Assessing the robustness of projected precipitation changes over central Africa on the basis of a multitude of global and regional climate projections

Andreas Haensler · Fahad Saeed · Daniela Jacob

Abstract It is well accepted within the scientific community that a large ensemble of different projections is required to achieve robust climate change information for a specific region. For this purpose we have compiled a state-of-the-art multi-model multi-scenario ensemble of global and regional precipitation projections. This ensemble combines several global projections from the CMIP3 and CMIP5 databases, along with some recently downscaled regional CORDEX-Africa projections. Altogether daily precipitation data from 77 different climate change projections is analysed; separated into 31 projections for a *high* and 46 for a *low* emission scenario. We find a robust indication that, independent of the underlying emission scenario, annual total precipitation amounts over the central African region are not likely to change severely in the future. However some robust changes in precipitation characteristics, like the intensification of heavy rainfall events as well as an increase in the number of dry spells during the rainy season are projected for the future. Further analysis shows that over some regions the results of the climate change assessment clearly depend on the size of the analyzed ensemble. This indicates the need of a "large-enough" ensemble of independent climate projections to allow for a reliable climate change assessment.

1 Introduction

The central African region is a region with a high vulnerability to potential future climate change. Available studies highlight the fact that a large portion of the regions population bases their livelihood on agriculture and the goods and services from the Congo basin forests (Sonwa et al. 2012; Bele et al. 2013). Therefore changes in the climate and especially in rainfall characteristics are expected to have a strong impact on the living conditions of the population

A. Haensler (✉) · F. Saeed · D. Jacob
Climate Service Center (CSC), Helmholtz-Zentrum Geesthacht, Fischertwiete 1, Hamburg, Germany
e-mail: andreas.haensler@hzg.de

D. Jacob
Max Planck Institute for Meteorology, Bundesstraße 53, Hamburg, Germany

in the Congo basin. Decreasing rainfall amounts or increasing dry spells would negatively affect crop yields in the region as well as hydropower capacities. Increasing rain amounts, especially during the dry season, however, would have a positive effect as the cultivation period of staple crops could be extended. In order to estimate potential impacts of climate change and to identify and finance suitable adaptation options, information on the magnitude of projected climate change signals and on the robustness of these projections is required.

In general the information obtained from a climate model about future climate change is presented as projection, without any information about the likelihood that the projected changes will occur in the future (e.g. Cubasch et al. 2001). This means that any projected climate change signal per se is subject to a large uncertainty. This uncertainty might not have to be quantified in process studies dealing with potential climate change impacts on the functioning of the dynamic climate system itself. However when it comes to the definition of adaptation strategies in order to cope with potential consequences of climate change not only the magnitude but also the uncertainty or positively speaking the robustness of the projected changes has to be included in to the analysis. Especially while defining adaptation strategies a clear robustness of the underlying climate change information might serves as an important decision criterion and can fasten the process of defining adaptation strategies (e.g. Dessai and Hulme 2007; Hallegatte 2009).

The overall uncertainty associated to model projections of future climate change can generally be assigned to the uncertainty contribution from three different sources: i) from uncertainty in future emissions of greenhouse gases (GHGs) and other anthropogenic and natural factors that can affect climate, ii) from uncertainty arising from the natural internal climate variability and iii) from uncertainty inherent in the modeling systems in order to estimate the response of the climate system to a particular GHG forcing. The contribution of these three different sources to the overall uncertainty of the projected climate change signal changes with the time horizon (lead time) of the projections (Hawkins and Sutton 2011). Whereas the internal climate variability is the major source of uncertainty in projections with a focus on a future time horizon of less than 10 years the underlying emission scenario and the applied modeling systems are the major source of uncertainty in the long-term climate change projections. As this study deals with the long-term projected changes in the climate system, uncertainty from internal climate variability can be considered to be less important.

In order to cope with the uncertainties from the GHG emissions and the model system, the approach which is normally adopted is to use a sufficiently large and independent multi-model ensemble for different scenarios in order to provide ranges of potential future climate change that are supposed to have a certain probability of occurrence. This approach was introduced to a larger public in the 4th Assessment report of the IPCC (AR4, Solomon et al. 2007) and assumes that projected changes are more likely to occur if a large number of models agree on a given magnitude of change. This approach of course implies that the result of such a study is directly dependant on the size and nature of the analysed ensemble. Furthermore the independence of the single models forming the ensemble has to be given (Masson and Knutti 2011). The approach of defining future climate change signal on the basis of a multi-model ensemble of course always implies that not only one single value of future change can be provided but always a bandwidth of possible futures has to be considered (e.g. Meehl et al. 2007a).

To establish an as large as possible dataset we compiled a state of the art multi-model multi-scenario ensemble on the basis of already existing and published projections of global models in combination with bias-corrected projections as well as some recently conducted dynamically downscaled projections over the CORDEX Africa domain. By combining different approaches (e.g. general circulation models–GCMs vs. regional climate models–RCMs) and also different

model generations (e.g. GCM with static vegetation, with GCM with dynamic vegetation) we assume that we reach a higher degree of model independence within the ensemble, than just focusing on any sub-ensemble consisting of only the same kind of models.

The central African region was indicated in AR4 to be a region where so far available GCM projections show a substantial spread – especially with respect to projected changes in precipitation. Although the median projection of change was for a slight increase of 5 to 10 %, almost half of the models projected a decrease in precipitation amounts (Christensen et al. 2007). Therefore, the information available so far has to be considered to be less robust. A reason for the substantial spread of the model results over the region (also with respect to current climate – see section 3 and Haensler et al. 2013) might be the complex non-linear interplay between different processes controlling the formation of precipitation in the region. A large portion of precipitation is generated from mesoscale systems which are strongly influenced by the location and intensity of tropospheric jets (Farnsworth et al. 2011). Several studies (e.g. Jenkins et al. 2002) suggested that the coarse resolution GCMs struggle to resolve the important features in the region. Improved representation of these features might be achieved with regional climate models. However, when it comes to downscaling of global climate projections quite a few studies are available for the western and southern parts of Africa compared to the central African region.

