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Article

Sensitivity of summer precipitation simulated by the CLM with respect to initial and boundary conditions

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Abstract

The knowledge of the uncertainty resulting from the sensitivity of a regional climate model to physical parameterisation schemes, horizontal resolution, domain size and location, as well as to initial and boundary conditions is crucial for the interpretation of model results, e.g. for dynamical downscaling of global climate predictions. In this study, we assess some of these aspects by investigating daily precipitation statistics simulated by the regional climate model CLM (Climate version of the Local Model). Different sensitivity experiments related to initialisation date, domain size and location and to the lateral boundary forcing have been performed for the summer of 1974. The evaluation domain is Germany, located approximately in the centre of the model domain. Comparisons to the control run show that the spatially averaged precipitation statistics can be significantly affected by this modification, not only in specific regions, but also in entire Germany. The results also indicate that the strength of the lateral boundary forcing has a crucial influence on the simulated characteristics.

Zusammenfassung

Die Kenntnis der Sensitivität regionaler Klimamodelle in Bezug auf die Parametrisierung physikalischer Prozesse, horizontale Auflösung, Größe und Lage des Modellgebiets, sowie Anfangs- und Randbedingungen und der damit verbundenen Unsicherheit ist entscheidend für die Interpretation von Modellergebnissen, z.B. für das dynamische Downscaling von globalen Klimamodellläufen. In der vorliegenden Arbeit werden einige dieser Aspekte quantitativ abgeschätzt. Dazu werden statistische Größen des täglichen Niederschlags aus Simulationen des regionalen Klimamodells CLM (Climate version of the Local Model) abgeleitet und untersucht. Für den Sommer 1974 wurden verschiedene Studien zur Sensitivität bezüglich des Initialisierungsdatums, der Größe und Lage des Modellgebiets und der seitlichen Randbedingungen durchgeführt. Das Untersuchungsgebiet Deutschland liegt zentral im Modellgebiet. Der Vergleich mit dem Kontrolllauf zeigt, dass räumlich gemittelte statistische Größen durch die genannten Modifikationen nicht nur für bestimmte Regionen, sondern auch für ganz Deutschland signifikant beeinflusst werden können. Die Ergebnisse deuten ferner darauf hin, dass der Antrieb durch die seitlichen Randbedingungen einen entscheidenden Einfluss auf die simulierten Werte hat.

1 Introduction

Global and regional climate model simulations play a crucial role in the understanding of climate variability and change. In the last decade, progress has been made in the development and improvement of regional climate modelling techniques (e.g. GIORGI and MEARNS, 1999; WANG et al., 2004). Such regional climate models (RCMs) are forced by large scale fields of Atmosphere-Ocean General Circulation Models (AOGCM) or global reanalyses. They are intended to reproduce the large scale patterns of the driving model and to add information of climatic variables on finer scales. The value added by dynamical downscaling, however, is still an important topic which has to be addressed (CASTRO et al., 2005; LO et al., 2008; ROCKEL et al., 2008). Many studies dealing with RCMs are focused on the evaluation of models and the understanding of physical processes as a necessary first step for climate change simulations (e.g. CHRISTENSEN et al., 1998; ACHBERGER et al., 2003; FREI et al., 2003). Biases in the important climatic variables temperature and precipitation pose still a problem (BÖHM et al., 2006; JÄGER et al., 2008). Several of these studies have also examined the sensitivity of regional climate models to modified initial and boundary conditions (e.g. JACOB and PODZUN, 1997; SETH and GIORGI, 1998; WU et al., 2005). These studies indicate that due to non-linear physics and dynamics of the models, even small changes in the initial conditions or in the boundary forcing can lead to quite different model results. JACOB and PODZUN (1997), for example, performed sensitivity studies with the hydrostatic regional climate model REMO, in which the dependence of model results on domain size, horizontal resolution, initial conditions and lateral boundaries was examined. They conclude that the results of the regional model are not only strongly dependent on the forcing fields but also on the domain size and simulation length.

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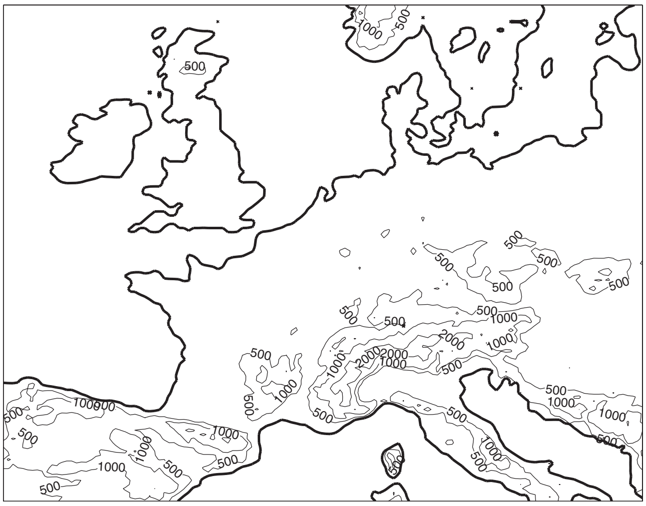

Figure 1: Coastlines of model domain with 500, 1000, and 2000 m height contour intervals.

These studies can unveil deficiencies in the performance of models and may eventually lead to improvements in the model formulation. The knowledge of the performance and the magnitude of uncertainty of the climate models in present climate simulations are of key importance in order to accurately interpret the results of future climate scenarios.

