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# Progress in regional downscaling of west African precipitation

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## Abstract

**We review the recent progress in dynamical and statistical downscaling approaches for west African precipitation and perform a regional climate model (RCM) intercomparison using the novel multi-model RCM data set from the Ensembles-based Predictions of Climate Changes and Their Impacts (ENSEMBLES) and African Monsoon Multidisciplinary Analyses (AMMA) projects. Present RCMs have distinct systematic errors in terms of west African precipitation varying in amplitude and pattern across models. This is also reflected in a relatively large spread in projected future precipitation trends. Altogether, the ENSEMBLES RCMs indicate a prevailing drying tendency in sub-Saharan Africa. Statistical post-processing of simulated precipitation is a promising tool to reduce systematic model errors before application in impact studies.** 

**Keywords: dynamical downscaling; statistical downscaling; model intercomparison; West Africa; climate change**

## 1. Introduction

The assessment of climate change in West Africa has until recently relied on coarse-grid global general circulation models (GCMs) (IPCC, 2007 and previous IPCC reports). With a typical grid-box size in the range of 150–400 km, GCMs cannot account for the regional heterogeneity of climate variability and change and, hence, are not suitable for producing climate projections at the regional-to-national scale needed to assess impacts and devise adaptation policies. Practically, all impact studies in the sector of African food security (Paeth *et al*., 2008), ecosystems (Philippon *et al*., 2009) and water resources (Lebel *et al*., 2000) require fine-scale climate information. Therefore, different dynamical, statistical and combined approaches can be used to downscale coarse-grid data sets from GCMs to the regional and local scale in order to account for the effects of complex topographical, land-use and other fine-scale forcings (Garric *et al*., 2002; Paeth *et al*., 2006; Paeth and Diederich, 2010; Rummukainen, 2010).

Here, we review the recent progress in regional downscaling for West Africa, including the most recent contributions offered by the African Monsoon Multidisciplinary Analyses (AMMA) and Ensembles-based Predictions of Climate Changes and Their Impacts (ENSEMBLES) projects. Our focus is on west African precipitation, which is probably the most relevant climatic feature in the region. We mostly assess progress in dynamical downscaling (Section 2), although some considerations on recent statistical downscaling work are also presented (Section 3). Avenues for future improvements in the provision of regional-to-local climate change information for West Africa are then highlighted (Section 4).

## 2. Progress in dynamical downscaling

Dynamical downscaling mostly makes use of limited area regional climate models (RCMs) driven at the lateral boundaries by time-dependent global reanalysis or GCM meteorological fields (Giorgi and Mearns, 1999). The first RCM simulations for West Africa were limited to individual rainy seasons and aimed at a general understanding of the climate drivers over the region. Vizy and Cook (2002) completed seasonal time slices with an extended version of the MM5 model to study the response of the west African monsoon system to tropical oceanic heating. Gallée *et al*. (2004) showed that the RCM, Modele Atmospherique Regional (MAR), is able to reproduce the observed intra-seasonal variability when driven by European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses and Messager *et al*. (2004) used the same model for idealised sensitivity studies with respect to sea surface temperature (SST) anomalies. Afiesimama *et al*. (2006) investigated the climatology and inter-annual variability of west African climate in a RegCM3 simulation for the 1979–1990 period, while very high resolution (7 km) simulations were performed for a few days with the non-hydrostatic model FOOT3DK over central Benin with the objective of assessing the small-scale interactions between land-cover changes and atmospheric processes (Sogalla *et al*., 2006).

