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LETTER

A tale of two futures: contrasting scenarios of future precipitation for West Africa from an ensemble of regional climate models

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Abstract
The results of a large ensemble of regional climate models lead to two contrasting but plausible scenarios for the precipitation change over West Africa, one where mean precipitation is projected to decrease significantly over the Gulf of Guinea in spring and the Sahel in summer, and the other where summer precipitation over both regions is projected to increase.

Dry and wet models show similar patterns of the dynamic and thermodynamic terms of the moisture budget, although their magnitudes are larger in the dry models. The largest discrepancies are found in the strength of the land-atmosphere coupling, with dry models showing a marked decrease in soil moisture and evapotranspiration.

Some changes in precipitation characteristics are consistent for both sets of models. In particular, precipitation frequency is projected to decrease in spring over the Gulf of Guinea and in summer over the Sahel, but precipitation is projected to become more intense.

1. Introduction

West Africa, with a fast population growth and an economy reliant on rain-fed agriculture, is one of the regions most affected by climate variability (Sultan and Gaetani 2016, Sylla et al 2018). The annual cycle of precipitation over the region is linked to the passage of the West African Monsoon (WAM), which produces annual rainfall up to around 2500 mm (Raj et al 2019). In the Sahel, in particular, the WAM accounts for about 80% of annual precipitation (Steinig et al 2018). As a consequence, West Africa is particularly vulnerable to the impact of future climate change (Niang et al 2014).

A comprehensive effort has therefore been undertaken by the scientific community to portray future precipitation behaviour over West Africa. Both General Circulation Models (GCMs) participating in the Coupled Model Intercomparison Project (e.g. CMIP5, Taylor et al 2012) and Regional Climate Models (RCMs) within the framework of the World Climate Research Programme CORDEX (COordinated Regional-climate Downscaling EXperiment, Giorgi and Gutowski 2015) have been shown to be able to reproduce the general features of the African precipitation climatology (e.g. Nikulin et al 2012, Diaconescu et al 2015, Gbobaniyi et al 2014, Akinsanola et al 2018, Gibba et al 2018). However, these studies also demonstrated that climate models still show significant limitations in simulating complex systems like the WAM, which is driven by the interaction of atmosphere, ocean, and land-surface (e.g. Steiner et al 2009), and strongly related to mid-tropospheric circulation (Cook 1999).
In consequence, large uncertainties still remain over the projected precipitation change (Niang et al 2014, Monerie et al 2017, Dosio et al 2019). In particular, according to the methodology of Dosio et al (2019), West Africa is one of the regions where model projections are ‘uncertain’, i.e. the majority of models project a statistically significant change in mean precipitation, but they do not agree on its sign.

The mechanisms that control present and future rainfall variability have been investigated by many studies (e.g. Poan et al 2016, Akinsanola and Zhou 2019b, Raj et al 2019); in particular, the analysis of atmospheric moisture fluxes and, in particular, the thermodynamic and dynamic components of the moisture budget has proved particularly helpful in understanding future changes in precipitation at global and regional scale (e.g. Endo and Kitoh 2014, Pomposi et al 2015, Giannini et al 2018). Lee et al (2017) and Tamoffo et al (2019) used RCMs to investigate the relative contribution of dynamic and thermodynamic moisture budget components over East Asia and Central Africa, respectively; however, their studies were based on the results of either several RCMs downscaling a single GCM, or a single RCM forced by several GCMs.

Another mechanism controlling precipitation variability and change is the coupling between land and atmosphere, especially in transition zones between wet and dry climates where precipitation is closely dependent on soil moisture (Koster et al 2004, Taylor 2008, Seneviratne et al 2010, Berg et al 2017, Yang et al 2018).

In this study, we use the results of a large ensemble of GCM-driven RCMs to investigate the change in future precipitation characteristics (mean, frequency and intensity) over West Africa. We do not investigate the detailed physical mechanisms and the reasons behind differences in model results; other studies provide a comprehensive, process-based analysis (including the vertical structure of circulation features) of regional climate projections over Africa (e.g. James et al 2015). In this work, for the first time to our knowledge and contrary to many previous studies, we not only provide multi-model ensemble results but, analysing the different characteristics amongst RCM results of e.g. future land–sea warming, dynamic and thermodynamic components of the moisture budget, and land-atmosphere coupling, we identify two possible, contrasting but physically plausible future scenarios (or storylines) for precipitation over West Africa, one characterized by marked drying over the coast of the Gulf of Guinea and the Sahel, and the other by wetting.

2. Data and methods

2.1. Climate data

Daily precipitation data for the period 1981–2010 (defined as reference) and 2071–2100 (future scenario) were obtained from a large ensemble of models participating in the CORDEX-Africa initiative (supplementary information table S1). Four different RCMs were used to downscale the results of 6 CMIP5 GCMs for a total of 17 runs. In contrast to Dosio et al (2019), we used only RCMs that downscaled at least two GCMs and GCMs that have been downscaled by at least two RCMs, thus avoiding single GCM–RCM combinations.