In the assessment of present-day climate variability and future climate change, the modelling of precipitation is of particular importance since precipitation determines a variety of interactions in natural processes as well as many socio-economic activities. Furthermore, it is presumed that the risk of extreme events like floods and droughts which are directly linked to precipitation increases in the future (CHRISTENSEN et al., 2007). Such events occur on regional scales. In this context, the question arises if precipitation properties such as intensity or extreme events and their distribution in space and time can be well simulated by a regional climate model. Therefore, we focus on precipitation as the evaluation variable.

The formation of precipitation is the result of a complex chain of chemical and physical processes leading to complex precipitation patterns in time and space. The correct simulation of such patterns is therefore a challenging task not only in regional climate modelling but also for numerical weather prediction. This is because the processes leading to precipitation often occur on small scales, especially in convective situations, which cannot be resolved by the model. Thus, the implemented physical parameterisations of a model play a crucial role for the quality of precipitation simulations. Previous studies indicate that the simulation of summer precipitation in particular is a challenge compared to that of other seasons not least because of its convective nature. Model biases for the summer months June, July, and August (JJA) seem to be larger (FREI et al., 2003) and the results of different regional climate models deviate stronger from each other (KOTLARSKI et al., 2005). VIDALE et al. (2003) suggest that the predictability of the regional climate is generally weaker during summer.

In this context, our study gives insight into the ability of a particular regional climate model, the CLM, to simulate daily variability of summer precipitation and its statistical properties. The CLM has been and is applied in various evaluation studies. These studies include the evaluation of different atmospheric variables in terms of comparisons between model and observations and/or the forcing data itself (BÖHM et al., 2004; BÖHM et al., 2006; JÄGER et al., 2008), as well as in terms of sensitivity experiments with respect to different physical parameterisations (e.g. BACHNER et al., 2008). In most of these studies, the CLM is validated in respect to annual or monthly mean conditions and larger spatial scales (e.g. JÄGER et al., 2008). In contrast, we focus on the simulation and validation of JJA precipitation statistics in Germany and in single subregions and assess the sensitivity of different precipitation statistics to modified initial and boundary conditions. Our work supplements the studies by BACHNER et al. (2008), who concentrate on another sensitivity of CLM simulations, namely the sensitivity to physical parameterisation schemes using the same model configuration.

Such sensitivity studies are useful for the interpretation of model results, particularly with regard to the CLM regional present day and future climate scenarios forced by the AOGCM ECHAM5 (BÖHM et al., 2006; LEGUTKE et al., submitted).

The paper is organised as follows. In chapter 2, a short description of the model, the applied configurations and an overview of the performed simulations are given. Chapter 3 summarises our investigation strategy, while chapter 4 contains the results of the different model runs including a discussion. A summary and an outlook are presented in chapter 5.

2 Model and simulations

The CLM has been developed from the limited area model COSMO, formerly known as the Local Model of the Deutscher Wetterdienst (DWD). A description of the general model features can be found in WILL et al. (submitted); we focus thus on the chosen model configurations. The model domain comprises wide parts of Europe (Figure 1) with a horizontal grid spacing of 1/6° (about 18 km) and a vertical resolution of 20 atmospheric layers and 9 soil layers. Grid-scale clouds and precipitation are parameterised by a Kessler-type bulk water continuity scheme (KESSLER, 1969). The scheme applied in our studies includes four water classes: water vapour, cloud water, precipitation water, and precipitation ice. Moist convection is described by a Tiedtke mass-flux convection scheme (TIEDTKE, 1989). Initial and boundary data are provided by the ERA40 data set

Table 1: Overview of simulations performed for JJA 1974 with the corresponding modifications with respect to the control run BASE.

Name of simulation	Parameter changed	Value in run BASE	Value in this run
APRIL-21 APRIL-29 MAY-07 MAY-09	Initialisation date	2 May 1974	21 April 1974 29 April 1974 7 May 1974 9 May 1974
PLUS15GP	Number of grid points in x-direction	132	147
SHIFTDOM	Geographical coordinates of the lower left grid point of the model domain	-7.24°E, 38.72°N	-5.46°E, 41.13°N
WEIGHT-A WEIGHT-B	Weighting curve parameters (see Eq. 2.1)	$a = 0.5$, $b = 0.75$	$a = 0.25$, $b = 1$ $a = 0.125$, $b = 1$

(UPPALA et al., 2005). This data has a spatial resolution of 1.125° and is available four times a day (00, 06, 12, 18 UTC). It was customised to the finer CLM grid in a pre-processing step and fed to the model every six hours. The boundary information is assigned at the lateral boundaries and at the upper boundary and relaxed towards the model domain using the relaxation technique by DAVIES and TURNER (1977).

In a first step, a control run (simulation BASE) was performed for JJA 1974. The summer season of 1974 has been chosen because it shows average conditions in summer precipitation in Germany. BACHNER et al. (2008) also investigated rainfall statistics for this particular summer. Furthermore, they analysed precipitation statistics of extreme summer seasons, i.e. five wet and five dry summers.

