Response to Reviewer #2

1. Brief summary of the manuscript

In their manuscript, Dr. Mehboob and co-workers applied a regional climate model coupled to a dynamic vegetation module to quantify the effects of vegetation feedback on drought over West (Sahel and Gulf of Guinea) and Central Africa (Congo Basin) under present-day and future climate. To identify drought conditions, the authors use the Standardized Precipitation Evapotranspiration Index (SPEI) as defined by Vicente-Serrano et al. (2010) by combining monthly precipitation and potential evapotranspiration (PET). To assess the added value of representing the dynamics of vegetation processes (e.g., plant shift, growth), Mehboob et al. performed numerical experiments with and without the dynamic vegetation module. In addition, they accounted for uncertainties in the atmospheric forcing by taking boundary lateral conditions from four global climate models (GCMs). The main results are:

- In experiments using the dynamic vegetation module, future drought lengthens and strengthens in the Sahel compared to experiments without the dynamic vegetation module, while the trend is less clear in the Gulf of Guinea and the Congo Basin.
- When forcing the regional climate model with different GCMs, results are consistent except for the Congo Basin where GCM diverge in reproducing drought frequency under present-day and future climate.

2. General comments

The study addresses relevant scientific questions that are within the scope of HESS and that are related to drought occurrence and intensity in a sensitive region such as West and Central Africa. In this sense, the study could provide interesting advance towards current knowledge and methodologies applied to project drought in Africa and other sensitive regions using RCMs. However, in my opinion, the quality of presentation is poor and confused; the Introduction, Methodology, and Results and Discussion Sections are not well laid out; some methodological choices are not well justified; and the significance of results is not discussed. Moreover, I would suggest to edit and proofread the manuscript to avoid redundancy and to simplify some confused sentences that make the reading difficult. In the following, I provide specific comments (major and minor) on the manuscript.

>> Thank you very much for the constructive comments. Here is the summary of our revision:

1) Add the model evaluations with the runs forced by the reanalysis data (ERA-Interim);
2) Re-arrange the results to better present our findings with updated figures;
3) Include additional and detailed literature review;
4) Discuss the significance on the results;
5) Improve the figures with re-arrangement and proper titles; Add the significant test results in the difference figures.

We have also proofread the manuscript thoroughly to avoid any confusing expressions. Please find the point-by-point responses to the specific comments below along with the revised manuscript.

3. Major comments

In my opinion, the **Introduction** does not provide enough information to readers on the target region, its climate features (also in terms of surface-atmosphere interactions) and on the vegetation feedback the manuscript will focus on. Although the authors cite some previous works that studied the same region, I think the authors should spend more words in summarizing the main results and limits of the cited works. This will allow the authors to clearly state their own original contribution to the tackled topic.

>> We have revised the introduction to include the additional and detailed literature review regarding the previous studies about the West African climate projects as well as the coupled climate-vegetation model development.

Page 2, Line 6: *"Recently, Akinsanola and Zhou (2019) investigated projected changes in extreme summer rainfall events over West Africa with data from the Coordinated Regional Climate Downscaling Experiment (CORDEX) models. Results showed the RCMs reasonably reproduced the observed pattern of extreme rainfall over the region. Future projections under the representative concentration pathways (RCPs) showed a statistically significant decrease in total rainfall and an increase in consecutive dry days and extreme rainfall."*

Page 2, Line 22: *"Cook and Vizy (2008) developed a vegetation model coupled with a RCM to estimate the influence of global warming on South America by allowing interactions between climate and vegetation. With the simulation of the future climate under the A2 scenario, the authors found a reduction in vegetation cover of almost 70% in the Amazon rainforest along with a widespread increase in grass and shrubland in the east by the end of 21st century. This highlights the importance of considering vegetation dynamics in RCMs. Garnaud et al. (2015) combined the Canadian Regional Climate Model (CRCM5) with the Canadian Territorial Ecosystem Model (CTEM) to investigate the impact of a vegetation model to simulate the present day climate over North America. The result showed that introducing vegetation dynamics improved the model's performance in some regions, along with introducing new biases in other regions, owing to biases in simulated leaf area index (LAI). This atmospheric-vegetation interaction also introduced long term memory, which was estimated using a lagged correlation between temperature/precipitation and LAI. Wu et al. (2016) utilized a regional earth system model coupled with the dynamic vegetation model, RCA-GUESS (Smith et al., 2011), and investigated the role of vegetation dynamics on climate in Africa under the RCP8.5 projected climate scenario. The authors showed that introducing vegetation processes amplifies the warming trend and enhanced precipitation reduction over rainforest areas, which highlights the impact of introducing vegetation processes in a climate model."*

Page 3, Line 3: *"Recently, Wang et al. (2016) introduced a dynamic vegetation feature into the International Center for Theoretical Physics Regional Climate Model (RegCM4.3.4) (Giorgi et al., 2012) with carbon–nitrogen (CN) dynamics and dynamic vegetation (DV) (RegCM-CLM-CN-DV) of the community land model (CLM4.5) (Lawrence et al., 2011; Oleson et al., 2010) and validated the coupled model over tropical Africa. With the RegCM-CLM-CN-DV, Yu et al. (2016) and Erfanian et al. (2016) examined the impacts of vegetation dynamics on the climate and ecosystems using multiple LBCs from past and future GCM simulations over West Africa. Yu et al. (2016) showed that climate projections of dynamic vegetation feedback was found mainly in semiarid areas of West Africa with little signal in the wet tropics. Erfanian et al. (2016) demonstrated the substantial sensitivity of the simulated precipitation, evapotranspiration, and* *soil moisture to vegetation representation. Including DV in the model eliminates potential inconsistencies between prescribed vegetation and climate, but it can cause climate drift (enhancing model biases) (Erfanian et al., 2016)."*

Ll 31 (pag. 2): "... on a balanced emphasis on all energy resources...": It is not clear to me what this mean. I suggest to rephrase this sentence and describe more explicitly the methodology of the cited work of Caminade and Terray (2010).

>> As per the reviewer's suggestion, the review on Caminade and Terray (2010) has been rephrased to clarify their methodology and results.

Page 1, Line 28: *"Caminade and Terray (2010) examined the simulated rainfall over the Sahel at the end of twenty-first century with the 21 models from the Coupled Model Intercomparison Project (CMIP) Phase 3 (CMIP3). They argued that different model projections are highly uncertain because future rainfall may be affected by changes in surface conditions (e.g., vegetation, land use and soil moisture) that have not been considered in CMIP3 models."*

Ll 36 (pag. 2): For sake of completeness, I would mention that RCM can be forced using re-analysis.

>> As per the reviewer's suggestion, we have added the phrase about RCM.

Page 2, Line 6: *"regional climate models (RCMs), which are forced with lateral boundary conditions (LBCs) derived from GCMs,"*

Ll 45–48 (pag. 2): I think it would be interesting to summarize the main findings of the study of Cook and Vizy (2008), in particular the effects on the regional climate of South America of a reduction of 70.

>> As per the reviewer's suggestion, we have rephrased the sentences to clarify the findings of Cook and Vizy (2008).

Page 2, Line 22: *"Cook and Vizy (2008) developed a vegetation model coupled with a RCM to estimate the influence of global warming on South America by allowing interactions between climate and vegetation. With the simulation of the future climate under the A2 scenario, the authors found a reduction in vegetation cover of almost 70% in the Amazon rainforest along with a widespread increase in grass and shrubland in the east by the end of 21st century. This highlights the importance of considering vegetation dynamics in RCMs."*

Ll 53 (pag. 2): "...climate draft...": Again, this expression is unclear to me, I suggest to express this differently.

>> We have revised it to *"climate drift"* in the revised manuscript.

Ll 55–63 (pag. 2): In my opinion, it is not clear why the authors have chosen the SPEI instead of other drought indexes. I would suggest to present the advantages and the limits of using the SPEI to identify and project drought.

>> As per the reviewer's suggestion, we have clarified the advantage of SPEI in Introduction. Further, recent studies on the estimation of the potential evapotranspiration have been discussed in Discussion and Conclusions.

Page 3, Line 13: *"Various drought indices (e.g., the Palmer Drought Severity index (Palmer, 1965) and the Standard Precipitation Index (SPI, McKee et al., 1993)) have been used to assess drought events. Vicente–Serrano (2010) suggested the standardized precipitation evapotranspiration index (SPEI). It uses the deficit between precipitation and potential evapotranspiration and can include the effects of temperature variability on drought assessment. Therefore, it can be closely related to hydrologic and ecological drought processes although it only uses climate conditions. Since the development of SPEI, various drought studies have adopted this index (Boroneant et al., 2011; Deng, 2011; Li et al., 2012a; Li et al., 2012b; Lorenzo–Lacruz et al., 2010; Paulo et al., 2012; Sohn et al., 2013; Spinoni et al., 2013; Yu et al., 2014a). For example, McEvoy et al. (2012) used SPEI as a drought index to monitor conditions over Nevada and Eastern California, proposing that SPEI was a convenient tool to describe the drought in arid regions. Recently, Diasso and Abiodun (2017) investigated the future impacts of global warming and reforestation on drought patterns simulated with the regional climate models over West Africa using the SPEI. Author showed that reforestation over the Savanna could reduce the future warming and increase the precipitation, but the impact of reforestation on the frequency of severe droughts could be doubled."*

Page 9, Line 7: *"The present study uses SPEI by calculating PET with the Thornthwaite approach, which considers air temperature as a governing feature of PET. However, there are various other methods to calculate PET. For example, the Penman–Montieth method is more physically realistic but requires a diverse input data set (i.e., humidity, radiation coefficient, and wind speed). Van der Schrier et al. (2011) calculated the change in the global Palmer Drought Severity Index (PDSI) using two distinct estimates for PET (e.g., Thornthwaite and Penman Monteith). The authors found that PSDI based on two PET estimates are identical in terms of trend, average values, and classifying severe wet or dry periods. Conversely, McVicar et al. (2012) suggests that climatic conditions other than temperature that affect PET, may balance temperature rise; therefore, further investigations with multiple approaches could inform future drought characteristics"*

In the **Methodology** section, I think the description of the dynamic vegetation module and its functioning should be more detailed. Moreover, I do not understand which parameterization scheme the authors have chosen to represent convection. Related to this point, to ensure the traceability of results, a summary table with all the selected parameterizations could be useful for readers that would like to apply the same modelling set-up over a different region.

