# Assessment of High Resolution Climate Change Data for Hydrological Impact Studies

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## Introduction

The Alps experience a significant change in climate. Since 1840, the mean temperature increased by 1.1 °C (Böhm et al., 2001) almost twice much as the global average of 0.6 °C (Brohan et al., 2006). For the coming decades climate model projections show various adverse effects, such as reduction in snow cover at low altitudes, receding glaciers and melting permafrost at higher altitudes and extreme precipitations events.

In the PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) project (Christensen and Christensen, 2007), an evaluation of available regionalized climate change data for various areas including the Alps has been performed. The geometrical resolution of the considered models was 0.5° by 0.5°. This resolution is, however, not sufficient if the climate change data is to be used in hydrological impact studies. Recently, some new high resolution data from Regional Climate Models (RCM) has become available opening the perspective on high resolution water balance studies.

The present article considers in broad terms the principle of climate change data downscaling and concentrates upon newly available high resolution data. In three investigation areas precipitations statistics of simulated present climate are compared to available observed climatology data and implications of the simulated future climate are discussed.

## Downscaling of Climate Change Data

The complex gridded and computer based General Circulation Models (GCM) are the best available tools for the construction of climate change scenarios. GCMs represent main components of the climate system in three dimensions and on global scale, coupled to a three dimensional representation of the ocean. The AOGCMs (Coupled atmosphere-ocean general circulation models) provide a consistent picture of possible climate change based on a set of various assumptions.

In order to study the consequences of global climate change on local scales the spatially coarse GCM data has to be downscaled by application of Regional Climate Models (RCM) or Statistical Downscaling Models (SDM). SDMs employ statistical relations between large scale forcing and station observed variables, e.g. via multiple regression, canonical correlation analysis or circulation pattern analysis. They are computationally very efficient, however a persistence of statistical relations under changing climate conditions has to be assumed. The RCMs are three dimensional atmospheric models, usually coupled atmosphere-land surface systems based on conservation laws and physical relations as well as parameterizations for subgridscale processes. They are computationally very expensive. Schmidli et al. (2007) found that in complex terrain RCM achieve better skills than SDMs.

The downscaling principle is shown in Figure 1. GCMs provide boundary forcings for the RCM/SDM. RCMs are often driven in a nested approach. The regional climate change results can be applied in further modeling i.e. hydrological models. Kunstmann et al. (2004) and Kunstmann and Stadler (2005) demonstrate the application of regional climate data of the MM5 model in an impact analysis for the Alpine catchments of the Ammer and Mangfall river (State of Bavaria, Germany)

Construction of a climate change scenario with a GCM involves a decision what emission scenario is used to calculate future atmospheric greenhouse gas and aerosol concentrations. In the year 2000, the IPCC published a set of scenarios for use in the Third Assessment Report (TAR) in the Special Report on Emission Scenarios – SRES (Nakicenovic, 2000). In total 40, different scenarios were defined and grouped in families: A1, A2 with more technological and B1 and B2 with more environmental background.

