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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 (stacks.iop.org/ERL/15/064007/mmedia)). 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 ($\Delta$) 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):

$$\Delta PR - \Delta E \sim DY + \Delta TH + \Delta TE + \Delta Res, \quad (1)$$

where $E$ is evaporation, and the thermodynamic ($\Delta TH$) and dynamic ($\Delta DY$) components are defined according to:

$$\Delta DY = -\frac{1}{\rho g}\nabla \cdot \int_0^{p_s} \bar{q}\Delta \boldsymbol{u} dp \quad (2)$$

$$\Delta TH = -\frac{1}{\rho g}\nabla \cdot \int_0^{p_s} \bar{\boldsymbol{u}}\Delta q dp, \quad (3)$$

where $q$ is the specific humidity, $\boldsymbol{u}$ the horizontal wind, $p_s$ 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:

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

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

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 (dryer) 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

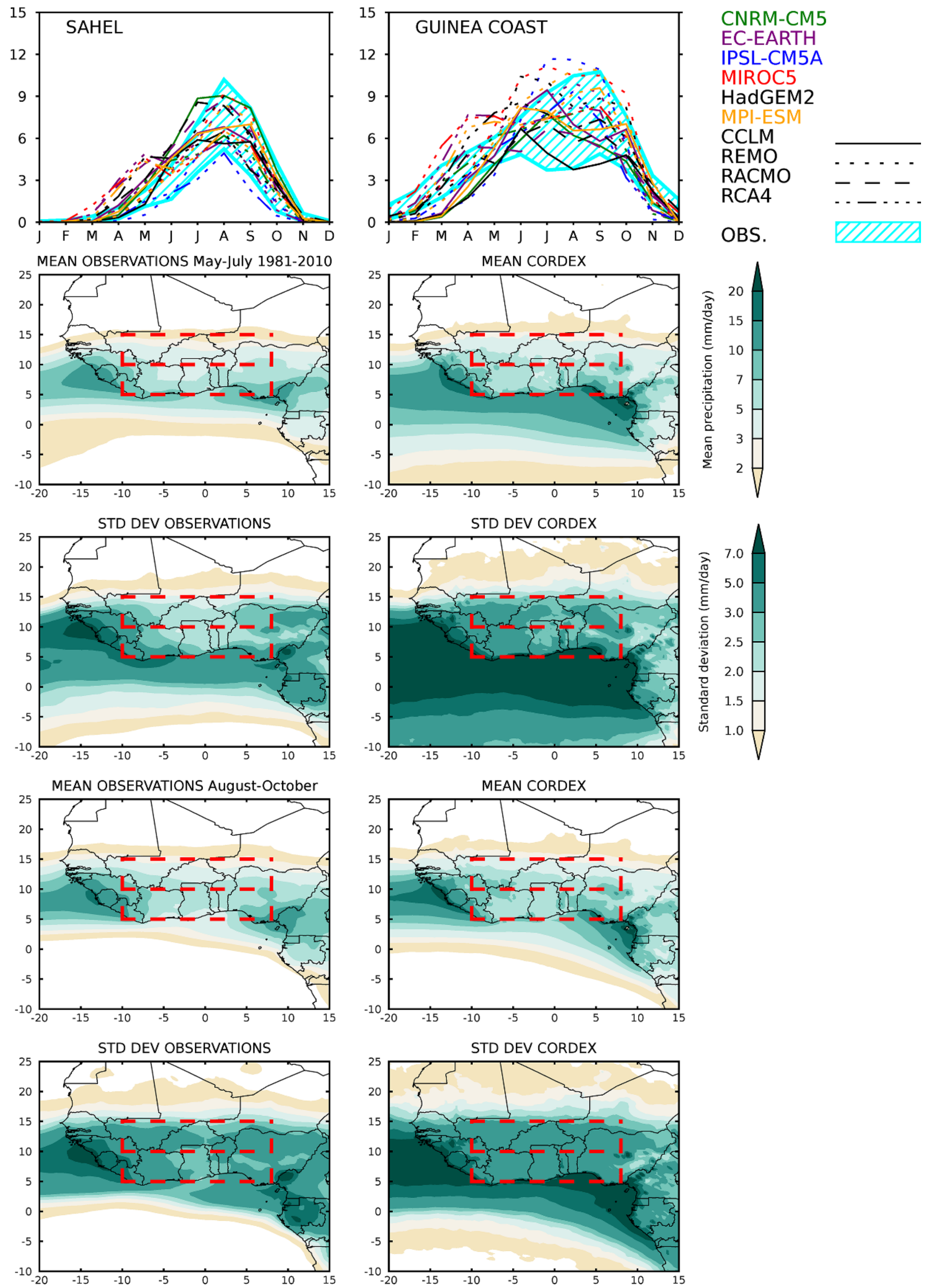


**Figure 1.** Evaluation of CORDEX-Africa RCMs: Top row: annual cycle of daily precipitation (mm/day) as simulated by the GCM-driven RCMs over the period 1981–2010 over the Sahel and coasts of the gulf of Guinea, identified by the red dashed lines in the underlying maps. Different colors refer to the 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 (2071–2100 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(i)). 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

