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# PRESENT AND FUTURE RETURN VALUES OF HEAVY PRECIPITATION IN COMPLEX TERRAIN - THE BLACK FOREST REGION IN GERMANY AS AN EXAMPLE

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## 1. INTRODUCTION

The Black Forest region in southern Germany is an example of complex mountainous terrain with steep slopes, narrow valleys, high variability of land use and strong convective activity. Population and trade reside mainly in valleys prone to flooding due to heavy precipitation which can cause severe damage due to rapidly rising water levels and short response times. Flooding in small catchments occurs more frequently than in larger catchments. The area coincides in large parts with the COPS campaign area presented in the parallel "Conference on Mountain Meteorology". The high spatial and temporal variability, especially of heavy summer precipitation, in this region has been established in detailed analyses of time series obtained from a dense network of climate stations beginning in the first decades of the last century. In the light of recent severe floodings in the region and the need to develop adaptation plans and maps of flood risk, the question how such events and patterns will develop under a changing climate is receiving now much attention and has been addressed in an integrated research project from which a selection of first results is presented here.

Of the many aspects which are involved in the problem (meteorology, hydrology, soil and vegetation, impact, risk and regional planning), we will focus on a very specific aspect, namely the statistics of heavy summertime precipitation, uncertainty and its projections into the near future, i.e. the period 2011 to 2040 using the IPCC A1B scenario (IPCC, 2001). Considering the near future is quite challenging due to the low signal to noise ratio, but bears much more relevance for planning and adaptation purposes.

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According to the Contribution of WG I to the 4th IPCC report (IPCC, 2007), the regional projections for mean and heavy precipitation in central Europe are quite uncertain. Although climate change occurs on a global scale, its impact varies substantially on local and regional scales (GOOD and LOWE, 2006). Global climate models (GCMs) with a coarse resolution are used to study the effects of rising greenhouse gas concentrations, but they are not suitable to estimate the impact of global change on the regional scale. Therefore, the information obtained by global scale models has to be transferred to smaller scales, e.g. via dynamical downscaling using regional (i.e. limited area) climate models (RCMs).

During the last decade the number of experiments studying climate change on the regional scale has grown largely (IPCC, 2007, chapter 11, CHRISTENSEN et al., 2007). The typical grid size of such simulations is in the order of 50 km. In most cases higher resolved applications cover only periods up to a few years (for instance KLEINN et al., 2005). However, for evaluation of the climatology a time span of several decades should be used (IPCC, 2001).

A study by JACOB et al. (2007) also includes a long-term evaluation of the precipitation for a large number of regional climate models driven by present day climate (PDC) forcing simulations. They found a common tendency of the models to over-estimate wintertime precipitation in Central Europe. For summertime there was no clear tendency for the model bias. The grid resolution of the model simulations within that study was about 50 km. This still seems to be too coarse to realistically describe the horizontal scales of some typical topographical structures in Europe and their effect on climate variables like precipitation.

Recently, two RCM simulations for Europe have become available with grid resolutions below 20 km. This is at the high end of current regional long-term climate simulations (IPCC, 2007, Chapter 11). Here we present statistical analyses of the results of present day (1971-2000) climate and one future scenario (A1B, 2011-2040) simulations with these two RCMs. This close time horizon is difficult to study because of its low signal/noise ratio, but it is highly relevant for designing adaptation measures under the paradigm of flexible infrastructure. The focus will be on the validation of the models for the present-day climate and on the comparison of the scenario results in terms of precipitation statistics.

For the evaluation, a very good data base with continuous daily precipitation observations from more than 200 sites, beginning in 1931, is available and has been analysed in several projects. With variations of orography (valleys, mountains) in the order of a few kilometres and less, small scale convective processes dominate precipitation in summer, when also most floodings in small catchments occur. We will therefore focus here on summertime precipitation (June-August (JJA) resp. hydrological summer).

The purpose of this paper is to quantify how well precipitation characteristics are simulated by two different RCMs with different simulation configurations. The analysis is intentionally restricted to a small region with a substantial topographical variation on scales very close to the resolutions of the models. The reproduction of the spatial precipitation distribution in such a region poses a great challenge for the state of the art RCMs. The comparison of both simulations provides an idea of how much regional climate simulations can differ (or agree).