We therefore seek with this study to fill in the existing gap by providing reliable and robust climate change information (based on GCM and downscaled climate change projections) on which further studies dealing with potential impacts of climate change as well as studies focusing on adaptation needs in the region can be built on in the future. As an analysis of potential climate changes on the basis of such a wealth of different climate projections has never been conducted before over the central African region, this study definitely can enhance the knowledge about the magnitude of future climate and the associated robustness.

The focus of this paper is given to the task to define robust ranges of projected changes in total rainfall amounts and related precipitation indices (see Table S2). In addition to this study an analysis of potential future changes in temperature related parameters has been conducted (see Haensler et al. 2013).

The above mentioned limited number of studies available for the central part of Africa might partly also be related to the scarcity of observations available in the region (see also Fig. 1a) which also has implications on the verification of the results of modeling studies. This of course also impacts the findings of our study, even though we tried to incorporate some station data into our analysis.

2 Data and method

We use daily precipitation output of a large set of global and downscaled climate change projections available for a historical period and two future periods for several emission scenarios. Global precipitation projections have been extracted form the CMIP3 (Meehl et al. 2007b) and CMIP5 (Taylor et al. 2011) data portals, respectively. Downscaled data consist of bias corrected and thereby statistical downscaled precipitation projections compiled within the EU-WATCH project (www.eu-watch.org; Hagemann et al. 2011; Piani et al. 2010) and dynamical downscaled regional climate projections for the CORDEX Africa domain (see Giorgi et al. 2009 for domain specifications). A summary of the analysed datasets, scenarios and the spatial and temporal coverage of the precipitation projections is given in Table S1. Altogether 77 different precipitation projections have been analysed,
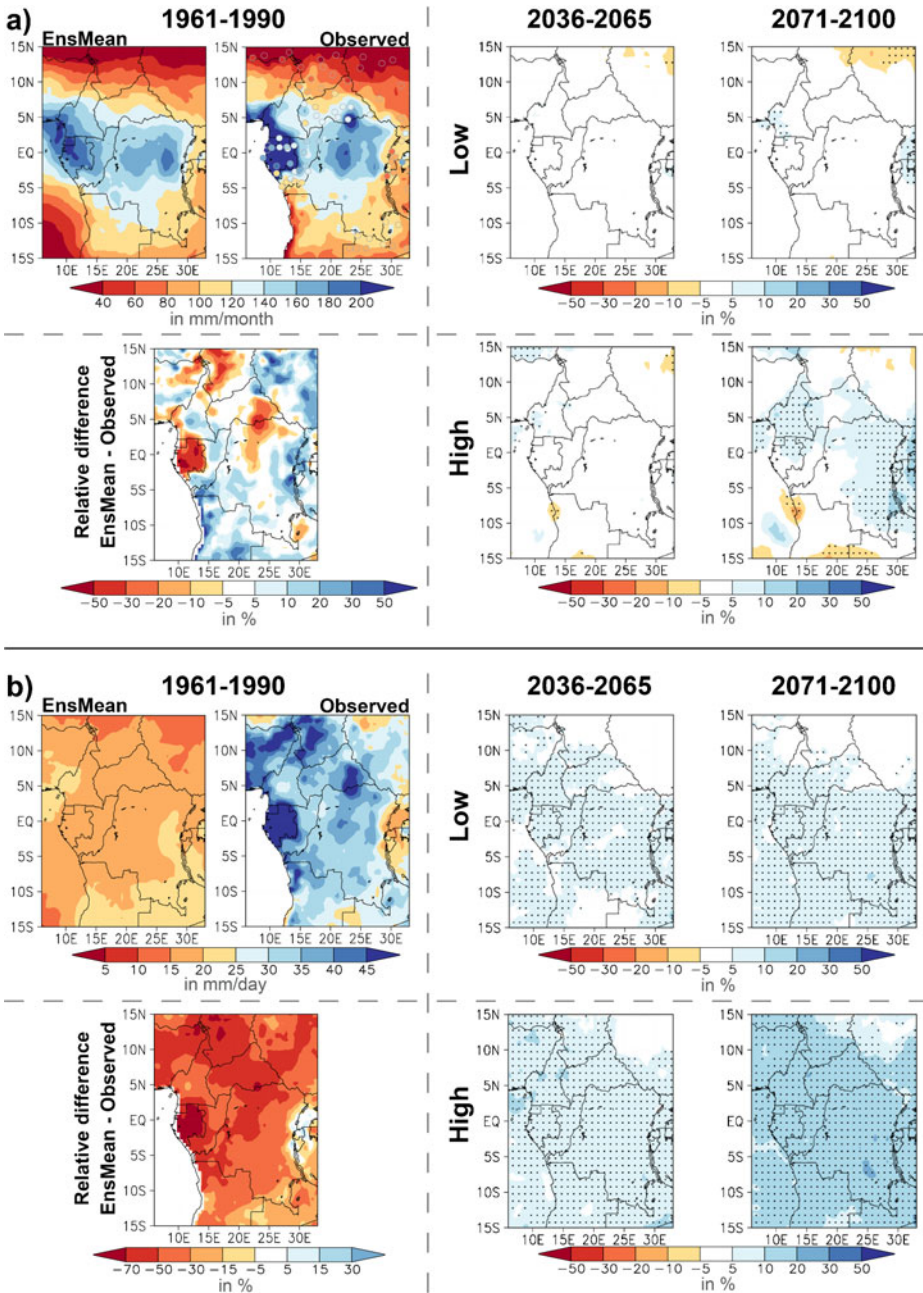
Fig. 1 Annual total precipitation (**a**) and intensity of heavy rainfall events (**b**) Left panels: Ensemble-Median simulated annual total rainfall averaged over the historical period 1961–1990 (top left) and observed annual total rainfall (*top right*) over the 1961–1990 period as provided from WFD and NCDC of NOAA. The bottom panel depicts differences between the simulations and the observations. Right panels: Ensemble-Median projected relative changes in annual total precipitation following the *low* (top row) and *high* (bottom row) emission scenario for the mid-21st (2036–2065; left column) and the end of 21st century (2071–2100; right column) with respect to the control period. The *black stipples* indicate regions in which at least 66 % of all projected changes agree in the sign of change

