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Evaluation of water balance components in the Elbe river catchment simulated by the regional climate model CCLM

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Abstract

For investigations of feedbacks between the hydrological cycle and the climate system, we assess the performance of the regional climate model CCLM in reconstructing the water balance of the Elbe river catchment. To this end long-term mean precipitation, evapotranspiration and runoff are evaluated. Extremes (90th percentile) are also considered in the case of precipitation. The data are provided by a CCLM present-day simulation for Europe that was driven by large-scale global reanalyses. The quality of the model results is analyzed with respect to suitable reference data for the period 1970 to 1999. The principal components of the hydrological cycle and their seasonal variations were captured well. Basin accumulated, averaged daily precipitation, evapotranspiration and runoff differ by no more than 10 % from observations. Larger deviations occur mainly in summer, and at specific areas.

Keywords: CCLM, Evaluation, Water balance

1 Introduction

In the last decade of the 20th century, dynamical regional climate modeling was developed based on such pioneering research as published e.g. in GIORGI (1990), GIORGI et al. (1990) or GIORGI and MEARNS (1991). Since then this physically-based downscaling approach has matured and is now widely applied for many regions around the world, as documented e.g. in CHRISTENSEN et al. (2007).

One important application of regional climate modeling concerns the assessment of the regional impact of climate change on surface hydrological processes. Therefore river routing schemes have been increasingly driven with simulated runoff from regional climate models (RCMs) in order to enable studies on the impact of climate change on streamflow and flooding of major river basins (LUCAS-PICHER et al., 2003; DANKERS et al., 2007; GAO et al., 2011). In order to overcome the offline nature of these hydrological simulations, in a next step additional hydrological processes such as routing or wetlands have been directly implemented in RCMs (ANYAH et al., 2008; FAN and MIGUEZ-MACHO, 2010; STEINER et al., 2005).

Before applying such coupled models and routing schemes in the analysis of hydro-meteorological processes, it is imperative to assess the baseline performance of RCMs regarding their ability to simulate components of the hydrological cycle. Therefore RCM simulated precipitation, evapotranspiration and consequently runoff have been frequently evaluated against observations as well as simulation results from detailed hydrological models. Examples of such efforts are DANKERS et al. (2007); BIEMANS et al. (2008); FEKETE et al. (2004); SCHUENEMANN and CASSANO (2009); SMIATEK et al. (2009); WANG et al. (2009) or FREI et al. (2003). Results show that model performance generally differs by season, typically with an underestimation in summer and an overestimation in winter (FREI et al., 2003; SMIATEK et al., 2009; WANG et al., 2009). Some studies show that RCM results improve with higher resolution, especially in mountainous regions (DANKERS et al., 2007; WANG et al., 2009). Specifically, when applying HIRHAM to the Upper Danube Basin, DANKERS et al. (2007) found that a 12 km model resolution improved the representation of orographic precipitation patterns in comparison with a 50 km resolution. Similarly, SMIATEK et al. (2009) conclude from their analysis of output from four RCMs (RegCM, REMO, HIRHAM and CCLM) for three selected areas in the Alps that higher spatial resolutions improve conditions for precipitation modeling in complex terrain. However, other studies, for instance JÄGER et al. (2008) or AHRENS et al. (2003), found no clear benefit in using higher resolutions. Differences in the RCM performance for convective vs. advective precipitation indicate the potential importance of physical parametrizations (KAIN and FRITSCH, 1990).

In this study we assess the performance of the regional climate model COSMO model in Climate Mode (CCLM, BÖHM et al., 2006), in reproducing spatial and temporal characteristics of total precipitation, i.e. liquid and solid, evapotranspiration and runoff in the European Elbe River catchment (Fig. 1) for a 30 year period (1970–1999). The Elbe river has a length of about

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Figure 1: The location and the orography of the Elbe River catchment.

1000 km and its basin covers an area of 150 000 km^2, making this Europe's fourth-largest river basin. The basin is located mostly in the Eastern part of Germany and the Czech Republic. Small parts lie in Poland and Austria. The basin is inhabited by 25 million people and therefore it is important to assess potential impacts of climate change in the catchment area.

We evaluate CCLM climate reconstructions from the HYDROCARE runs (HYDROlogical Cycle of the CAdses REgions; (Böhm et al., 2008). CADSES in turn abbreviates *C*entral European *A*driatic *D*anubian *S*outh-Eastern *E*uropean *S*pace regions. Since the result of the CORDEX runs (Jones et al., 2011) are not available yet, the HYDROCARE simulations are the most recent CCLM decadal high-resolution results available for Europe.

The CCLM HYDROCARE runs were performed over Europe for the years 1961–2000, driven by the ERA40 global analyses from the European Centre for Medium Range Weather Forecast (ECMWF) (Uppala et al., 2005) and with a spatial resolution of 18 km. Seasonal characteristics of near-surface air temperature and surface pressure were shown to be captured well by the model for the 30 year period (Böhm et al., 2008), while the model's performance for precipitation has not yet been assessed thoroughly. In this study CCLM simulated precipitation is evaluated against observations with a focus on precipitation characteristics that are important for runoff and subsequently river discharge. Long-term measurements of evapotranspiration and runoff for large regions such as catchment areas are not available. Therefore the CCLM simulated evapotranspiration and runoff is compared with results from the *Soil-Water Integrated Model* (SWIM, Krysanova and Wechsung, 2000). SWIM is a comparatively detailed ecohydrological model that has been fine-tuned and extensively evaluated for various aspects of the hydrological cycle in the Elbe catchment (Hattermann et al., 2008; Krysanova et al., 2008; Conradt et al., 2012a; Conradt et al., 2012b).

The investigations in this paper establish a baseline evaluation against which our future CCLM developments can be compared.

This work is limited to the analysis of previously carried out CCLM simulations, since those runs were subsequently used for investigating further hydrological processes, such as routing that have been implemented in CCLM. As a downside, this precludes any discussion or analysis of uncertainty. In order to overcome this limitation the run could be repeated with different initial conditions, or a slightly differently chosen grid ("twin experiment"). Another possibility could be an analysis of an ensemble of climate realization, such as the ENSEMBLE (Hewitt, 2005) data, however this would have a different focus than the investigation of the performance of CCLM. In a similar vein we refrain from discussing uncertainties of the hydrological variables.

In the next section we give a brief overview of the CCLM model setup, the HYDROCARE simulations and the observation data used. The simulation results are evaluated by means of these observations/data in Section 3. Finally we finish with conclusions and an outlook in Section 4.

2 Materials and methods

2.1 CCLM HYDROCARE simulations

CCLM is a nonhydrostatic unified model for weather and climate research. It can be used to simulate the climate at the mesoscale for up to centuries, while handling resolutions down to a few kilometers. More detailed information is given in (CCLM community, 2008).

In our investigations, we have made use of the HYDROCARE runs, i.e. existing climate reconstructions performed with CCLM. They represent the most recent reconstruction of the period 1961–2000 with CCLM version 4.0.

The model area is shown in Fig. 2. In a rotated longitude / latitude geographical coordinate system (rotated north pole at $\phi = 39.25\,^\circ$N, $\lambda = 162\,^\circ$W) it extends from $\phi = 22.2\,^\circ$S to $\phi = 22.5\,^\circ$N and from $\lambda = 25.0\,^\circ$W to $\lambda = 17.4\,^\circ$E. This area is covered by 271×257 grid points with a cell size of $0.165\,^\circ \times 0.165\,^\circ$ (≈ 18 km $\times$ 18 km). The vertical grid was defined on 32 pressure-based η-levels. The sponge zone is 85 km wide, and the internal time step amounts to 150 s. The model was driven by boundary conditions derived from global

Figure 2: CCLM model area covered by the HYDROCARE simulations. The gray-shaded area indicates the Elbe catchment, which is the evaluation region.