>> As per the reviewer's suggestion, we have added one table to show the selected parameterizations for this study.

Table 2. *Model parameterizations used in this study*

Model's feature	Selected schemes
Boundary layer	Holtslag PBL (Holtslag et al., 1990)

Cumulus convection	Emanuel scheme (Emanuel, 1991)
Precipitation and cloud	Sub-grid Explicit Moisture Scheme (Pal et al., 2000)
Radiation	Community climate model 3 (Kiehl et al., 1996)
Dynamics	Mesoscale model 5 (Grell et al., 1994)
Ocean flux	Zeng scheme (Zeng et al.,1998)
Anthropogenic aerosols/ Interactive aerosols	Tracer model (Solmon et al., 2006; Zakey et al., 2006, 2008)
Land Surface	Community Land Model 4.5 (Lawrence et al., 2011; Wang et al., 2016)

In terms of run experiments, in my opinion, the study lacks an experiment forced by re-analysis; this extra-experiment would provide a better term of comparison against observations to identify the model biases.

>> This study builds upon the previous studies of Wang et al. (2016) and Erfanian et al. (2016). In particular, Wang et al. (2016) provides extensive model evaluations with the re-analysis data. This point has been clarified in the revised manuscript. However, we agree that the model should be evaluated for capturing the drought characteristics in this study; thus, we have revised section 3.1 to provide the model evaluations with the runs with the ERA-Interim data along with added new figures (Figs 1, 2 and 3).

Page 5, Line 3: *"Wang et al. (2016) extensively evaluated the RegCM-CLM-CN-DV model for simulating regional climate and ecosystems in West Africa. The evaluation was performed using the LBCs from the ERA-Interim (1989-2008), and with and without vegetation dynamics. Yu et al. (2016) and Erfanian et al. (2016) also examined the impacts of vegetation dynamics on the climate and ecosystems using multiple LBCs from past and future GCM simulations. Building upon these previous studies, this study focuses on the impacts of vegetation dynamics on the regional drought characteristic (i.e., frequency, duration, and intensity) over the focal regions of the West African domain: the Sahel, the Gulf of Guinea, and the Congo Basin (Fig. 1)."*

Page 6, Line 5: *"**3.1 Model Performance for Present-day Droughts***

This section briefly evaluates the model performance with observed climate and vegetation and drought characteristics (Figs 1, 2 and 3). The runs with the ERA-Interim with and without vegetation dynamics for 1989-2008 (Table 1) are briefly presented for the model evaluation. Detailed evaluations of the model performance are documented in Wang et al. (2016). Relative to the observational data from the University of Delaware (UDEL), both EvalSV and EvalDV (Fig. 1) follow the observed spatial patterns of precipitation with slightly underestimating precipitation over the Sahel and overestimating over the Congo Basin. Such dry/wet biases lead to warm/cool biases in air temperature via the reduction/enhancement of evaporative cooling in the Sahel/Congo Basin. In general, the model performs slightly better with SV than with DV in the evaluation runs. But note that DV could eliminate potential consistencies between prescribed vegetation and climate particularly for the future projections.

With the addition of vegetation dynamics, the LAI (Fig. 2) is overestimated in the eastern *parts of Gulf of Guinea and the northern parts of Congo Basin, and it is underestimated in the Sahel (EvalDV-EvalSV). The run without vegetation dynamics (EvalSV) uses the Moderate Resolution Imaging Spectroradiometer (MODIS)-based monthly-varying climatological LAI values. Over the Sahel, the model underestimates the woody plants and grasses with a significant overestimation of bare ground area, which can be attributed to biases in the vegetation dynamics of CLM-CN-DV model as well as the RegCM physical climate, i.e., dry bias (Wang et al., 2016; Erfanian et al., 2016). The dry/wet bias in the atmospheric forcings over the Sahel/Congo Basin contributes to the underestimated/overestimated LAI, which then leads to additional decreases/increases in precipitation for that region.*

We also investigated the precipitation surplus/deficit (right column of Fig. 1) that is used for calculating the SPEI values to analyze the drought characteristics. We found that the differences of EvalDV and EvalSV for the precipitation surplus/deficit follow those of the precipitation in these cases. The estimated SPEI over three regions are compared in Fig. 3. While the general cycles of SPEI are limitedly captured in the model, the SPEI differences between UDEL and EvalSV may contribute to the limits of RegCM4. The difference between EvalSV and EvalDV is opposite between the Sahel and other regions, which corresponds to the bases of the precipitation surplus/deficit in Fig. 1. In the Sahel, the more severe and longer droughts are simulated for EvalDV compared with EvalSV. In the Gulf of Guinea and the Congo basin, the opposite was observed."

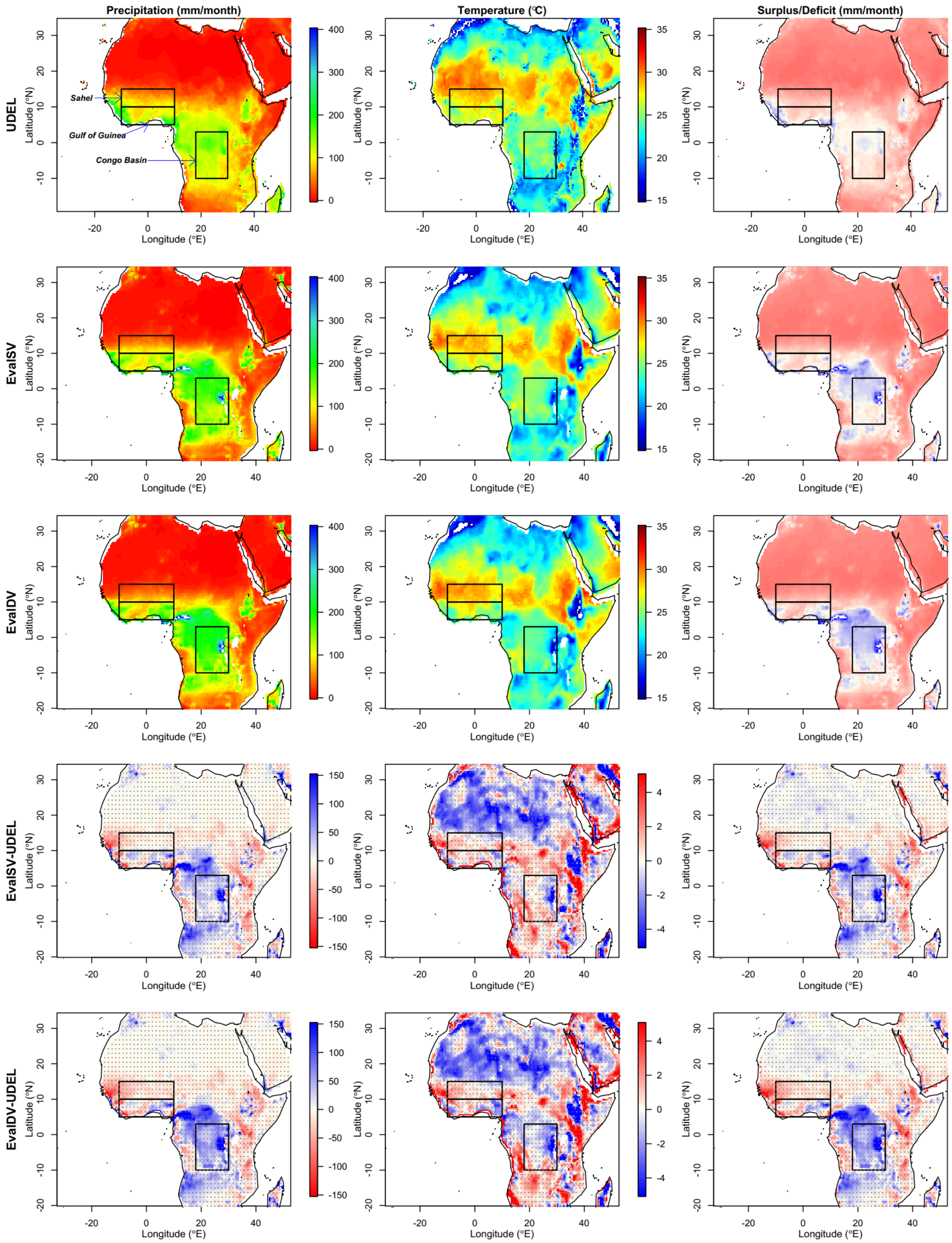


Figure 1. *Averages of precipitation (left column), air temperature (middle column) and precipitation surplus/deficit (right column) from 1989–2008 using datasets from the University of Delaware (UDEL; top row), evaluation run with SV (EvalSV; second row), the difference between EvalSV and UDEL (EvalSV-UDEL; third row), evaluation run with DV (EvalDV; fourth row) and the difference between EvalDV and UDEL (EvalDV-UDEL; bottom row). The boxes with the dashed lines show three focal regions of Sahel, Gulf of Guinea and the Congo Basin. Doted region shows areas passing the two-tailed confidence level with α=0.01.*