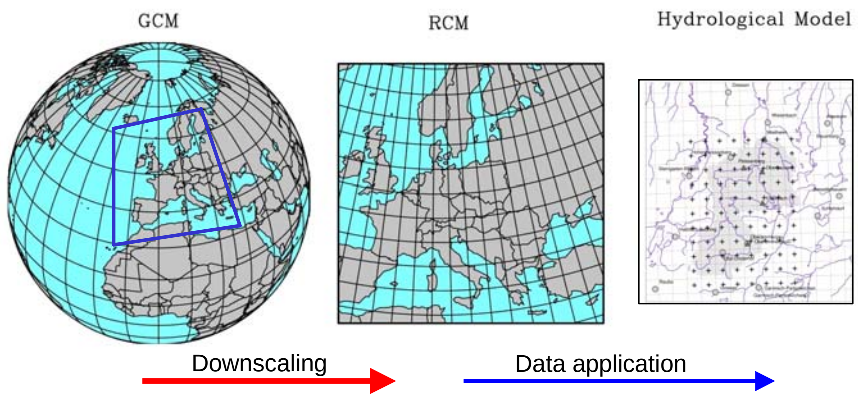


**Fig. 1** Principle of downscaling of gobal climate change data.

The scenarios were employed in experiments with various GCMs in the IPCC Third (TAR) and in the Fourth Assessment Report (AR4), completed in 2007 (IPCC, 2007). Table 1 depicts the GCM models used as boundary forcings of regional models considered in the present article. The UKMO (UK Meteorological Office) HadCM3 (Hadley Centre Coupled Model, version 3) GCM is a coupled atmosphere-ocean general circulation model. Atmosphere and Ocean exchange information once a day with exact conservation of heat and water fluxes. The climate change simulations for the period 1860 to 2100 with the HadCM3 model show a global mean SRES scenarios temperature increase in range from 2.6 to 5.3K (Johns et al., 2003). The Max-Planck-Institute for Meteorology, Hamburg, Germany (MPI) ECHAM model (Roeckner et al., 2003) has been developed from the ECMWF (European Centre for Medium-Range Weather Forecasts) model (EC) and a complex parameterization package developed in Hamburg (HAM) used to adjust the ECMWF Numerical Weather Prediction (NWP) model for climate simulations. The current version is ECHAM5.

## Available high resolution RCM data

In PRUDENCE, 13 different RCMs were evaluated. The present investigation discusses newly available climate change data at spatial resolutions below 20 km provided by four RCMs: CLM, HIRHAM, RegCM and REMO.

A high geometrical resolution is a key issue when RCM data is used as input into a hydrological model. Figure 2 depicts as example the catchment of the Ammer river located in the southern part of the Bavaria state. It is overlaid by the 0.5° by 0.5° grid as applied in PRUDENCE and a 10 arc

**Table 1** GCM data providing boundary forcings for RCM modes discussed in the present paper**.**

| Institution | Country | IPCC Report | Model | TRUNC | GRID | L | Scenario |
|---|---|---|---|---|---|---|---|
| METO | United | TAR | HadCM3 | - | 2.5° x3.75° | 19 | A1FI,A2(3),B1,b2(2) |
| | Kingdom | AR4 | HadCM3 | - | 2.5° x3.75° | 19 | A2,A1B,B1 |
| | | AR4 | HadGEM1 | - | 1.25°x1.875 | 38 | A2,A1B,B1 |
| MPI | | TAR | ECHAM/OPYC3 | T42 | 2.8°x2.8° | 19 | A2,B2 |
| | | AR4/ENS | ECHAM5/MPI-OM | T63 | 1.5°x 1.5° | 31 | A2(3),A1B(3),B1(3) |

minutes by 10 arc minutes grid. It can be seen that the coarse grid is entirely insufficient. Even the 10 arc minutes grid might lead to problems as any application of the RCM data should employ a scale of at least of 2 dx, where dx is the RCMs grid cell size. The model parameters, applied GCM forcings, as well as available time ranges are shown in Table 2 and the geographical areas in Figure 3.

The non-hydrostatic community climate model **CLM** is based on the Local Model (LM) of the German Weather Service (DWD)(Steppeler et al., 2003). It has the same dynamic and physical core as the LM. CLM employs a rotated spherical Arakawa C-grid in horizontal direction on regular latitude-longitude coordinates with a rotated pole, and on hybrid terrain-following coordinates in the vertical coordinate system. Lateral boundary in grid space is formulated after Davies (1976) with a relaxation zone of 10 grid cells. The RCM output is saved in NetCDF (Network Common Data Form) data format.

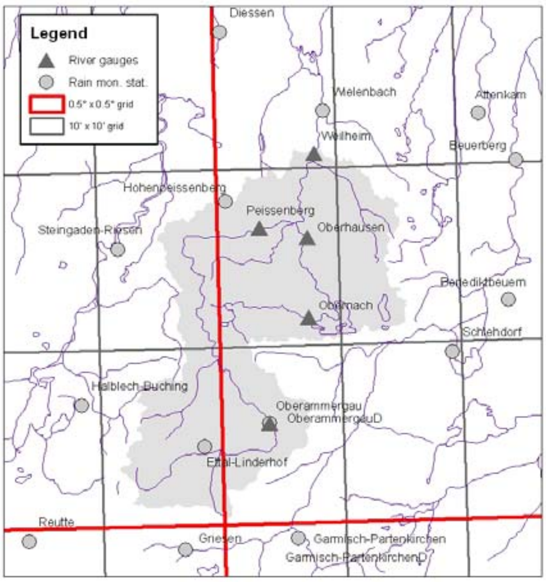


**Fig. 2** Catchment of the Ammer river (south Germany) overlaid by a 0.5°x0.° grid (red) and 10’ x 10’ grid (gray) .Catchment size 600 km2