grouped into 31 simulations for a *high* and 46 projections for a *low* emission scenario. The grouping of the scenarios was motivated based on the projected GHG emission pathways towards the end of the 21st century (see Nakićenović and Swart 2000; van Vuuren et al. 2011). Following this the group of projections collated under the *high* emission scenario combines precipitation projections of the CMIP3 and WATCH project following the SRES A2 scenario with projections of the CMIP5 and RCM projections following the RCP8.5 emission pathway. Likewise the *low* emission scenario combines SRES B1 projections (CMIP3 and WATCH) with RCP2.6 and RCP4.5 projections (CMIP5 and RCMs).

We analyze projected changes in precipitation totals but also for precipitation extremes and several precipitation indices (see Table S2 for details). For each of the analysed parameter the projected changes have been estimated on the individual model grids However to allow ensemble statistics the estimated climate change signals of all datasets have then been conservatively remapped (no interpolation of the signals) to a common regular latitude-longitude 0.5° global grid.

The analysis is conducted over the central African area spanning from 15°N to 15°S and from 7°E to 33°E (see Figure S1). However the precipitation characteristics of the study area show a lot of spatial variation. To take into account this spatial variability we defined five subzones on which most of the subsequent analysis presented in this study was conducted. The spatial extent of these subzones (including the spatial coordinates) is depicted in Figure S1. The zones represent some simplified climate zones, based on the Koeppen Geiger climate classification (e.g. Kottek et al. 2006 - also included in Figure S1) but also consider the north–south movement of the main rainy season.

To assess the robustness of the projected changes we use two measures, both well known in the scientific community as they both either have been applied or at least described in AR4. The first measure is the agreement of the different model projections in the direction of change as shown in the AR4 Summary for Policymakers (Solomon et al. 2007). We quantify an increase/decrease in the projected signal to be robust if at least 66 % of the models agree in the direction of change. However several studies highlight that it is not sufficient to consider the agreement on the direction of change, but also the magnitude of the projected change signals and their variability should be included (Knutti and Sedláček 2012; Tebaldi et al. 2011). Therefore we introduced a second measure, which considers the range of potential future changes derived from the different model projections into the analysis. This is motivated by the fact that a climate change signal can be considered to be robust even though less than 66 % of the model projections agree in the direction of change, but all models agree on a small change only (Power et al. 2012). An example for this is the theoretical case that 50 % of the models project an increase in a given climate parameter by less than 5 % and the second 50 % of the models project a decrease by less than 5 % in the same parameter. If just the direction of change is considered, the projected climate change signal of the ensemble is not quantified to be robust, even though all models agree on the magnitude of projected change with an ensemble bandwidth of 10 % (which is for many parameters well within the uncertainty range, when compared with observations). In general it is assumed that the smaller the overall range of projected future changes the more robust is the information about the future climate change. Nevertheless we do not include a fixed threshold for the range to be defined robust but interpret the projected ranges and associated robustness with respect to the absolute values of the respective parameter.

The second assumption of robustness becomes mostly important in regions where climate change projections of the assessed parameters are supposed to have only a small magnitude. Based on our current knowledge, this applies to projected changes in precipitation over the central African region.

Considering the full range of the projected changes of the analysed model ensemble would of course allow some few outlier models to substantially impact on the robustness assessment. Therefore we introduced a sub-range into the analysis which spans around the central 66 % of the projected changes of the models. According to the IPCC (Mastrandrea et al. 2010) climate change within this range of projected changes is like to occur in the future - we therefore name it the *likely* range. As it is defined centred around the median (from 17th to the 83rd percentile) it does exclude potential outliers. Of course the definition of such a subset is only valid if the analysed ensemble consists of a sufficient number of independent model projections. As we use these large ensembles for both of the scenario groups and also combine global and downscaled projections, we assume that this constraint is given, even though previous studies (e.g. Masson and Knutti 2011) indicated that many of the models used in CMIP3 (and therefore probably also in its successor CMIP5) use rather identical model components. So far however, a perfect model ensemble with a large set of completely independent climate change projections simply does not exist.

3 Results

We focus in this paper on the projected future changes in total precipitation amounts and related indices. Nevertheless it is of utmost importance to also assess the ability of the different models to simulate the observed precipitation characteristics in the region. In general we find that the observed precipitation characteristics (taken from the daily precipitation estimates of the so called WATCH forcing dataset; WFD; Weedon et al. 2011), in both, the mean state as well as in the extremes and indices are represented by the analysed ensemble. However substantial differences in the ranges of the individual models can be seen in the different datasets. The performance of the ensemble also differs in the individual zones. The best performance of the model ensemble is reached for total precipitation amounts, while especially for the intensity of heavy rainfall events a substantial underestimation (up to 70 % along the coast) is present in the median of the model projections (see also Fig. 1), independent of the analysed data set. But in each of the analysed sub-ensembles also some models are well able to reproduce the observed heavy rainfall intensities. Even some inabilities in describing the current precipitation characteristics are present in the ensemble; the overall performance of the models especially with respect to the simulation of the temporal patterns of the rainfall dynamics in the region did not make it necessary to exclude a model projection from the further analysis. A detailed analysis of the performance of the model simulations with respect to observations is described in Haensler et al. (2013).