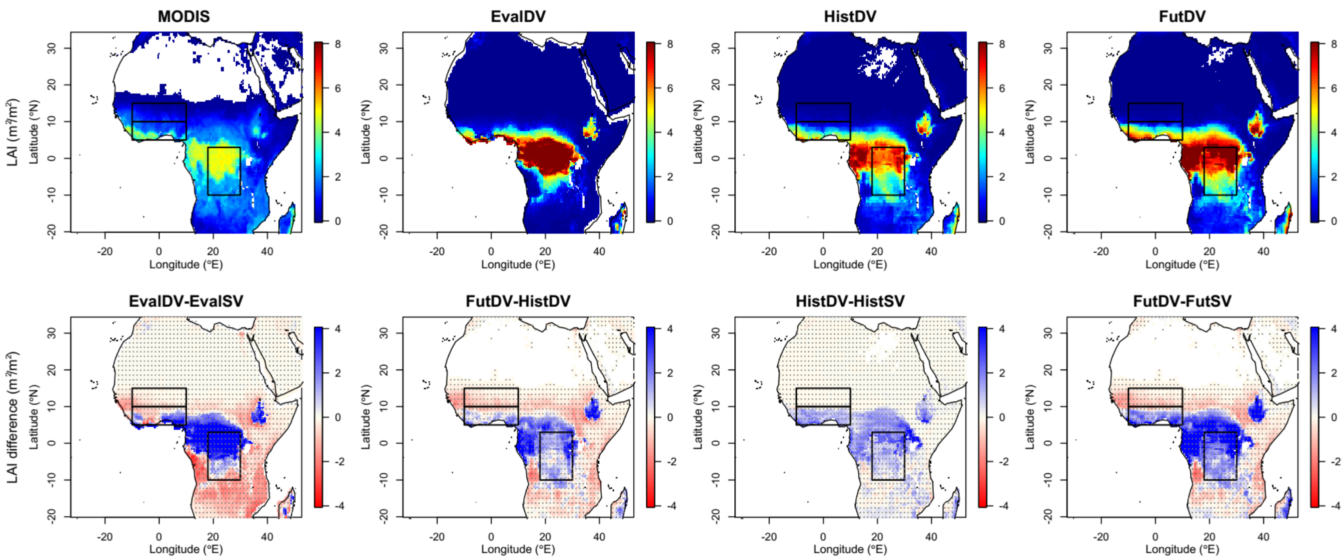


Figure 2. *Averages of leaf area index (LAI) from observation (MODIS), which is used for SV runs (EvalSV, HistSV and FutSV) and simulated in DV for evaluation run and experiment ensemble runs (EavlDV, HistDV and FutDV) in the first row, and their LAI differences in the second row. Doted regions show areas passing the two-tailed confidence level with α=0.01.*

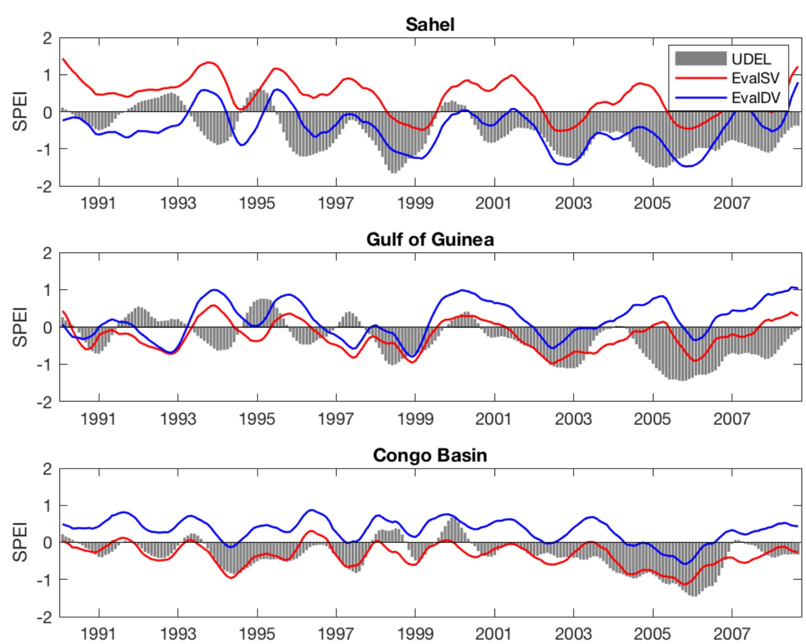


Figure 3. *Six-month moving averages of monthly SPEIs of observations (UDEL), EvalSV and EvalDV over three regions of the Sahel, the Gulf of Guinea, and the Congo Basin in 1989-2008. SPEI for UDEL is calibrated with the data from 1959-2008 (50 years).*

Regarding the SPEI index, I think its computation should be described in a clearer way. For example, the Thornthwaite method should be presented in more details to allow the readers to understand how the potential evapotranspiration is derived. Specifically, this method should also be shortly reviewed in comparison to other well-known methods (e.g., the Penman- Monteith equation), in a more detailed way than that reported on page 7 (ll. 7–11). Lastly, in the manuscript, the authors refer to drought frequency. However, it seems to me that they did not explicitly define how drought frequency has been calculated.

>> As per the reviewer's suggestion, we have included details on computing the SPEI in the Methodology. A comparison with Penman-Monteith has also been added in the Discussion and Conclusions.

Page 5, Line 10: *"In this study, we estimated the SPEI using the approach of Beguería and Vicente-Serrano (2013). While the precipitation is the simulated output of RegCM-CLM-CN-DV, the potential evapotranspiration (PET) should be derived from the model outputs. Owing to the simplicity and availability of the data set, we used Thornthwaite's (1948) approach that only requires the air temperature. Thornthwaite derived an equation to calculate PET as follows:*

$$PET = 16\left(\frac{10\,T}{I}\right)^{a} \quad (1)$$

$$I = \sum_{j=1}^{12}\left(\frac{T}{5}\right)^{1.514} \quad (2)$$

$$a = 6.75\times10^{-7}I^{3} - 7.7\times10^{-5}I^{2} + 17.92\times10^{-3}I + 0.492 \quad (3)$$

where PET is in mm per month, T is monthly mean temperature in Celsius, I is a heat index and the coefficient, a, is dependent on I.

For a given month, j, and year, i, the monthly water surplus or deficit, ($D_{i,j}$) is calculated by Eq. (4) given below:

$$D_{i,j} = PR_{i,j} - PET_{i,j} \quad (4)$$

where PR is precipitation and PET is potential evapotranspiration. Then, accumulated monthly water surplus or deficits at time scale k ($X_{i,j}^{k}$) is calculated based on $D_{i,j}$. In this study, we chose 12 months for the time scale.

As suggested in Vicente–Serrano et al. (2010), $SPEI_{i,j}^{k}$ is estimated by fitting $X_{i,j}^{k}$ to the log-logistic distribution by means of the L-moments method by Hosking (1990)) as given in Eq. (5).

$$f(y) = \left[1 + \left(\frac{\alpha}{y-\gamma}\right)^{\beta}\right]^{-1} \quad (5)$$

where $f(y)$ is the cumulative density function of a three-parameter log-logistic distribution and α, β and γ are the scale, shape, and origin parameters, respectively.

A drought event is defined when an $SPEI_{i,j}^{k}$ is less than -1. Drought frequency (F) for the study period can be calculated by the following equation:

$$F = \frac{n}{N}\times100 \quad (6)$$

where n is the number of months with SPEIs less than -1 and N is the total number of months of *the study period."*

Page 9, Line 7: *"The present study uses SPEI by calculating PET with the Thornthwaite approach, which considers air temperature as a governing feature of PET. However, there are various other methods to calculate PET. For example, the Penman–Montieth method is more physically realistic but requires a diverse input data set (i.e., humidity, radiation coefficient, and wind speed). Van der Schrier et al. (2011) calculated the change in the global Palmer Drought Severity Index (PDSI) using two distinct estimates for PET (e.g., Thornthwaite and Penman Monteith). The authors found that PSDI based on two PET estimates are identical in terms of trend, average values, and classifying severe wet or dry periods. Conversely, McVicar et al. (2012) suggests that climatic conditions other than temperature that affect PET, may balance temperature rise (McVicar et al., 2012); therefore, further investigations with multiple approaches could inform future drought characteristics."*

Ll 82 (pag. 3): "... aN ordered data structure ...", it is not clear to me what this refers to. I would suggest to make this explanation more explicit.

>> This expression has been deleted.

In my opinion, in the **Results and Discussions** section, the model evaluation should be performed using a simulation forced by re-analyses. In the model evaluation presented in the manuscript, it is difficult to understand how the divergent behavior of GCMs over the Congo Basin may influence the ensemble mean, which is compared to observations in Figure 2. In general, I found the presentation and discussion of results confused and hard to follow using the provided figures. My suggestion would be to (a) re-structure this section and the related figures, (b) include a more quantitative discussion in relation to other studies, and (c) asses the significance of the shown results.

>> As pointed earlier, this study builds upon the previous studies of Wang et al. (2016) and Erfanian et al. (2016). In particular, Wang et al. (2016) provides extensive model evaluations with the re-analysis data. However, we agree that the model should be evaluated for capturing the drought characteristics in this study; thus, we have revised section 3.1 to provide the model evaluations with the runs with the ERA-Interim data along with added new figures (Figs 1, 2 and 3).