One of the first multi-decadal RCM simulations over West Africa was carried out with the REMO RCM for the 1979–2003 period. It showed a good performance in terms of inter-annual variability, African Easterly Wave activity and regional-scale features of the west African monsoon system (Paeth *et al*., 2005). Similar results were demonstrated for the model HadRM3P in a 30-year simulation for the period 1961–1990 (Kamga and Buscarlet, 2006). The added value of RCMs in simulating African wave disturbances was investigated by Druyan *et al*. (2000) and Hsieh and Cook (2007), while diagnostic analyses of the June monsoon jump were conducted with the models MAR (Ramel *et al*., 2006), MM5 (Sijikumar *et al*., 2006; Hagos and Cook, 2007) and MRF (Drobinski *et al*., 2009) for individual rainy seasons. The added value of RCMs *versus* GCMs was also highlighted by Sylla *et al*. (2009), who concluded that the systematic errors in their RCM were driven only to a minor extent from the errors in the driving large-scale GCM fields and, thus, were tied to the representation of local/regional processes. More recent papers have illustrated improvements in the same RCM performance in reproducing the seasonal and intra-seasonal variability of west African climate (Sylla *et al*., 2010a, 2010b).

Rockel and Geyer (2008) compared the skill of the Climate Local Model (CLM) in various regions of the globe and noted that a careful adjustment of physical parameterisations is required for each different model domain. Indeed, Montmerle *et al*. (2006) found different error statistics for weather forecasts in West Africa compared to those in Europe, and this conclusion might also hold for regional climate simulations. The importance of soil moisture initialisation in seasonal RCM runs over West Africa has recently been highlighted by Moufouma-Okia and Rowell (2010). Furthermore, the parameterisation scheme for convection has a crucial influence on the simulated west Africa precipitation (Meinke *et al*., 2007), and increasing resolution does not necessarily increase the quality of the simulation (Druyan *et al*., 2008). Finally, Vanvyve *et al*. (2008) give a measure of the unpredictable noise component arising from the difference between pairs of simulations differing only in initial conditions. This is summarised in terms of spatio-temporal scales in Figure 1. Smaller/shorter scales are associated with larger random errors.

Among the first RCM projections of future west African climate are the 10-year time slice experiments with MM5 by Jung and Kunstmann (2007). Their model simulates a warmer and mostly wetter climate under increased greenhouse gas (GHG) forcing for the period 2030–2039, with a clear shift of the monsoon cycle in the Volta region. MM5 was also coupled to a hydrological model to quantify the interactions with land-surface processes (Kunstmann and Jung, 2007) and the consequences for river discharge (Neumann *et al*., 2007). The effects of transient radiative forcing by GHGs and aerosols were investigated by Caminade *et al*. (2006) with the variable-resolution version of ARPEGE: a general drying along the Guinean coast region was contrasted by more humid conditions in the Sahel Zone. Given the role of human-induced land-cover changes in future climate (Feddema *et al*., 2005; Abiodun *et al*., 2008), land-use scenarios for tropical Africa have recently been implemented in long-term integrations with REMO, resulting in a substantial warming and drying over the whole of sub-Saharan Africa (Paeth *et al*., 2009).

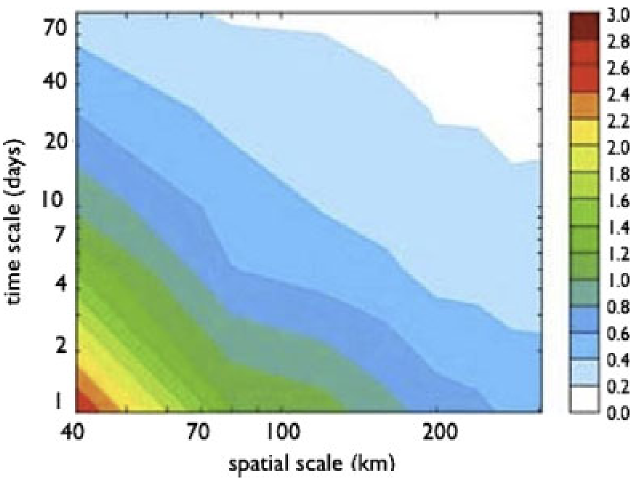


**Figure 1.** The maximum standard deviation in precipitation anomaly (mm/day) over west Africa associated with the noise component of a comparison between two RCM integrations, plotted as a function of temporal and spatial averaging scale. Note logarithmic axes (modified from Vanvyve *et al*., 2008).