Due to the spin-up time of the model, the simulation was started on 2 May 1974. In the second step, a small ensemble of simulations was created by changing the model configuration in different ways (Table 1). To assess the impact of different initial conditions on the precipitation statistics, we varied the initialisation date of the model. To obtain the maximal amplitude of variation due to the influence of the initial conditions in terms of the initialisation date, days on which the synoptic condition is quite different from that of the control simulation were selected; i.e. compared to the control run, the selected days show low spatial correlation in temperature and circulation pattern. The result is a set of four simulations: APRIL-21, APRIL-29, MAY-07, and MAY-09. Lateral boundary conditions are indirectly changed by a modification of the model domain, i.e. a slight enlargement (simulation PLUS15GP) and a displacement (simulation SHIFTDOM). The strength of the boundary forcing was varied (simulations WEIGHT-A and WEIGHT-B) by changing the relaxation weights α according to HERZOG et al. (2002). The α-weight of a grid point depends on the distance of the grid point to the boundary. Let j be the index which labels the grid points of a grid row inwards with the boundary point $j = 0$,

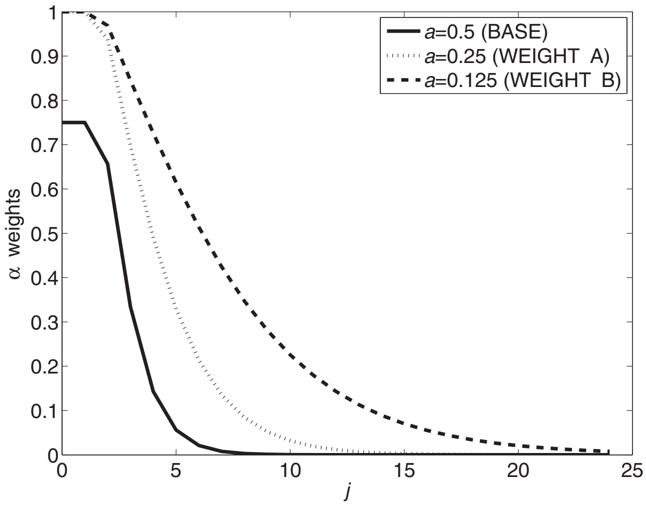

Figure 2: Boundary weight curve as a function of distance of a gridpoint j for three different slope parameters $a = 0.5$, 0.25 and 0.125. For $a = 0.5$, b is 0.75, otherwise it is set to 1.

then the α-weights are calculated by

$$\alpha(j) = b \cdot (1 - \tanh(aj)) \tag{2.1}$$

Our modifications of the slope parameter a and the intercept parameter b result in the boundary weight curves shown in Figure 2. In the simulations WEIGHT-A and WEIGHT-B, these parameters are chosen such that the boundary information can penetrate deeper into the interior of the model domain than in the control run.

3 Observations and evaluation strategy

We evaluate the model results by comparing them to daily precipitation measurements from rain gauge stations of the DWD measurement network. Only those stations with continuous records from 1 June to 31 August 1974 were chosen leading to a set of 4365 rain

Table 2: $BIAS^{base}$ of MEAN (mm/day) and FREQ (%) for different sensitivity experiments (JJA1974). Biases significant at the 5 %-level are indicated by an asterisk."

	MEAN (mm/day)					FREQ (%)				
	Germ.	WEST	ODER	BF	BAV	Germ.	WEST	ODER	BF	BAV
APRIL-21	-0.13*	-0.13*	-0.25*	-0.12	-0.27	-1.30*	-1.52	-0.92	-0.17	-1.87
APRIL-29	-0.02	0.01	-0.11	0.15	0.10	0.06	0.37	0.95	-0.40	-0.13
MAY-07	-0.03	-0.03	-0.16*	-0.31	0.10	-0.08	0.55	0.20	-0.34	0.13
MAY-09	-0.01	0.10*	-0.19*	-0.20	-0.02	0.80*	1.89*	1.30	0.46	0.30
PLUS15GP	-0.05	0.06	-0.27*	-0.18	-0.28	-0.20	0.48	-0.78	-0.24	-0.17
SHIFTDOM	-0.15*	0.04	-0.56*	-0.41	0.07	-2.13*	-1.77*	-4.50*	0.00	1.54
WEIGHT-A	-0.03	0.24*	-0.52*	0.23	0.33	-0.39	-0.82	-2.97*	0.06	2.39*
WEIGHT-B	-0.04	-0.06	-0.55*	-0.82*	0.72	-0.88*	-0.74	-6.42*	-1.09	6.37*

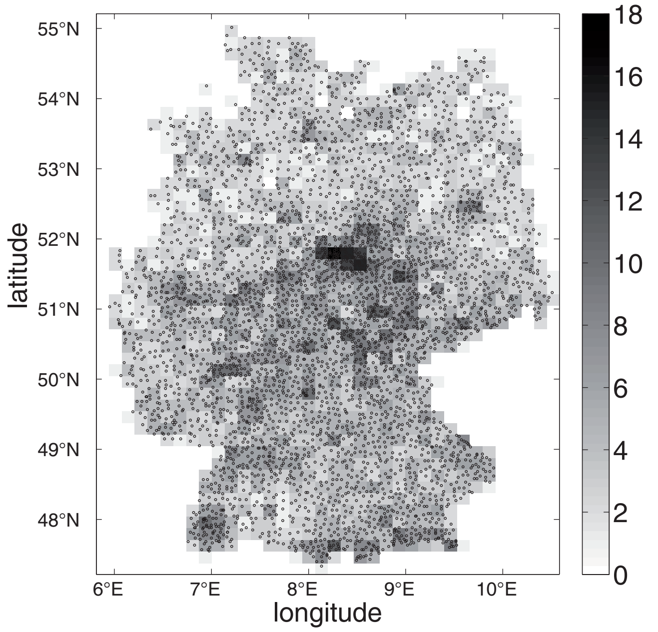

Figure 3: Location of continuously measuring stations (dots) in JJA 1974 and corresponding number of stations per grid box (shaded areas) in the evaluation domain (Germany).