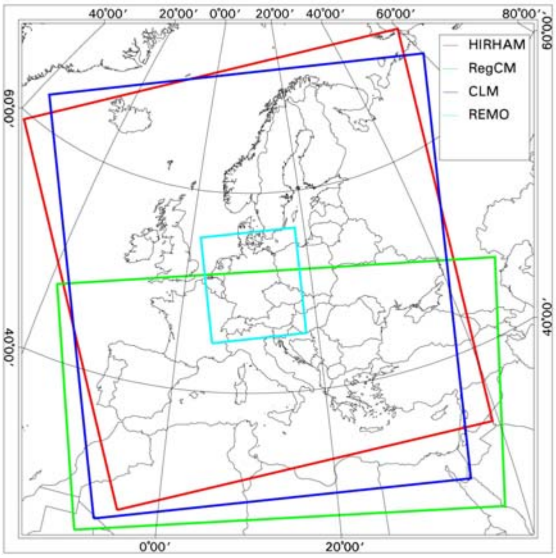


**Fig. 3** Extent of the available high resolution regional climate change data**.**

The International Centre for Theoretical Physics (ICTP), Trieste, Italy, regional climate model **RegCM** was originally developed by Giorgi et al. (1993). The dynamical core of the RegCM is equivalent to the hydrostatic version of the NCAR/Penn State University meso-scale model MM4 and the models projection is rotated Lambert Conformal. Boundary layer physics are formulated following a non-local vertical diffusion scheme with a relaxation zone in transition from GCM to RCM of 11 grid cells. The output is available in GraDS (Grid Analysis and Display System) format.

**HIRHAM** is the RCM of the Danish Meteorological Institute (DMI). The dynamical part originates from HIRLAM (High Resolution Limited Area Model) version 2 and the physical part from ECHAM. The recent model version HIRCAM5 is a completely new RCM combining most recent versions of HIRLAM and ECHAM. The model is run on regular latitude-longitude coordinates with rotated pole and applies the lateral boundary condition after Davis (1976) with a relaxation zone from GCM to RCM of 10 grid cells. The model output is saved in NetCDF or GRIB (GRidded Binary) format.

The regional hydrostatic climate model **REMO** (Jacob et al., 2003) of the Max-Planck Institute of Hamburg has two parameterization schemes: the German Weather Service (DWD) physics and additional schemes of the ECHAM4 global climate model. REMO employs a spherical Arakawa-C grid on regular latitude-longitude coordinates with a rotated pole and resolutions between 0.05° to 1°.The transition zone from the GCM forcing to REMO is 8 grid boxes. REMO climate change data is available in IEG data format.

**Table 2** Available high resolution regional climate change data**.** CNTR – control run , SCEN – scenario run, temporal resolution H – hourly, D – daily; M – monthly and S seasonal data. CERA – www.cera.de, PRUDENCE: www.prudence.dk

| **Model** | **CLM 2.4** | **HIRHAM** | **RegCM** | **REMO** |
|---|---|---|---|---|
| **Institution** | M&D | DMI | ITCP | MPI |
| **GCM** | ECHAM5 | HAD3M | HAD3M | ECHAM5 |
| **SRES scenario** | B1,A1B(2), A2 (2) | A2 | B2, A2 | B1, A1B, A2 |
| **Projection** | Rotated | rotated | Lambert | rotated |
| **Resolution** | 0.165° | 0.11° | 20km | 0,08° |
| **CNTR** | 1950-2001 | 1960-1990 | 1960-1990 | 1955-2001 |
| **SCEN** | 2001-2100 | 2070-2100 | 2070-2100 | 2001-2100 |
| **Temporal Resolution** | H,D | D,M,S | D | H,D,M |
| **Data source** | CERA | PRUDENCE | ITCP | CERA |

## Climate of the 20$^{th}$ century

The evaluation of the RCM models is preformed in three investigation areas ALPS, NORTH and SOUTH. ALPS area covers the entire Alpine region as defined in PRUDENCE (5°-15°E and 44°-48N). The coordinates of further smaller areas are: NORTH 9°50’-13°E and 46° 50’-48°N) north of the main Alpine ridge and SOUTH 8°-11°50’E and 45°30’-46°30’N located south of the main ridge. The model data were accessed in they original map projections without any interpolation. This is especially important for the models employing the rotated pole coordinates. The precipitation statistics were derived from daily data with 30 day month in case of data generated with Had3CM GCM forcings and real calendar in case of data driven by the ECHAM5 GCM. Thus, al least 900 values were available for each month allowing robust frequency and distribution characteristics. The daily statistics of each cell were averaged over the years and over the investigation area.