The paper is structured as follows: Section 2 gives an overview over the RCMs evaluated and the high-resolution observed precipitation climatology used for the validation. The model evaluation is described in section 3. In section 4 we discuss the changes between future and present in terms of annual means and return values. Conclusions are given in section 5.

## 2. DESCRIPTION OF MODELS, SIMULATIONS AND OBSERVATION DATA

Within this study we use the results of two RCM simulations, namely the REMO-UBA simulations (grid resolution: 0.088°, ≈10 km) commissioned by the German Federal Environmental Agency (UBA) with the hydrostatic regional Model REMO (JACOB, 2001) and the so-called consortium runs (CLM-CR hereafter, HOLLWEG et al., 2008; resolution: 0.165°, ≈18 km) performed with the non-hydrostatic model CLM. An overview regarding models and the simulation setup used is given in Table 1. Both models were derived from routine weather prediction models which were adapted for climate applications.

| Model | CLM | REMO |
|---|---|---|
| Reference | STEPPELER et al., 2003 (LM) | JACOB (2001) |
| Based on | Local Model LM (non-hydrostatic) | Europamodell (hydrostatic) with parameterizations of ECHAM4 |
| Experiment | Consortium Runs (CLM-CR) | UBA Simulations (REMO-UBA) |
| Resolution | 0.165° (≈18km) | 0.088° (≈10km)<br>0.44° (≈50km) coarse grid |
| Grid points | 257 x 271 | 109 x 121 |
| Vertical layers | 32<br>11 layers below 2000m | 27<br>8 layers below 2000m |
| Dataset citation | CLM-CR: KEULER and LAUTENSCHLAGER (2006) | REMO-UBA: JACOB (2005) |

**Table 1:** Description of the CLM and REMO model setups.

The following analysis is based on model experiments for PDC simulations with anthropogenic forcing for the 20th century (C20) which cover the period from 1960 to 2000. The WMO climate period between 1971 and 2000 was chosen. Both models are driven with data from the global climate model ECHAM5 (ROECKNER et al., 2006a; HAGEMANN et al., 2006; ROECKNER et al., 2006b). The ECHAM5 simulation uses observed anthropogenic forcings for $CO_2$, $CH_4$, $N_2O$, CFCs, $O_3$, and sulphate initialised by a pre-industrial control simulation, but neglects natural forcings from volcanoes and changes of the solar activity. The grid resolution is T63 (1.87°) with 31 layers; it was run in a coupled mode with the Max-Planck-Institute ocean model MPI-OM. The CLM-CR simulations were nested directly into the ECHAM5 fields. For REMO-UBA a two step nesting was applied, see Table 1.

Our study area encompasses the region from 7.5°E to 10.5°E and 47.5°N to 50°N and covers the federal state of Baden-Württemberg (Figure 1), Germany. The horizontal extensions are about 225 km x 255 km. It coincides roughly with the area of the COPS experiment and is characterized by a complex topography including orographic features like e.g. the Rhine valley, the Black Forest, the Swabian Jura, and the valleys of the Neckar and the upper Danube. Large changes of orography height occur on scales of several 100 m to a few kilometres. The Black Forest extends approximately in north-south direction. Its highest elevation is the Feldberg with nearly 1500 m above MSL which is represented by a grid cell elevation of 1041 m at REMO-UBA and 952 m at CLM-CR resolution. Adjacent are the rivers Rhine to the south and west, the Danube to the south-east and the Neckar to the north-east. The Swabian Jura is a high plateau between Neckar and upper Danube with an altitude up to 1000m MSL. South of the Danube begin the northern foothills of the European Alps.