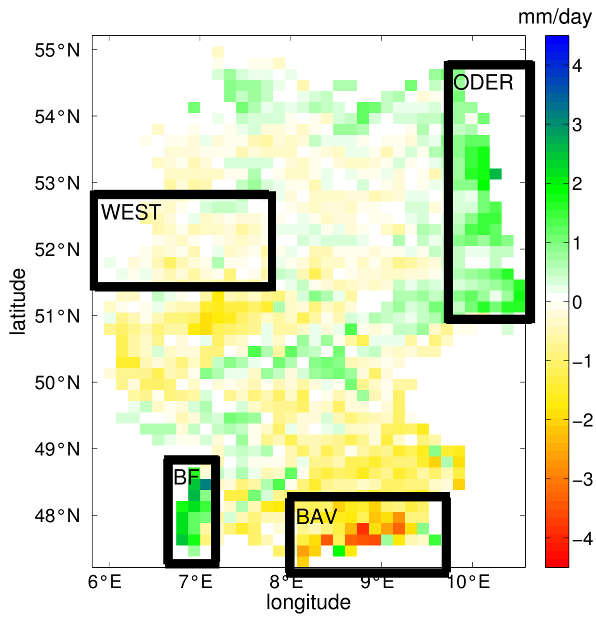

Figure 4: Differences in MEAN (mm/day) for JJA 1974: control run minus observations. The chosen subregions WEST, ODER, BF, and BAV are indicated by frames.

gauge time series. We note that the types of data compared to each other, i.e. rain gauge observations and the modelled precipitation sums, are of different nature, because rain gauge measurements are point measurements and model values might be interpreted as averages over the model's grid box. In addition, rain gauge measurements tend to underestimate the precipitation amount due to wind drift of precipitation, wetting and evaporation, while the precipitation variability within a grid box, especially over complex terrain, is not taken into account by the model. To compare model and observations, we compute the arithmetic mean of all rain gauges in one grid box. Figure 3 shows the station density in Germany which achieves an average value of about 4 stations/(18 km)^2.

The following statistics of daily precipitation were compared for JJA 1974:

– Mean precipitation (MEAN, mm/day): total rainfall amount of JJA divided by the number of days in this analysis period,
– Mean precipitation intensity (INT, mm/day): average precipitation per wet day,
– 90 %-quantile of the empirical distribution of wet-day amounts (Q90, mm/day), and
– Frequency of wet days (FREQ, %).

To distinguish between wet and dry days, a threshold of 1 mm/day is chosen. This value seems to be adequate since a smaller value would make the evaluation too sensitive to the measurement/observer accuracy and to the tendency of some models to simulate very frequently very low precipitation amounts (FREI et al., 2003).

To quantify the deviation between the control run and a run with a modified model setup, two distance measures are applied, the root-mean-square difference (RMSD) and the average difference (BIAS) in accordance with the study of GIORGI and BI (2000). For the mean precipitation, for example, the RMSD is given by

$$RMSD = \sqrt{\sum_i \frac{\left(MEAN_i^{sens} - MEAN_i^{base}\right)^2}{N}} \tag{3.1}$$

where $MEAN^{base}$ is the result of the control run and $MEAN^{sens}$ the result of a sensitivity experiment. The summation is carried out over the number of grid boxes N within a given region. The BIAS is defined by

$$BIAS^{base/obs} = \sum_i \frac{MEAN_i^{sens} - MEAN_i^{base/obs}}{N} \tag{3.2}$$

To avoid confusion, $BIAS^{base}$ will be used, if results of a sensitivity experiment are compared to those of the control run, and $BIAS^{obs}$, if the model results are related to observations. To test the significance of a bias, a two-sided Student's t-test is performed at the 5 %-level (95 % significance).

The correspondence of the modelled and observed spatial structure of the precipitation indices is assessed by means of the Spearman's rank correlation coefficient. For MEAN, for example, the correlation is calculated by $\rho = 1 - 6\frac{\sum_i d_i^2}{N(N^2-1)}$ with

$$d_i = rank\left(MEAN_i^{CLM}\right) - rank\left(MEAN_i^{obs}\right) \tag{3.3}$$

Again, the summation is carried out over the number of grid boxes.

The evaluation of the model results and the intercomparison of the different simulations are performed for various regions of interest. The statistics are calculated for entire Germany, i.e. those grid boxes in Germany, which contain at least one rain gauge (cf. Figure 3), as well as for a set of subregions. For dynamical downscaling of future climate scenarios, the effects on regional scales might be of particular interest. Figure 4 depicts the difference in MEAN between modelled (control run) and observed values. The indicated subregions WEST, ODER, BF, and BAV have been selected with regard to the varying capability of the model to simulate the regional precipitation statistics of JJA 1974 (see section 4.2) and to their difference in orography and climatology. In the region WEST, moderate westerly winds from the Atlantic Ocean prevail leading to moderate temperatures. The terrain is rather flat, with the Rhine valley in the south-west of the region and hills in the north-east not exceeding 300 m.