The model simulations are compared to climatology data provided by CRU (Climate Research Unit, Norwich, UK, in a spatial resolution of 10 arc minutes (ALP-IMP and CRU 1.2) and from the University Delaware in 0.5° resolution. As a part of the ALP-IMP projects a high resolution gridded climatic fields have been generated for the Greater Alpine Region of Europe. The extent of the Alpine data is 4°-19°E and 43°-49°N- The monthly precipitation totals data for the 1800–2003 period are based on 192 long-term homogenized precipitation series from meteorological stations (Efthymiadis et al., 2006). CRU TS 1.2 climatology is an additional dataset gridded at 10 arc minutes covering the European land surface. The available climatic variables are: cloud cover, DTR (Diurnal Temperature Range), precipitation, temperature and vapour pressure.

Figure 4 shows the annual cycle of precipitation in the ALPS area as an area average of the period 1961 - 1990. It can be seen that there is a substantial uncertainty in the climatology data used in the comparison. This creates still a large difficulty in any model evaluation. Frei et al. (2003) evaluated daily precipitations statistics from four regional climate models. They point out that the domain bias of measured data resulting from biases in measurements and in the network was in range of -16%. The observations underestimate the real precipitation.

The RCM models tend to overestimate the measured precipitation. (see Figure 4). The overestimation in the winter season is in magnitude of 30 %. It might have adverse effects in a further hydrological application even when the summer precipitation amount is less uncertain. Possibly overestimated snow coverage will influence the runoff in the later seasons. The magnitude of the bias is in the same order as in PRUDENCE (Jacob et al., 2007). The RCMs (and the GCM) models still have problems in the reproduction of the precipitation magnitude and patterns in topographically complex areas.

As shown in Figure 4 B and Figure 4 C there is also a disagreement between the investigated models in the fraction of days with precipitation over 1mm/day in the winter season and substantial differences in the fraction of days with precipitation over 15 mm/day. The biases in the monthly mean precipitation in the smaller investigation areas (see Figure 5) appear higher in the winter season in the NORTH area.