All the studies mentioned above show a substantial progress in the simulation of the west African monsoon dynamical and physical features in present-day RCMs. However, they also show that the models are sensitive to physics parameterisations, resolution and internal variability. This implies that an ensemble model approach is needed to provide climate change information that can be evaluated in the light of uncertainties arising from model characteristics, emission scenarios and unknown initial conditions.

Therefore, as a new benchmark in dynamical downscaling over West Africa, a multi-model assessment of past and future climate was recently achieved with contributions by the ENSEMBLES and the AMMA projects (Van der Linden and Mitchell, 2009). To simulate present-day climate and validate the models, different RCMs were forced by the same lateral and lower boundary conditions from the ECMWF re-analysis (ERA) Interim re-analysis for the period 1990–2007, mostly for the same model domain and horizontal resolution (~50 km). The aim was to investigate systematic model errors by comparison with observations. Figure 2 shows an observed 1990–2007 annual precipitation climatology (top left) and the systematic differences from this pattern in nine individual RCMs participating in ENSEMBLES along with the multi-model ensemble (MME) mean error (remaining panels). Observations are from the Global Precipitation Climatology Centre (GPCC) observational data set, which is a gridded product from statistical interpolation of available station data (Rudolph, 1995). All RCM fields were interpolated onto the GPCC 0.5° grid. It is obvious that most models present a bias compared to the observed climatology. Nonetheless, the individual model errors vary considerably in space and from model to model (cf. Druyan *et al.*, 2010). For example, three RCMs show prevailing dry biases over central equatorial Africa (REMO, HIRHAM-DMI, HIRHAM-METNO), whereas HadRM3P, RCA and PROMES overestimate the annual rainfall regionally by up to 50%. In addition, the RCMs differ noticeably in terms of their seasonal cycle and interannual variability (not shown). This implies that the considered RCMs do not simply inherit the bias from the ERA-Interim re-analysis as a common boundary condition to all runs. This is also true for the linear precipitation trends during the 1990–2007 period, which is basically different from model to model and, hence, not dominated by the trends in the ERA-Interim reanalyses (not shown).

Given that all RCMs have the same boundary conditions and resolution, the differences between the RCMs mainly arise from their different dynamical schemes and physical parameterisations. This highlights the importance of thorough model validation for West Africa (cf. Rockel and Geyer, 2008; Druyan *et al.*, 2010). In the MME mean, some of the individual model errors compensate each other but still a wet bias of around 20% prevails in the southern Sahel Zone,