The region ODER is dominated by a continental climate with a large seasonal temperature variance. This region is among the driest regions in Germany. Hills with elevations of up to 500 m can only be found at the southern most grid boxes. The Black Forest (BF) is one of the wettest regions in Germany affected by a mostly southwesterly flow. The simulation of precipitation in this low mountain range is much more complex since orographically-induced and convective precipitation systems dominate the precipitation climate. Thus the westward-facing slopes receive the highest rainfall from maritime air masses. The region BAV comprises some parts of the Alpine foreland and the Alpine region. The highest elevations in Germany, where the model topography shows values up to 1500 m can be found in this region.

4 Results

The evaluation of the precipitation variability in summer 1974, simulated by the control run and eight sensitivity experiments, focuses on two aspects: (i) the model uncertainty in different characteristics of daily precipitation resulting from the sensitivity to the modification of the initial and boundary conditions in respect to the control run, and (ii) the model capability to simulate these characteristics with respect to the observations.

4.1 Model sensitivity

First, we will focus on the model sensitivity to the initialisation date, the model domain size and location, and to the lateral boundary forcing. In the control run, the largest MEAN values of about 9 mm/day can be found in the Alpine region in Southern Bavaria. Regions with enhanced simulated precipitation are the Black Forest (up to 6 mm/day) and other low mountain ranges in Germany, as well as Eastern Germany along the border to Poland. Precipitation amounts are generally low in the South-West and in some parts of Eastern Germany. In principle, the mean precipitation intensity and the 90 %-quantiles go along with MEAN. The spatial structure of simulated precipitation frequency differs from the spatial patterns of the other statistics, with the highest precipitation frequencies in Bavaria, especially in the Alpine region, and in Eastern Germany along the Ore Mountains (>60 %). Precipitation events also often occur in parts of North-Western and Western Germany. These main features of the precipitation statistics can be generally found for the various model experiments, although on smaller scales pattern and amounts can differ significantly. Since a meaningful comparison of the spatial patterns of the different simulations is hardly possible by visual judgement, the results of a Student's t-test applied to the $BIAS^{base}$ of the precipitation statistics MEAN and FREQ are summarised in Table 2. This test reveals that significant differences between the control

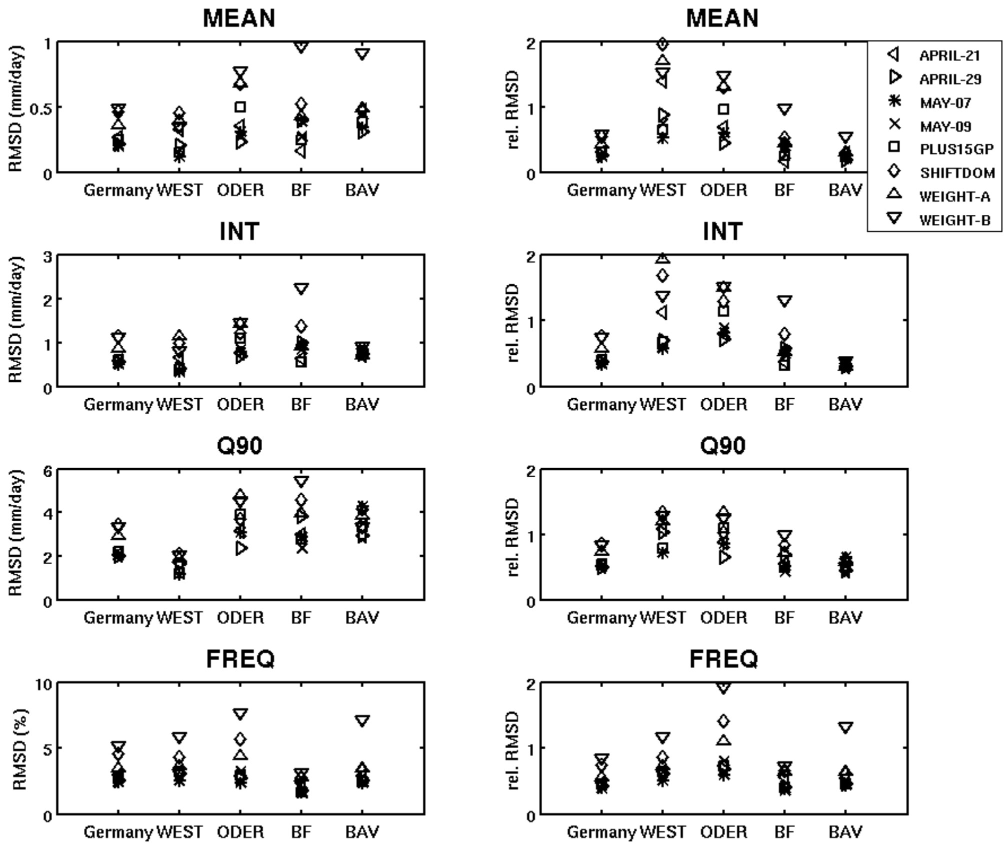

Figure 5: RMSD of MEAN (mm/day), INT (mm/day), Q90 (mm/day), FREQ (%) for entire Germany and the four subregions WEST, ODER, BF, and BAV. The left column shows the absolute RMSD, the right panel the relative RMSD. The relative RMSD is the RMSD divided by the corresponding spatial standard deviation of the control run.

run and the sensitivity experiments can be found for entire Germany and also on smaller scales. The mean precipitation amount in Germany is significantly changed in simulations APRIL-21 and SHIFTDOM. For nearly all sensitivity experiments significant differences in MEAN can be found for the region ODER. One reason for the relatively large sensitivity in this area, i.e. the large number of significant changes, might be the short distance to the eastern model boundary. The model solution in this region may be affected by the lateral boundary forcing more strongly than in other regions of interest. For INT and Q90, similar results have been found (not shown). Regarding the precipitation frequency, significant differences can be found for entire Germany in four simulations (APRIL-21, MAY-09, SHIFTDOM, WEIGHT-B). In contrast to MEAN, significant deviations occur also in the region BAV. In region BF, solely an enhanced boundary forcing (simulation WEIGHT-B) caused significant differences not only in MEAN but also in INT and Q90 (not shown). Summarising our results, each of the modifications, even the shift of the initialisation date by a few days, led to significant changes in the summer precipitation statistics in at least one of the investigated regions, compared to the control run.

