return periods.

CHR08 and E-OBS tend to underestimate the winter 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.

Discussion and conclusions 4

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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 catch-25 ments 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

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

- 5 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 10 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







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 contact). In addition, the E-OBS Version 4 precipitation data set was validated. The two precipitation 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 in hydrological applications in the following ways: firstly, by extrapolation of the available
records to a 1/100 years return period; secondly, by evaluation of annual mean, winter maximum and summer minimum; and at last by comparing statistics of daily steps for a range of sub-catchments.

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). The CHR08 discharge reduces the error of the 95% confidence interval of simulated discharge by approximately 5% and the 10-day annual precipitation sum by 4%.

Although E-OBS decreased the error of the 95% confidence interval by 8% and gives 6% lower 10day annual precipitation sum with a 1/100 year return interval which ²⁰ is consistent with the corresponding error of the CHR08, the annual maximum discharge of the 1/100 years return period is much lower than the corresponding one of CHR, CHR08 and the 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. The performance in Cochem and Raunheim is possibly affected by the lack of representing wires and structures in these areas by HBV-96. 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 Nr, for a number of smaller sub-basins, CHR08 outperformed 5 E-OBS and ERA-Int in almost everywhere, proving that the good performance of the CHR08 is present in the entire basin of the Rhine River. The low scores in Erft are probably due to the fact that the discharge dynamics of the river Erft are dominated by technical measures related to brown coal mining.

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 of them have the ability to generate valid flows and extreme hydrological events for the entire Rhine

- ¹⁵ basin. Their 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. The CHR08 data set, as described here, is already being used in recently started research project
 ²⁰ called Knowledge for Climate Research related to climate change in the Rhine basins.
- 20 called Knowledge for Climate Research related to climate change in the Rhine basins Details can be found in http://knowledgeforclimate.climateresearchnetherlands.nl/.

Finally, we acknowledge some limitations in our study. Firstly, developments in the representation of the potential evapotranspiration of the HBV-96 model could help eliminate the bias in the summer months of the CHR08. A preliminary analysis showed that

there is room for improvements related to the correction factors applied in the HBV-96 model.

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data set for the Swiss basin.

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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 /day)			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 (27088)	0.86	0.85	0.21	142	153	358	0.85	0.83	0.08
Main (27142)	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 (14000)	0.71	0.68	0.08	79	79	158	0.62	0.62	-0.51
Maxau (50196)	0.87	0.89	0.12	197	182	876	0.85	0.57	-1.92
Basel (35897)	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







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

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

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

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

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Fig. 5. As in Fig. 4 for (a) Raunheim and (b) Basel.

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

Fig. 7. As Fig. 6 for Cochem.

Fig. 8. As Fig. 6 for Raunheim.

Fig. 9. As Fig. 6 for Basel.

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