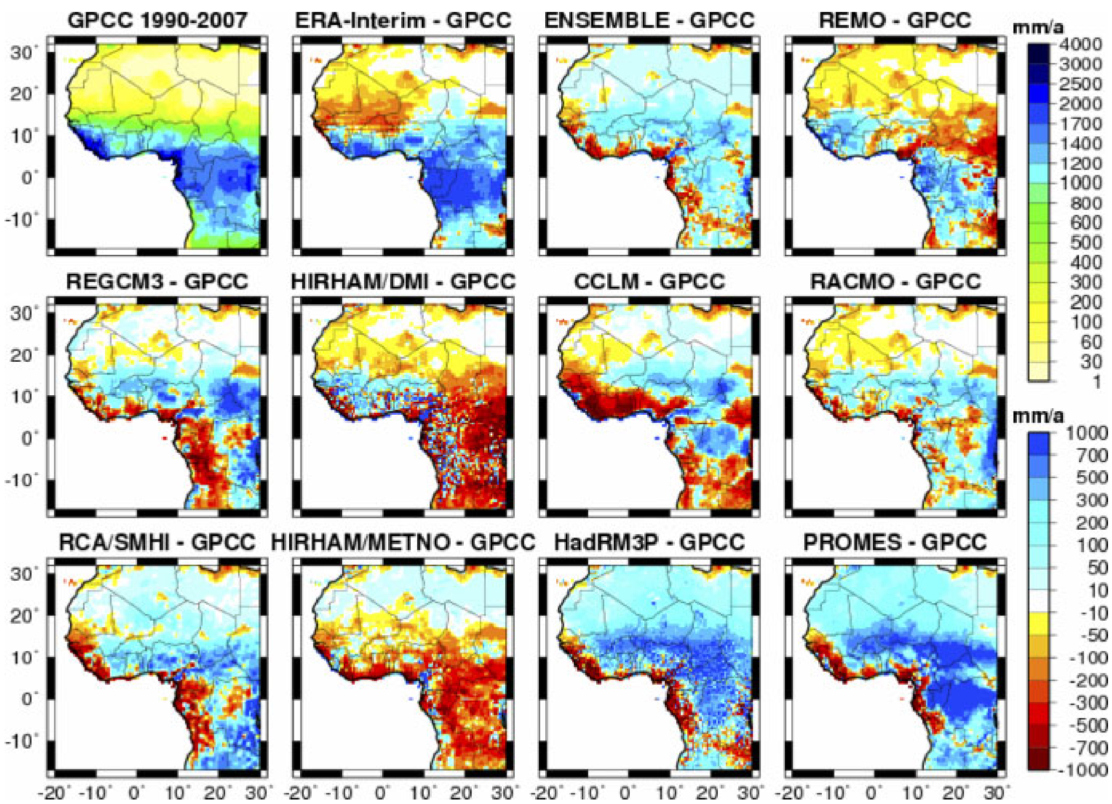


**Figure 2.** Observed 1990–2007 annual precipitation climatology from GPCC (top left) and related systematic errors in nine individual RCM simulations driven by ERA-Interim reanalyses in the MME mean and in the ERA-Interim reanalyses (remaining panels). Detailed information about the individual RCMs can be obtained from the ENSEMBES homepage under http://ensemblesrt3.dmi.dk.

 

while precipitation along the Guinean Coast region is systematically underestimated, likely due to the fact that in several RCMs orography in coastal grid boxes in the 50-km resolution tends to incite the convection scheme too strongly in the off-shore grid boxes. This deficiency could probably be reduced in higher resolution RCMs. The fact that the MME mean generally outperforms the skill of the individual models illustrates the advantages of multi-model assessments for past and future African climate. In addition, the ERA-Interim re-analyses as driving data have a much larger and spatially extended bias in most parts of Africa, particularly in tropical Africa where annual rainfall is overestimated by up to 2700 mm (Figure 2) than most RCMs. Thus, while some individual models have comparable biases, the MME has a clear added value with respect to the ERA-Interim precipitation. This implies that accounting for higher resolution land–surface interactions and synoptic atmospheric processes such as African Easterly Waves (Paeth *et al.*, 2005) leads to a better presentation of the observed African rainfall in RCMs compared with lower resolution model products.

Scenario simulations in the project covered the period 1990–2050 under the A1B GHG forcing scenario, with the participating RCMs being driven by different GCMs. The projected linear trends of annual precipitation over the 2001–2050 period are shown in Figure 3 for nine RCMs, and for an additional RCM experiment including the effect of projected land-cover changes, which consist of deforestation, desertification and increased urbanisation (cf. Paeth *et al.*, 2009). The precipitation trends for the MME mean with and without the RCM simulations with land-use scenario are also shown. The RCMs shown in the bottom row [HIRHAM (METNO version), HadRM3P, PROMES and RCA] are driven by HadCM3 experiments, while all other RCMs are nested in ECHAM5. All trend patterns are characterised by substantial regional variations. However, different RCMs do not agree in terms of the future precipitation changes in western and tropical Africa: in three models, tropical Africa becomes wetter; in three models, negative trends predominate and three models show a more mixed signal. A spatially more homogeneous trend pattern is only simulated by one RCM when future land-cover changes are taken into account. As such runs are not available from other RCMs, it is difficult to assess whether the response to land-cover changes in REMO is representative or specific for the particular model or land-use scenario used. In the MME mean trend pattern, a slight precipitation decrease of the order of 5–20% is found in most areas of tropical and western Africa.