>> Furthermore, we have re-constructed the results section as *"3.1 Model Performance for Present-day Droughts; 3.2. Projected Future Changes in Droughts; 3.3 Impact of Vegetation Dynamics on Future Droughts"* and revised the results analysis to clearly explain our findings along with the updated figures. We have re-arranged and re-drawn all of the difference figures by indicating the statistically significant differences with the dots. Please see the revised manuscript as it follows.

Ll. 15 (pag. 4): "... different RCMs ...", by checking the study of Erfanian et al. (2016), I think the authors are referring to different GCMs.

>> We have corrected this.

Ll. 18 (pag. 4): "... overestimating precipitation ...", it is hard to compare the figures and to distinguish the differences between observations and simulations, however it seems to me that precipitations are under-estimated over the Gulf of Guinea and the Congo Basin. A plot showing the differences between observations and model experiments will ease the identification and interpretation of model bias.

>> The comparison between HistSV and UDEL in the original manuscript is not appropriate. Instead, we have added the difference between EvalSV and UDEL in Fig.1. The phrase mentioned above has been removed.

Ll. 25–26 (pag. 5): This sentence is not clear to me. In RCM experiments, the climate forcing is prescribed, hence I do not understand how "a change in vegetation could impact climate forcings".

>> As per reviewer's suggestion, we have clarified it with changing it to *"how the change of vegetation could impact RCM-simulated climate conditions"*.

Ll. 45–46 (pag. 5): It is not clear to me that the experiments using the dynamic vegetation module clearly capture the "more severe and longer droughts". I think to support this statement an observation-based SPEI would be needed. If the authors could compute SPEI based on observations, I would suggest to add a line in Figure 6 that shows the monthly observation-based SPEI.

>> The comparison between HistSV and UDEL in the original manuscript is not appropriate. Instead, we have added the difference between EvalSV and UDEL in Fig.1. The phrase mentioned above has been removed.

Ll. 35 (pag. 5): " (Fig. 2c-3)" It is not clear to me if the authors are referring to Figure 2c and the whole Figure 3 or to something else. In my opinion, the figures are not well laid out because title and units are only inserted in the figure caption. Since all the figures are multi-panel, the reading becomes even more complex. Moreover, in Figure 1 the three boxes are nearly invisible. I would suggest to highlight better the three target regions and to draw these boxes on all the maps that are presented in the study.

>> As per reviewer's suggestion, we have re-drawn all the maps, re-arrange them and added the boxes of the three focal areas. We also revised the titles to include the details of all figures instead of the alphabet series. Please see the revised manuscript as it follows.

4. Minor comments

Below, I list typos and errors, and I point to sentences that I would suggest to rephrase in a clearer way.

LL 14–15 (pag. 1): I would suggest to replace "With utilizing ..." with "Using ..."

>> As suggested, we have corrected it.

LL 16–17 (pag. 1): I would suggest to replace "With the vegetation dynamics ..." with "By considering vegetation dynamics ..."

>> As suggested, we have corrected it.

LL 33 (pag. 2): "... that western end of Sahel ... whereas eastern Sahel..." should be replaced with "...that the western end of Sahel ... whereas the eastern Sahel ..."

>> As suggested, we have corrected it.

LL 36 (pag. 2): I would suggest to remove the comma between "... remain ..." and "... because ..."

>> As suggested, we have corrected it.

LL 42 (pag. 2): "... variability, he claimed ..." should be replaced with "... variability; the authors claimed ..."

>> As suggested, we have corrected it.

LL 43 (pag. 2): "Various studies ... have been documented ..." should be replaced with "... Various studies documented biosphere-atmosphere interactions ..."

>> As suggested, we have corrected it.

LL 51–54 (pag. 2): I would suggest to rephrase these two sentences to make them clearer and avoid redundancy.

>> The sentences have been revised as it follows:

Page 3, Line 11: *"Including DV in the model eliminates potential inconsistencies between prescribed vegetation and climate, but it can cause climate drift (enhancing model biases) (Erfanian et al., 2016)."*

LL 55 (pag. 2): "...Draught ..." should be replaced with "... Drought ..."

>> As suggested, we have corrected it.

LL 57 (pag. 2): "..., which ..." should be replaced with "... that ..."

>> As suggested, we have corrected it.

LL 79 (pag. 3): A space is missing before "Cloud"

>> As suggested, we have corrected it.

LL 81 (pag. 3): I would suggest to correct and simplify this expression: " While solving a surface biogeochemical, biogeophysical, ecosystem dynamical and hydrological processes ..."

>> As per reviewer's suggestion, we have simplified it with *"To solve various processes in the model (e.g. surface bio-geochemical and bio-geophysical processes, ecosystem dynamics, and hydrological process)"*.

LL 88 (pag. 3): "... distribution and vegetation distribution ... is established ..." should be replaced with "... distribution and vegetation distribution ... are established ... "

>> As suggested, we have corrected it.

LL 91–93 (pag. 3): I would suggest to rephrase the sentences that describe the different simulations to make them clearer and avoid redundancy.

>> As per reviewer's suggestion, we have clarified the different simulations as follow:

Page 4, Line 22: *"A total of 18 different numerical simulations are used in this study as in Table 1 with two evaluation runs and 16 experimental runs with the climate change scenarios. Numerical simulations are carried out in two distinct configurations, one in which the CN-DV module is activated (i.e, DV runs) and the other in which the CN-DV module is not activated (i.e., SV runs). Additionally, the LBCs are derived from ERA-Interim for the evaluation runs (EvalSV and EvalDV) and from four GCMs for the historical (1981–2000) (i.e., HistSV and HistDV) and future (2081–2100) runs (i.e., FutSV and FutDV) uner the RCP8.5 scenarios. The GCMs used in this study include the Community Earth System Model (CESM, Kay et al., 2015), the Geophysical Fluid Dynamics Laboratory Model (GFDL, Tim et al., 2004), the Model for Interdisciplinary Research on the Climate–Earth System Model (MIROC, Watanabe et al., 2011), and the Max Planck Institute Earth System Model (MPI-ESM, Giorgetta et al., 2013)."*

Ll 05 (pag. 4): The acronym PET has not been previously introduced.

>> As suggested, we have corrected it by adding the full name: potential evapotranspiration (PET).

Ll. 56 (pag. 5): "CO2" should be replaced with "CO2.

>> As suggested, we have corrected it.

Ll. 75 (pag. 6): The comma between "ensembles" and "show" should be removed because it divides the subject from the verb.

>> As suggested, we have corrected it.

Ll. 35 (pag. 7): "... CCSM show somewhat ..." should be replaced with "... CCSM shows somewhat ..."

>> As suggested, we have corrected it.

Ll. 08 (pag. 7): There is an extra "that" which needs to be removed.

>> As suggested, we have corrected it.

Projected effects of vegetation feedback on drought characteristics of West Africa using a coupled regional land–vegetation–climate model

[1]Muhammad Shafqat Mehboob, [1]Yeonjoo Kim, [1]Jaehyeong Lee, [2]Myoung-Jin Um, [3]Amir Erfanian, [4]Guiling Wang

[1]Department of Civil and Environmental Engineering, Yonsei University, Seoul, 03722, South Korea
[2]Department of Civil Engineering, Kyonggi University, Suwon-si Gyeonggi-do, 16227, South Korea
[3]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, 90095, USA
[4]Department of Civil and Environmental Engineering, University of Connecticut, Storrs, 06269, USA

Correspondence*:* Yeonjoo Kim (yeonjoo.kim@yonsei.ac.kr)

Abstract. This study investigates the projected effect of vegetation feedback on drought conditions in West Africa using a regional climate model coupled to the National Center for Atmospheric Research Community Land Model, the carbon-nitrogen (CN) module, and the dynamic vegetation (DV) module (RegCM-CLM-CN-DV). The role of vegetation feedback is examined based on simulations with and without the DV module. Simulations from four different global climate models are used as lateral boundary conditions (LBCs) for historical and future periods (i.e., historical: 1981–2000; future: 2081–2100). Using the standardized precipitation evapotranspiration index (SPEI), we quantify the frequency, duration and intensity of droughts over the focal regions of the Sahel, Gulf of Guinea, and Congo Basin. By the vegetation dynamics being considered, future droughts become more prolonged and enhanced over the Sahel, whereas for the Gulf of Guinea and Congo Basin, the trend is opposite. Additionally, we show that simulated annual leaf greenness (i.e., the Leaf Area Index) correlates well with annual minimum SPEI, particularly over the Sahel, which is a transition zone, where the feedback between land-atmosphere is relatively strong. Furthermore, we note that our findings based on the ensemble mean are varying, but consistent among three different LBCs except for one LBC. Our results signify the importance of vegetation dynamics in predicting future droughts in West Africa, where the biosphere and atmosphere interactions play a significant role in the regional climate setup.