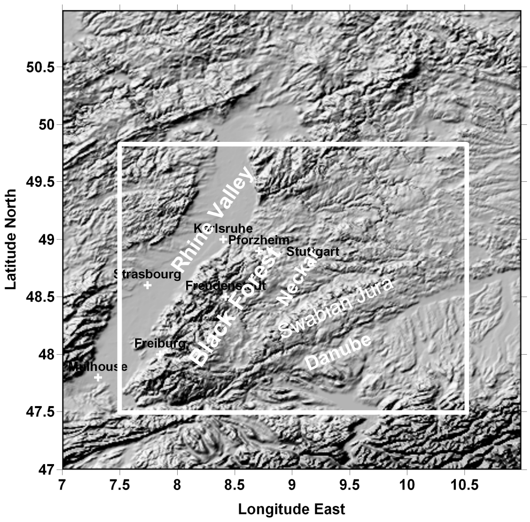


**Figure 1:** Orography of south-western Germany. The box indicates the region used for this study.

For the validation we used daily observed precipitation data which were interpolated onto the respective model grids of CLM-CR and REMO-UBA. We employ the high resolution (1.25' ≈2 km) climatology for the Alpine region (SCHWARB, 2001; SCHWARB et al., 2001; FREI AND SCHÄR, 1998), complemented by the precipitation climatology provided by the German Weather Service (DWD; MÜLLER-WESTERMEIER, 1995). The method is described in detail in FRÜH et al. (2006) and FRÜH et al. (2007).

Uncertainties and errors like network bias and undercatch of the observational climatology are addressed in FREI et al. (2003). The observed climatology was not corrected for these errors due to the lack of information on the exposure of the stations in the network. However, these uncertainties have to be kept in mind for the interpretation of the model deviations.

The observed precipitation reflects the effects of the orography combined with the main wind direction west to southwest with high precipitation amounts in the Black Forest, the Swabian Jura and the foothills of the Alps. The annual precipitation amount ranges from about 550mm in the Rhine valley to 2000mm in the Black Forest. There is also a pronounced lee effect to the east of the Black Forest with reduced precipitation.

For the Rhine, Danube and Neckar region the typical annual precipitation amount ranges between 600 and 1000mm and for the Swabian Jura between 900 and 1400mm. The seasonal precipitation sums averaged over the region of interest are 226mm (March-May, MAM), 285mm (June-August, JJA), 228mm (September-November, SON) and 214mm (December-February, DJF).

The observed annual cycle of precipitation in Baden-Württemberg exhibits in general higher precipitation in summer than in winter with the exception of the Black Forest. The annual precipitation cycle of the Black Forest shows two maxima: one in summer and another, slightly higher one in winter. This enhanced winter precipitation is caused by orographic lifting mainly on the western side, which is exposed to the dominant flow regime during this season.

In contrast to the annual mean, heavy precipitation events and their trends are much less linked to orography, but exhibit an even more pronounced small-scale variability with frequent events in the relatively dry river valleys. The highest retutn values (RVs) occur during summer. Ten year RVs (RV10) are around 40-60 mm/d in the Rhine valley and around 60-100 mm/d in the Black Forest. A recent flooding event in a small river catchment in the lee of the Black Forest with severe damages and casualties had an amount of 65 mm/d. As to the trends of heavy precipitation, there are significant increases and decreases in the Black Forest/Suebian Jura region close to each other, but also significant increases in drier regions like the Neckar Valley.

### 3. MODEL EVALUATION 1971-2000

Summer is the season which is most prone to heavy precipitation. Here, we will therefore discuss only summer precipitation statistics. Results for other seasons can be found in Feldmann et al. (2008) and Früh et al. (2008). Both models are compared to the observations adjusted to their respective spatial resolution to account for the different representation of topography and land cover of both models. A running 3x3-point smoothing was applied to the model data to account for the effective model resolution, which is known to be coarser than the grid size.

Comparing the means of the annual total precipitation of CLM-CR and REMO-UBA with gridded observations, the orographic influence on precipitation becomes apparent. As observed, a higher amount of precipitation is located in the Black Forest and the Swabian Jura, whereas the river valleys are much dryer. The observed average July-August (JJA) precipitation for the region is 285 mm. Both models produce slightly higher averages (CLM-CR +5% compared to the observations, REMO-UBA +9%). The regional variation of the differences between observations and model results is large. For both models, we found over- and underestimations up to several ten percent, varying over quite short distances. Among the difficult-to-simulate regions for the models are the slopes of the Black Forest due to the steep and complex orography, but also because the area affected by orographically increased precipitation extends too far into the Rhine valley, i.e. upstream. This misplacement occurs with both models, but for REMO to a larger extent. In general CLM-CR agrees well with observations in nearly all parts of the domain with a slight tendency to overestimation. The REMO-UBA precipitation shows a considerably higher spatial variability compared to the observations and the CLM-CR results. This large variation cannot be explained by the higher horizontal resolution of REMO alone, but has to be attributed to the excess precipitation on the orographic slopes with western exposure (“weather side”) and a comparable deficit on the eastern slopes in combination with the misplacement of the precipitation field mentioned above. The luff/lee contrast for CLM-CR is much less pronounced and no marked precipitation deficit can be found east of the Black Forest.