A large model spread with positive, negative or no significant rainfall trends was also reported for global GCM projections over Africa (IPCC, 2007, see below). Interestingly, a systematic relationship between the RCM trend patterns and the driving GCM

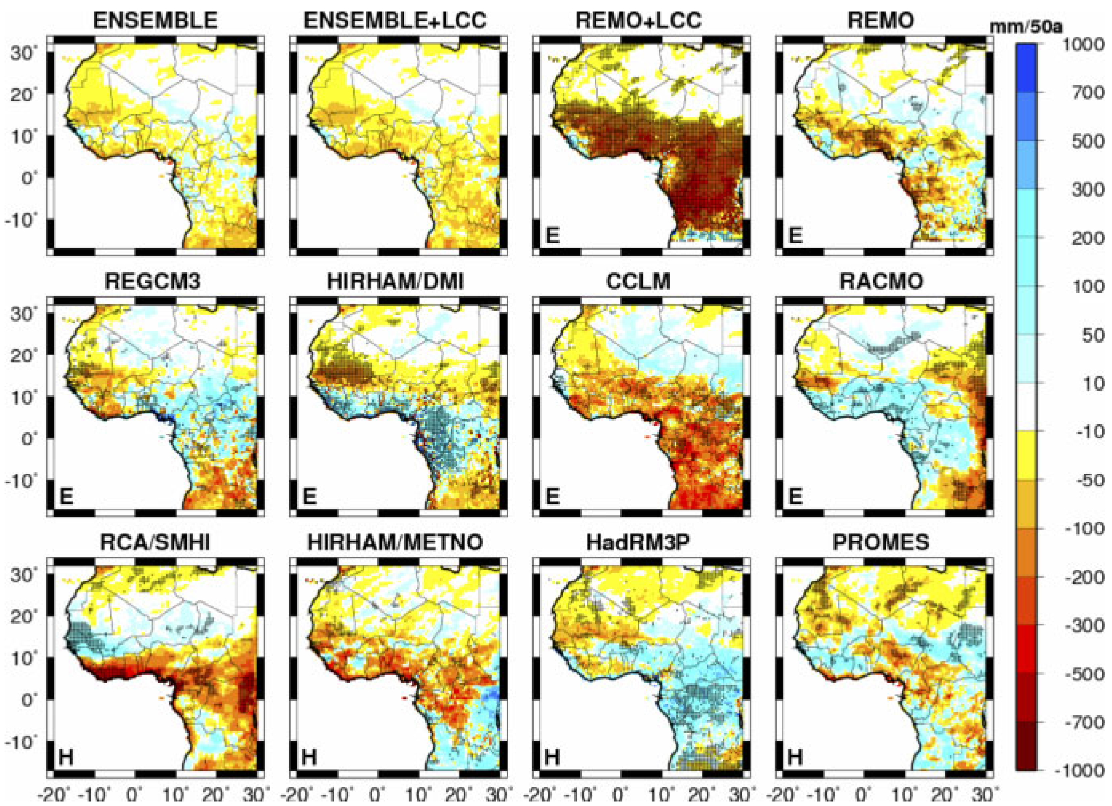


**Figure 3.** Linear changes of annual precipitation during the 2001–2050 period from ten individual RCM experiments and the MME mean under the A1B emission scenario. The top middle panels also account for projected land-cover changes (see text for further explanation). Note that the REMO trends in both panels arise from a three-member ensemble, whereas all other RCMs are represented by one single simulation. Trends statistically significant at the 5% level are marked by black dots.

 