ECMWF analyses, the ERA40 data (initially covering 40 years starting 1957 but later extended to 2002, see Uppala et al. (2005)), with an update frequency of six hours. Model output is stored at least daily, but shorter intervals are possible. For the HYDROCARE simulations the Tiedtke convection scheme (Tiedtke, 1989) was used. Further details can be found in Böhm et al. (2008).

To provide lower boundary conditions over land, CCLM includes the land surface parametrization scheme TERRA_ML (Schrodin and Heise, 2001; Doms et al., 2008). The multi-layer TERRA_ML scheme describes hydrological and thermal soil and vegetation processes. In the hydrological part, bare soil evaporation, plant transpiration and evaporation from the interception and snow store are calculated, the Richards equation for vertical soil moisture transport is solved and melting effects in the snow reservoir, water exchange between different reservoirs and the soil, and runoff formation are accounted for. In the thermal part, the heat conduction equation is solved. Furthermore thermal effects such as snow melting or freezing are considered. Similarly, TERRA_ML tracks liquid water/ice separately in each soil layer. Note that only vertical fluxes are represented, as the horizontal displacement can be neglected at the presently used grid sizes (≈ 20 km). This also holds for the runoff which is formed within a grid cell and not transported to any of the adjacent cells. The number of soil levels was set to 10, and the layer thickness increases with soil depth from 0.01 m at the surface to 7.68 m at the bottom, following an exponential law. Soil types are provided as an external two-dimensional array based on the UNESCO/FAO soil map of the world (Paris, 1974).

TERRA_ML provides a stability and roughness-length dependent formulation of the surface turbulent fluxes which constitute the lower boundary conditions for the atmosphere. Plant transpiration is parametrized by a resistance approach following Dickinson (2000). Plant cover and the leaf area index are computed from maximum and minimum values depending on the actual day in relation to the beginning and duration of the vegetation period, while also depending on latitude and altitude.

Surface runoff is formed by summarizing contributions from the interception and snow store, and due to a limited infiltration rate into the soil. Furthermore, contributions from the hydrologically active soil layers in case of oversaturation are added to form the subsurface runoff.

2.2 Observational data for CCLM model evaluation

For assessing the quality of the HYDROCARE runs in the Elbe river catchment in terms of hydrological quantities, we used reference data from different sources.

In the case of precipitation we used daily accumulated data provided by DWD (Germany), ČMI (Czech) and ZAMG (Austria). The stations are shown in Fig. 3. The data were subsequently corrected for precipitation undercatch according to Yang (1999). This scheme corrects for wind induced losses, wetting losses of Hellmann gauges, losses due to evaporation and errors due to trace precipitation. Since the corrections are stronger for snow, winter is the season that is most affected. Subsequently, the precipitation data were interpolated to the CCLM model grid by an interpolation routine based on the inverse distance paradigm. Because of the high station density in the Elbe catchment, as well as the performed correction for undercatch we did not use other available precipitation data sets, such as E-OBS (Haylock et al., 2008). Note that the station density is considerably lower in the Czech Republic than in Germany.

Long-term measurements of evapotranspiration and runoff for large regions such as catchment areas are difficult to obtain. One possibility would be to use a data set produced with the VIC land surface model (Nijssen et al., 2001a; Nijssen et al., 2001b; Sheffield and Wood, 2007) which however has a too low resolution of 2 ° × 2 ° for the purpose of this study. In order to evaluate the CCLM/TERRA_ML simulated evapotranspiration and runoff for the Elbe-river catchment we used results from the ecohydrological model SWIM (Krysanova and Wechsung, 2000). The model SWIM is a process-based tool for hydrological and water quality modeling in mesoscale or larger watersheds. Hydrological processes include evapotranspiration, percolation, surface runoff, subsurface runoff for soil columns with different layers, water balance for shallow aquifers including ground water recharge, capillary rise to the

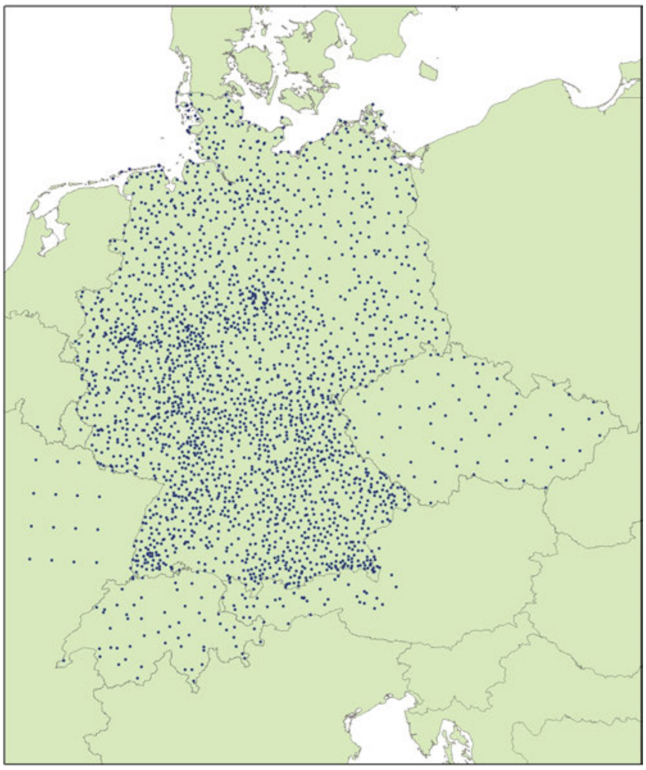

Figure 3: A map of the stations from which the precipitation data were obtained. The stations are operated by DWD (Germany), ČMI (Czech), ZAMG (Austria) and MeteoSchweiz (Switzerland). The gridded points in France, Belgium and Luxemburg match the E-OBS data set, but are far away from the Elbe catchment and thus not used.

soil profile, lateral flow and percolation to a deeper aquifer and river discharge.

The model is parametrized using various information such as topographical features, river cross-sections or the mean river width, the hydraulic structure for regulated rivers, ground water maps, soil textures and land use / land cover. Due to incomplete information various parameters need to be calibrated, the constraint here is a close matching of simulated and observed river hydrographs. Land use and land cover determine SWIM's smallest spatial units, the so called hydrotopes. Hydrotopes are homogeneous with respect to their hydrological response and represent SWIM's principal simulation unit (Hattermann et al., 2008; Krysanova et al., 2008; Conradt et al., 2012a; Conradt et al., 2012b). SWIM then describes the water and nutrient displacement from the subbasins to the river outlet in which the sum of the hydrotopes' runoff equals the subbasin discharge. The runoff from all subbasins is routed by means of the Muskingum method (Maidment, 1993).

Potential evapotranspiration is calculated according to Turc-Ivanov with linear modifications due to land use and humidity (ATV-DVWK, 2002). Plant transpiration and soil evaporation are calculated according to Ritchie (1972) with consideration of water limitation due to limited soil water availability for plant roots. Plant access to groundwater is also considered in SWIM.

For our study the Elbe river basin was divided into 2268 subbasins and 41 640 hydrotopes. For details on soil and land use and groundwater influenced areas, see Hattermann et al. (2008); Krysanova et al. (2008). SWIM is driven by daily weather data (precipitation, relative humidity, minimum, maximum and average air temperature, solar radiation). For the simulations weather input data obtained from the stations depicted in Fig. 3 are interpolated to each subbasin. As mentioned previously, with only about 60 weather stations the network is much less dense in the Czech Republic which leads to a possible decrease in observational accuracy in this area. For a calibration period 1981–1989 SWIM was calibrated for the entire basin in such a way that it reproduces the discharge time series at the gauge station in Neu Darchau. Neu Darchau is the last hydrograph in the Elbe river before the signal starts to deteriorate due to interfering tides. The model performance was then evaluated by its ability to accurately simulate the discharge at Neu Darchau during the 1970–1980 prediction period (Fig. 4). The Nash-Suttcliffe index amounts to 0.83, and the deviation in the water balance is −3 % (Huang et al., 2010). Furthermore, the spatial distributions of evapotranspiration, runoff and the groundwater recharge have been compared to "Hydrologischer Atlas von Deutschland" (HAD, engl. hydrologic atlas of Germany) (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2000) in Huang et al. (2010) for the period 1961–1990. HAD is based on measurements and input of local experts on the *"Länder"* i.e. federal state level. The close agreement of the spatial distribution seen there is the rationale for using SWIM simulation results as "observations."