3.1 Projected changes in total precipitation

In the maps depicted in Fig. 1a the ensemble median of the simulated annual total precipitation over the historical period (1961–1990; upper left panel) and the ensemble median of the projected changes in annual total precipitation for the two scenario periods (2036–2065 and 2071–2100; right panels) is given for the *low* emission scenario (upper row) and the *high* emission scenario (lower row). Also the annual mean precipitation amount of the observation dataset (WFD and station data) is included in the figure (bottom left). In general, the median of all model simulations over the control period represents the observed rainfall patterns very well. Only in the coastal zones along the equator, a substantial dry bias is visible in the model estimate. However in this region, the available station data (available on

a monthly time scale; taken from the National Climatic Data Center (NCDC) from NOAA; http://www.ncdc.noaa.gov/land-based-station-data) included as the circles in the figure suggest that the gridded observation dataset overestimates precipitation amounts strongly. But also the station observations are subject to high uncertainty, as some of the stations do not cover the complete 1961 to 1990 time period (all stations available for at least 15 years within the 1961 to 1990 period have been included into the analysis).

Projected relative changes are depicted in the right part of the figure. For the mid-of century period (2036–2065) the median projection of change in annual total rainfall is for almost no change over the whole study area (median of projected signals below ±5 %), independent of the underlying emission scenario. Towards the end of the century a tendency for a slight increase in annual total precipitation can be seen under the *high* emission scenario. Here, over some regions in the eastern part of the study area (eastern parts of Democratic Republic of the Congo; Burundi; Rwanda) and over Cameroon in the western parts of the study area, the median projection of change in annual total precipitation is for a slight (below +10 %) but robust (black stipples; at least 66 % of the analysed projections agree in the sign of change) increase. However for the major part of the study area no agreement of the majority of the model projections in the direction of change is given and therefore no robust information can be derived.

In the maps only the median projection of change has been displayed. If such a multitude of different model projections is analyzed, however it is not enough to simply focus on the median projection of change but also the range of projected changes from the different models has to be taken into account. For this purpose the projected changes of each model are spatially averaged over the five zones introduced in Figure S1. For each of the zones the full range of projected changes is assessed for both scenarios and the two time periods in the middle and the end of the 21st century (see Fig. 2 – *low* scenario – blue colored bars; *high* scenario – orange and dark-red colored bars). Nevertheless one has to keep in mind that the full range of the projected changed might be influenced by the extreme changes of a few models which might be considered as outliers. In order to avoid this also the median of the projected changes (indicated by the black line) and the *likely* range (darker colored sub-area centered on the median) of the projected changes was included in the figures.

The results of the analysis of the ensemble ranges are depicted in Fig. 2 for projected changes in annual and seasonal total rainfall amounts. In general, the bandwidth of projected changes is largest in the dryer areas (e.g. zone 1) and during the respective dry season (DJF in zone 1 and 2, JJA in zone 5). The range of projected changes is however substantially reduced, if only the central 66 % (*likely* range) is considered. Although, even under the *likely* range, some of the projections show an increase and others a decrease in annual total precipitation amounts, the rather small ranges especially in the more humid zones 2 to 5 (*likely* range of change is largest in zone 2 for the high emission scenario from −8 to +12 %) indicate that robust precipitation changes are projected over much larger areas as indicated by the stippled areas in Fig. 1a. On the basis of the analysis of the bandwidth of the projections it becomes clearer (and more robust) that total precipitation amounts over the study area are likely to not change drastically in the future. This conclusion holds true for both the *low* and the *high* emission scenarios, but the model spread is slightly larger under the *high* emission scenario.

As for all of the zones the median projection for annual total precipitation amounts is slightly positive (also for both of the scenarios) a higher probability for a slight increase in future annual total precipitation amounts can be estimated on the basis of the analyzed multi-model multi-scenario data set.
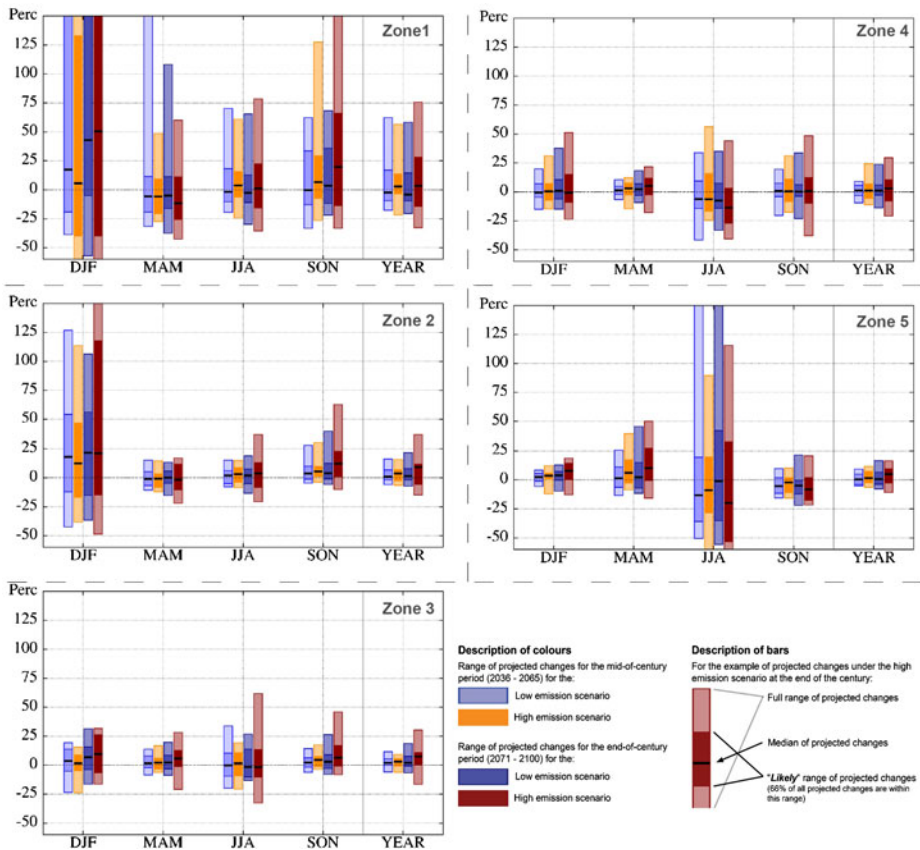
Fig. 2 Total precipitation: Full and *likely* ranges of projected changes in total rainfall amount for the different seasons (*left part of panels*) and averaged for the whole year (*right part of panels*) spatially averaged over the 5 zones indicated in figure S1. The bars with *bluish colors* represent the projected ranges under the *low* emission scenario (*light-blue* –mid-21st century; *darker blue* –end of 21st century); the bars with *orange* and *red colors* represent the projected ranges under the *high* emission scenario (*orange*– mid-21st century; *red* – end of 21st century). The less-transparent sub-range in each bar indicates the *likely* range of change (defined by the range that includes 66 % of all projected changes) and is centered on the respective median, indicated by the *black line*