1 Introduction

West Africa is significantly vulnerable to climate change yet projecting its future climate is a challenging task (Cook, 2008). From the 1970s, a long period of drought was observed over West Africa, lasting until the late 1990s. While it is important to reduce the uncertainties and improve the reliability of future climate projections, there is no clear consensus about whether the future of the West African hydroclimate will be drier or wetter. Some studies projected drying trends (Hulme et al., 2001), whereas others predicted a wetter future (Hoerling et al., 2006; Kamga et al., 2005; Maynard et al., 2002). Caminade and Terray (2010) examined the simulated rainfall over the Sahel at the end of twenty-first century with the 21 models from the Coupled Model Intercomparison Project (CMIP) Phase 3 (CMIP3). They argued that different model projections are highly

Deleted: With utilizing
Deleted: Standardized Precipitation Evapotranspiration Index
Deleted: severity
Deleted: the
Deleted: the
Deleted: With
Deleted: Gulf
Deleted: well-
Deleted: ,
Deleted: still
Deleted: outlook
Deleted: reviewed
Deleted: A1B scenarios
Deleted:
Deleted: coupled
Deleted:), which focused on a balanced emphasis on all energy resources, for the Sahel
Deleted:
Deleted:

uncertain because future rainfall may be affected by changes in surface conditions (e.g., vegetation, land use and soil moisture) that have not been considered in CMIP3 models. Roehrig et al. (2013) combined the CMIP3 and CMIP Phase 5 (CMIP5) global climate models (GCM) and found that the western Sahel shows a drying trend whereas the eastern Sahel shows an opposite trend. Limited-area models, i.e., regional climate models (RCMs), which are forced with lateral boundary conditions (LBCs) derived from GCMs, are often used as they can capture finer details compared with GCMs (Kumar et al., 2008) since the physics of RCMs dominate the signals imposed by large-scale forcings (i.e., LBCs from GCMs). Recently, Akinsanola and Zhou (2019) investigated projected changes in extreme summer rainfall events over West Africa with data from the Coordinated Regional Climate Downscaling Experiment (CORDEX) models. Results showed the RCMs reasonably reproduced the observed pattern of extreme rainfall over the region. Future projections under the representative concentration pathways (RCPs) showed a statistically significant decrease in total rainfall and an increase in consecutive dry days and extreme rainfall.

Because climate and greenhouse gas concentrations continuously change, a noticeable change is expected in the vegetation as well (Yu et al., 2014b). Thus, the global and regional climate models should incorporate more representative and reliable prognostic vegetation dynamics instead of prescribed vegetation composition and structure, particularly for the regions where biosphere-atmosphere interactions are significant (Alo and Wang, 2010; Patricola and Cook, 2010; Wramneby et al., 2010; Xue et al., 2012; Zhang et al., 2014). Charney et al. (1975) first suggested that precipitation could change dynamically in response to vegetation variability; the authors claimed that changes in precipitation over the Sahel are due to reduction in vegetation and increase in albedo. Various studies documented biosphere–atmosphere interactions (Wang and Eltahir, 2000; Patricola and Cook, 2008; Kim and Wang, 2007), but there are a few studies in which a RCM including the prognostic vegetation dynamic is used because their developments are in their initial stages (Cook and Vizy, 2008; Garnaud et al., 2015; Wang et al., 2016; Yu et al., 2016).

Cook and Vizy (2008) developed a vegetation model coupled with a RCM to estimate the influence of global warming on South America by allowing interactions between climate and vegetation. With the simulation of the future climate under the A2 scenario, the authors found a reduction in vegetation cover of almost 70% in the Amazon rainforest along with a widespread increase in grass and shrubland in the east by the end of 21st century. This highlights the importance of considering vegetation dynamics in RCMs. Garnaud et al. (2015) combined the Canadian Regional Climate Model (CRCM5) with the Canadian Territorial Ecosystem Model (CTEM) to investigate the impact of a vegetation model to simulate the present day climate over North America. The result showed that introducing vegetation dynamics improved the model's performance in some regions, along with introducing new biases in other regions, owing to biases in simulated leaf area index (LAI). This atmospheric-vegetation interaction also introduced long term memory, which was estimated using a lagged correlation between temperature/precipitation and LAI. Wu et al. (2016) utilized a regional earth system model coupled with the dynamic vegetation model, RCA-GUESS (Smith et al., 2011), and investigated the role of vegetation dynamics on climate in Africa under the RCP8.5 projected climate scenario. The authors showed that introducing vegetation processes amplifies the warming

Deleted: found no clear evidence of precipitation trending over Africa
Deleted: end of
Deleted: Regional Climate Models (RCMs)
Deleted: as
Deleted: to
Deleted:). The
Deleted: forcing
Deleted: forces with boundary conditions derived from GCMs). However, discrepancies still remain, because
Deleted: have distinct systematic errors with West African precipitation, varying in amplitude and
Deleted: across models (Druyan et al., 2009; Paeth et al., 2011).
Deleted: is expected
Deleted: A
Deleted: model requires incorporation of dynamic
Deleted: (DV)
Deleted: static
Deleted: (SV)
Deleted: conceptualized the idea
Deleted: , he
Deleted: is
Deleted: of
Deleted: have been documented
Deleted: et al.,
Deleted:)
Deleted: coupled
Deleted: -DV
Deleted: . Such studies
Deleted: For example,
Deleted: introduced
Deleted: coupled potential
Deleted: into an
Deleted: American
Deleted: They
Deleted: highlighting
Deleted: using DV
Deleted:
Deleted:

trend and enhanced precipitation reduction over rainforest areas, which highlights the impact of introducing vegetation processes in a climate model.

Recently, Wang et al. (2016) introduced a dynamic vegetation feature into the International Center for Theoretical Physics Regional Climate Model (RegCM4.3.4) (Giorgi et al., 2012) with carbon–nitrogen (CN) dynamics and dynamic vegetation (DV) (RegCM-CLM-CN-DV) of the community land model (CLM4.5) (Lawrence et al., 2011; Oleson et al., 2010) and validated the coupled model over tropical Africa. With the RegCM-CLM-CN-DV, Yu et al. (2016) and Erfanian et al. (2016) examined the impacts of vegetation dynamics on the climate and ecosystems using multiple LBCs from past and future GCM simulations over West Africa. Yu et al. (2016) showed that climate projections of dynamic vegetation feedback was found mainly in semiarid areas of West Africa with little signal in the wet tropics. Erfanian et al. (2016) demonstrated the substantial sensitivity of the simulated precipitation, evapotranspiration, and soil moisture to vegetation representation. Including DV in the model eliminates potential inconsistencies between prescribed vegetation and climate, but it can cause climate drift (enhancing model biases) (Erfanian et al., 2016).

Various drought indices (e.g., the Palmer Drought Severity index (Palmer, 1965) and the Standard Precipitation Index (SPI, McKee et al., 1993)) have been used to assess drought events. Vicente–Serrano (2010) suggested the standardized precipitation evapotranspiration index (SPEI). It uses the deficit between precipitation and potential evapotranspiration and can include the effects of temperature variability on drought assessment. Therefore, it can be closely related to hydrologic and ecological drought processes although it only use climate conditions. Since the development of SPEI, various drought studies have adopted this index (Boroneant et al., 2011; Deng, 2011; Li et al., 2012a; Li et al., 2012b; Lorenzo–Lacruz et al., 2010; Paulo et al., 2012; Sohn et al., 2013; Spinoni et al., 2013; Yu et al., 2014a). For example, McEvoy et al. (2012) used SPEI as a drought index to monitor conditions over Nevada and Eastern California, proposing that SPEI was a convenient tool to describe the drought in arid regions. Recently, Diasso and Abiodun (2017) investigated the future impacts of global warming and reforestation on drought patterns simulated with the regional climate models over West Africa using the SPEI. Author showed that reforestation over the Savanna could reduce the future warming and increase the precipitation, but the impact of reforestation on the frequency of severe droughts could be doubled.

In this study, we aim to understand the impacts of vegetation feedbacks on the future of droughts over West Africa. Specifically, SPEI is used to depict vegetation feedbacks on drought characteristics according to frequencies, intensity, and duration over West Africa. Following the previous studies with RegCM-CLM-CN-DV (Wang et al., 2016; Yu et al., 2016; Erfanian et al., 2016), we examined the drought characteristics simulated with and without vegetation dynamics for the historical and future periods and showed the signals of DV on the drought processes in three selected regions of West Africa.

Deleted: DV
Deleted: Carbon–Nitrogen
Deleted:). They
Deleted: (Wang et al., 2016;
Deleted: .,
Deleted:). The advantage
Moved (insertion) [1]
Deleted: simulating
Deleted: discrepancies
Deleted: the climate conditions and bioclimatic conditions required to
Deleted: create
Deleted: draft, i.e., biases in the
Deleted: Additionally, such a model is advantageous, because it provides a capacity to simulate future terrestrial ecosystems as the climate evolves.
Deleted: Among various
Deleted: Draught
Deleted: ,
Deleted: Standardized Precipitation Evapotranspiration Index
Deleted:), which
Deleted: .
Deleted: researchers
Deleted: for drought studies
Deleted: Wang et al., 2016; Yu et al., 2014a; Yu et al., 2014b). Abiodun et al. (2013) studied the climate change and corresponding extreme events caused by afforestation in Nigeria while defining the drought events using SPEI.
Deleted: impact
Deleted: feedback
Deleted: feedback
Deleted: severity
Deleted: Four sets of GCMs are used to force
Deleted: RCM
Deleted: . By comparing the drought characteristics between
Deleted: two simulation sets, we show
Deleted: different
Deleted:
Deleted:

2 Methodology

2.1 Model Description

This study uses state-of-the-art RegCM-CLM-CN-DV (Wang et al., 2016). Specifically, RegCM4.3.4 (Giorgi et al., 2012) and CLM4.5 (Lawrence et al., 2011; Oleson et al., 2010) with CN dynamics and DV are coupled to simulate various atmospheric, land, biogeochemical, vegetation phenology, and vegetation distribution processes. RegCM is a regional model that uses an Arakawa B-grid finite differencing algorithm along with a terrain-following σ-pressure vertical coordinate system. Grell et al. (1994) introduced an additional dynamic component in the model that is taken from the hydrostatic version of the Pennsylvania State University Mesoscale Model version 5. From the Community Climate Model (Kiehl et al., 1996) a radiation scheme was added. The model covers four different convection parameterization schemes namely 1) the modified-Kuo scheme (Anthes et al., 1987), 2) the Tiedtke scheme (Tiedtke, 1989), 3) the Grell scheme (Grell, 1993) and 4) the Emanuel scheme (Emanuel, 1991) along with the non-local boundary layer scheme of Holtslag et al. (1990). The cloud and precipitation scheme comes from the physics package (Pal et al., 2000). The aerosols algorithm follows Solmon et al. (2006) and Zakey et al. (2006).