The frequency of occurrence of precipitation events and their intensity is an important quantity both for model evaluation and for prognoses with regard to floods. The daily precipitation in each grid cell over the 30-year time period was binned for the gridded observations and both the REMO and the CLM model simulations. In general, the observed distribution is well reproduced by the models. The fraction of low and moderate precipitation days is marginally lower in the simulations. Both models have a higher percentage of days with more than 25mm precipitation, amounting to 3.1% for CLM-CR and 3.9% REMO-UBA (at 18 km resolution; 4.6% at 10 km resolution) compared to 2.5% in the observations (also at 18 km resolution). We can therefore expect RVs which are too high.
Since the spatial patterns of the return values for 5, 10 and 20 years return period are quite similar, we will only discuss the 10 year return value (RV10) here. RVs and quantiles are complementary possibilities (amount vs. time) to characterise heavy precipitation events. RVs can be derived from cumulative distribution functions and tell us what amount of (in our case) daily precipitation is to be expected for a specific return period, e.g. in years. To select the interesting portion of the data we used the peak over threshold method and obtained the parameters of the suitable distribution using the L-moments method (Hosking and Wallis, 1997). Various candidates of distribution functions were considered, among them the kappa and the generalised pareto distribution (KD and GPD, respectively). We found that in our case the KD with a 90th percentile threshold is most appropriate to describe heavy daily precipitation in complex terrain. More details on these issues can be found in Früh et al. (2008).

Figure 2 shows the map of RV10 for the observations gridded to 10 km resolution (OBS10) and for REMO-UBA (top row, panels a, b). The corresponding maps for the CLM-CR simulation in comparison with 18 km gridded observations (OBS18) are shown in the bottom row of Figure 2. For both models as well as for the observations, the spatial pattern of RV10 is very similar. REMO-UBA simulates a more distinct rise of RV10 at the western side of the Black Forest and the northern foothills of the Alps compared to the observations and the more coarsely resolved fields of CLM-CR. This pattern can be explained by the higher resolution of REMO-UBA compared to CLM-CR and the already mentioned misplacement of precipitation. The highest deviation of REMO-UBA from the observations is located at the western slope of the Black Forest. The deviation pattern of CLM-CR is not as strongly correlated with the orography as REMO-UBA. Whereas the other simulated seasonal means agree quite well with observations, JJA is the season of maximum deviation of the simulated RV 10 with an overestimation of more than +40% by REMO-UBA and about +20% by CLM-CR. Both REMO-UBA and CLM-CR overestimate the observed RV for all return periods, with the deviation to the observed RV increasing with increasing return period and being smaller for CLM-CR than for REMO-UBA. This was already reflected in the higher frequency of occurrence of heavy precipitation discussed earlier, and also in the higher contributions of heavy precipitation to total precipitation (not shown).