All RCMs were integrated over the same numerical domain covering continental Africa at horizontal resolution of 0.44° following the CORDEX protocol http://www.corDEX.org/wp-content/uploads/2017/10/corDEX_general_instructions.pdf.

Historical runs, forced by observed changes in natural and anthropogenic atmospheric composition, cover the period until 2005. For the future climate, in order to maximize the projected climate change signal, only the projections forced by the Representative Concentration Pathways 8.5 (RCP8.5, van Vuuren et al 2011) are used. The precipitation time series over the reference period (1981–2010) is therefore constructed using the last 25 years of the historical runs (1981–2005) and the first five (2006–2010) of the scenario runs, as done for instance in other studies over Africa (e.g. Dosio et al 2019) and Europe (e.g. Dosio and Fischer 2018).

2.2. Observational data

A large ensemble of gridded observational datasets is used for model evaluation. Observations include reanalysis (20CR, ERAINT, NCEP-2, WATCH_WFDEI, JRA-55, CFSR, MERRA-2), satellite-based (TAMSAT, ARC2, CHIRPS, PERSIANN-CDR) and gauge-based (CPC, GPCC_FDD, REGEN_ALL) products that are available at daily mean output frequency over the period 1981–2010. Observations were bilinearly interpolated to the same 0.44° grid as the RCM ensemble. Details for each dataset are provided in table S2.

2.3. Moisture flux analysis

The change (Δ) in precipitation between present (1981–2010) and future (2071–2100) climate can be interpreted by means of a moisture budget analysis as follows (Seager et al 2010):

\[ \Delta PR = \Delta E + \Delta D + \Delta T + \Delta R \]

where \( \Delta P \) is evaporation, and the thermodynamic (\( \Delta T \)) and dynamic (\( \Delta D \)) components are defined according to:

\[ \Delta D = - \frac{1}{\rho g} \nabla \cdot \int_0^{P_T} \vec{q} \Delta p \mathrm{d}p \]  

\[ \Delta T = - \frac{1}{\rho g} \nabla \cdot \int_0^{P_T} \vec{u} \Delta q \mathrm{d}q, \]

with \( \rho \) being the air density, \( g \) the acceleration due to gravity, \( P_T \) the total pressure and \( q \) the specific humidity.
where \( q \) is the specific humidity, \( u \) the horizontal wind, \( p_t \) the surface pressure, \( \rho \) the density of water and \( g \) gravity. Overbars indicate the climatological mean of the daily values over the present climate (1981–2010), for the season of interest. By means of equation (1), change in projected precipitation can be related to the change in atmospheric moisture (thermodynamic term) and to that in atmospheric mean circulation (dynamic term). Based on GCM results, Endo and Kitoh (2014) showed that \( \Delta TH \) is positive over the world monsoon regions (and negative over the subtropics) and its spatial pattern is strongly correlated to that of present-day precipitation: in fact, as moisture is projected to increase in a warmer world (\( \Delta q > 0 \)) the sign of \( \Delta TH \) depends on the divergence of the wind field in the lower troposphere, where moisture is concentrated (‘wet-get-wetter’ mechanism). On the other hand, the dynamic term is related to circulation changes, and, over the tropics, largely balances the thermodynamic term.

The transient (\( \Delta TE \)) and residual (\( \Delta Res \)) terms in equation (1) are not considered here (similarly to e.g. Giannini et al (2018)) as their contribution is usually small over the tropics (see also Endo and Kitoh 2014, Lee et al 2017).

Unfortunately, CORDEX outputs have been stored at only very few vertical levels (\( q \) in particular is provided only at 850 hPa), thus preventing us from computing the vertical integrals in equations (2) and (3). Therefore, following Lee et al (2017) we restrict our analysis to the horizontal components of the moisture flux convergence (instead of the vertical integral), and we compute the dynamic and thermodynamic components at 850 hPa only. Consequently, equations (2) and (3) become:

\[
\Delta DY = -\nabla \cdot (\bar{q}\Delta u)_{850} \tag{4}
\]

\[
\Delta TH = -\nabla \cdot (\bar{u}\Delta q)_{850} \tag{5}
\]

Although this approach is clearly an approximation, results based on ERA-interim data show that the vertically integrated moisture flux convergence (i.e. the right-hand side of equation (1)) is positively correlated with the horizontal moisture flux convergence at 850 hPa over the Gulf of Guinea and the Sahel especially during the wet season (JJA and SON, figure S1), suggesting that our analysis can be useful to investigate precipitation change over the study area.

Note also that in our qualitative analysis of the moisture budget we relate the patterns of the thermodynamic and dynamic terms to those of the precipitation changes only (\( \Delta PR \)), instead of \( \Delta PR-\Delta E \). However, during the rainy season over the study area, the geographical distribution of \( \Delta PR-\Delta E \) is very similar, over land, to that of \( \Delta PR \) (figure S2).