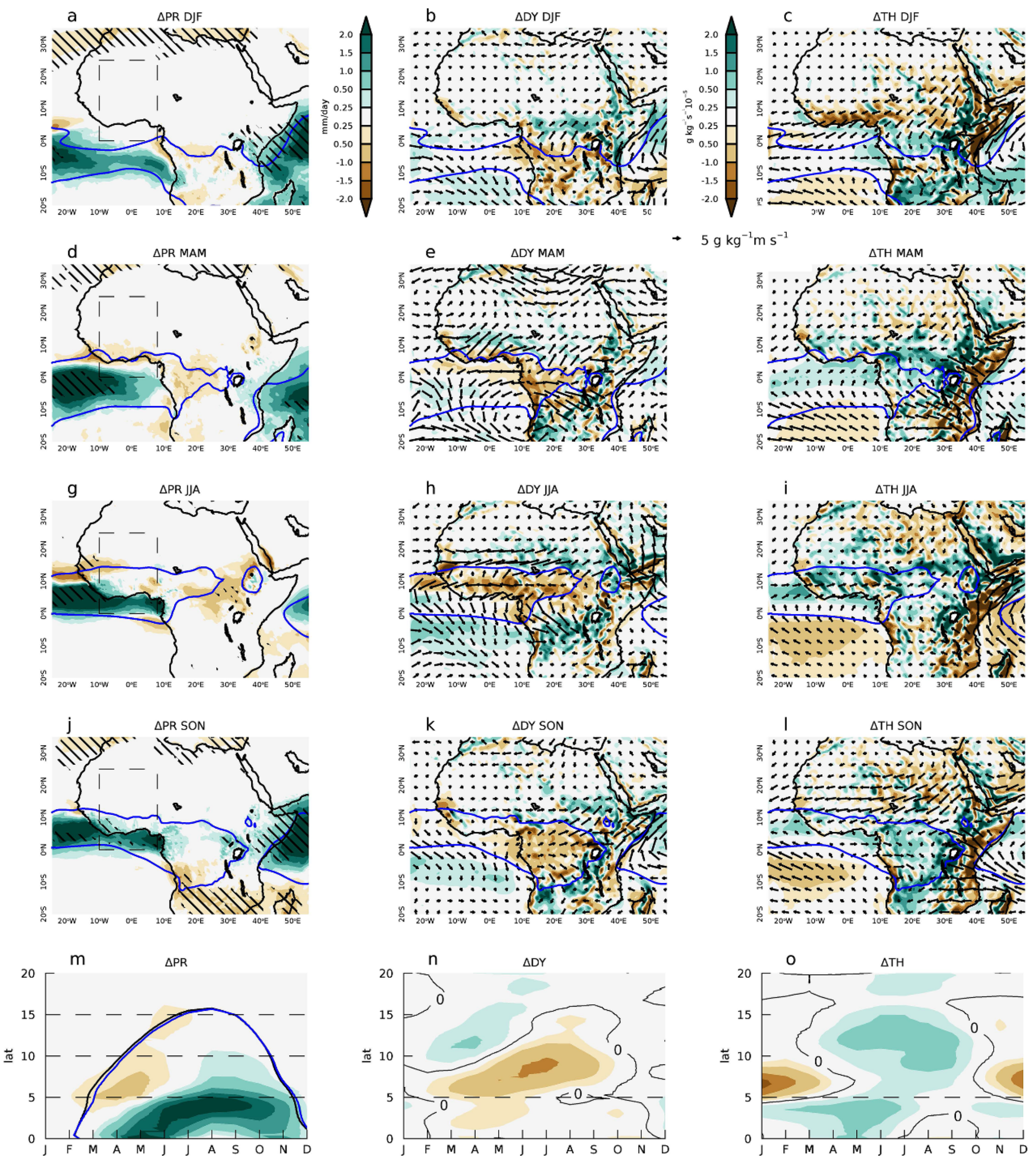

**Figure 2.** (a)–(l) Change (2071–2100 vs. 1981–2010) in seasonal mean precipitation, the dynamic (second column) and thermodynamic (third column) terms of the moisture budget (equations (4) and (5)). Results are shown as multi-model mean. Hatching indicates where the change is smaller than the inter-model 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°W–10°E. Horizontal dashed lines in (m) separates, indicatively, the ocean (longitudes < 5°N), the Gulf of Guinea (land only, 5°N–10°N) and the Sahel (10°N–15°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°N–15°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