Absolute and relative RMSD values of the precipitation statistics were calculated for the different regions (Figure 5). The absolute values were divided by the spatial standard deviation of MEAN, INT, Q90, and FREQ of simulation BASE in the corresponding region in order to obtain relative measures. These relative values are more useful to identify possible regions and precipitation statistics of highest or lowest sensitivity to modified initial and lateral boundary conditions.

Regardless of variable and region, differences due to the modified model domain or due to modified lateral boundary conditions are larger than those due to different initialisation dates. The finding that the lateral boundary forcing has a strong influence on the model solution is in agreement with JONES et al. (1995) and JACOB and PODZUN (1997), who investigated the effects of the domain size and the location of the lateral boundaries on regional climate model results. Note,

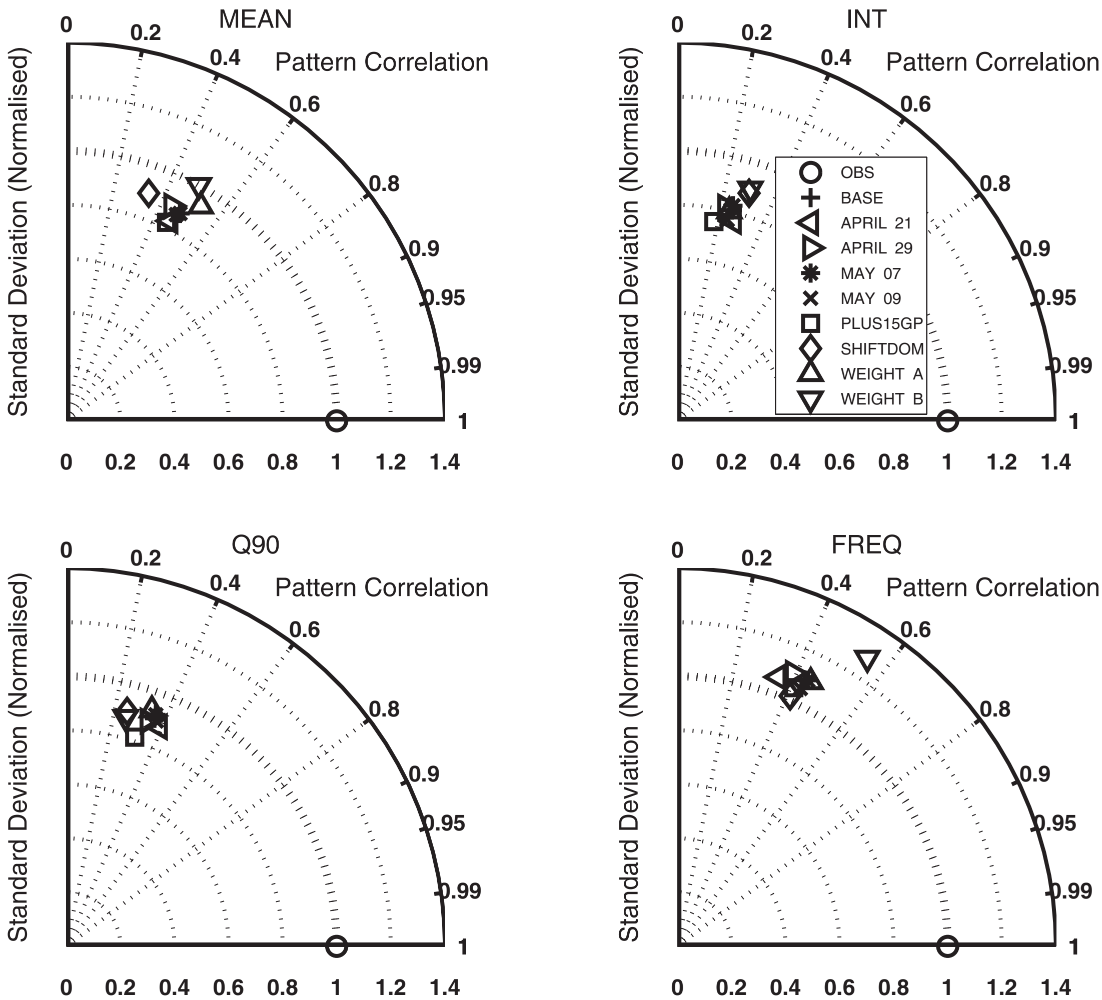

Figure 6: Taylor diagrams for different statistics: MEAN, INT, Q90, and FREQ. The pattern correlation is given as the angle from the abscissa and the normalised standard deviation (modelled value divided by observed) as the radial distance from the origin. The thick dashed line indicates the observed standard deviation.

however, that the derived sensitivities presented in our work cannot be directly compared to each other, since the variation amplitude for initial and boundary conditions differs among the different sensitivity experiments. GIORGI and BI (2000) applied small, random perturbations with a prescribed maximum perturbation amplitude on the initial and lateral boundary data. With their normalisation, they found that both types of modification lead to similar effects in daily precipitation and temperature of the lower troposphere in a regional climate model. Due to the different types of modification, these results are not contradicted by our investigations.