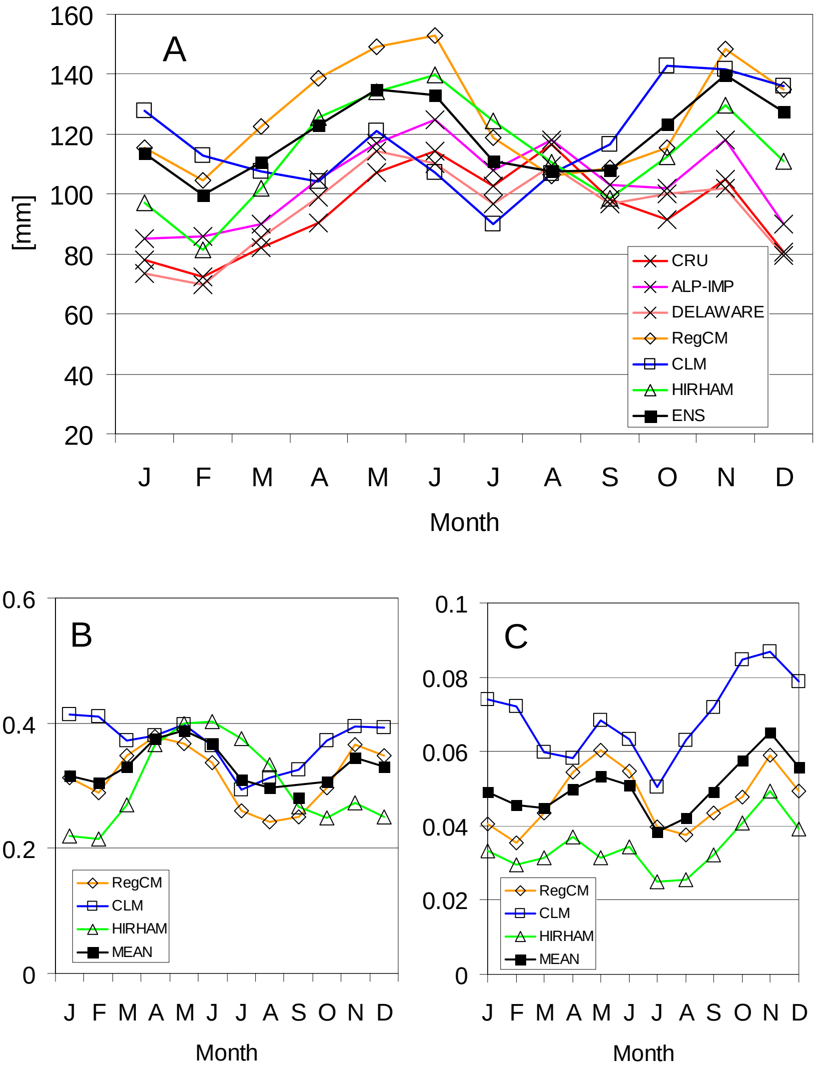


**Fig. 4** Annual cycle of precipitation statistics 1961 – 1990 averaged of the Alpine region (5°-15°E, 44°-48°N, grid points over sea and missing excluded. (A) monthly precipitation; (B) frequency (fraction) of days with precipitation above 1mm/day; (C) frequency (fraction) of days with precipitation above 15 mm/day

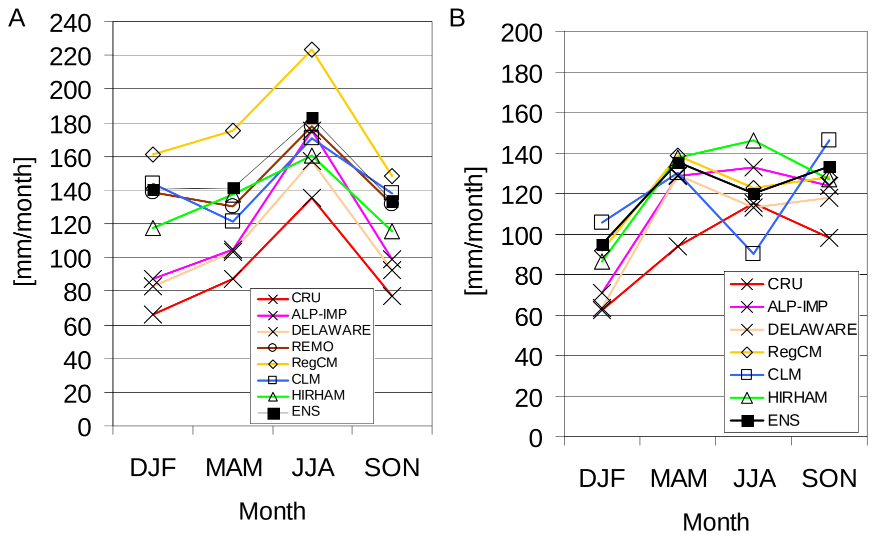


**Fig. 5** Seasonal precipitation 1961-1990 averaged over the investigation areas NORTH (A) and SOUTH (B)**.**

## Future Climate

The small number of available high resolution climate change with 2 (ALPS and SOUTH) or 3 (NORTH) does not allow for building and considering ensemble mean values. Therefore, the single models and the A2 SRES scenario results of the HIRHAM, RegCM and REMO model are shown in Figure 6 as ratio between the area averaged scenario mean 2071-2100 to the 1961-1990 mean of the control run. The transient CLM data will only be released en of 2007. The results indicate, as well as in PRUDENCE, a decrease of the summer precipitation in the range of more than 20% and a precipitation increase in the winter season of approximately up to 30%. In PRUDENCE, an ensemble mean of the 25 investigated models showed in the SRES A2 scenario a relative seasonal mean precipitation change of +20% in winter, +2% in spring (MAM), -26% in summer (JJA) and -7% in autumn.