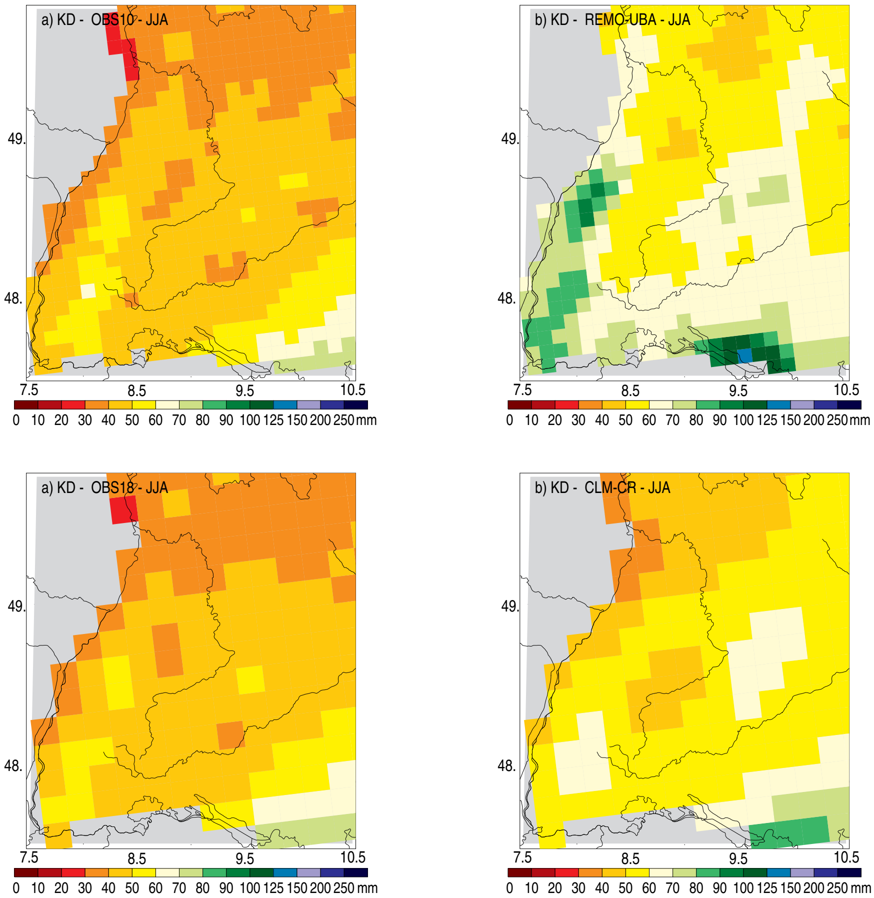


**Figure 2:** Evaluation of RV10 for the period 1971 – 2000 [mm]. The observations are displayed in the left column (top: REMO, bottom:CLM), the model simulations are displayed in the right column (top: REMO, bottom: CLM).

**4. FUTURE CHANGES 2011-2040**

According to the regional prognoses in IPCC AR4, mean summertime precipitation in Central Europe will decrease, with the possibility of an increase of number and intensity of heavy precipitation. However, from an ensemble of 21 GCMs, 5-7 project an increase of summertime precipitation to the end of this century. Our analysis of the RCM runs indicates that mean summertime precipitation in the Black Forest region will continually decrease during this century. In this section, we will discuss the changes of RV10 between 1971-2000 and 2011-2040 predicted by the two RCMs.

Figure 3 shows the change of RV10 relative to the present value according to REMO (left) and to CLM (right). Green and blue colours indicate a moderate (10-25%) and marked (25-50%) increase, yellow and red colours indicate a moderate (10-25%) and marked (25-50%) decrease of RV10 in the future.

The models agree that there will be a decrease in the eastern and southeastern parts of the region and an increase in the northwestern part, but results differ in the western part. Both models also agree on an increase in parts of the Neckar valley and parts of the Rhine valley. Also a large small scale variability is apparent in the REMO results with increases and decreases nearby.

We used the Wilcoxon test to see if the precipitation time series 1971-2000 and 2011-2040 were significantly different for REMO and CLM respectively. It turned out that REMO indicates more and more significant differences than CLM, especially for rare events, i.e high quantiles.

At this stage, we are not really able to judge the results – neither where they disagree nor where they agree. More independent simulations are necessary to combine their results on a statistical (ensemble) basis.