3 Results and discussion

3.1 Precipitation

In order to assess CCLM's performance, we compare observed and simulated precipitation averages for the Elbe River catchment from 1970–1999. In addition, intense precipitation characteristics, which are particularly important for runoff and flood generation, are evaluated.

Fig. 5 shows the precipitation for each month from 1970–1999, averaged over the basin area, while Fig. 6 shows the accumulated values of Fig. 5. Generally, CCLM captures the seasonal precipitation values rather well. We see good agreement between observation and simulation, although there seems to be a tendency towards underestimation. This is confirmed by Table 1, which shows, among other things, the basin-wide observation, simulation and bias averages of precipitation. Overall we find that, on average, precipitation is slightly, i.e. around −10 %, underestimated.

Fig. 7 shows for each meteorological season the observed daily averages of the total precipitation (mean of the 30 year simulation period, left column). The middle column shows the abso-

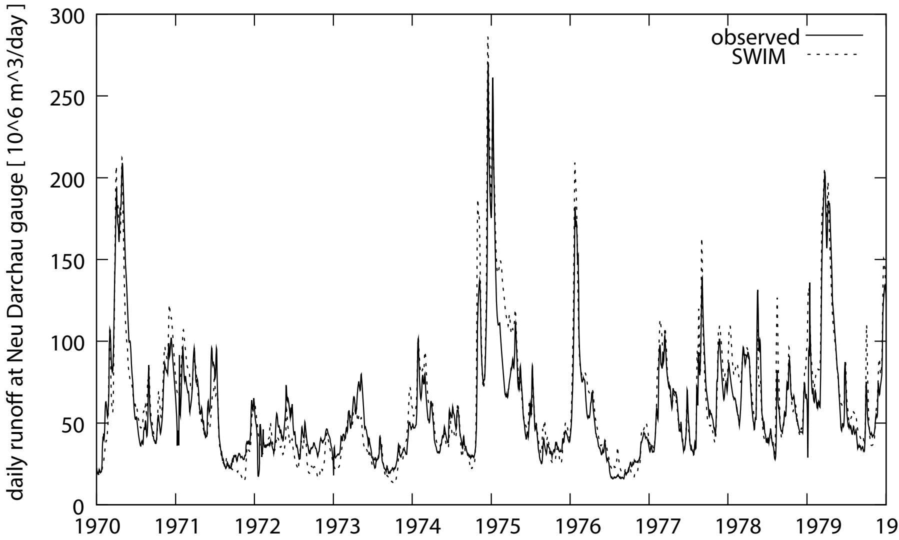

Figure 4: The observed runoff at Neu Darchau (solid line) compared to the result of SWIM (dashed line). This plot shows the validation period 1970–1980. The Nash-Suttcliffe index is 0.83.

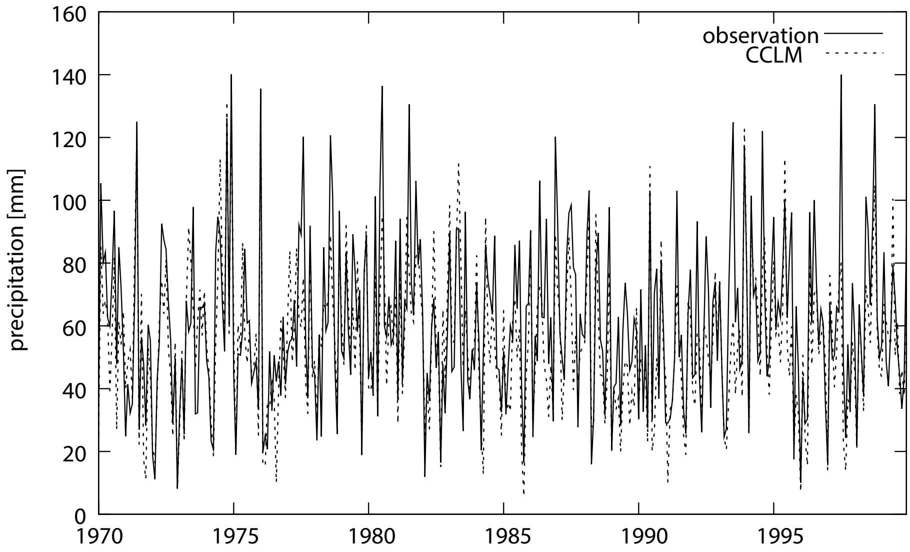

Figure 5: Elbe basin averaged monthly precipitation [mm] from Jan 1970 until Dec 1999. The solid line represents the observed precipitation while the dashed line depicts the CCLM result.

lute difference (simulation−observation) between simulated and observed values, while the right column depicts the relative difference between the two ((simulation−observation)/observation).

Observed precipitation is similar in winter (DJF), spring (MAM) and fall (SON), and on average less than 2 mm/day throughout most of the basin. The highest precipitation amounts occur in summer (JJA), particularly in the mountains (such as Bavarian Forest, Ore Mountains) (up to 4 mm/day).

Total precipitation is reproduced well by CCLM in winter and spring for the German lowlands. There the differences between simulated and observed values amount to about ±20 %. Significantly larger deviations occur for the mountainous regions (cp. Fig. 1) where winter precipitation is underestimated by as much as 40 %.

Summer is particularly noteworthy in that precipitation is underestimated all across the basin, even in the northern lowlands. According to Böhm et al. (2008) the negative summer precipitation bias in CCLM is linked to a summer drying of the soil (reduction of soil moisture during the initial simulation years) together with a reduced cloud cover in JJA nearly everywhere over the CADSES regions. This also holds true for the Elbe river catchment.

The simulation results for fall show errors of similar magnitude as the results for summer (−30 %. . . 10 %),

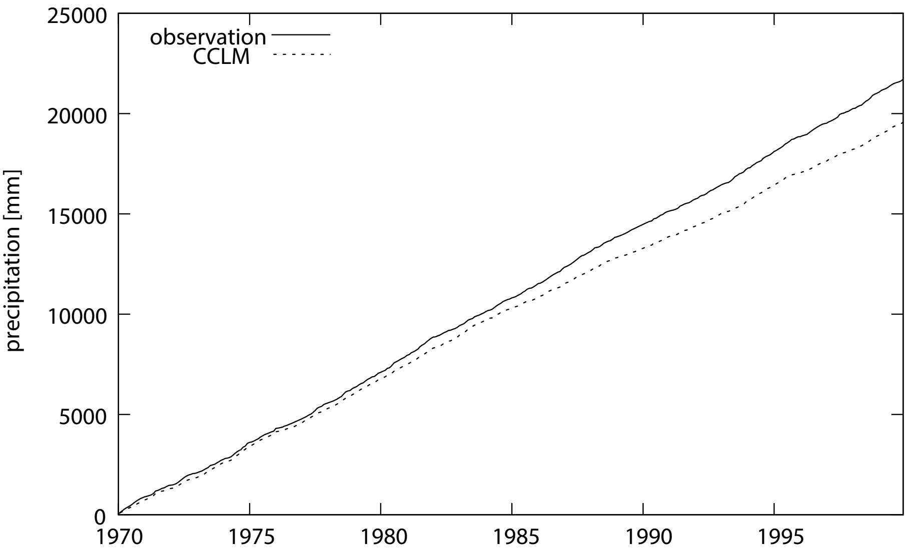

Figure 6: Elbe basin averaged precipitation [mm] accumulated from Jan 1970 until Dec 1999 (s. Fig. 5). The solid line represents the observed precipitation while the dashed line depicts the CCLM result.