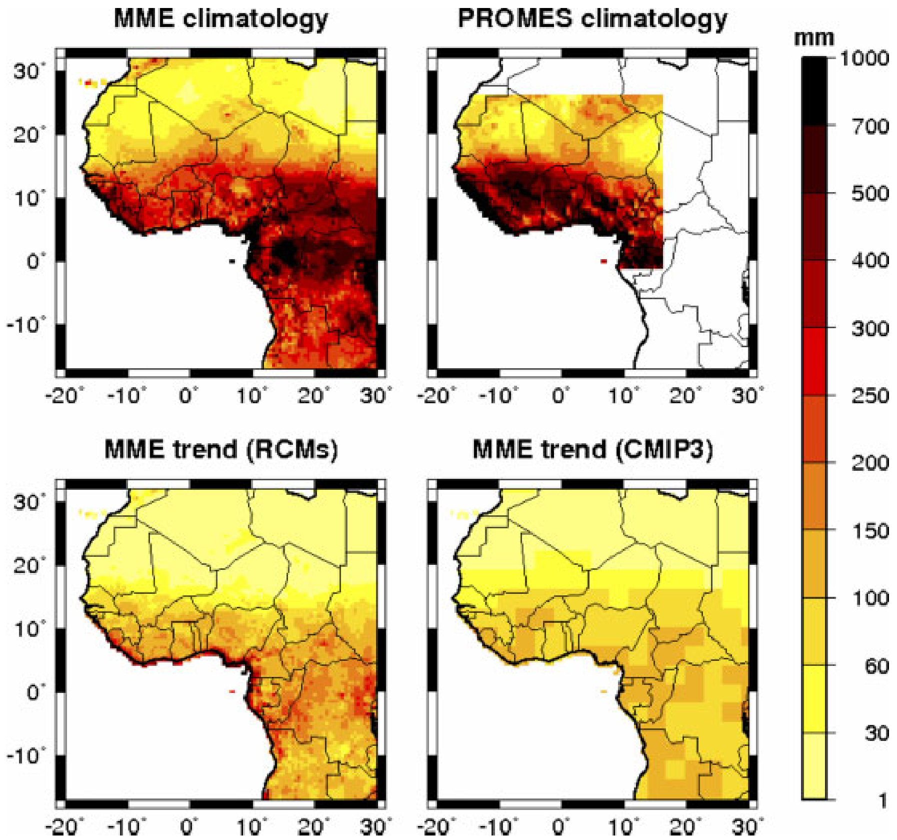


**Figure 4.** Standard deviation of 1990–2007 annual precipitation climatologies within the MME (top left), standard deviation of 2003–2005 annual precipitation climatologies within the PROMES mixed-physics ensemble (top right), standard deviation of 2001–2050 annual precipitation trends within the MME from RCMs including REMO with land-cover changes (bottom left) and standard deviation of 2001–2050 annual precipitation trends within the CMIP3 MME from global GCMs (bottom right). Note that the sample sizes differ in each panel.

cannot be identified, in contrast to similar studies over the United Kingdom and Europe (Rowell, 2006; Deque *et al*., 2007). In fact, substantial differences in the projected trends are also found across models that use the same driving GCMs. This could imply that for this region the lateral boundary forcing does not have an entirely dominant effect on the simulated regional precipitation change signal.

Some quantitative measures of model uncertainty are given in Figure 4. The standard deviation of the individual RCM 1990–2007 climatologies peaks over tropical Africa with a minimum in the Sahara desert, which is not surprising given the low total precipitation amount in this region as a basic feature captured by all RCMs. This indicates that RCMs differ most in the humid and semi-humid regions of the area considered (left panel). In contrast, relative model uncertainty scaled by present-day rainfall totals is highest in the arid and semi-arid regions and reaches 150% (not shown). Model uncertainty is also evident in a mixed-physics ensemble experiment with PROMES (middle panel): the five ensemble members differ in terms of the radiation scheme, the complexity of soil hydrology and the activation of shallow convection. Note that PROMES has a relatively large bias in the precipitation climatology (cf. Figure 2), which might be reduced with an optimisation of the parameter setting. In terms of future precipitation trends, the model spread is remarkable as well (right panel): relative uncertainty of the RCM projections partly exceeds 1000% of the MME mean changes. Given that the spread of model climatologies (i.e. model errors) is much larger than the responses, it is possible that errors in the model responses dominate this spread. This would imply that the suggestion above that the lateral boundary forcing does not have a dominant effect on the responses must not necessarily be true. We have also computed the standard deviation of precipitation trends across the available global GCM projections under A1B scenario from the CMIP3 MME (Figure 4, cf. IPCC, 2007). In fact, the RCM and GCM model spread cannot directly be compared with each other because many more GCM runs (36) exist and trend patterns of the lower-resolution GCMs (here interpolated on a common $3^\circ \times 3^\circ$ grid) are generally much smoother and have lower amplitudes than those in RCMs. In fact, the high degree of resolved synoptic-scale structures in RCMs and the associated small-scale variability implies higher uncertainty among different RCMs. The ultimate added value of RCM projections finally depends on their ability to reproduce higher spatial details of the observed trend patterns compared with coarse-grid models – a matter for current research.