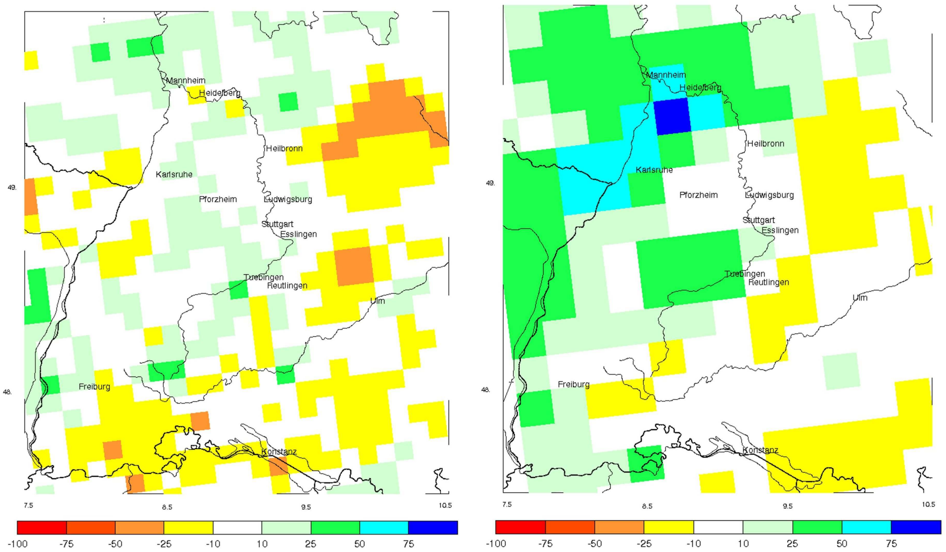


**Figure 3:** Percentage change of RV10 between 2011-2040 and 1971-2000 for REMO (left) and CLM (right).

### 5. SUMMARY AND CONCLUSIONS

In this study we evaluated the summertime precipitation fields derived from long-term simulations of two state of the art high resolution regional climate models (RCM), namely REMO and CLM which were both driven by data from the GCM ECHAM5. Therefore, differences in the results of the two simulations arise from the different model formulations and setups and not from the large scale forcing. The focus was on the evaluation/validation of present day climate simulations with the RCMs.

The study was performed for the greater Black Forest region in south-western Germany with complex topography presenting is a great challenge for the models. The selected region is in the transition area between the northern European and the Mediterranean climate zone, which are expected to develop significantly different during climate change (IPCC, 2007), the former becoming wetter in summer, the latter becoming dryer.

The analyses covered several important aspects of the precipitation fields: their regional distribution, frequency distributions and return values, especially the 10 year return value. The evaluation indicates that with a resolution below 20 km both models are better able to resolve the orographical scales which are typical in Central Europe than the 50 km resolution of the previous generation RCM simulations (e.g. JACOB et al., 2007). The statistics of the simulated mean precipitation fields showed a good agreement with the observations, with a slight overestimation. The overestimation of precipitation at the upwind side of mountainous areas and a corresponding underestimation downstream is a characteristic deficiency of both RCMs. We recently experimented with a version of CLM including a so-called prognostic precipitation scheme, where this misplacement did not occur.

The frequency of occurrence of simulated precipitation days agreed reasonably well with the observations for the period 1971 – 2000. Both models overestimate the frequency of high intensity precipitation events. The contribution to the total precipitation is slightly shifted from medium intensities towards the extreme events. These effects are more pronounced for REMO-UBA than for CLM-CR.

To calculate the RVs, the observed time series of the 24 h precipitation of the 30-years time period 1971-2000 at each grid point was fitted to several test distributions, including the generalized Pareto distribution and the Kappa distribution, using the L-moments method. We found that generally the kappa distribution gives the best agreement with the observed distribution. Our results show that the observed spatial pattern of the RVs can be reproduced reasonably well by the models. Quantitatively, the RVs are overestimated by the models, one possible reason being the precipitation misplacement mentioned above. Averaged over the investigation area, an small increase of the RVs of a few percent between present and future is predicted, which is in the range of the global model predictions. The small scale variability, however, is quite high with increases and decreases of the RVs in the order of several 10 percent with no obvious correlation to the average precipitation of the respective area. Obviously, several small scale processes contribute, underlining the importance and added value of high resolution downscaling.

We conclude that high-resolution climate models are able to reproduce many aspects of the regional precipitation fields realistically. The increased spatial resolution has a positive effect on the model results.

Our next steps will include simulations with higher resolution (7 and 2.8 km), ensemble simulations with driving data from other GCM families and with different RCM settings, followed by Bayesian model averaging. Similar to GCM and weather forecast ensembles, RCM ensembles are expected to give more reliable results and estimates of their uncertainty.

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