Table 1: Basin-wide averages for the investigated variables for the four seasons as well as the annual values. Values in [mm] refer to daily values.

	DJF	MAM	JJA	SON	annual
total precipitation					
observation	1.84 mm	1.79 mm	2.47 mm	1.81 mm	1.98 mm
simulation	1.76 mm	1.70 mm	2.04 mm	1.62 mm	1.78 mm
abs. difference	−0.08 mm	−0.09 mm	−0.43 mm	−0.19 mm	−0.20 mm
rel. difference	−4.34 %	−5.02 %	−17.40 %	−10.49 %	−10.10 %
number of wet days					
observation	32.74	31.23	34.43	30.06	128.47
simulation	34.98	32.02	29.61	28.64	125.26
abs. difference	2.24	0.79	−4.82	−1.42	−3.21
rel. difference	6.84 %	2.52 %	−13.99 %	−4.72 %	−2.49 %
wet day precipitation					
observation	4.62 mm	4.91 mm	6.29 mm	5.08 mm	5.26 mm
simulation	4.24 mm	4.60 mm	6.07 mm	4.88 mm	4.92 mm
abs. difference	−0.38 mm	−0.31 mm	−0.22 mm	−0.20 mm	−0.34 mm
rel. difference	−8.22 %	−6.31 %	−3.49 %	−3.93 %	−6.46 %
90th percentile of wet day precipitation					
observation	5.70 mm	5.39 mm	7.43 mm	5.59 mm	6.00 mm
simulation	5.44 mm	4.98 mm	5.94 mm	5.06 mm	5.34 mm
abs. difference	−0.26 mm	−0.41 mm	−1.49 mm	−0.53 mm	−0.66 mm
rel. difference	−4.56 %	−7.60 %	−20.05 %	−9.48 %	−11.00 %
evapotranspiration					
observation	0.22 mm	2.17 mm	2.42 mm	0.67 mm	1.38 mm
simulation	0.33 mm	1.70 mm	2.57 mm	0.77 mm	1.35 mm
abs. difference	0.11 mm	−0.47 mm	0.15 mm	0.10 mm	−0.03 mm
rel. difference	50.00 %	−21.65 %	6.19 %	14.92 %	−2.17 %
total runoff					
observation	0.90 mm	0.66 mm	0.14 mm	0.32 mm	0.50 mm
simulation	0.75 mm	0.41 mm	0.36 mm	0.18 mm	0.42 mm
abs. difference	−0.15 mm	−0.25 mm	0.22 mm	−0.14 mm	−0.08 mm
rel. difference	−16.66 %	−37.87 %	157.14 %	−43.75 %	−16.00 %

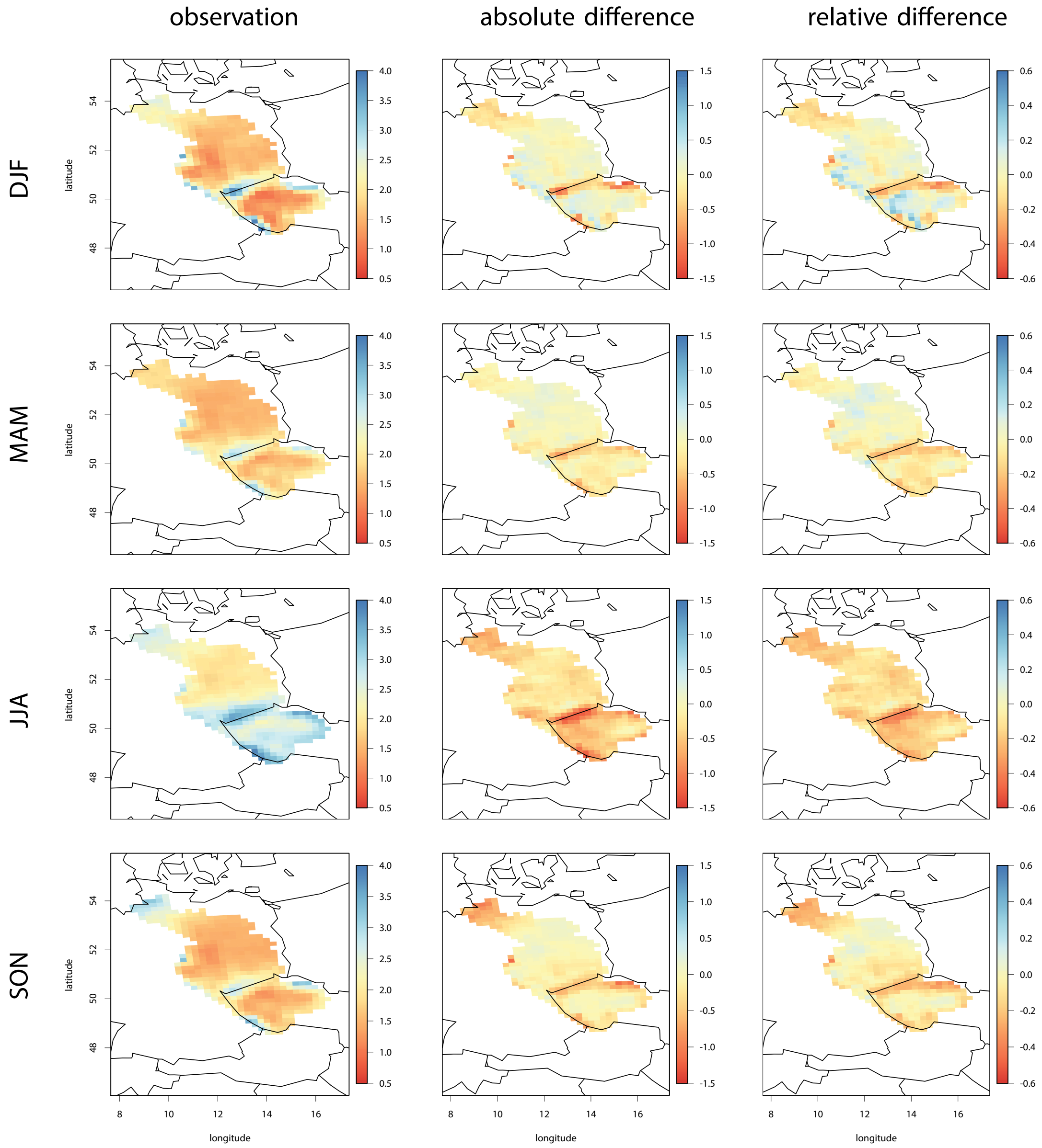

Figure 7: The total precipitation in the Elbe catchment. The left-most column shows the seasonal daily average from 1970–1999, as observed by DWD. The middle column gives the absolute bias of the CCLM simulations (simulation–observation), while the third column depicts the relative biases ((simulation–observation)/observation). The unit in all plots is [mm/day].

however, unlike in summer, there is no consistent pattern of over- or underestimation.

Overall, we can identify a clear and consistent negative summer bias in the simulated precipitation. Also, the bias in the mountainous regions and in parts of the Czech Republic is larger than in the lowlands. This is in agreement with previous studies as referenced in Section 1.

An important precipitation characteristic with respect to runoff is the number of wet days (days with precipitation > 1 mm) and the precipitation on these days. On wet days the soil could become saturated and runoff can be produced. The Elbe basin-wide averaged values are given in Table 1.