3. Results

CORDEX-Africa RCMs have been extensively evaluated in the past not only for mean climatology, but also for extreme events, land-atmosphere coupling, circulation patterns, and the added value of downscaling. Several previous works investigated ERA-interim-driven runs over West Africa (e.g. Nikulin et al 2012, Gbobaniyi et al 2014, Panitz et al 2014, Akinsanola et al 2015, Sarr et al 2015, Klutse et al 2016, Careto et al 2018), as well as GCM-driven runs (e.g. Hernández-Díaz et al 2013, Teichmann et al 2013, Dosio et al 2015, Dosio 2017, Nikiema et al 2017, Akinsanola et al 2018, Akinsanola and Zhou 2019a, Gibba et al 2018, Kumi and Abiodun 2018, Quenum et al 2019). Here, therefore, we perform only a basic evaluation of the RCM performances in simulating present-day precipitation climatology. Results show (figure 1) that in the mean, RCMs are able to satisfactorily simulate the seasonal mean precipitation rate over both coasts of the Gulf of Guinea (defined here as the region between 10°W–10°E, 5°N–10°N) and the Sahel (10°W–10°E, 10°N–15°N). Large differences exist amongst RCMs in the simulated position, extension and intensity of the band of high rainfall (figure S4); however, when models are compared to a similarly large ensemble of observational datasets, the uncertainty in both ensembles (measured as the standard deviation across the time-averaged ensemble members) is remarkably similar, especially during the rainy season from May through October (see also e.g. Diaconescu et al 2015, Panitz et al 2014). In addition, Nikiema et al (2017) showed that CORDEX RCMs are usually able to add value to the performance of the driving GCM over West Africa, and that the CMIP5 and CORDEX multi-model ensembles have similar values of inter-model spread.

Relating future projections to the model skill at simulating present climate is not straightforward. In particular, Dosio et al (2019) showed that a wet (dry) bias in the present climate does not necessarily imply a tendency towards wetter (drier) future precipitation characteristics, making any attempt to select a ‘best-performing’ RCM, or even linking future projections to simulation skills over the present climate, very challenging. Also Monerie et al (2017) and Rowell et al (2016) claim that future precipitation changes over Africa (in the Sahel) are not related to model performance in the present. Our results confirm that although there are clear biases in both precipitation and temperature that are RCM dependent (e.g. all CCLM runs show a dry bias over the Gulf of Guinea in MAM, RACMO shows a general wet bias over the Sahel, and RCA a dry bias, see figure S4), there is not a simple way to weight the results or exclude simulations purely based on the present climate RCM performance (e.g. Weigel et al 2010). Finally, Dosio
Figure 1. Evaluation of CORDEX-Africa RCMs: Top row: annual cycle of daily precipitation (mm/day) as simulated by the GCM-driven RCMs over the period 1981–2010 over the Sahel and coasts of the gulf of Guinea, identified by the red dashed lines in the underlying maps. Different colors refer to the driving GCMs. The cyan shaded area represents the spread of a large ensemble of observational products, including reanalysis, satellite-and gauge-based products (table S2). Second and fourth rows show the mean of the observational products (left) and CORDEX RCMs (right), for May–July and August–October, respectively. Third and fifth rows show the inter-model (or inter-observational) standard deviation computed, at each grid point, after first computing the climatological (1981–2010) seasonal means (May–July and August–October). It reflects the spread amongst model results (observations) over the entire reference period during the peaks of the precipitation season.
et al (2019) showed that the results of the large CGM-RCM ensemble are robust and independent of the choice of GCM and/or RCM. In particular, where projections are uncertain (such as over West Africa), a simple sub-selection of model results based on either GCM or RCM averaging will not reduce the uncertainty significantly, nor change the overall message.

Figure 2 shows the projected change (2017–2100 vs. 1981–2010) in seasonal mean daily precipitation as modelled by the RCM ensemble. Focusing on West Africa (defined as the region 10°W–10°E, 0°N–25°N), we note a reduction in future precipitation during the first half of the year, followed by an increase from July to November (figure 2(m)). This is consistent with other RCM studies (Kumi and Abiodun 2018), which claim delayed onset and shorter rainy season over the western Sahel and the coast along the Gulf of Guinea, and CMIP5 results (Seth et al 2013, Monerie et al 2017), although some GCMs show precipitation increases also north of 10°N. The thermodynamic component of the moisture budget is mostly positive over the areas affected by the monsoon (see for instance West Africa in JJA or Central Africa in SON, figures 2(i) and (l), respectively); as mentioned, since specific humidity is projected to increase with warmer temperature, the sign of \( \Delta TH \) is mainly controlled by the divergence of the present-day wind (see equation (5) and Endo and Kitoh 2014). However, the ‘wet-get-wetter’ mechanism (e.g. Seager et al 2010) is counterbalanced by the dynamic component \( \Delta DY \), which shows strong negative values over the areas affected by the monsoon (figures 2(b), (e), (h) and (k)), consistent with weaker convergence (stronger horizontal divergence, see equation (4); Endo and Kitoh 2014, Giannini et al 2018).