3.2 Projected changes in precipitation extremes and indices

The spatial patterns of the median projection of change for the intensity of heavy rainfall events on an annual basis are depicted in Fig. 1b. For both analyzed future time periods and emission scenarios, the median projection of change for the intensity of heavy rainfall events is for a robust increase, strongest towards the end of the century and under the *high* emission scenario. Only in some northern and northeastern areas, no clear signal of change is projected by the model ensemble.

The full and *likely* ranges of projected changes for the intensity of heavy rainfall events (on an annual and seasonal basis) are depicted in Figure S2. As previously highlighted for projected changes in annual total rainfall amounts also the full and *likely* ranges of projected changes in the intensity of heavy rainfall events are especially enlarged in the drier northern zones and also during the respective dry seasons. If just the *likely* range is considered, a clear

(and due to the smaller bandwidth also robust) signal - especially in the moisture parts of the study domain - for an increase in the intensity of heavy rain events is projected towards the end of the century (by up to ~14 % for the *low* and up to about 27 % for the *high* scenario in zone 2). This holds true for both scenarios, even though the *likely* range is slightly shifted (by ~5 to 10 %) towards higher rainfall intensities under the *high* emission scenario. Larger changes are only projected to occur during the respective dry seasons and should not be overestimated due to the minimum intensities observed during this time of the year.

The range of projected changes of the four additionally analyzed precipitation indices is given in Figure S3. For the total rainfall sum during the respective rainy season (left panels in Figure S3), the *likely* range of projected changes is for all zones mainly positive for both scenarios and both future time periods, but also some possibility for a slight decrease is given. But as in the case of annual total precipitation, the *likely* ranges are relatively small (maximum range ~20 to 25 % - especially in the humid zones 2–5), indicating a large agreement of the models on no substantial change for the future. For the high emission scenario the *likely* range is slightly larger. Whereas for the duration of the rainy season (second panels from right in Figure S3) the models agree on a small change (*likely* range always between ±5 %) and the projections therefore can bee classified to be robust, a very large uncertainty is assigned to projected relative changes in number of dry spells (second panels from left in Figure S3). This is however partly related to the fact that during the control period only very few dry spells per rainy (usually less then 3 dry spells) season have been simulated and observed. Nevertheless, even though a large uncertainty also remains in the case of the *likely* changes, there seems to be a clear tendency in all zones and scenarios for a substantial increase in the number of dry spells during the rainy season. For the case of the maximum 10 day precipitation amounts (right panels in Figure S3) projected changes are – as expected – rather similar to the projected changes in the intensity of heavy rainfall events. For all zones and for both scenarios the projections of change indicate a robust increase in 10 day maximum rainfall amounts for the end of the 21st century up to about 20 % (30 %) in the humid zones under the *low* (*high*) emission scenarios, respectively. Also for this parameter, the *likely* range is restricted to a rather small band around the median, indicating a large model agreement, which is slightly higher in the case of the *low* emission scenario.