In both cases the results largely follow the pattern for the total precipitation, i.e. there is good agreement between observed and simulated values for the Northern lowlands in winter and spring (not shown). The bias there amounts to a few percent. In winter the model overestimates the number of wet days and the amount of wet day precipitation in the Harz mountains and parts of the Czech Republic by up to 30 %. . . 40 %. The deviations decrease in spring.

In summer, the average number of wet days is consistently underestimated across the whole study area, amounting to relative errors of $-20\,\%$ or larger. The amount of precipitation on wet days, on the other hand, is reproduced well, i.e. with a quality similar to that of the other seasons. This confirms the results for the average total summer precipitation for which the simulations show a negative bias across the basin.

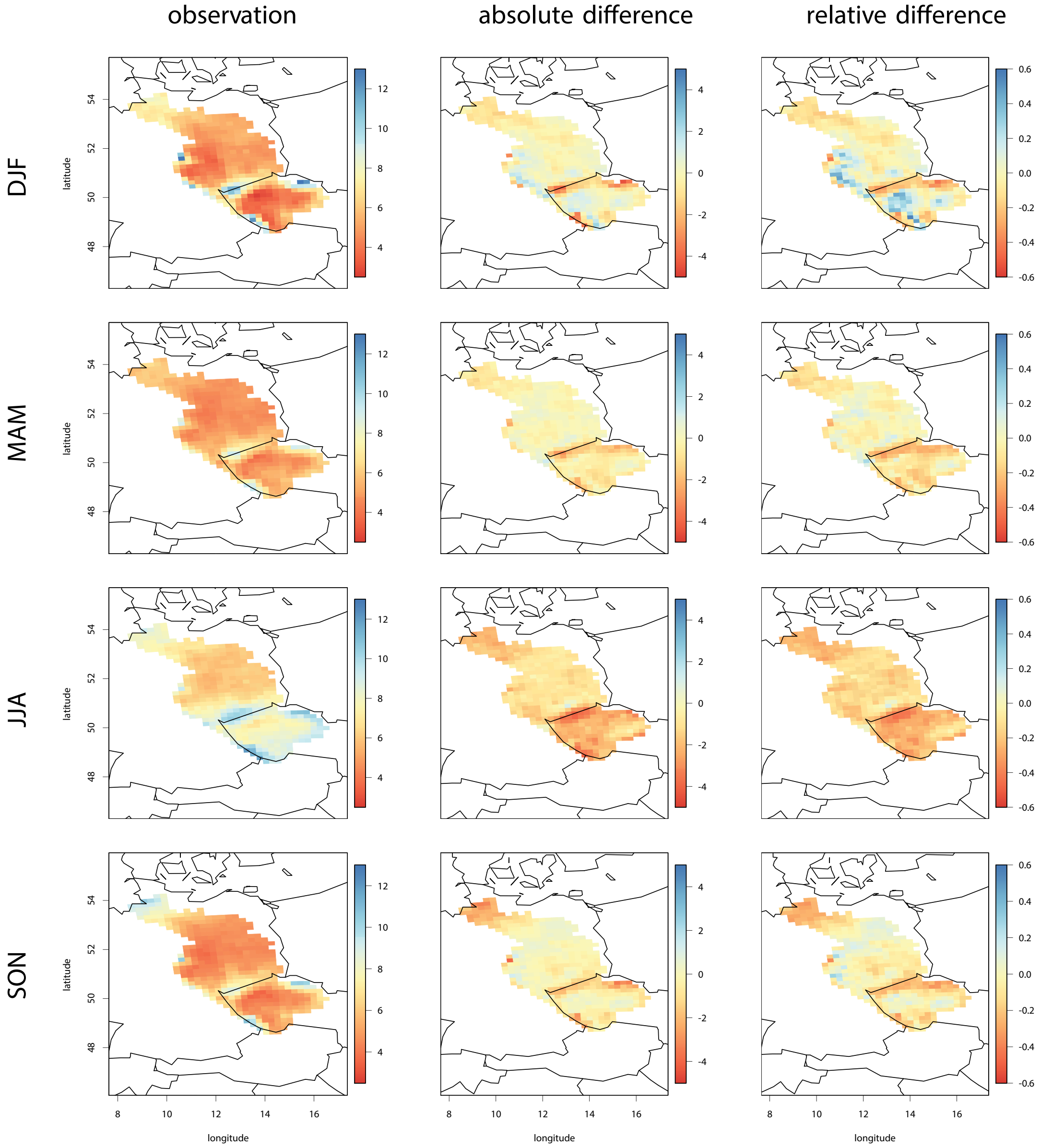

Figure 8: The 90th percentile of wet day precipitation in the seasons from 1970–1999. The columns, as in Fig. 7, depict observed seasonal daily values, and the absolute and relative differences of the CCLM simulations. Again, all values are measured in [mm/day].

In fall the number of wet days is over/underestimated by up to ±15 % at some locations, and the amount of precipitation on wet days is reproduced with a similar quality. In agreement with the results for total precipitation there is a tendency to overestimate/underestimate precipitation in the lowlands/mountainous regions, respectively.

In order to gain some insight into the performance with respect to extreme values, we show the 90th percentile of wet day precipitation for the time period 1970–1999 (per season) in Fig. 8. Again, observed values as well as absolute and relative differences are depicted. One can see that the highest precipitation values occur in summer, particularly in the mountains and the Eastern part of the Czech Republic.

In winter we see a mixed pattern of overestimation and underestimations of the 90th percentile of wet day precipitation across the basin. The largest overestimations occur in the Harz mountains, the Thuringian Forest and in the Czech Republic, resembling the pattern of the number of wet days, and of wet day precipitation. There are also some spots showing an underestimation. Spring values are reproduced better, with a model behavior similar to that of the other variables, i.e. lower biases in the problematic areas in comparison with values of the lowlands. Summer is again consistently underestimated, with bias values of −10 %. . . −40 %. For fall we see a similar pattern with moderate over- and underestimations in the lowlands and stronger underestimations in the mountains. When comparing the simulation results to observations, one needs to keep in mind that the interpolation, which has been performed on the precipitation data, tends to smooth out extremes.

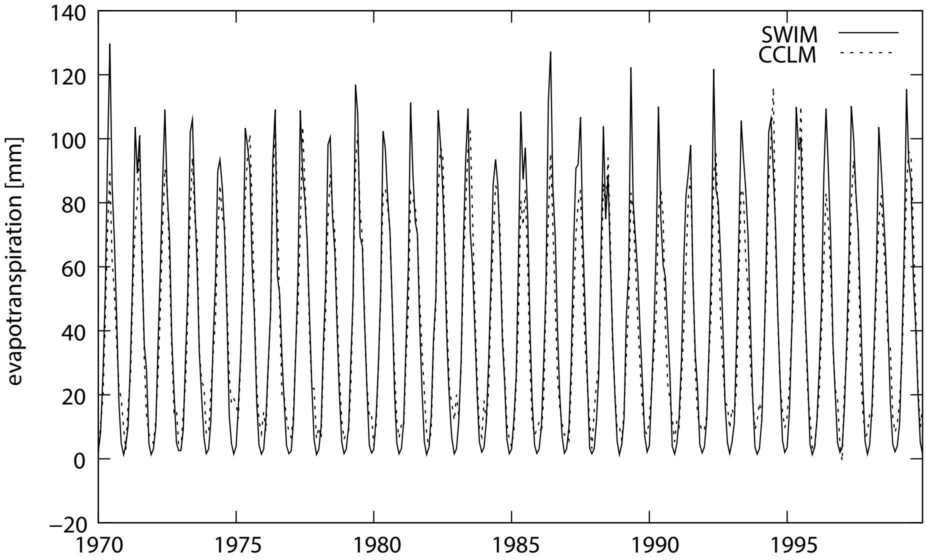

Figure 9: Elbe basin averaged monthly evapotranspiration [mm] from Jan 1970 until Dec 1999. The solid line represents the evapotranspiration produced by SWIM while the dashed line depicts the CCLM result.