These ensemble mean-based results, however, largely undermine the discrepancies between model results, in agreement with previous studies using both RCMs and GCMs (e.g. Monerie et al 2017, Dosio et al 2019), which show disagreement on the sign of precipitation change amongst models. When analysing individual model projections, differences are striking, with some simulations showing a marked drying over land throughout the year, others a general wetting, and some a bipolar pattern with drying in the first part of the year followed by wetting (figure S3). While large-scale circulation features and temperature projections are mainly influenced by the driving GCM (figure S3 and e.g. Dosio 2017), precipitation results are mostly dependent on the RCM, with e.g. both CCLM and REMO projecting a general drying, and RACMO and RCA wetting; however, in some cases, the influence of the driving GCM is also visible, with both CNRM-CM5 downscaled runs showing (mostly) wetting and both CM5A driven simulations showing drying over the Gulf of Guinea from April to July.

From figure S3(e) we note that model uncertainty in future precipitation projection (over land) is particularly large over the coasts of the Gulf of Guinea from April to July, with RCMs nearly equally split in projecting a ‘dry’ or ‘wet’ future (figure 3(i)). Interestingly, this precipitation change is related to the differential 850 hPa temperature warming between the ocean and the Sahara, for which the intermodal regression equals –0.47 (figure 3(ii)). In other words, those RCMs with the largest increase in lower-tropospheric temperature gradient between the Sahara and Gulf of Guinea at the beginning of the rainy season experience negative precipitation changes, and vice versa. Previous studies highlighted the importance of this differential warming and related circulation on the precipitation climatology in West Africa (e.g. James et al 2015, Pomposi et al 2015, Lavaysse et al 2016, Dixon et al 2017, Vizy and Cook 2017), especially in summer. In particular, CMIP5 results (Dunning et al 2018) linked the increasing strength of the Saharan Heat Low (SHL) to a northward shift of the tropical rain belt in August–December and later onset/cessation of the wet season. This dynamic mechanism is consistent with the results of the wet RCMs (figure 3(d)). On the contrary, the dry RCMs show marked drying and a contraction of the monsoon belt from March to October (figure 3(c)). The analysis of the moisture budget (figures 3(e) and (f)) shows negative values of \( \Delta DY \) from March to October over the Gulf of Guinea for both sets of simulations; however, dry RCMs project much lower values of \( \Delta DY \) in spring (see also figure S5), linked to the pressure gradient and related enhanced land/sea temperature contrast (figure 3(a)). In the dry models, the enhanced wind divergence over the coasts of the Gulf of Guinea in March–May (figure S5) tends to shift moisture away from the region during a period in which precipitation is already small (being at the beginning of the rainy season: compare the band of precipitation in between dry and wet models in MAM, figure S5) therefore enhancing the drying over the region.

Changes in mean precipitation are accompanied by variations in precipitation characteristics. Particularly for the Gulf of Guinea, \( \Delta DY \) strongly correlates with the change in the number of rainy days (RR1, i.e. the number of days with precipitation greater than 1 mm, see figure 3(j) and figure S6), which in turn, is the main contributor to the decrease in mean precipitation over the area (figure 3(c)). On the other hand, precipitation intensity (simple daily precipitation intensity, SDII see e.g. Zhang et al 2011) is projected to increase, especially during the summer, over both the Gulf of Guinea and the Sahel (figures 4(a) and (b)). This increase is consistent with previous studies based on both models (GCMs and RCMs, Vizy et al 2013, Klutse et al 2018, Han et al 2019) and observations in
Figure 2. (a)–(l) Change (2071–2100 vs. 1981–2010) in seasonal mean precipitation, the dynamic (second column) and thermodynamic (third column) terms of the moisture budget (equations (4) and (5)). Results are shown as multi-model mean. Hatching indicates where the change is smaller than the inter-model standard deviation. The blue lines indicate the area of future (2071–2100) high precipitation intensity (monsoon band), i.e. where precipitation exceeds 4 mm day\(^{-1}\). Vectors show the dynamic and thermodynamic change in moisture flux (at 850 hPa), computed, respectively, as the change in specific humidity multiplied by the climatological horizontal wind, and the change in horizontal wind multiplied by the climatological specific humidity (i.e. they are the quantities within brackets in equations (4) and (5)). See e.g. Giannini et al. (2018). (m)–(o) Time-latitude diagram of the changes averaged over longitudes 10\(^{\circ}\)W–10\(^{\circ}\)E. Horizontal dashed lines in (m) separates, indicatively, the ocean (longitudes < 5\(^{\circ}\)N), the Gulf of Guinea (land only, 5\(^{\circ}\)N–10\(^{\circ}\)N) and the Sahel (10\(^{\circ}\)N–15\(^{\circ}\)N). Black and blue lines define regions where present (black) and future (blue) precipitation exceeds 4 mm day\(^{-1}\).

the past decades (e.g. Taylor et al. 2017, Panthou et al. 2018).

Note that during June-September, both dry and wet RCMs project increased precipitation intensity but decreased frequency over the Sahel (10\(^{\circ}\)N–15\(^{\circ}\)N) (compare figures 4(a), (b) and 3(g), (h)); however, the reduction in RR1 is much stronger for the dry models, accompanied by a weaker increase in SDII, which results in the opposite sign of mean precipitation signal between dry and wet models (figures 3(c) and (d)). In spring, on the other hand, dry and wet RCMs show opposite signs in the changes of SDII over the Gulf of Guinea (figures 4(a), (b) and S7).