The spread of the RMSD values provides information about the extent of the model uncertainty related to different initial and boundary conditions. In general, the RMSD values are of a similar magnitude as the spatial variability of the corresponding precipitation statistics. The largest effect can be found on the mean precipitation and the mean precipitation intensity with relative RMSD values between 0.2 and 2. The regions WEST and ODER exhibit the highest sensitivity to the modified initial and boundary data and to the type of the modification. For the region ODER, this might be explained by its location near to the eastern boundary. A small spread can generally be found for the region BAV indicating that this region is less sensitive to the different types of modification.

Table 3: $BIAS^{obs}$ of MEAN (mm/day), INT (mm/day), Q90 (mm/day), and FREQ (%) for entire Germany and the four subregions (JJA 1974). Significant biases at the 5 %-level are indicated by an asterisk.

	Germany	WEST	ODER	BF	BAV
MEAN (mm/day)	-0.14*	-0.15*	0.95*	1.42*	-1.53*
INT (mm/day)	-0.69*	-0.70*	1.48*	1.09*	-3.17*
Q90 (mm/day)	-1.07*	-1.08*	1.57*	7.44*	-9.17*
FREQ (%)	-0.03	1.33	6.01*	4.75*	-0.43

4.2 Model performance

In the next step, we will answer the question, how well the observed precipitation characteristics in summer 1974 can be simulated by the CLM and in which extend they vary depending on the different sensitivity experiments. SETH and GIORGI (1998) have shown that models are in better agreement with observations when the influence of the lateral boundary conditions, the reanalysis data, is enhanced. However, we assume that the initialisation date has not a noticeable effect on the quality of the model results compared to the control run.

Table 3 shows that the control run underestimates significantly the observed indices MEAN, INT and Q90 in entire Germany and in the regions WEST and BAV. In the region BAV, these indices fall below the observed values in the order of about 30 % (i.e. by – 27 %, –27 % and –34 % for MEAN, INT and Q90, respectively). In the region WEST, however, the negative biases are considerably lower than in the region BAV. In contrast, significant overestimation of the indices MEAN, INT, and Q90 occurs in the region BF and ODER. The highest positive bias can be noted in heavy precipitation (Q90) in region BF.

The precipitation frequency (FREQ) for entire Germany and in region BAV is not significantly lower than in the observations, while in the other regions, especially in region ODER, the modelled FREQ is significantly overestimated.

A reason for the underestimation of the indices MEAN, INT and Q90 might be that the forcing data itself has a dry bias. This has already been recognised for Europe by HAGEMANN et al. (2005). However, the model performance exhibits a strong regional variability (Figure 4, Table 3). The underestimation could also originate from the fact that the occurrence of precipitation events is correctly simulated, but with too small amounts, yielding a significant underestimation of MEAN, INT, and Q90, but not of FREQ.

The overestimation of all precipitation indices in the regions ODER and BF may be attributed to two effects: (i) the overestimation of precipitation at single (individual) days, at which rainfall has also been observed, and (ii) the generation of spurious precipitation events, which have not been observed at all. The last effect would lead to an overestimation of the precipitation frequency, which is obviously the case for the regions ODER and BAV. First studies to support these explanations have been carried out in form of an analysis of time series of daily precipitation. All these results indicate that the performance of the CLM standard configuration (control run) to simulate correctly the observed precipitation characteristics for different regions in the one selected summer is low.

If we compare the results of the control run and of the eight sensitivity experiments with the observed precipitation indices for entire Germany, we can in general conclude that the applied modifications, even a strengthening of the boundary forcing, do not affect the skill of the model on the indices related to precipitation intensity, while the frequency index is affected (Table 4). In all simulations the MEAN, INT and Q90 are significantly underestimated. In most cases, this is also valid for the precipitation frequency (FREQ). In general, the most evident effects of the applied modifications are visible in FREQ. Here the model capability strongly depends on the performed simulation. Four simulations (APRIL-29, MAY-07, SHIFTDOM, WEIGHT-B) reveal a significant $BIAS^{obs}$ in the precipitation frequency. The applied modifications even have an effect on the sign of the $BIAS^{obs}$ value.

The results of the analysis of spatial variability and of pattern correspondence of the modelled and observed precipitation indices are summarised in Taylor-diagrams (TAYLOR, 2001). Figure 6 shows the normalised spatial standard deviation and the pattern correlation: the observations are always represented as a point at unit distance to the origin on the abscissa and well-performing simulations are close to this point. The normalised standard deviation is the ratio between the modelled and the observed standard deviation, which is a measure for the spatial variability of a precipitation statistic. If the normalised standard deviation of a simulation is larger (smaller) than 1, the spatial variance of the precipitation statistic is overestimated (underestimated). The diagrams reveal that the pattern correlation is low in all simulations. The results do not differ much among the different simulations. Only for FREQ, the pattern correlation in simulation WEIGHT-B is about 25 % higher than in the other simulations. The spatial variances of MEAN, INT, and Q90 are slightly underestimated in almost all simulations, while the spatial variance of FREQ is overestimated, especially for simulation WEIGHT-B. This means that the spatial structure within the regions is not well simulated by the CLM.