To solve the various processes in the model (e.g. surface bio-geochemical and bio-geophysical processes, ecosystem dynamics, and hydrological processes), CLM4.5 considers fifteen soil layers, sixteen distinct plant functional types (PTF), up to five snow layers in each grid cell (Lawrence et al., 2011). An optional component present in this model is the CN and DV module. The CN module not only simulates CN cycles and plant phenology and maturity but also estimates vegetation height, stem area index and LAI. The DV module projects the fractional coverage of different plant functional types (PFTs) and corresponding temporary variations at yearly time steps developed using a CN-estimated carbon budget. It also accounts for plant existence, activity, and formation. If CN and DV modules are inactive, the distribution and vegetation composition in the model are established according to the observed data sets (i.e., static vegetation, hereafter referred to as SV).

2.2 Numerical Experiments

A total of 18 different numerical simulations are used in this study as in Table 1, with two evaluation runs and 16 experimental runs with the climate change scenarios. Numerical simulations are carried out in two distinct configurations, one in which the CN-DV module is activated (i.e, DV runs) and the other in which the CN-DV module is not activated (i.e., SV runs). Additionally, the LBCs are derived from ERA-Interim for the evaluation runs (1989-2008) (i.e., EvalSV and EvalDV) and from four GCMs for the historical (1981–2000) (i.e., HistSV and HistDV) and future (2081–2100) runs (i.e., FutSV and FutDV) under the RCP8.5 scenario. The GCMs used in this study include the Community Earth System Model (CESM, Kay et al., 2015), the Geophysical Fluid Dynamics Laboratory Model (GFDL, Tim et al., 2004), the Model for Interdisciplinary Research on the Climate–Earth System Model (MIROC, Watanabe et al., 2011), and the Max Planck Institute Earth System Model (MPI-ESM, Giorgetta et al., 2013). The model grid is configured using a 50-km horizontal grid spacing and 18 vertical layers, from the surface to 50 hPa. The model parameterizations are the same as the those used in the previous studies over the

Deleted: Model
Deleted: Cloud
Deleted: Aerosols
Deleted: While solving a
Deleted: biogeochemical, biogeophysical
Deleted: dynamical
Deleted: ,
Deleted: and a ordered data structure
Deleted: Erfanian et al., 2016;
Deleted: ; Wang et al., 2016).
Deleted: leaf area index (
Deleted:).
Deleted: ,
Deleted: it
Deleted: it means that
Deleted: is
Deleted: This study focuses on the West African region with emphasis on three regions over the study domain (see Fig. 1): the Sahel, the Gulf of Guinea, and the Congo Basin.
Deleted: 16
Deleted: performed (
Deleted:). To investigate the impacts of DV, simulation of model is
Deleted: for the RCMs
Deleted: four GCMs: the Community Earth System Model (
Deleted: model,
Deleted: . These eight simulations are performed for two different periods: the present (i.e., 1981–2000) (CMIP5-historical) and the future (i.e., 2081–2100) (CMIP5-RCP8.5).
Deleted: one used by Wang et al. (2016) and
Moved down [2]: Yu et al.
Deleted: (2016), which was optimized with
Deleted: applications
Deleted:
Deleted:

same region (Alo and Wang, 2010; Saini et al., 2015; of Wang et al., 2016) as the list of parameterizations used in this study are summarized in Table 2.

Wang et al. (2016) extensively evaluated the RegCM-CLM-CN-DV model for simulating regional climate and ecosystems in West Africa. The evaluation was performed using the LBCs from the ERA-Interim (1989-2008), and with and without vegetation dynamics. Yu et al. (2016) and Erfanian et al. (2016) also examined the impacts of vegetation dynamics on the climate and ecosystems using multiple LBCs from past and future GCM simulations. Building upon these previous studies, this study focuses on the impacts of vegetation dynamics on the regional drought characteristic (i.e., frequency, duration, and intensity) over the focal regions of the West African domain: the Sahel, the Gulf of Guinea, and the Congo Basin (Fig. 1).

2.3 SPEI

In this study, we estimated the SPEI using the approach of Beguería and Vicente-Serrano (2013). While the precipitation is the simulated output of RegCM-CLM-CN-DV, the potential evapotranspiration (PET) should be derived from the model outputs. Owing to the simplicity and availability of the data set, we used Thornthwaite's (1948) approach that only requires the air temperature. Thornthwaite derived an equation to calculate PET as follows:

$$PET = 16\left(\frac{10\,T}{I}\right)^{a} \qquad (1)$$

$$I = \sum_{j=1}^{12}\left(\frac{T}{5}\right)^{1.514} \qquad (2)$$

$$a = 6.75\times10^{-7}I^{3} - 7.7\times10^{-5}I^{2} + 17.92\times10^{-3}I + 0.492 \qquad (3)$$

where PET is in mm per month, T is monthly mean temperature in Celsius, I is a heat index and the coefficient, a, is dependent on I.

For a given month, j, and year, i, the monthly water surplus or deficit, ($D_{i,j}$) is calculated by Eq. (4) given below:

$$D_{i,j} = PR_{i,j} - PET_{i,j} \qquad (4)$$

where PR is precipitation and PET is potential evapotranspiration. Then, accumulated monthly water surplus or deficits at time scale k ($X_{i,j}^{k}$) is calculated based on $D_{i,j}$. In this study, we chose 12 months for the time scale.

As suggested in Vicente–Serrano et al. (2010), $SPEI_{i,j}^{k}$ is estimated by fitting $X_{i,j}^{k}$ to the log-logistic distribution by means of the L-moments method by Hosking (1990)) as given in Eq. (5).

$$f(y) = \left[1 + \left(\frac{\alpha}{y-\gamma}\right)^{\beta}\right]^{-1} \qquad (5)$$

where $f(y)$ is the cumulative density function of a three-parameter log-logistic distribution and α, β and γ are the scale, shape, and origin parameters, respectively.

A drought event is defined when an $SPEI_{i,j}^{k}$ is less than -1. Drought frequency (F) for the study period can be calculated by the following equation:

Deleted: and Alo, 2012; Yu

Deleted: 2014b). Its performance and simulation details with ERA-interim and future projections were documented by

Moved down [3]: Wang et al.

Moved up [1]: Erfanian et al.

Deleted: (2016) and

Deleted: (2016), respectively.

Moved (insertion) [3]

Moved (insertion) [2]

Deleted: Vicente–Serrano et al. (2010) gave a simple approach to estimate SPEI. Thornthwaite (1948) method is used to calculate monthly PET in first step, this method utilizes three parameters 1) temperature, 2) latitude and 3) time.

Deleted: 1

Deleted: .

Deleted: 1

Deleted: Where

Deleted: In the second step

Deleted: , ($X_{i,j}^{k}$),

Deleted: i.e., 12 months) in a given month, j, and year, i,

Deleted: D. Finally,

Deleted: mean

Deleted: (

Deleted:). In this study, we define

Deleted: with

Deleted: of

Deleted:

Deleted:

$$F = \frac{n}{N} \times 100 \quad (6)$$

where n is the number of months with SPEIs less than -1 and N is the total number of months of the study period.

3 Results Analysis

3.1 Model Performance for Present-day Droughts

This section briefly evaluates the model performance with observed climate and vegetation and drought characteristics (Figs 1, 2 and 3). The runs with the ERA-Interim with and without vegetation dynamics for 1989-2008 (Table 1) are briefly presented for the model evaluation. Detailed evaluations of the model performance are documented in Wang et al. (2016). Relative to the observational data from the University of Delaware (UDEL), both EvalSV and EvalDV (Fig. 1) follow the observed spatial patterns of precipitation with slightly underestimating precipitation over the Sahel and overestimating over the Congo Basin. Such dry/wet biases lead to warm/cool biases in air temperature via the reduction/enhancement of evaporative cooling in the Sahel/Congo Basin. In general, the model performs slightly better with SV than with DV in the evaluation runs. But note that DV could eliminate potential consistencies between prescribed vegetation and climate particularly for the future projections.

With the addition of vegetation dynamics, the LAI (Fig. 2) is overestimated in the eastern parts of Gulf of Guinea and the northern parts of Congo Basin, and it is underestimated in the Sahel (EvalDV-EvalSV). The run without vegetation dynamics (EvalSV) uses the Moderate Resolution Imaging Spectroradiometer (MODIS)-based monthly-varying climatological LAI values. Over the Sahel, the model underestimates the woody plants and grasses with a significant overestimation of bare ground area, which can be attributed to biases in the vegetation dynamics of CLM-CN-DV model as well as the RegCM physical climate, i.e., dry bias (Wang et al., 2016; Erfanian et al., 2016). The dry/wet bias in the atmospheric forcings over the Sahel/Congo Basin contributes to the underestimated/overestimated LAI, which then leads to additional decreases/increases in precipitation for that region.