Although the thermodynamic component of the moisture budget shows similar patterns with positive values during the rainy season (figures 4(e) and (f)), the change in evapotranspiration (ET) is strikingly different, with dry RCMs showing strong decrease over land (apart from a weak increase over the Gulf
of Guinea during August–November), and wet RCMs a strong increase. Notably, changes in evapotranspiration are strongly correlated with those of SDII especially over the first months of the rainy season in both the Gulf of Guinea and the Sahel (figure 4(i)).

The importance of land-atmosphere coupling in climate variability and change has been highlighted in many studies (e.g. Koster et al 2004, Seneviratne et al 2010, Yang et al 2018). In particular, the soil moisture (SM) feedback and coupling with evapotranspiration have been analysed at the global scale by Berg and Sheffield (2018) and specifically over Africa by Berg et al (2017). Recently, Careto et al (2018) investigated the land-atmosphere coupling in ERA-interim-driven CORDEX-Africa RCMs and have found the Sahel and West Africa as regions of strong soil moisture-temperature coupling. Dosio and Panitz (2016) analysed CCLM precipitation projections and found that, with the exception of the CNRM-CM5 driven simulation over West Africa, the RCM responds as expected as in a moisture limited evapotranspiration regime, with decreasing precipitation, soil moisture and latent heat flux.

Differences in future changes in total SM across models are striking (figure S8); although comparison between models can be only qualitative (as total SM depends on the number and depth of soil layers),
dry models are characterized by a strong reduction in SM, which, in the wet models is much less marked (figures 4(g) and (h)).

Following the approach of Berg and Sheffield (2018) we define a simple metric for the land atmosphere coupling strength (SM, ET) defined as the interannual correlation (using monthly mean values) between total SM and ET (as, for CORDEX RCMs, surface SM is unavailable). There is a strong negative intermodal correlation between the (SM, ET) coupling and precipitation, in both the present and future climates over the monsoon region (figure 4(j)). The intermodal positive (negative) correlation between present day (SM, ET) coupling and future changes in temperature (evapotranspiration) (figure S9): models that are more soil moisture limited in the present tend to warm more and project more negative changes in ET, a finding similar to that based on CMIP5 GCMs by Berg and Sheffield (2018).

4. Discussion and concluding remarks

From the analysis of a large ensemble of GCM-RCM simulations we foresee two possible but contrasting scenarios, or storylines, for West Africa future precipitation. Here, the term storyline is used as in Shepherd et al. (2018) i.e. describing physically plausible, self-consistent future events not necessarily associated with specific probabilities.

Over the Gulf of Guinea, RCMs show the largest uncertainty in projected mean precipitation change during the early phase of the rainy season (April–July): based on this finding, we separate model results into two classes, namely ‘wet’, i.e. those projecting an
increase in mean precipitation, and ‘dry’, i.e. those projecting a decrease.

We note that, for the dry models, the change in mean precipitation in spring and early summer is a consequence of the large reduction in the precipitation frequency (number of rainy days, RR1), which, in turn, is positively correlated with the dynamic component term (ΔDY) of the moisture budget equation, over the Gulf of Guinea. This weakening of the dynamic term over the Gulf of Guinea and its strengthening over the Sahel is driven by an enhanced temperature gradient between the sea and the Sahara under global warming, which, in turn, results in a net transport of moisture away from the coast and, consequently, in a reduction of precipitation during the beginning of the rainy season. In addition to this dynamic mechanism, dry models show a marked reduction in soil moisture and evapotranspiration, whose change is positively correlated to that of precipitation intensity (SDII) over the Gulf of Guinea in spring. The drying is subsequently shifted northwards into the Sahel during summer, following the evolution of the monsoonal rainbelt, whereas precipitation over the coast is projected to slightly increase mainly due to the large increase over the sea. However, the characteristics of future summer precipitation are projected to change over both the Gulf of Guinea and the Sahel, with precipitation projected to become less frequent but more intense; in particular, the change in precipitation intensity over the Gulf of Guinea is found to be strongly positively correlated with the value of the thermodynamic component of the moisture budget.

On the contrary, wet models show nearly no change in future mean precipitation over the Gulf of Guinea in spring (note also that the change in land-sea temperature gradient is notably smaller than in the dry models), but a marked increase over both the coast and the Sahel in summer. The negative dynamic term of the moisture budget (and consequent reduction in the number of rainy days) is contrasted by the positive value of the thermodynamic term and by an increase in evapotranspiration. In contrast to dry models, wet models project only a weak reduction in total soil moisture over the Gulf of Guinea coast from April to July.

It is worth noting that, generally, dry and wet models show similar patterns of the dynamic and thermodynamic components of the moisture budget, although their magnitudes are larger in the dry models, especially that of the dynamic term. However, the largest discrepancies are found in the different strengths of the coupling between land and atmosphere, with dry models showing a marked decrease in soil moisture and evapotranspiration, opposite to the results of wet models.