5 Summary and outlook

In the presented study, we wanted to provide an insight into the ability of the CLM in representing the statistical properties of JJA precipitation in Germany. Furthermore, sensitivity studies demonstrated the dependence of the simulated precipitation statistics on changes of initial conditions, domain size and location, and boundary forcing and therefore the uncertainty of the precipitation statistics in this respect. Neither the model performance of the CLM in simulating summer precipitation statistics nor the according sensitivity has been evaluated in such a way before. The sensitivity experiments revealed significant inter-simulation differences in the precipitation statistics for entire Germany as well as on smaller scales. Obviously, the lateral boundary forcing has a strong influence on the model solution. Comparisons between simulated and observed values demonstrated that the ability of the CLM to simulate the mean

Table 4: $BIAS^{obs}$ of MEAN (mm/day), INT (mm/day), Q90 (mm/day), and FREQ (%) for all simulations for entire Germany. Significant biases at the 5 %-level are indicated by an asterisk.

	MEAN (mm/day)	INT (mm/day)	Q90 (mm/day)	FREQ (%)
BASE	-0.14*	-0.69*	-1.07*	-0.03
APRIL-21	-0.14*	-0.66*	-1.12*	-0.11
APRIL-29	-0.12*	-0.79*	-1.35*	0.77*
MAY-07	-0.24*	-0.72*	-1.27*	-1.32*
MAY-09	-0.14*	-0.65*	-1.01*	0.04
PLUS15GP	-0.16*	-0.69*	-1.25*	-0.23
SHIFTDOM	-0.26*	-0.84*	-1.23*	-2.15*
WEIGHT-A	-0.14*	-0.80*	-0.86*	-0.42
WEIGHT-B	-0.15*	-0.97*	-1.22*	-0.90*

summer precipitation statistics is not satisfying yet. Our study detected some deficiencies which can be summarised as follows:

- significant underestimation of mean precipitation, mean precipitation intensity, and extreme precipitation in Germany,
- strong regional variability of model performance (over- or underestimation of precipitation statistics depends on considered region),
- low correspondence of the spatial structure, and
- possible spurious generation of extreme events in certain subregions.

Since the main focus of this paper was not to find reasons for the discrepancies between modelled and observed precipitation, but rather to get an insight in the model performance and sensitivity, this topic should be addressed in future studies. These studies could include an analysis of specific events leading to extreme precipitation. For this purpose, a dataset with high spatial and temporal resolution would be needed, so that the evolution of single events can be analysed in more detail. With a data set of higher temporal resolution, an investigation of the diurnal cycle would also be an interesting subject, since regional models often exhibit problems in this respect (see e.g. VAN LIPZIG et al., 2005, for the COSMO model). Differences between modelled and observed precipitation may have many sources of error. To unveil these deficiencies a thorough investigation of other variables is needed. This demanding task was not the main focus of this study, since we wanted to get an insight in the simulation of the statistics of daily precipitation, and not only of long-term means. As mentioned before, other quantities than precipitation have been investigated for the CLM, e.g. by BÖHM et al. (2006) and JÄGER et al. (2008).

Because of the potential randomness of the results of one single summer simulation, our evidence of the model deficiencies should be considered with caution. In a next step, simulations of more summer seasons are needed to establish a representative data basis for a detailed validation of the model performance.

It has to be verified whether discrepancies similar to those found for 1974 also occur in other summer seasons. Our results indicate that studies of other summer seasons should also include sensitivity studies concerning for example the boundary forcing. The model domain size should be chosen large enough so that the influence of the boundary forcing on the investigated regions is not too strong, as it might have been the case for the region ODER. Other studies with the CLM (ROCKEL et al., 2008, JÄGER et al., 2008) also investigate the effect of the spectral nudging instead of the relaxation technique. JÄGER et al. (2008) performed a sensitivity study with additional spectral nudging and showed that, in contrast to applying the relaxation technique by DAVIES and TURNER (1977) alone, the use of spectral nudging improves the simulated large-scale circulation, but not precipitation and temperature. Moreover, ROCKEL et al. (2008) found indications that, in the CLM, the large-scale variability is not retained when using the relaxation technique by DAVIES and TURNER (1977) alone. The additional application of a 4D grid nudging technique retains the large scale variability but ROCKEL et al. (2008) also show that more added variability at smaller scales is achieved when applying spectral nudging.". The application of a 4D internal nudging technique retains the large scale variability but ROCKEL et al. (2008) also show that more added variability at smaller scales is achieved when applying spectral nudging. This suggests that if an internal nudging is applied in addition to the standard boundary relaxation the use of spectral nudging instead of a 4D grid nudging technique should also be studied in future simulations. Because of the strong regional variability of the model performance, the analysis should not only focus on mean statistics for large scales (Germany) but also for smaller subregions.

Nevertheless, our results give a first impression of the ability of the CLM as a tool for climate downscaling and might therefore assist in analysing the results of the future climate scenarios (BÖHM et al., 2006; LEGUTKE and LAUTENSCHLAGER, 2008). It seems to be problematic to make statements for regional scales, because the model performance and the model sensitivity exhibit a strong regional variability, making model results less reliable on small spatial scales. The assessment and overcoming of such deficiencies will enhance the ability of the CLM to serve as a tool for climate change impact studies in future.

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