We also investigated the precipitation surplus/deficit (right column of Fig. 1) that is used for calculating the SPEI values to analyze the drought characteristics. We found that the differences of EvalDV and EvalSV for the precipitation surplus/deficit follow those of the precipitation in these cases. The estimated SPEI over three regions are compared in Fig. 3. While the general cycles of SPEI are limitedly captured in the model, the SPEI differences between UDEL and EvalSV may contribute to the limits of RegCM4. The difference between EvalSV and EvalDV is opposite between the Sahel and other regions, which corresponds to the bases of the precipitation surplus/deficit in Fig. 1. In the Sahel, the more severe and longer droughts are simulated for EvalDV compared with EvalSV. In the Gulf of Guinea and the Congo basin, the opposite was observed.

Deleted: and Discussions
Deleted: 3.1
Moved down [4]: Historical
Deleted: Climate, Vegetation and Drought
Deleted: study
Deleted: presents
Deleted: present-day
Deleted: ,
Deleted: ,
Deleted: droughts, simulated
Deleted: RegCM-CN-DV
Deleted: , as detailed
Deleted: performance, including the
Deleted: according to different RCMs, which was already provided by Erfanian et al.
Deleted: Fig. 1
Deleted: SV
Deleted: DV ensembles (Figs. 2a and 2b
Deleted: and air temperature
Deleted: overestimating
Deleted: and southern parts of the Congo Basin. But over S ... [1]
Deleted: region and southern and northern parts of the Con ... [2]
Deleted: , where
Deleted: LAI represents
Deleted: -
Deleted: values (Figs. 3a, 3b, and 3e). It seems that ... [3]
Deleted: Such dry biases lead to warm bias in air temperat ... [4]
Deleted: The
Deleted: Eq. (1),
Deleted: 2c) was
Deleted: in
Deleted: frequency. Precipitation minus potential ... [5]
Deleted: (Fig. 2c-3)
Deleted: that
Deleted: and temperature, as expected. ... [6]
Moved down [5]: CCSM
Deleted: presents increase in drought frequency in DV rela ... [7]
Deleted: estimated in Fig. 6.
Deleted: clearly captured for the present-day DV ensemble ... [8]
Deleted: is found because of the vegetation dynamics. Also ... [9]
Deleted:
Deleted:

3.2 Projected Future Changes in Droughts

This section investigates the changes in climate and vegetation and drought characteristics between the future and historical periods in the experimental runs (Table 1). First, the projected changes in the climate conditions in the future, relative to the historical periods, are examined in Fig. 4. Similar spatial patterns of changes are shown in both SV and DV ensembles. In the SV ensemble (FutSV-HistSV, first row of Fig. 4), small decreases in precipitation are found in the Sahel and Congo Basin. For the DV ensemble (FutDV-HistDV, second row of Fig. 4), it is clearly visible that the band of precipitation below 10 °N increases up to 56.4 m/month. As expected, atmospheric warming caused by the increased CO_2 concentration in the future scenario leads to widespread increases in temperatures for both SV and DV ensembles.

Consistent with such changes in climate conditions, there are changes in LAI (FutSV-HistSV and FutDV-HistDV of Fig. 2) because of atmospheric warming and CO_2 fertilization. Over the regions below 10 °N, widespread increases in future LAI in FutDV are found, compared with that from HistDV. Beyond 10 °N, vegetation cover is sparse and there are no noticeable changes in future LAI. Note that LAI does not differ for either HistDV or FutDV.

In the future, the precipitation surplus/deficit shows a general decline for both SV and DV ensembles (FutSV-HistSV and FutDV-HistDV in the right column of Fig. 4). Only local increases in precipitation surplus/deficit near 10 °N are captured by the DV ensemble. Such changes in precipitation surplus/deficit lead to similar changes in drought frequencies between the future and historical periods for both SV and DV ensembles (Fig. 5). Corresponding to the band of precipitation increase, a slight decrease in drought frequency of up to 15 % is observed in the DV ensemble.

3.3 Impact of Vegetation Dynamics on Future Droughts

A vegetation dynamic component should be included in a land-atmospheric coupled model for future climate projections, although including this property makes the model more complex it is closer to a realistic scenario. In this section, we focus on the role of vegetation dynamics in future ensembles (i.e., the difference between DV and SV for the future; i.e., FutDV-FutSV).

Investigating the difference of LAI between DV and SV for the future period (FutDV-FutSV of Fig. 2), we find that the LAI for the DV ensemble is smaller than that of SV over the Sahel and larger below 10 °N. LAI differences between SV and DV ensembles show similar patterns both in historical and future periods and LAI biases are caused by the biases from both CLM-CN-DV and RegCM in the historical period, as well as in the future period (FutDV-FutSV vs. HistDV-HistSV). Note that the underestimated LAI in the Sahel is not necessarily a bias in the future simulations, because the future LAI in SV is assumed to be identical to historical climatological LAI as in the historical SV ensemble.

Differences between DV and SV in precipitation and air temperature (FutDV-FutSV of Fig. 4) follow the LAI differences. As examined in Erfanian et al. (2016), along with lower LAI in the Sahel, when comparing DV with SV, higher albedo, lower cooling, lower evapotranspiration, and lower precipitation is simulated, this is due to a strong land-atmosphere coupling that is known in regions like the Sahel. Note that such changes in LAI do not always accompany changes in the

Deleted: Predicted…rojected Future Climate, Vegetati … [11]

Deleted: In this…his section, we focus on…investigates the projected future…hanges in climate,…and vegetation, and droughts, simulated with…and without vegetation dynamics.…rought characteristics between the future and historical periods in the experimental runs (Table 1). First of all,… the projected precipitation…hanges in the climate conditions in the future period of … relative to the historical periods, are examined in Fig. 4. Similar spatial patterns of changes are shown in both SV and DV ensembles (Figs. 7a and 7b) shows the similar spatial patterns to that of the past with different regional changes.… In the SV ensemble (FutSV-HistSV, first row of Fig. 7a-3…), small decrease…ecreases in precipitation are found in the Sahel and the …ongo Basin. For the DV ensemble (FutDV-HistDV, second row of Fig. 7a-…), it is clearly visible that the band of precipitation below 10 °N increases up to 56.4 m/month. As expected, atmospheric warming caused by the increased CO_2 concentration in the future scenario leads to widespread increases in temperatures for both SV and DV ensembles (Figs. 7b-3 and 7b-4). … [12]

Deleted: vegetation state (i.e., LAI) …here are changes in LAI (FutSV-HistSV and FutDV-HistDV of Fig. 2) because of atmospheric warming and CO_2 fertilization. In…ver the DV ensemble (Figs. 3d and 3e),…egions below 10 °N, widespread increases in future LAI in FutDV are found, compared to…ith that from the historical period over the regions below 10 °N…istDV. Beyond 10 °N, vegetation cover is sparse and there are no noticeable changes in future LAI. Note that LAI does not differ for both historical or future periods in SV … [13]

Deleted: Figs. 7c-3 and 7c-4).…utSV-HistSV and FutDV-HistDV in the right column of Fig. 4). Only local increases in precipitation surplus/deficit near 10 °N are captured by the DV ensemble. Such changes in precipitation surplus/deficit lead to similar changes in drought frequencies between the future and historical periods for both SV and DV ensembles (Figs. 4b and 4c…ig. 5). Corresponding to the band of precipitation increase, a slight decrease of…n drought frequency of up to 15 % is shown … [14]

Deleted: vegetation dynamics…egetation Dynamics on future droughts … [15]

Deleted: It is desired to include… vegetation dynamic component should be included in a land-atmospheric coupled model for future climate projections, although including this property makes the model more complex but …t is closer to a realistic model. … [16]

Deleted: 3f…), we find that the LAI for the DV ensemble is smaller than that of SV over the Sahel and larger below 10 °N. Such different responses of vegetation can be attributed to dominant vegetation types over the regions as grasses and trees are dominant over the Sahel and below the 10°N respectively. We note that …AI differences between SV and DV ensembles,…show quite …imilar patterns both in historical and future periods (Figs. 3c …nd 3f) with…LAI biases are caused by climate…he biases from both CLM-CN-DV and RegCM in the historical period being similarly shown… as well as in the future period. … [17]

Deleted: Figs. 7a-5 and 7b-5…utDV-FutSV of Fig. 4) follow the LAI differences of the … [18]

Deleted: … PAGE * MERGEFORMAT 7 … [10]

dominant vegetation types. With increased LAI in the future there will be more grass in the Sahel, and changes in land cover from grasses to woody plants will be found in the Gulf of Guinea.

Over the region below 10 °N, wetter and colder climate conditions are predicted with the DV ensemble compared with the SV ensemble, resulting in increased precipitation surplus (FutDV-Fut SV in the right column of Fig. 4). Consequently, the frequencies of drought events decrease up to 40 % over the Gulf of Guinea and increases up to 43 % over the Sahel, based on the ensemble averages (FutDV-Fut SV of Fig. 5). Such characteristics in the ensemble averages are captured in the difference of drought frequency between DV and SV of each ensemble member to different extents (Fig. 6). While the Sahel and Guinea Coast regions present relatively similar differences in the drought frequency, the central Congo Basin shows different trends among the different LBCs. CCSM presents increases in drought frequency in DV relative to SV, but MIROC presents the opposite trend. GFDL and MPI-ESM presents relatively weak differences.