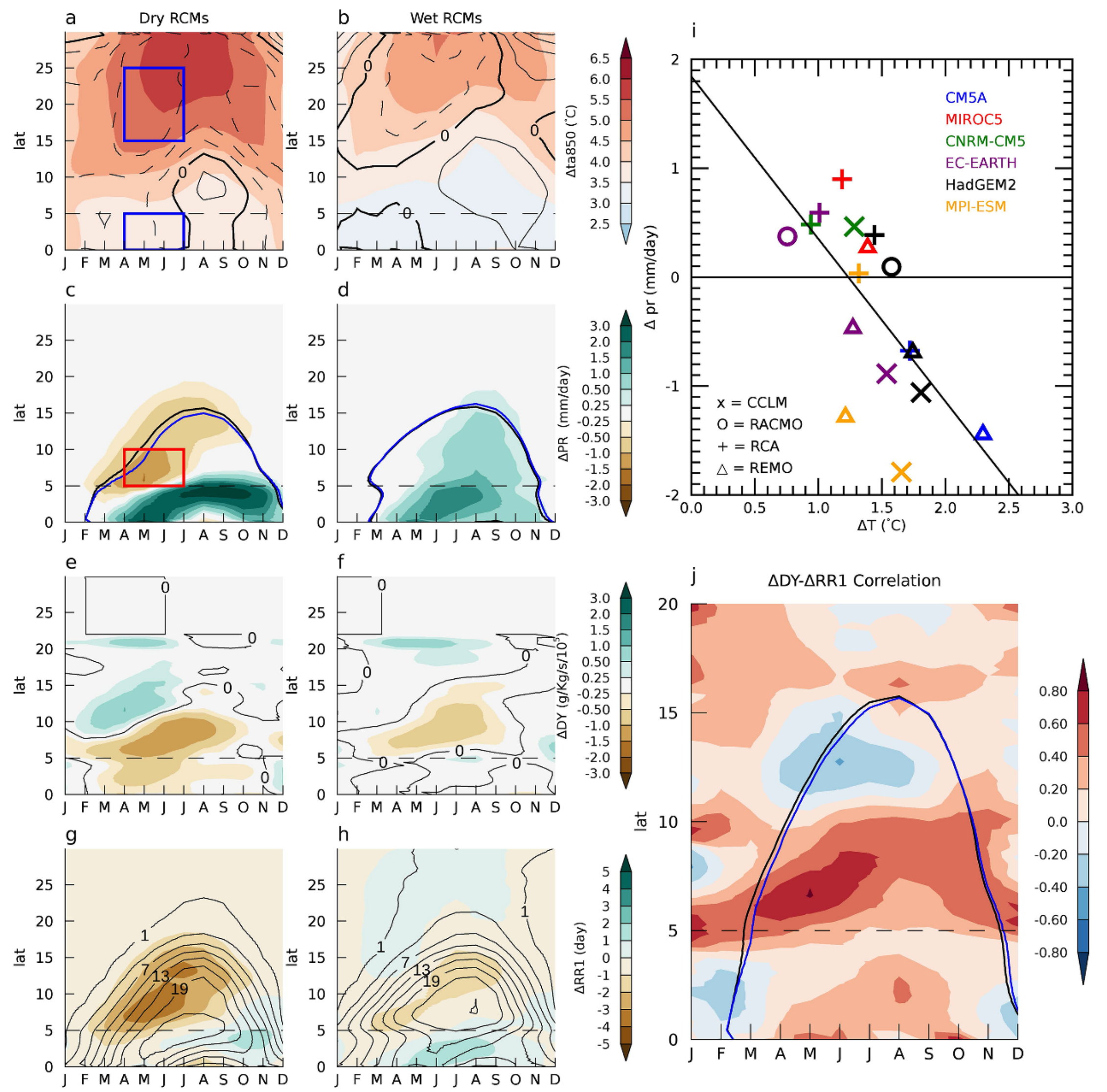


**Figure 3.** Latitude-time diagram of changes in 850 hPa temperature ($\Delta ta850$, colors) and sea level pressure (contours) (a) and (b), change in precipitation (c, d where the black and blue lines define where present and future precipitation exceeds 4 mm day$^{-1}$), dynamical term of the moisture budget (e ) and (f) and change in number of rainy days ($\Delta RR1$) (g, h, where contours denote the present climate value of RR1) for the 'Dry' RCMs (first column) and 'Wet' RCMs (second column). To separate dry and wet RCMs, in (i) model results are shown for the change in precipitation during April–July in the Gulf of Guinea (red area in c) against the difference in 850 hPa temperature between the Sahara and the ocean (blue areas in a). The metric thereby indicates how much the Sahara has warmed more than the Gulf of Guinea. The diagonal line represents the inter model regression. (j) Latitude-time diagram of inter-model correlation between the dynamic component $\Delta DY$ and the change in precipitation frequency ΔRR1. The blue and black lines mark areas with present and future daily precipitation rates higher than 4 mm/day.