Note that this behaviour is not necessarily a characteristic of a specific RCM (i.e. the specific soil parameterization and land scheme); when driven by different GCMs, the same regional climate model can project contrasting (opposite) changes in both soil moisture and evapotranspiration. In fact, here we have shown that when analysing the results of a GCM-RCM ensemble, especially for phenomena as complex as the West African Monsoon that is influenced by drivers at both large (e.g. SST patterns) and small (e.g. land-atmosphere coupling) scales, the results are greatly influenced by both the driving GCM and the downscaling RCM. For instance, CCLM driven by MPI-ESM can be considered as the driest model; however, the same RCM driven by CNRM-CM5 projects a strong precipitation increase, thus highlighting the sensitivity of RCMs to large-scale driving atmospheric conditions. It must be noted, however, that the drying could be a result of a strong nonlinear feedback, involving not only local land-atmosphere coupling but also large-scale dynamical processes, such as teleconnections, an aspect that has not been investigated in this study.

It is important to understand that our analysis is partially based on an approximation of the moisture budget equation (as we calculate only the horizontal moisture flux divergence instead of the vertically integrated one) and, therefore, limited. This said, the main outcomes of our study hold: in fact, they are based on the relationship between the differential land-sea warming and the change in spring precipitation (which provides the basis for the grouping of models simulations in ‘dry’ and ‘wet’). Similarly, the strong correlation found between ΔDY and ΔRR1 (and in turn ΔPR) is still valid, as is the analysis of the land-atmosphere coupling and feedback. The goal of this study is not to provide a thorough analysis of the relationship between moisture budget and precipitation, as done for instance by Giannini et al. (2018) using GCMs and Tamoffo et al. (2019) using the only available RCM providing outputs at necessary vertical levels. Rather, here we identified and analysed some of the aspects that can lead to such large differences in future precipitation change. The different way in which ‘wet’ and ‘dry’ models simulate the various moisture budget terms (or at least their horizontal components at 850 hPa) is striking (and independent from their approximate definitions in equations (4) and (5)) as is their very different response to soil-atmosphere coupling.

Finally it is also worth noting that relating future projections to model skill over the present climate is very challenging (see for instance the discussion in Dosio et al. 2019), and it would require a thorough assessment of the model (both driving GCMs and downscaling RCMs) ability at reproducing the physical processes and drivers of the African climate, a task even more challenging when available model outputs and observational datasets are scarce and incomplete.

Summarizing, we showed that the results of CORDEX Africa RCMs can lead to two contrasting but plausible storylines for the precipitation
characteristics over West Africa; one where mean precipitation is projected to decrease significantly over the Gulf of Guinea in spring and the Sahel in summer, and the other one where summer precipitation over both regions is projected to increase. These results could be troubling and have important implications for policy makers with regards to water resources planning in the context of future climate change. However, despite the differences, some changes in precipitation characteristics are robust, being similar and consistent for both sets of models (and the driving GCMs; e.g. Dosio et al 2019). In particular, precipitation frequency is projected to decrease in spring over the Gulf of Guinea and in summer over the Sahel, although precipitation is projected to become more intense.