4 Discussion

So far the respective ensembles of precipitation projections following the *low* and *high* emission scenarios have been regarded as a homogeneous unit. While interpreting the findings it has to be considered that the results definitely are dominated by the GCM projections generated within the CMIP3 and CMIP5 projects, simply because of their large number. Percent wise GCM data accounts for 87 % (85 %) of the simulations in the case of the *high* (*low*) emission scenario ensemble.
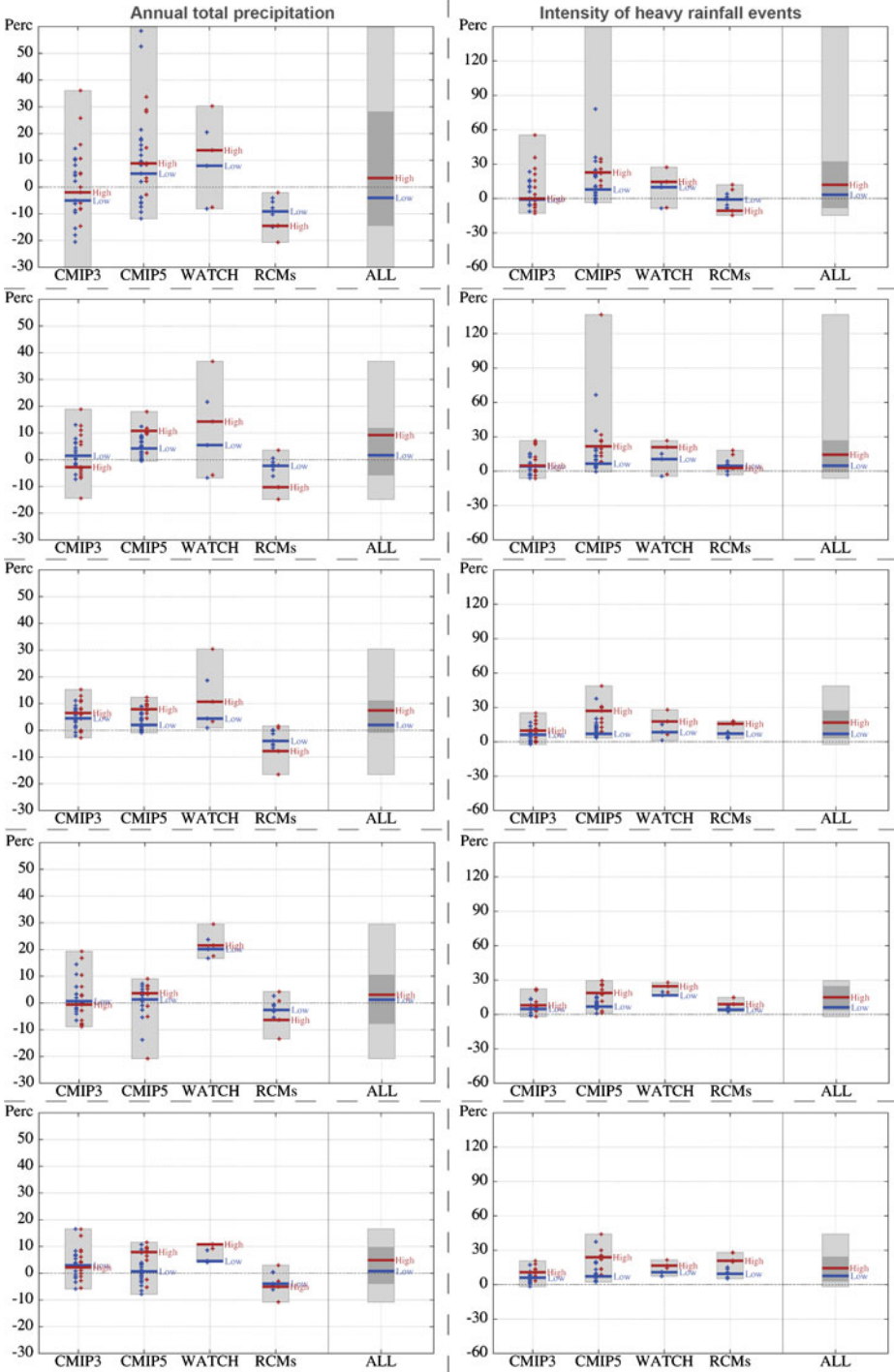
To estimate the contributions of the different sub-ensembles (GCMs vs. downscaled) we analysed projected changes of each dataset separately over the different zones. This analysis on the one hand will indicate if substantial changes occur between projections of GCMs and downscaled projections (e.g. RCMs). Even though we only included projections from two different RCMs the robustness of the projected change signals of course would be highest if both GCMs and RCMs projections are uniformly distributed within the full ensemble range and do not cluster at on end of the distribution. Another interesting aspect that can be tackled with this analysis is if the projections of the most recent CMIP5 ensemble agree with the projections from the already better known CMIP3 ensemble. In Fig. 3 we summarize the

Fig. 3 Full ranges of projected changes in annual total precipitation amounts (*left column*) and intensity of heavy rainfall events (*right column*) for the end of the century averaged over the 5 zones depicted in figure S1 as projected by the different sub-ensembles (*left panel*) and for all analysed projections together (*right panel*). Median of the projected changes for the two different scenarios (*low – blue lines*; *high – red lines*) is depicted, as well as the projected changes of each model simulation via the colored crosses (*low – blue crosses*; *high – red crosses*). The *likely* ranges for each scenario are included as dark-grey sub-range. However as they always overlap, they appear as single area only

findings of the sub-ensemble analysis for projected changes in annual total precipitation and in the intensity of heavy rainfall events for all of the 5 zones for the end of the century period. The light grey bars in the figure represent the full ranges, the median of the respective scenario is also depicted (*high –red line*; *low – blue line*). As the full range can substantially be influenced by a few outlier models, also the projected change of each single model is indicated for both scenarios (red and blue crosses) in the range of the sub-ensembles.

The agreement between the projected changes of the different sub-ensembles is substantially larger for the intensity of heavy rainfall events (Fig. 3, right column). A large overlap between the sub-ensembles is present for all zones. The very large range in the CMIP5 dataset present in zones 1 and 2 for both scenarios and zones is caused by the same single outlier model. In these zones the median projection of the *high* and *low* scenarios are similar for the CMIP3 ensemble and also in the sub-ensemble of the RCM simulations in zone 2. In zone 1, the RCMs median projection of change in the intensity of heavy rainfall events is for a slight decrease in the case of the *high* emission scenario and for no change under the *low* scenario. This is opposite to the behaviour of the other sub-ensembles, in which projected increase in heavy rainfall intensity is generally larger under the *high* emission scenario. However in the dry regions (zones 1 & partly 2) relative changes should not be overemphasised, whereas in the more humid zones 3–5 the projected relative changes are in the same range, independent of the analysed data set and also independent of the simulated heavy rainfall intensity during the control period which is generally slightly higher in the RCM simulations when compared to the forcing GCM simulations. This definitely enhances the robustness of the projected changes, especially if the few outliers are excluded from the analysis and only the *likely* ranges are considered. The large agreement between the sub-ensembles in the more humid regions – and therefore regions which are not moisture limited – is most likely related to the fact that heavy rainfall intensity is closely related to the water holding capacity in the atmosphere, which in turn is related to the atmospheric temperature, due to the law of Clausius Clapeyron (Trenberth et al. 2003). However if moisture availability is limited a temperature increase might leads to a decrease in heavy rain intensity (see zone 1). In such regions the soil formulation of the individual models becomes of higher importance and therefore the spread within and between the sub-ensembles is larger.