Frei et al. (2006) have shown that precipitation extremes tend to increase in the winter season north of about 45°N, while there is an insignificant change in the southern part of the Alps.  Figure 7 depicts the change the precipitation distribution within the NORTH area as simulated by the

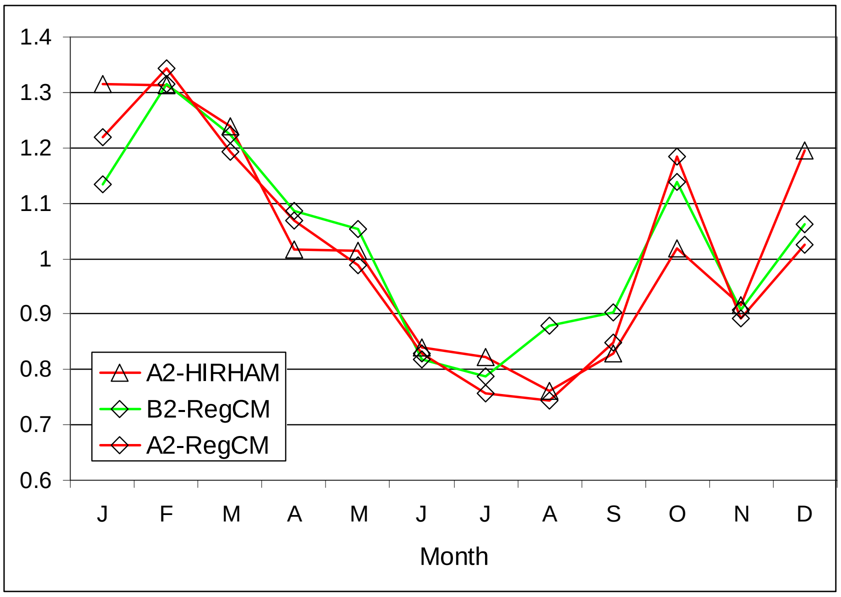


**Fig. 6**Simulated annual precipitation ratio SRES Scenario 2071-2100 to control run 1961-1990 for the ALPS area.

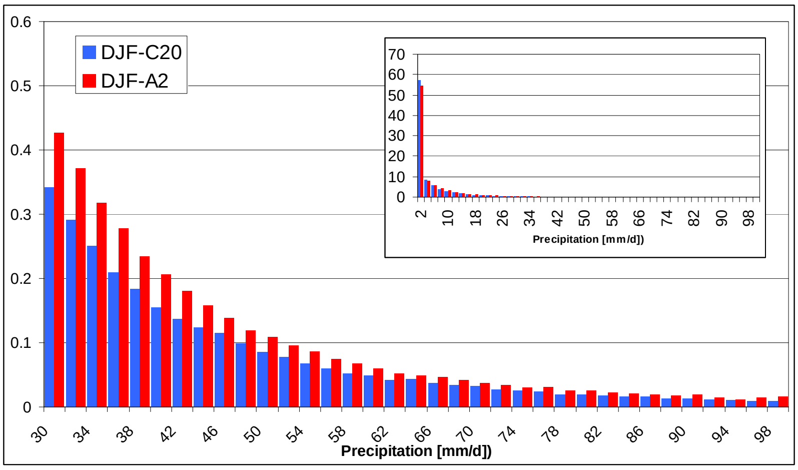


**Fig. 7** Simulated precipitation distribution for the winter season (DJF) and the area NORTH with the REMO model. C20 – 1961-1990 area mean control run and A2 – 2071-2100 area mean SRES A2 run

REMO model. The results indicate an increasing frequency of strong precipitation events. This change can be seen in the NORTH area in all models in the winter and summer season. The southern part (SOUTH) some models simulate this change for the winter season only.

## Conclusions

There is steadily increasing knowledge concerning the climatic change and the expected effects. For the Alpine region a substantial decrease in precipitation in summer and increase in the winter season can be expected. With the increasing spatial resolution of the regional climate models as well as with increasing computational resources, assessment of the climate changes effects even in small river catchments will be possible. While the bias of simulated mean temperatures is in range of 1K, i.e. 0.8°K ensemble mean in Winter (DJF)(Jacob, 2007) there is still a limited reproduction of the major precipitation statistics in comparison to observed values. This fact implicates the application of a bias correction to the regional climate change precipitation data prior application in a hydrological model.

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