 

## 3. Progress in statistical downscaling

Given the uncertainty of present-day RCMs and their high computational needs, statistical downscaling represents a valuable complementary approach either to directly downscale GCM information or to post-process RCM simulations. There are three major and partly combined targets for statistical downscaling (Wilby *et al*., 1998): (1) coarse-grid data sets are statistically interpolated to a finer resolution; (2) climate model data from GCMs or RCMs are adjusted to observational data by removing systematic errors (bias correction) and (3) climate data are statistically linked to local data needed for impact research or seasonal prediction. Starting with the last aspect, Mo and Thiaw (2002) as well as Ndiaye *et al*. (2009) have applied canonical correlation analysis in order to test the seasonal forecast potential for Sahelian rainfall by linking dynamical predictors with observed precipitation. A similar issue for the west African summer monsoon was approached by Paeth *et al*. (2006) using a multiple regression model. Finally, Hewitson and Crane (2006) empirically downscaled six different GCM projections over the entire African continent and showed that the downscaling process, based on large-scale dynamical predictors, leads to increased convergence of the precipitation response.

There is some agreement that the combination of dynamical and statistical approaches may be the best option for seasonal prediction systems (Garric *et al*., 2002). Paeth *et al*. (2008) have used model output statistics to determine the statistical transfer functions between various climate parameters from their RCM and crop yield data from Benin and have derived a statistical forecast for future crop security. Similarly, Philippon *et al*. (2009) have linked dynamical predictors from a GCM to photosynthetic activity of Sahelian vegetation.

As another example of the advantage of the combined downscaling approach, Paeth (2010) has developed a cross-validated model output statistics approach to post-process monthly precipitation from REMO over West Africa by using dynamical predictors from the model and monthly rainfall from CRU (New *et al*., 2000) as predictand. By this method, for example, while the simulated precipitation climatology has a considerable dry bias (Figure 5, left panel), the observed rainfall pattern can be reproduced by a linear combination of dynamical variables from the model (Figure 5, right panel). As a consequence, the resulting model bias is much lower than that in any panel of Figure 2. This procedure basically improves the seasonal cycle and inter-annual variability of simulated west African precipitation. As all predictors are taken from the model, the method can also be applied to time periods for which observational data are not available. This is a promising method for seasonal forecasting, although for climate change issues the assumption that precipitation–dynamics relationships remain stationary under increased GHG forcing would need to be carefully assessed.

For some applications in impact research, the post-processing of simulated monthly precipitation is not sufficient. In particular, hydrological models require daily rainfall series with realistic statistical distribution (Lebel *et al*., 2000). In this regard, Gerbaux *et al*. (2009) use GCM simulations to drive a statistical model of Sahel rainfall, which is in turn used to drive a simple runoff model. They find that projected changes in rainfall can have consequences for runoff of the same order of magnitude as land-use changes. Local information may also be needed for impact applications. Within this context, Messager *et al*. (2006) have developed a temporal disaggregation scheme for rainfall simulated by MAR, while an extended weather generator with physical and stochastic elements has been used by Paeth and Diederich (2010) in order to improve the interface between their RCM and hydrological models for Benin. Various examples on the use of model output statistics and weather generator-corrected RCM output in impact studies on hydrology, soil science, agronomy, socio-economy and health have been compiled by Speth *et al*. (2010) for west and northwest Africa.