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References

Akinsanola A, Ajayi V, Adejare A, Adeyeri O, Gbode I Ogunjobi K et al 2018 Evaluation of rainfall simulations over West Africa in dynamically downscaled CMIP5 global circulation models Theor. Appl. Climatol. 132 437–50
Akinsanola A A, Gbode I O, Ajayi V O 2015 Assessing the capabilities of three regional climate models over CORDEX Africa in simulating West African summer monsoon precipitation Adv. Meteorol. 2015 1–13
Akinsanola A A and Zhou W 2019a Projections of West African summer monsoon rainfall extremes from two CORDEX models Clim. Dyn. 52 2017–28
Akinsanola A A and Zhou W 2019b Dynamic and thermodynamic factors controlling increasing summer monsoon rainfall over the West African Sahel Clim. Dyn. 52 4501–14
Berg A, Lintner B R, Findell K and Giannini A 2017 Uncertain soil moisture feedbacks in model projections of Sahel precipitation Geophys. Res. Lett. 44 6124–33
Berg A and Sheffield J 2018 Soil moisture–evapotranspiration coupling in CMIP5 models: relationship with simulated climate and projections J. Clim. 31 4865–78
Careto J A M, Cardoso R M, Soares P M M and Trigo R M 2018 Land-atmosphere coupling in CORDEX-Africa: hindcast regional climate simulations J. Geophys. Res. Atmos. 123 11,048–11,067
Cook K 1999 Generation of the African easterly jet and its role in determining West African precipitation J. Clim. 12 1165–84
Diaconescu E P, Gachon P, Scinocca J and Laprise R 2015 Evaluation of daily precipitation statistics and monsoon onset/retreat over western sahel in multiple data sets Clim. Dyn. 45 1325–54
Dixon R D, Daloz A S, Vimont D J and Biasutti M 2017 Saharan heat low biases in CMIP5 models J. Clim. 30 2867–84
Dosio A 2017 Projection of temperature and heat waves for Africa with an ensemble of CORDEX regional climate models Clim. Dyn. 49 493–519
Dosio A, Jones R G, Jack C, Lennard C, Nikulin G and Hewitson B 2019 What can we know about future precipitation in Africa? robustness, significance and added value of projections from a large ensemble of regional climate models Clim. Dyn. 53 5833–58
Dosio A and Fischer E M 2018 Will half a degree make a difference? robust projections of indices of mean and extreme climate in europe under 1.5 °C, 2 °C, and 3 °C global warming Geophys. Res. Lett. 45 935–44
Dosio A and Panitz H J 2016 Climate change projections for CORDEX-Africa with COSMO-CLM regional climate model and differences with the driving global climate models Clim. Dyn. 46 1599–625
Dosio A, Panitz H J, Schubert-Frisius M and Lüthi D 2015 Dynamical downsampling of CMIP5 global circulation models over CORDEX-Africa with COSMO-CLM: evaluation over the present climate and analysis of the added value Clim. Dyn. 46 2637–61
Dunning C M, Black E and Allan R P 2018 Later wet seasons with more intense rainfall over Africa under future climate change J. Clim. 31 9719–38
Endo H and Kito H 2014 Thermodynamic and dynamic effects on regional monsoon rainfall changes in a warmer climate Geophys. Res. Lett. 41 1704–11
Gbobaniyi E, Sarr A, Sylla M B, Diallo I, Lennard C Dosio A et al 2014 Climatology, annual cycle and interannual variability
of precipitation and temperature in CORDEX simulations over West Africa. J. Climatol. 34: 2241–57
Giannini A, Lyon B, Seager R and Vignaud N 2018 Dynamical and thermodynamic elements of modeled climate change at the East African margin of convection Geophys. Res. Lett. 45: 992–1000
Gibba P, Sylla M B, Okogbue E C, Gaye A T, Nikiema M and Kebe I 2018 State-of-the-art climate modeling of extreme precipitation over Africa: analysis of CORDEX added-value over CMIP5 Theor. Appl. Climatol. 1–17
Giorgi F and Gutowski W J 2015 Regional dynamical downscaling and the CORDEX initiative Annu. Rev. Environ. Res. 40: 467–90
Han E, Cook K H and Vizy E K 2019 Changes in intense rainfall events and dry periods across Africa in the twenty-first century Clim. Dyn. 53: 2757–77
Hernández-Díaz L, Laprise R, Sushama L, Martynov A, Winger K and Dugas B 2013 Climate simulation over CORDEX Africa domain using the fifth-generation canadian regional climate model (CRCM5) Clim. Dyn. 40: 1415–33
James R, Washington R and Jones R 2013 Process-based assessment of an ensemble of climate projections for West Africa. J. Geophys. Res. Atmos. 120: 1221–38
Klutse N A B, Ayaji V O, Gbobi-Wan E O, Egbeyeji T S, Kusado K, Nikumam P et al 2018 Potential impact of 1.5 ◦C and 2 ◦C global warming on consecutive dry and wet days over West Africa Environ. Res. Lett. 13: 055013
Klutse N A B, Sylla M B, Djallo I, Sarr A, Dosio A Diedhiou A et al 2016 Daily characteristics of West African summer monsoon precipitation in CORDEX simulations Theor. Appl. Climatol. 123: 369–86
Koster R D, Dirmeyer P A, Guo Z, Bonan G, Chan E Cox P J et al 2004 Regions of strong coupling between soil moisture and precipitation Science 305: 1138–40
Kumi N and Abiodun B J 2018 Potential impacts of 1.5 ◦C and 2 ◦C global warming on rainfall onset, cessation and length of rainy season in West Africa Environ. Res. Lett. 13: 055009
Lavaysse C, Flament C, Evan A, Janicot S and Gaetani M 2016 Recent climatological trend of the Saharan heat low and its impact on the West African climate Clim. Dyn. 47: 5479–90
Lee D, Min S-K, Jin J, Lee J-W, Cha D-H Suh M-S et al 2017 Thermodynamic and dynamic contributions to future changes in summer precipitation over Northeast Asia and Korea: a multi–RCM study Clim. Dyn. 49: 4121–39