This argumentation can also be applied to the case of the projected changes in annual total precipitation, where the intra and inter sub-ensemble spread is again substantially larger in the dry areas (Fig. 3, left column). But also in the wettest part of central Africa (zone 3 and 4) substantial differences are visible between the different data sets. In the central tropics (zone 3) the majority of the GCMs agree on an increase in annual total precipitation, whereas the RCM sub-ensemble indicates a decrease (even though some of the forcing model projections show a substantial increase in total rainfall). In a recent study by Saeed et al. (2013) it is shown that the projected drying in the REMO RCM projections (which comprises the majority of the RCM sub-ensemble – see Table S1) is partly related to the depletion of soil moisture caused by high-intensity rainfall events, which leads on the long run to a less intense hydrological cycle over the region.

In the coastal zone 4 the bias-corrected projections of the WATCH sub-ensemble substantially deviate from the rest of the analysed projections. In this area, the bias correction substantially increases the projected change signal, as the CMIP3 ensemble also consists of the non-corrected version of the WATCH dataset. It is well known that statistical bias correction alters the projected climate change signals of the corrected GCMs (e.g. Hagemann et al. 2011) and we actually use this fact to justify that we include the WATCH projections as independent data set into the analysis. However over this region it has to be noted that the WFD dataset used to bias-correct the GCMs strongly overestimates annual mean rainfall amounts when compared to station observations (see Fig. 1). Therefore it might be possible that in this region the bias-correction enhances the projected precipitation signal too strongly.

However due to the relatively small size of the RCM and WATCH sub-ensemble, the *likely* ranges in both zones are not affected by the different behaviour of the two sub-ensembles. This might be a positive effect in the case of the probably to strong correction of the GCM rainfall projections in zone 4, however in the case of the RCM projections a larger number of projections from further GCM-RCM combination would be helpful, as the changes are supposed to be caused by differences in physical processes between forcing GCM and RCM. These processes have the strongest effect in regions over which the RCM has the largest degree of freedom, which definitely is true for the central tropics which on one hand are characterized by a strong local soil-atmosphere coupling (Koster et al. 2004) and are one the other hand located in the centre of the CORDEX Africa model domain used for the downscaling.

A further result of this separate assessment is that the projected changes over the central African region for the two parameters are rather similar in the CMIP3 and CMIP5 ensemble. This finding is surprising at the first glance as at least some of the CMIP5 simulations incorporate also dynamic vegetation and land use changes – both expected to have substantial impacts on the central African area (e.g. Nogherotto et al. 2013). However a detailed study on this topic is beyond the scope of this paper.

5 Summary and conclusion

Projected changes in future precipitation amounts and extremes have been analysed for the central African region on the basis of a multi-model multi-scenario ensemble of different GCM and downscaled climate change projections. Altogether 77 different projections have been included into the analysis. A comparable analysis on the basis of such a wealth of different climate change projections has never been done before for the central African region. The large size of the underlying data set allowed not only analysing the magnitude of projected changes but also investigating the robustness of these changes. This is especially of importance when it comes to the development of adaptation strategies, often connected with large investments (Hallegatte 2009).

As of today the major part of the region receives sufficient amount of annual total rainfall any future rainfall changes in the range of ±15 % can be considered to not have a substantial impact on the over all water availability in the region. Given the results described in the previous sections it can be concluded with a rather large degree of robustness that for the major part of the central African region climate change will not lead to accelerated water scarcity in the region. In fact the projections indicate a rather constant precipitation input over the 21st century with a tendency for a slight increase. This finding is independent of the underlying emission scenario and therefore even has to be considered to be even more

robust. In the course of the year the degree of robustness of the projections slightly changes with larger bandwidths (lower robustness) during the dry periods in the year (DJF in Zone1 and 2; JJA in Zone 5) and smaller bandwidths (higher robustness) in the wetter seasons.

Although the annual total precipitation amounts might not change dramatically rainfall characteristics are projected for a robust change. An example for this is that the intensity of heavy rainfall events is likely to increase in the future (*likely* range for most parts of the study region positive, up to 25 %). Also the frequency of dry spells during the rainy season is for most parts of the domain projected to substantially increase in the future. Both results indicate that the temporal distribution of precipitation will be less homogenous in the future.

As highlighted in the introduction, the livelihood of the population in the Congo basin is very sensitive to potential changes in future water availability. Therefore the robust increase in annual total increase as identified in this study definitely can be seen as good news for the region. However, the analysed climate models also suggest a tendency for more intense heavy rainfall events as well as an increased frequency of dry spells during the rain season. Both features will have a direct impact on the water availability in the region and require adaptation of the established socio-economic systems in the region to ensure their functioning in the future.

Finally, it is worth stating that the conclusions drawn from this research would have been different if only one of the ensemble subsets had been analysed, for example the RCM data, which shows a decrease in annual total precipitation over large parts of the region, whereas the majority of the GCMs project an increase. This underscores on the one hand the importance of the analysis of a large multi-model multi-scenario dataset when it comes to the assessment of possible future changes and also to reduce or to highlight the related uncertainties. On the other hand, this finding also indicates the need for new approaches to transfer the bandwidth resulting from the diverse climate change projections into the chain of climate impact assessment and the potential development of mitigation and adaptation strategies. Up to date impact models are often forced with only a subset of available climate change information which potentially could also represent a set of outliers. A first step to incorporate the full information of available climate projections is to classify the forcing projections within the full ensemble of projected changes (e.g. Haensler et al. 2013). However as the impacts of future climate change is in most cases not linearly connected to the forcing signal (e.g. Arnell 1999) a more sophistic approach has to be developed.