Frei et al. (2003) analyzed RCM-simulated precipitation (ARPEGE, CHRM, HadRM, HIRHAM, REMO) for the Alps (50 km spatial resolution) including the frequency and mean precipitation of wet days as well as percentiles. All models show an underestimation in summer and an overestimation in winter precipitation. Throughout the year, the RCMs (except ARPEGE and HIRHAM) captured the observed frequency of wet days well, nonetheless there is a tendency to underestimate their number in August and September. Precipitation intensity on these days is simulated by most models either with relatively high accuracy, or underestimated. The 90th percentiles are consistently underestimated.

The above-mentioned study by Smiatek et al. (2009) used similar measures to investigate the precipitation performance. They considered days with precipitation of > 15 mm as well as the maximum number of consecutive dry days. For summer and winter an overestimation of all precipitation characteristics, except the number of consecutive dry days, was found for all models.

Another study was carried out by Jäger et al. (2008), where the performance of different CCLM setups/ versions over Europe from 1958–2001 was investigated. The resolutions considered were 0.22 ° and 0.44 °. Unlike us, they found that CCLM reproduces summer average precipitation in the central European region well, however they used a different observation dataset (CRU by New et al. (2002)) than we did. Looking more closely at their results, one can see that three of their four CCLM setups slightly underestimated summer precipitation, while one setup, the then newly released version 4.0, overestimated precipitation. For winter Jäger et al. (2008) found mainly overestimations for all their setups, these weren't excessive, though.

In summary, we conclude that all aspects of precipitation that were investigated here, are reproduced reasonably well for the German lowlands located in the Elbe River catchment area, i.e. with Elbe basin averaged biases of −5 %. . . 10 % for DJF, MAM and SON, except for summer where we found a consistent underestimation of total precipitation across the whole basin −20 %. Also, the Czech lowlands proved somewhat more problematic. The reason could be related to the lower density of meteorological stations used to derive the spatially interpolated precipitation field. Overall, the quality of our results is in line with other dynamical climate models, and the magnitudes of the errors are comparable as well.

3.2 Evapotranspiration

As previously stated, we examined evapotranspiration climatology in the CCLM HYDROCARE simulation by means of using the SWIM model output as a surrogate "observation". The spatially averaged daily evapotranspiration rate for each month during the years 1970–1999 is shown in Fig. 9. Fig. 10 shows the accumulated values of Fig. 9. Overall, there is good agreement between the models. From Table 1 one can see that CCLM generally overestimates evapotranspiration in winter and fall, while summer evapotranspiration is underestimated. Across the year these biases almost even out, leaving an annual bias of about −2 %.

Fig. 11 shows the spatial distribution of daily evapotranspiration through the four seasons (1970–1999), analogously to Fig. 7. In winter CCLM overestimates evapotranspiration for most of the basin. The overestimation is highest in the Havel-Spree area, where relative errors rise above 200 %. These high relative deviations can be explained by the small values of evapotranspiration of about 0.2 mm/day. In the mountainous areas (Ore Mountains, Bavarian Forest), on the other hand, we see an underestimation of daily evapotranspiration. Because of the low absolute values in winter, these deviations contribute little to the overall bias of the accumulated evapotranspiration.

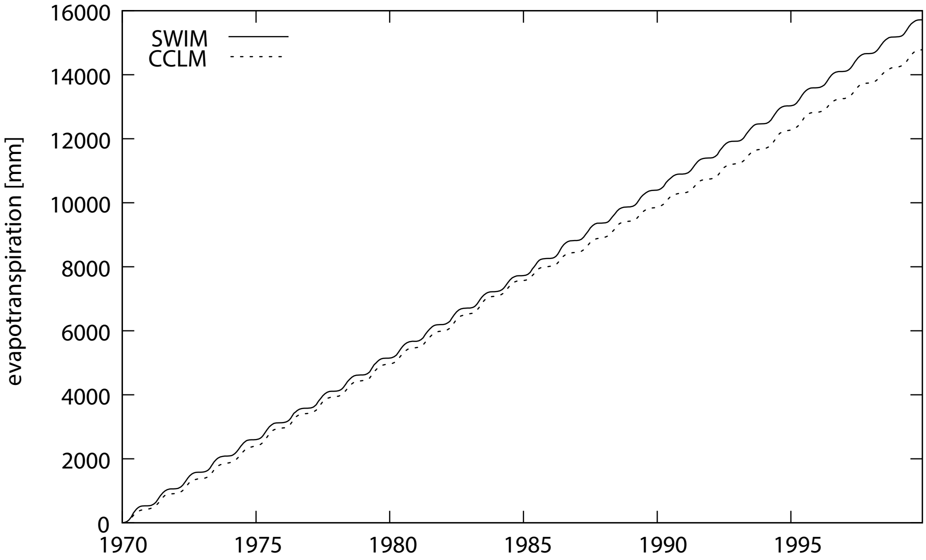

Figure 10: Elbe basin averaged evapotranspiration accumulated [mm] from Jan 1970 until Dec 1999 (s. Fig. 9). The solid line represents the evapotranspiration produced by SWIM while the dashed line depicts the CCLM result.

In spring evapotranspiration is underestimated across the basin. Of all seasons, spring shows the largest absolute bias when averaged across the basin, see Table 1.

In summer, the spatial distribution of absolute and relative errors shows larger deviations between the two models than in winter and fall. Generally, in areas with the highest evapotranspiration rates the CCLM simulations show the largest underestimation of evapotranspiration. In contrast, for regions with lower evapotranspiration rates CCLM tends to overestimate evapotranspiration, however with comparatively small absolute deviations from the SWIM model output.

In fall evapotranspiration is reproduced well by CCLM with a mixed pattern of over- and underestimations. As in winter, the small magnitudes involved result in rather large relative errors and the contribution to the deviations between SWIM and CCLM results in accumulated evapotranspiration is small.

Jäger et al. (2008) also investigated the performance of CCLM with respect to evapotranspiration. Even though they used a different observation data set, and their study area doesn't quite overlap with ours, they found an overall overestimation of evapotranspiration in winter, whereas summer evapotranspiration was underestimated. The study only provides areal averages though, so a more thorough comparison is not possible.

The SWIM generated evapotranspiration (Fig. 11) and runoff (Fig. 14) show some outliers at some points in Czech and also close to the mouth of the Elbe river. This are due to discrepancies in the areas that CCLM resp. SWIM consider to be the Elbe basin. SWIM uses an organic, nonrectangular area while CCLM uses latitude-longitude square grids cells. The SWIM results are subsequently interpolated to the CCLM grid points, and the interactions of the area discrepancies with the interpolation scheme lead to the clearly visible outliers.

3.3 Runoff

For the simulated CCLM runoff we considered the sum of the surface and the subsurface runoff in each grid cell. As in the case of evapotranspiration we used SWIM simulation results as "observations", i.e. the combined SWIM surface and subsurface runoff.

Fig. 12 shows the spatially averaged runoff for the Elbe basin for each month during 1970–1999. Fig. 13 shows the accumulated values of Fig. 12. Overall, Fig. 12 shows a good general agreement in the simulated seasonal course of runoff for the two models. However, the spring peaks are often overestimated by CCLM, even though all of spring is generally underestimated, see Table 1. Fig. 13 shows that there is an overall underestimation of the runoff in the basin.

We now consider Figs. 6, 10 and 13 together. Precipitation is underestimated, after 30 years by about, though not quite, 3000 mm. Similarly, evapotranspiration is underestimated by ≈ 2000 mm, and runoff by ≈ 1000 mm, so these figures are consistent in terms of the overall water balance.