The examples cited in this section thus emphasise how the combined use of dynamical (RCM) and statistical downscaling tools can lead to the production

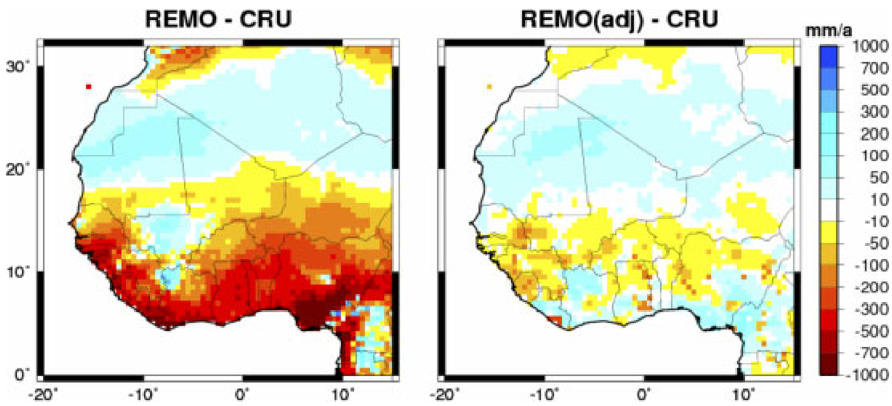


**Figure 5.** Systematic biases in the 1979–2003 annual precipitation climatology from REMO with respect to CRU, based on the original (left) and post-processed (right) model data (modified from Paeth, 2010).

of climate products better suited for use in impact studies.

## 4. Conclusions

During recent years, considerable progress has been achieved in dynamical and statistical downscaling of west African precipitation. The AMMA and the ENSEMBLES projects have provided important contributions towards this goal by leading to the generation of the first multi-model multi-decadal RCM simulations and by extending the observational database for model validation, statistical downscaling and RCM post-processing. Projects such as AMMA, ENSEMBLES and west African Monsoon Modeling and Evaluation (WAMME, Druyan *et al*., 2010) and the resulting RCM data sets are, therefore, milestones for the assessment of the African regional climate. The model inter-comparison presented in this study reveals that some important systematic errors still persist in present-day RCMs over West Africa. In addition, the spread of the twenty-first-century rainfall projections is large, even when the RCMs use the same lateral boundary forcing fields. This suggests that both the model errors and the internal model physics and dynamical processes can contribute to determining the simulated changes.

These findings indicate that, on the one hand, the skill of RCMs in West Africa can and should be further improved. An interesting option to adjust RCMs to the specific characteristics of west African climate is to improve model parameterisations by using the extensive observations from the AMMA special observing period. On the other hand, an ensemble approach is needed to characterise uncertainties in projections of west Africa precipitation changes. In this regard, the inception of the new international project Coordinated Regional Climate Downscaling Experiment (CORDEX, Giorgi *et al*., 2009), which will have Africa as its first priority focus region, will provide a common framework for inter-comparing and evaluating RCM simulations and producing a new generation of climate change projections over regions worldwide.

One key issue is the evaluation of model physics with respect to the specific conditions of West Africa. The added value of RCMs compared to GCMs has to be quantified and the relative importance of GCM and RCM sources of uncertainty must be assessed systematically. An interesting alternative option would be to realise a multi-GCM downscaling approach with one single RCM with relatively good performance in the twentieth century. With this, it could be evaluated to what extent the spread of the GCMs can be reduced in the higher resolution runs when land–surface interactions and meso-scale atmospheric processes are better accounted for. For impact studies, RCM experiments can be combined with statistical post-processing methods such as model output statistics and weather generators to provide reliable climatic drivers with sufficient detail (Messager *et al*., 2006; Paeth, 2010; Paeth and Diederich, 2010).

Another challenge for understanding climate change over West Africa is the role of human-made land-cover changes, interactions with land-surface processes and atmospheric aerosols (Abiodun *et al*., 2008; Paeth *et al*., 2009). The preliminary experiments presented here indeed suggest that changing land-cover can strongly affect the west Africa precipitation change signal. Finally, observational networks in West Africa need to be extended and maintained in order to validate high-resolution RCMs and to feed downscaling methods. A valuable perspective will be the integration of the AMMA data-base and the ENSEMBLES downscaling experience to support impact studies conducted by African partners.

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