Monerie P-A, Sanchez–Gomez E and Boé J 2017 On the range of future sahel precipitation projections and the selection of a sub-sample of CMIP5 models for impact studies Clim. Dyn. 48: 2751–70
Niang I, Ruppel O, C, Abdrabo M A, Essel A, Lennard C, Padgham J et al 2014 Africa ClimateChange 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working GroupII to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, ed V R Barros, C B Field, D J Dokken, M D Strandrandra, K Mach J T E Bilir et al (Cambridge: Cambridge University Press) pp 1199–265
Nikiema P M, Sylla M B, Ogundohoji K, Kebe I, Gibba P and Giorgi F 2017 Multi-model CMIP5 and CORDEX simulations of historical summer temperature and precipitation variabilities over West Africa Int. J. Climatol. 37: 2438–50
Nikulin G, Jones C, Giorgi F, Aras G, Büchner M Cerezo-Mota R et al 2012 Precipitation climatology in an ensemble of CORDEX–Africa regional climate simulations J. Clim. 25: 6027–78
Panitz H J, Dosio A, Büchner M, Lüthi D and Krueger K 2014 COSMO–CLM (CCLM) climate simulations over CORDEX–Africa domain: analysis of the ERA-interim driven simulations at 0.44 ◦C and 0.22 ◦C resolution Clim. Dyn. 42: 3015–38
Panthou G, Labé T, Visschel T, Quantin G, Sane Y Ba A et al 2018 Rainfall intensification in tropical semi-arid regions: the Sahelian case Environ. Res. Lett. 13: 064013
Poan E D, Gachon P, Dueymes G, Diaconescu E, Laprise R and Seidou Sanda I 2016 West African monsoon intraseasonal activity and its daily precipitation indices in regional climate models: diagnostics and challenges Clim. Dyn. 47: 3113–40
Pomposi C, Kusunir Y and Giannini A 2015 Moisture budget analysis of SST-driven decadal Sahel precipitation variability in the twentieth century Clim. Dyn. 44: 3303–21
Quenum G M L D, Klutse N A B, Dieng D, Laux P, Arnault J, Kodja J D et al 2019 Identification of potential drought areas in West Africa under climate change and variability Earth Syst. Environ. 3: 429–44
Raj J, Bangalath H K and Stenchikov G 2019 West African monsoon: current state and future projections in a high-resolution AGCM Clim. Dyn. 52: 6441–61
Rowell D P, Senior C A, Vellinga M and Graham R J 2016 Can climate projection uncertainty be constrained over Africa using metrics of contemporary performance? Clim. Change 134: 621–33
Sarr A B, Camara M and Diba I 2015 Spatial distribution of cordeX regional climate models biases over West Africa Int. J. Geosci. 6: 061018–31
Seager R, Naik N and Vecchi G A 2010 Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming J. Clim. 23: 4651–68
Seneviratne S I, Corti T, Davin E L, Hirschi M, Jaeger E B Lehner I et al 2010 Investigating soil moisture–climate interactions in a changing climate: a review Earth Sci. Rev. 99: 125–61
Seth A, Rauscher S A, Biaisit M, Giannini A, Carmargo S I and Rojas M 2013 CMIP5 projected changes in the annual cycle of precipitation in monsoon regions J. Clim. 26: 7328–51
Shepherd T G, Boyd E, Calel R A, Chapman S C, Deass S, Dima-West I M et al 2018 Storylines: an alternative approach to representing uncertainty in physical aspects of climate change Clim. Change 151: 555–71
Steiner A L, Pal Jr S, Rauscher S A, Bell J L, Diffenbaugh N S, Boone A et al 2009 Land surface coupling in regional climate simulations of the West African monsoon Clim. Dyn. 33: 869–92
Steinig S, Harlass J, Park W and Latif M 2018 Sahel rainfall strength and onset improvements due to more realistic Atlantic cold tongue development in a climate model Sci. Rep. 8: 2569
Sultan B and Gaetani M 2016 Agriculture in West Africa in the twenty-first century: climate change and impacts scenarios, and potential for adaptation Front. Plant Sci. 7
Sylla M B, Pal J S, Faye A, Dimobe K and Kunstmann H 2018 Climate change to severely impact West African basin scale irrigation in 2 ◦C and 1.5 ◦C global warming scenarios Sci. Rep. 8: 14395
Tamoffo A T, Moufouma-Okia W, Dosio A, James R, Pokam W M, Vondou D A et al 2019 Process-oriented assessment of RCA4 regional climate model projections over the Congo Basin under 1.5 ◦C and 2 ◦C global warming levels: influence of regional moisture fluxes Clim. Dyn. 53: 1911–35
Taylor C M 2008 Intraseasonal land–atmosphere coupling in the West African monsoon J. Clim. 21: 6636–48
Taylor C, M, Belusco D, Guichard F, Parker D J, Visschel T Bock O et al 2017 Frequency of extreme Sahelian storms tripled since 1982 in satellite observations Nature 544: 475–8
Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design Clim. Change 113: 3–28
Teichmann C, Eggert B, Elizalde A, Haensler A, Jacob D Kumar P et al 2013 How does a regional climate model modify the projected climate change signal of the driving GCM: a study
over different CORDEX regions using REMO Atmosphere
van Vuuren D P, Edmonds J, Kainuma M, Riahi K, Thomson A
Hibbard K et al 2011 The representative concentration
pathways: an overview Clim. Change
109 5—31
Vizy E K and Cook K H 2017 Seasonality of the observed
amplified sahara warming trend and implications for sahel
rainfall J. Clim. 30 3073–94
Vizy E K, Cook K H, Créat J and Neupane N 2013 Projections of
a wetter Sahel in the twenty-first century from global and
regional models J. Clim. 26 4664–87
Weigel A P, Knutti R, Liniger M A and Appenzeller C 2010 Risks
of model weighting in multimodel climate projections
J. Clim. 23 4175–91
Yang L, Sun G, Zhi L and Zhao J 2018 Negative soil moisture-
precipitation feedback in dry and wet regions Sci. Rep.
8 4026