The spatial distribution of the seasonal daily runoff averages over 30 years (1970–1999) is shown in Fig. 14. In winter and spring we have the largest runoff production in the Elbe catchment, which is underestimated by CCLM with relative errors of up to −50 % across the basin.

In winter, quite strong absolute underestimations can be seen in the Elbe mouth area. This is in line with the underestimations of wet day precipitation and the 90th percentile in the region. Furthermore, there are patches of overestimations sprinkled across an otherwise underestimated Elbe basin. Generally, this underestimation amounts to about 50 %.

In summer the runoff is the lowest of all seasons, therefore even higher relative errors are to be expected.

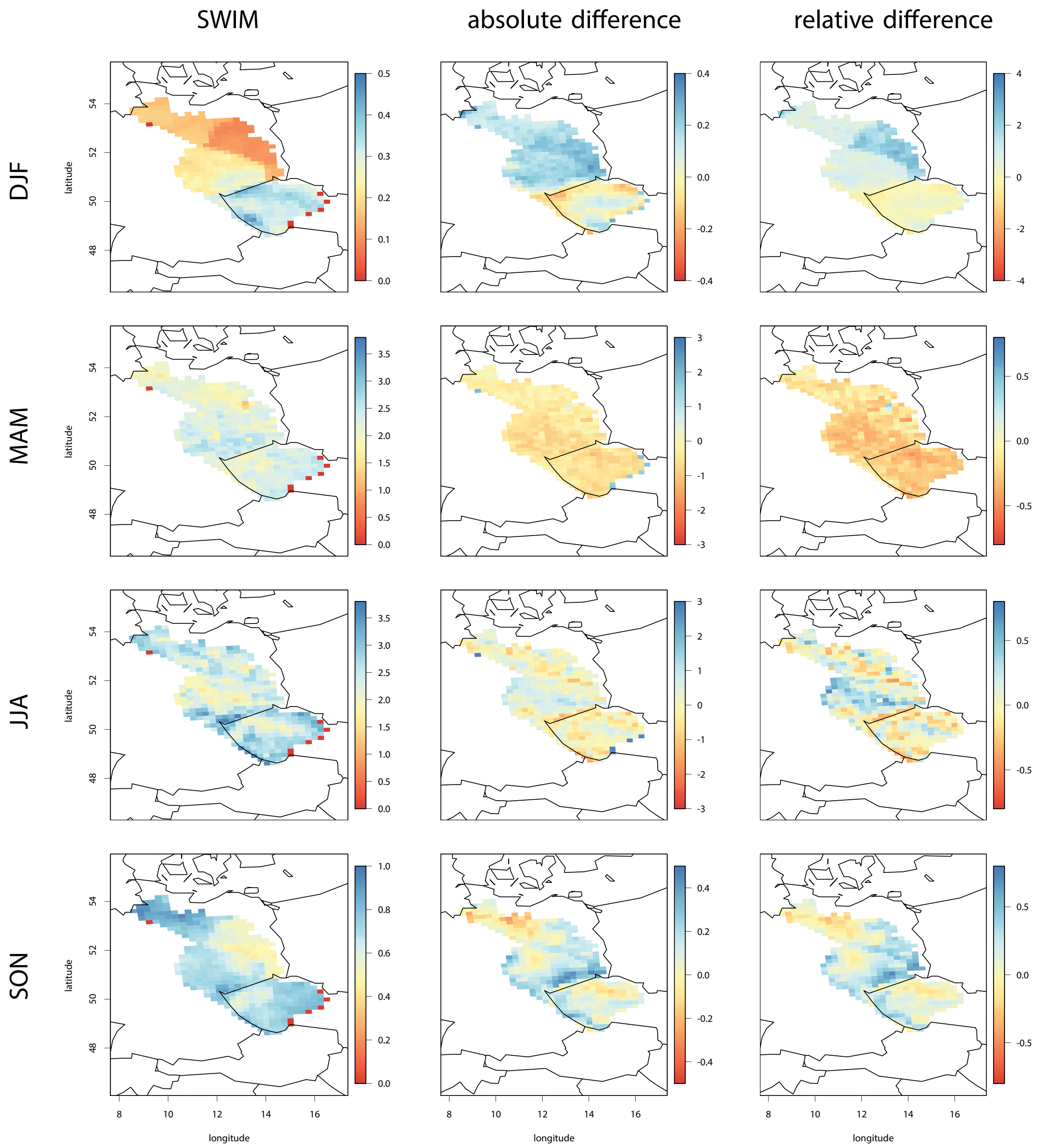

Figure 11: Evapotranspiration in the Elbe catchment. The above show daily seasonal means from 1970–1999. The columns show (from left to right) seasonal daily "observations" (SWIM), the absolute and the relative bias of CCLM. Note that the seasons use different scales. The outliers on the borders are due to a discrepancy between the basin borders in SWIM and CCLM, see the discussion in Section 3.2. The unit is [mm/day].

Indeed, even though the absolute differences between SWIM and CCLM are comparable to spring, we find large relative errors.

In fall the runoff values are rather small and apart from the Elbe mouth area we see good agreement between SWIM and CCLM. Also, the bias is changing sign relative to summer; in most of the Elbe basin we see an underestimation, but patches with overestimated runoff are sprinkled across the basin.

4 Conclusions and outlook

We presented a comprehensive evaluation of hydrological components (total precipitation, evapotranspiration and runoff) of the CCLM (COSMO in CLimate Mode) dynamical regional climate model for the Elbe river basin. Specifically, we used previous simulation results (HYDROCARE runs) and compared these to suitable reference data. In addition to providing a measure of CCLM's performance with respect to hydrology, these investigations provide a baseline for our future developments.

For precipitation we found a good agreement between observations and simulations, when put into the perspective of dynamical RCMs. Overall we find a bias of only $-10\,\%$ in the Elbe basin. This not only true for the basin accumulated precipitation, but for the spatial and temporal distribution as well. The main deviations occur in the mountains, a problem common to dynami-

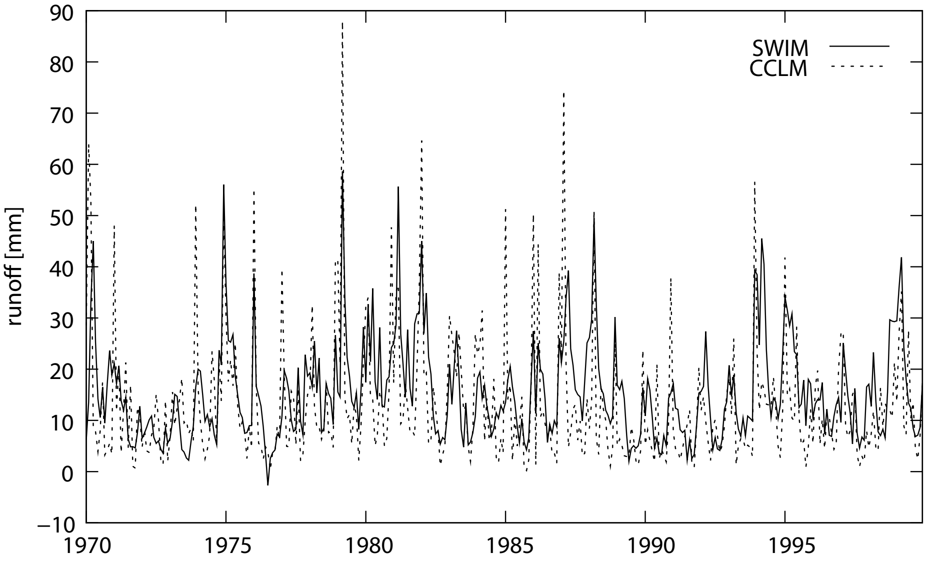

Figure 12: Elbe basin averaged monthly runoff (surface+subsurface) [mm/day] from Jan 1970 until Dec 1999. The solid line represents the runoff produced by SWIM while the dashed line depicts the CCLM result.