References

Arnell NW (1999) The effect of climate change on hydrological regimes in Europe: a continental perspective. Glob Environ Chang 9(1):5–23

Bele MY, Tiani AM, Somorin OA, Sonwa DJ (2013) Exploring vulnerability and adaptation to climate change of communities in the forest zone of Cameroon. Clim Change. doi:10.1007/s10584-013-0738-z

Christensen J, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli R, Kwon W, Laprise R, Magaña Rueda V, Mearns L, Menéndez C, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Cubasch U, Meehl GA, Boer GJ, Stouffer RJ, Dix M, Noda A, Senior CA, Raper S, Yap KS (2001) Projections of future climate change. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden P, Dai X, Maskell K, Johnson CI (eds) Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 881

Dessai S, Hulme M (2007) Assessing the robustness of adaptation decisions to climate change uncertainties: a case study on water resources management in the east of England. Glob Environ Chang 17(1):59–72

Farnsworth A, White E, Williams CJR, Black E, Kniveton DR (2011) Understanding the large scale driving mechanisms of rainfall variability over central Africa. In: Williams CJR, Kniveton DR (eds) African climate and climate change. Advances in Global Change Research 43, doi:10.1007/978-90-481-3842-5_5

Giorgi F, Jones C, Asrar GR (2009) Addressing climate information needs at the regional level: the CORDEX framework. Bull World Meteorol Organ 58(3):175–183

Haensler A, Saeed F, Jacob D (2013) Assessment of projected climate change signals over central Africa based on a multitude of global and regional climate projections. In: Haensler A, Jacob D, Kabat P, Ludwig F (eds) Climate change scenarios for the Congo basin, climate service center report no. 11, Hamburg, Germany, ISSN: 2192–4058. Available online at www.climate-service-center.de/imperia/md/content/csc/csc-report11_optimized.pdf

Hagemann S, Chen C, Haerter JO, Heinke J, Gerten D, Piani C (2011) Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models. J Hydrometeorol 12(4):556–578

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. Glob Environ Chang 19(2):240–247

Hawkins E, Sutton R (2011) The potential to narrow uncertainty in projections of regional precipitation change. Climate Dynam 37:407–418

Jenkins GS, Adamou G, Fongang S (2002) The challenges of modeling climate variability and change in West Africa. Clim Change 52(3):263–286

Knutti R, Sedláček J (2012) Robustness and uncertainties in the new CMIP5 climate model projections. Nat Clim Chang 3:369–373. doi:10.1038/nclimate1716

Koster RD, Dirmeyer PA, Guo Z, Bonan G, Chan E, Cox P, Gordon CT, Kanae S, Kowalczyk E, Lawrence D, Liu P, Lu C-H, Malyshev S, McAvaney B, Mitchell K, Mocko D, Oki T, Oleson K, Pitman A, Sud YC, Taylor CM, Verseghy D, Vasic R, Xue Y, Yamada T (2004) Regions of strong coupling between soil moisture and precipitation. Science 305(5687):1138–1140

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Koppen-Geiger climate classification updated. Meteorol Z 15(3):259–263

Liebmann B, Blade I, Kiladis G, Carvalho L, Senay G, Allured D, Leroux S, Funk C (2012) Seasonality of African precipitation from 1996 to 2009. J Clim 25:4304–4322

Masson D, Knutti R (2011) Climate model genealogy. Geophys Res Lett 38(8)

Mastrandrea M et al. (2010) Guidance note for lead authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties, IPCC. Available online at www.ipcc-wg2.gov/meetings/CGCs/index.html

Meehl GA, Covey C, Taylor KE, Delworth T, Stouffer RJ, Latif M, McAvaney B, Mitchell JFB (2007a) The WCRP CMIP3 multimodel dataset: a new era in climate change research. Bull Am Meteorol Soc 88(9):1383–1394

Meehl G, Stocker T, Collins W, Friedlingstein P, Gaye A, Gregory J, Kitoh A, Knutti R, Murphy J, Noda A, Raper S, Watterson I, Weaver A, Zhao Z-C (2007b) Global climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Nakićenović N, Swart R (eds) (2000) IPCC special report on emissions scenarios. Cambridge Univ. Press, New York

Nogherotto R, Coppola E, Giorgi F, Mariotti L (2013) Impact of Congo basin deforestation on the African monsoon. Atmos Sci Lett 14:45–51

Piani C, Weedon G, Best M, Gomes S, Viterbo P, Hagemann S, Haerter J (2010) Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models. J Hydrol 395(34):199–215

Power S, Delage F, Colman R, Moise A (2012) Consensus on twenty-first-century rainfall projections in climate models more widespread than previously thought. J Clim 25:3792–3809

Saeed F, Haensler A, Hagemann S, Jacob D (2013) Representation of extreme precipitation events leads to opposite climate change signals over the Congo basin. Atmosphere. doi:10.3390/atmos4030254

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K, Tignor M, Miller H (eds) (2007) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Sonwa DJ, Somorin OA, Jum C, Bele MY, Nkem JN (2012) Vulnerability, forest-related sectors and climate change adaptation: the case of Cameroon. For Policy Econ 23:1–9

Taylor KE, Stouffer RJ, Meehl GA (2011) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93(4):485–498

Tebaldi C, Arblaster JM, Knutti R (2011) Mapping model agreement on future climate projections. Geophys Res Lett 38, L23701. doi:10.1029/2011GL049863

Trenberth KE, Dai A, Rasmussen RM, Parsons DB (2003) The changing character of precipitation. Bull Am Meteorol Soc 84(9):1205–1217

van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt G, Kram T, Krey V, Lamarque J-F, Masui T, Meinshausen M, Nakicenovic N, Smith S, Rose S (2011) The representative concentration pathways: an overview. Clim Change 109:5–31

Weedon GP, Gomes S, Viterbo P, Shuttleworth WJ, Blyth E, Österle H, Adam JC, Bellouin N, Boucher O, Best M (2011) Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century. J Hydrometeorol 12(5):823–848