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),

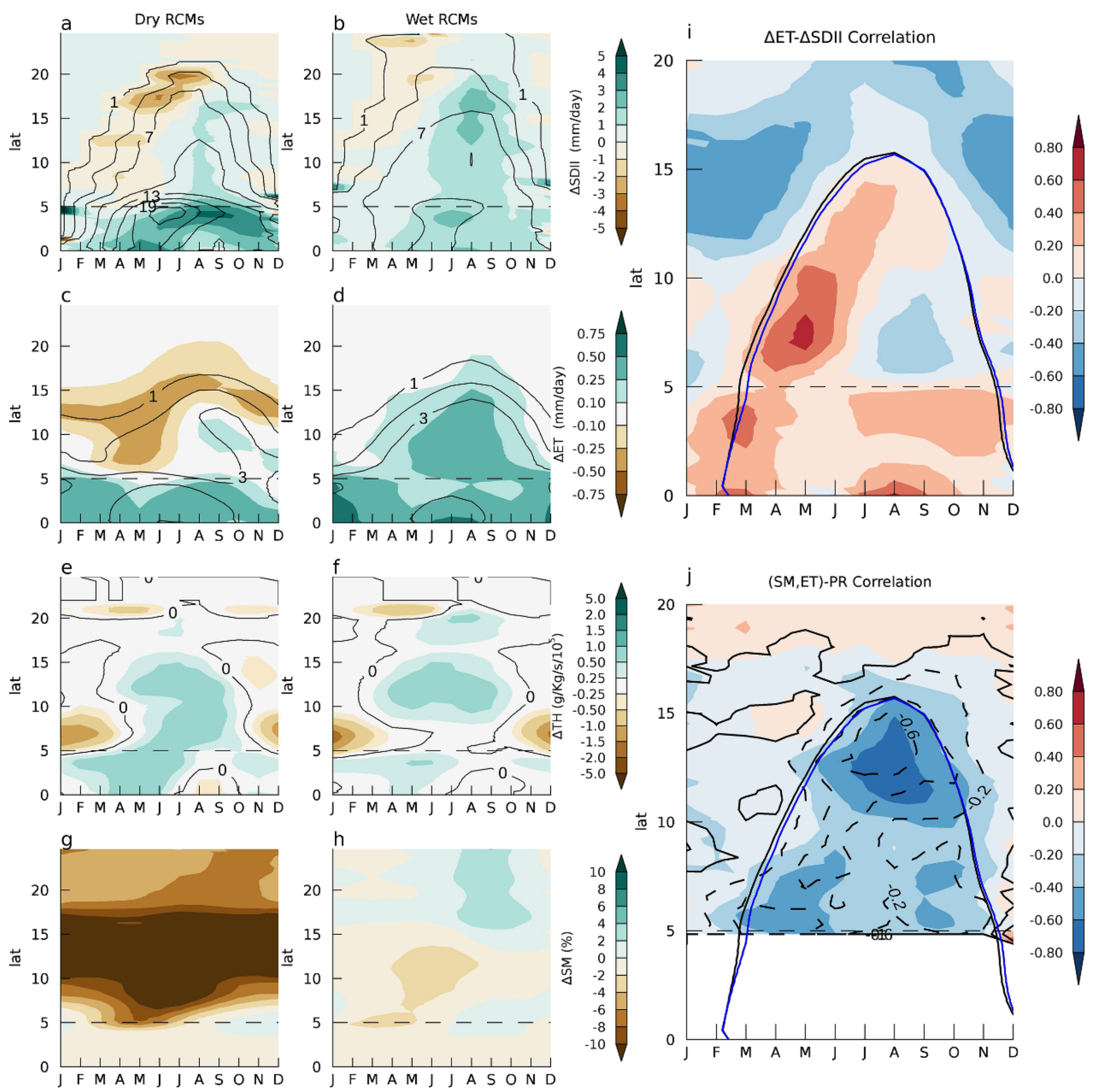


**Figure 4.** Latitude-time diagram of changes in precipitation intensity (SDII) (a) and (b), evapotranspiration (c) and (d), thermodynamic term of the moisture budget (e) and (f) and total soil moisture (g), (h) for the 'Dry' RCMs (first column) and 'Wet' RCMs (second column). In (a)–(d) black lines denote present day values. (i) Inter model correlation between the change in evapotranspiration and precipitation intensity. (j) Inter model correlation between soil moisture-evapotranspiration coupling (SM,ET) and precipitation for the end of the century (shading) and the present climate (contour lines). The blue and black lines mark present and future daily precipitation rates higher than 4 mm $day^{-1}$.

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 ($\Delta DY$) 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, Ogunjobi K O, Gbode I E and 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 downscaling of CMIP5 global circulation models over CORDEX-Africa with COSMO-CLM: evaluation over the present climate and analysis of the added value *Clim. Dyn.* **44** 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 Kitoh A 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 *Int. J. Climatol.* **34** 2241–57

Giannini A, Lyon B, Seager R and Vigaud 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 F, 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 2015 Process-based assessment of an ensemble of climate projections for West Africa *J. Geophys. Res. Atmos.* **120** 1221–38

Klutse N A B, Ajayi V O, Gbobaniyi E O, Egbebiyi T S, Kouadio K Nkrumah F *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, Diallo 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 *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, Flamant 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** 3479–98

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 Afria *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 Mastrandrea, K J Mach T E Bilir *et al* (Cambridge: Cambridge University Press) pp 1199–265

Nikiema P M, Sylla M B, Ogunjobi 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, Asrar G, Büchner M Cerezo-Mota R *et al* 2012 Precipitation climatology in an ensemble of CORDEX-Africa regional climate simulations *J. Clim.* **25** 6057–78

Panitz H-J, Dosio A, Büchner M, Lüthi D and Keuler K 2014 COSMO-CLM (CCLM) climate simulations over CORDEX-Africa domain: analysis of the ERA-interim driven simulations at 0.44 ° and 0.22 ° resolution *Clim. Dyn.* **42** 3015–38

Panthou G, Lebel T, Vischel 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, Kushnir 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.* **06** 1018–31

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, Biasutti M, Giannini A, Camargo S J 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, Dessai 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 J 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, Belusic D, Guichard F, Parker D J, Vischel 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 *Bull. Am. Meteorol. Soc.* **93** 485–98

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* **4** 214–36

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, Crétat 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