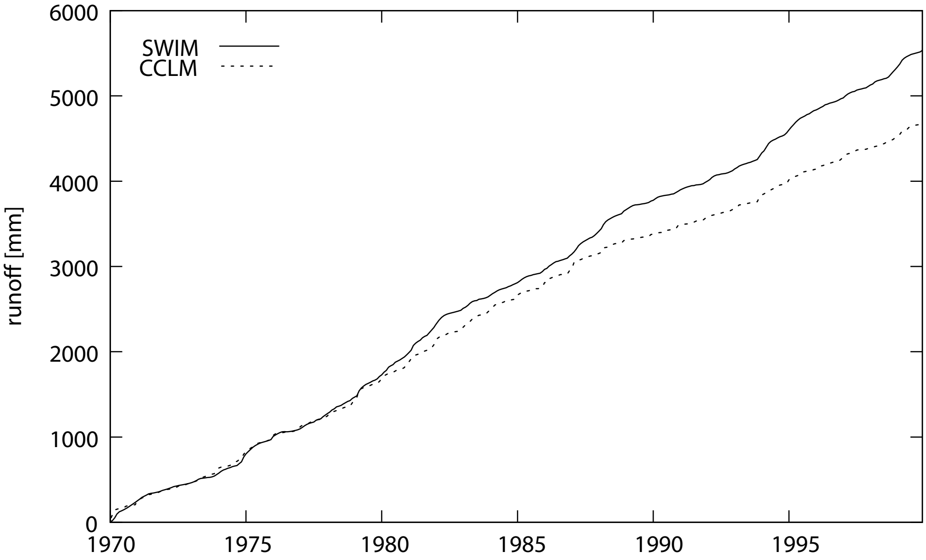

Figure 13: Elbe basin averaged runoff (surface+subsurface) [mm] accumulated from Jan 1970 until Dec 1999 (s. Fig. 12). The solid line represents the runoff produced by SWIM while the dashed line depicts the CCLM result.

cal RCMs. These problems might be attributed in part to a too coarsely resolved orography and subsequent errors in convective precipitation. Also, summer precipitation is generally underestimated. It is important to note that the results are also dependent on the scheme chosen for correcting precipitation undercatch.

Similarly we find good agreement between SWIM and CCLM simulated evapotranspiration, basin-wide accumulated evapotranspiration for the 30 year period is underestimated by only 2 %. This is not a trivial achievement, considering that SWIM and CCLM use different soil and vegetation models/maps.

The largest deviations, in basin total (−16 %) as well as in the spatial and temporal distribution, are found in the runoff production. This is to be expected, since runoff is generally the smallest number in the water balance when compared to precipitation and evapotranspiration. This means that small changes in the latter two might cause relatively large changes in the runoff.

While the variables are reproduced well at the level of the whole basin, larger deviations between observed and simulated values were detected in certain areas and seasons.

In summary, these results hint at CCLM providing a reasonable foundation for implementing further hydrological processes, such as routing and wetlands. River routing would enable the investigation of pressing issues such as irrigation, water supply for populations and industry under climate change, while also providing fresh water influx for ocean models. Floods and

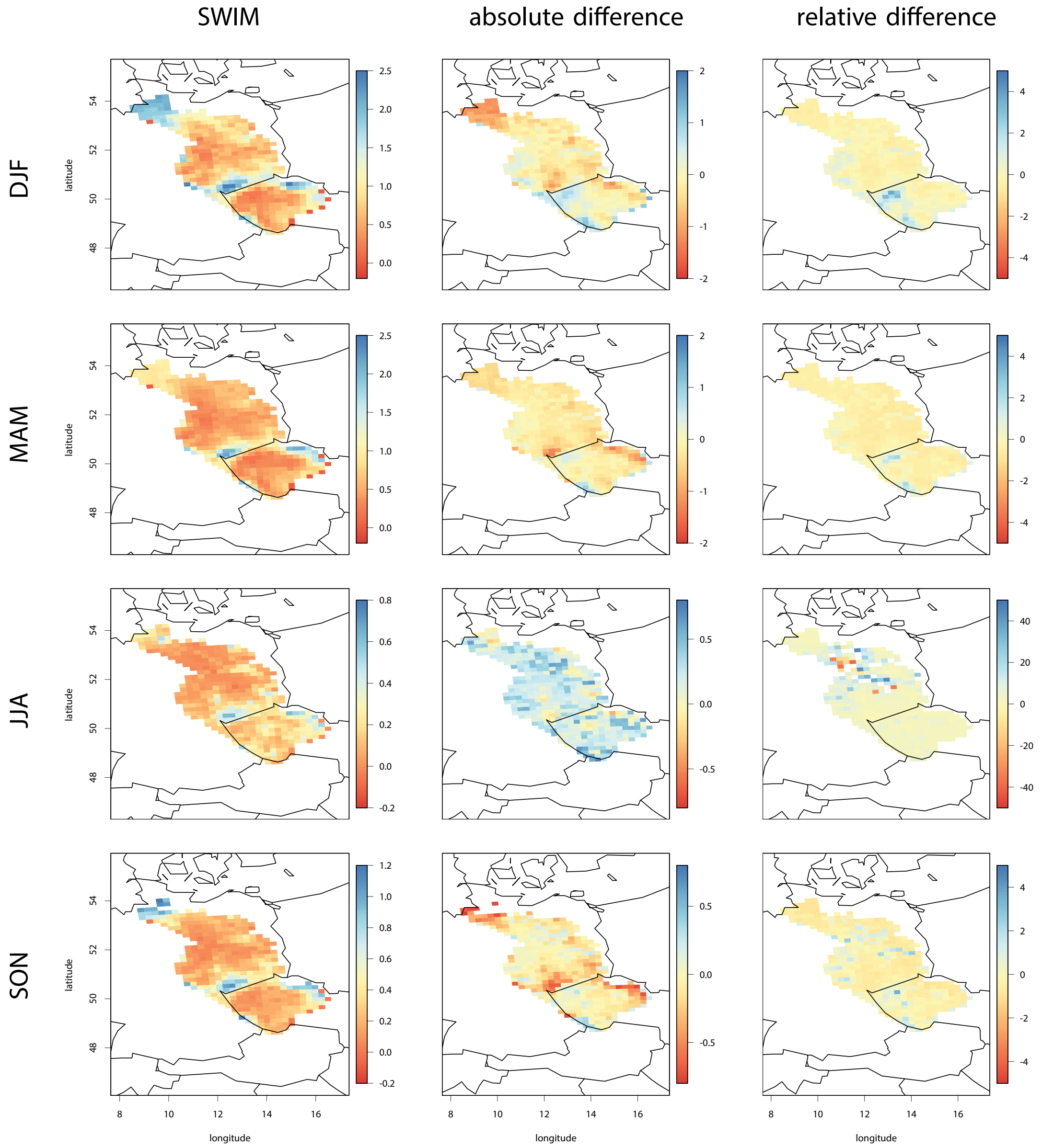

Figure 14: The total runoff in the Elbe catchment. Shown is the daily average for the four seasons in the years 1970–1999. The left column shows the seasonal daily SWIM results, which we consider to be "observations." The middle column shows the absolute bias (simulation−observation), and the right columns depicts the relative biases. As in the case of evapotranspiration, the outliers at the fringes are due to a discrepancy in the simulation area between SWIM and CCLM, see the discussion in Section 3.2. Note that the plots use different scales. Again, the unit used in these plots is [mm/day].

droughts could also be studied. With wetlands included, feedbacks on the regional climate could be investigated in new areas such as large river deltas.

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