The differences of regional averages of SPEI over the three different regions (the last rows in each panel of Fig. 7) present the impact of vegetation dynamics on future drought intensity and duration. Ensemble averages show that more prolonged and more severe droughts are projected over the Sahel and vice versa for the Gulf of Guinea and the Congo Basin. Among ensemble members with different LBCs, CCSM presents different results from other LBCs, by not capturing the decreased droughts for the Gulf of Guinea and the Congo Basin.

Figure 8 presents the correlation coefficients between annual maximum LAI and annual minimum SPEI over the regions for both historical and future periods. With drought events, as reflected in the relatively lower annual minimum SPEI, the annual maximum LAI should be smaller, because leaf growth is limited during such events. Such interactive responses of vegetation to climate conditions are only captured in the DV ensemble (no correlation in the SV ensemble, not shown). When DV is active, a large portion of West Africa has a strong positive association between the maximum LAI and minimum SPEI. Relatively strong correlations with the coefficient up to 0.91 are found along the Sahel, which may be due to feedbacks between land–atmosphere is relatively strong in transition zones.

4 Discussion and Conclusions

In this study, we employed the drought index (i.e., SPEI) to quantitatively assess the effects of vegetation dynamics on projected future droughts over West Africa. The impact of vegetation feedbacks on drought projection was examined both with and without considering vegetation dynamics. This study suggests that, with the vegetation dynamics considered, drought is prolonged and enhanced over the Sahel, whereas for the Gulf of Guinea and Congo Basin, the trend is clearly the opposite. Such opposite changes could be attributed to amplified differences because a feedback exists between climate and vegetation in a dynamic vegetation model, as well as due to the bioclimatic inconsistency in the static vegetation model. These results are consistent over three different LBCs; however, the LBC with CCSM shows opposite results for the Congo Basin. Furthermore, we show that simulated annual leaf greenness (i.e., LAI) was correlated well with annual minimum SPEI, particularly over the Sahel, which is a sensitive, transition zone, where the feedback between land–atmosphere is relatively strong.

Deleted: state (i.e., LAI).
Deleted: to
Deleted: , as shown
Deleted: 7c-5.
Deleted: Fig. 4d). Among the runs with different LBCs, the inconsistency in the
Deleted: is found over
Deleted: with
Deleted: , as already pointed out in the historical simulations.
Deleted: see
Deleted: 6
Deleted: severity
Deleted: Gulf
Deleted: a bit
Deleted: Gulf
Deleted: We next present
Deleted: (Fig. 8).
Deleted: .
Deleted: attribute to the fact that feedback
Deleted: 4 Conclusion
Deleted: drought
Deleted: feedback
Deleted: Gulf
Deleted: attribute
Deleted: biases
Deleted: quite
Deleted: 3
Deleted: while
Deleted: show somewhat
Deleted: well
Deleted:
Deleted:

While most future drought characterization studies with climate model predictions have been carried out without considering the role of vegetation (e.g., Cook et al., 2015; Huang et al, 2018), this study suggests the necessity of the comprehensive understanding of biosphere–atmosphere interactions in future drought projections. Furthermore, it has been pointed out that such land–atmosphere feedbacks could exacerbate droughts under future climate projections (Dirmeyer et al., 2013; Zhou et al., 2019). Therefore, these drought studies are critical for not only the Sahel but also over other regions where positive feedbacks between land and atmosphere are strong, such as the interior of North America (Kim and Wang, 2007).

The present study uses SPEI by calculating PET with the Thornthwaite approach, which considers air temperature as a governing feature of PET. However, there are various other methods to calculate PET. For example, the Penman–Montieth method is more physically realistic but requires a diverse input data set (i.e., humidity, radiation coefficient, and wind speed). Van der Schrier et al. (2011) calculated the change in the global Palmer Drought Severity Index (PDSI) using two distinct estimates for PET (e.g., Thornthwaite and Penman-Monteith). The authors found that PSDI based on two PET estimates are identical in terms of trend, average values, and classifying severe wet or dry periods. Conversely, McVicar et al. (2012) suggests that climatic conditions other than temperature that affect PET, may balance temperature rise; therefore, further investigations with multiple approaches could inform future drought characteristics.

This study points out the potentially prolonged and enhanced drought events over the Sahel. Furthermore, many African countries are expected to experience population growth, and a majority of the population increase rates are found in neighboring countries in the Sahel, Niger and Chad (Ahmadalipur et al., 2019). Combined with the high likelihood of prolonged and enhanced drought and population growth there will likely be an increase in water demand. This will further exacerbate the risks of future drought and will present challenges for climate change adaptation for managing water needs in the region.

Data Availability. Observed data was collected from University of Delaware and model output data are available in https://github.com/yjkim1028/RegCM-CN-DV_data. In addition, a map with the country boundaries is drawn with 'mapdata' package of R-studio.

Author contribution. YK and GW designed the study and AE performed the simulations. MSM, JH and MU performed the results analysis. MSM, YK, AE and GW wrote the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This study was supported by the Basic Science Research Program through the National Research Foundation of Korea, which was funded by the Ministry of Science, ICT & Future Planning (2018R1A1A3A04079419) and the Internationalization Infra Fund of Yonsei University (2018 Fall semester).

Deleted: We note

Deleted: the

Deleted: the

Deleted: via

Deleted: that

Deleted: There

Deleted: one of them

Deleted: Penman method that that include many other variables

Deleted:) to calculate PET. Due to temperature rise, there may be limited effects on drought via increased PET because other

Deleted: affecting PET

Deleted: for

Deleted: (McVicar et al., 2012).

Deleted:

Deleted:

References

Abiodun, B. J., Salami, A. T., Matthew, O. J., and Ededokun, S.: Potential impacts of afforestation on climate change and extreme events in Nigeria, Climate dynamics, 41, 277-293, 2013.

Ahmadalipour, A., Moradkhani, H., Castelletti, A., and Magliocca, N.: Future drought risk in Africa: Integrating vulnerability, climate change, and population growth, Science of the Total Environment, 662, 672-686, 2019.

Akinsanola, A., and Zhou, W.: Projections of West African summer monsoon rainfall extremes from two CORDEX models, Climate Dynamics, 52, 2017-2028, 2019.

Alo, C. A., and Wang, G.: Role of dynamic vegetation in regional climate predictions over western Africa, Climate dynamics, 35, 907-922, 2010.

Anthes, R. A., Hsie, E.-Y., and Kuo, Y.-H.: Description of the Penn State/NCAR mesoscale model version 4 (MM4), NCAR Boulder, CO., 1987.

Beguería, S., and Vicente-Serrano, S. M.: SPEI: calculation of the standardized precipitation-evapotranspiration index, R package version, 1, 6, 2013.

Boroneant, C., Ionita, M., Brunet, M., and Rimbu, N.: CLIVAR-SPAIN contributions: seasonal drought variability over the Iberian Peninsula and its relationship to global sea surface temperature and large scale atmospheric circulation, WCRP OSC: Climate Research in Service to Society, 24-28, 2011.

Caminade, C., and Terray, L.: Twentieth century Sahel rainfall variability as simulated by the ARPEGE AGCM, and future changes, Climate Dynamics, 35, 75-94, 2010.

Charney, J., Stone, P. H., and Quirk, W. J.: Drought in the Sahara: a biogeophysical feedback mechanism, science, 187, 434-435, 1975.

Cook, K. H.: Climate science: the mysteries of Sahel droughts, Nature Geoscience, 1, 647, 2008.

Cook, K. H., and Vizy, E. K.: Effects of twenty-first-century climate change on the Amazon rain forest, Journal of Climate, 21, 542-560, 2008.

Cook, K. H., Vizy, E. K., Launer, Z. S., and Patricola, C. M.: Springtime intensification of the Great Plains low-level jet and Midwest precipitation in GCM simulations of the twenty-first century, Journal of Climate, 21, 6321-6340, 2008.

Cook, B. I., Ault, T. R., and Smerdon, J. E.: Unprecedented 21st century drought risk in the American Southwest and Central Plains, Science Advances, 1, e1400082, 2015.

Dirmeyer, P. A., Jin, Y., Singh, B., and Yan, X.: Trends in land–atmosphere interactions from CMIP5 simulations, Journal of Hydrometeorology, 14, 829-849, 2013.

Deng, F.: Global CO2 Flux Inferred From Atmospheric Observations and Its Response to Climate Variabilities, 2011.

Druyan, L. M., Fulakeza, M., Lonergan, P., and Noble, E.: Regional climate model simulation of the AMMA Special Observing Period# 3 and the pre-Helene easterly wave, Meteorology and atmospheric physics, 105, 191-210, 2009.

Deleted:

Deleted:

Emanuel, K. A.: A scheme for representing cumulus convection in large-scale models, Journal of the Atmospheric Sciences, 48, 2313-2329, 1991.
Erfanian, A., Wang, G., Yu, M., and Anyah, R.: Multimodel ensemble simulations of present and future climates over West Africa: Impacts of vegetation dynamics, Journal of Advances in Modeling Earth Systems, 8, 1411-1431, 2016.
Garnaud, C., Sushama, L., and Verseghy, D.: Impact of interactive vegetation phenology on the Canadian RCM simulated climate over North America, Climate Dynamics, 45, 1471-1492, 2015.
Giorgetta, M. A., Jungclaus, J., Reick, C. H., Legutke, S., Bader, J., Böttinger, M., Brovkin, V., Crueger, T., Esch, M., and Fieg, K.: Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5, Journal of Advances in Modeling Earth Systems, 5, 572-597, 2013.
Giorgi, F., Coppola, E., Solmon, F., Mariotti, L., Sylla, M., Bi, X., Elguindi, N., Diro, G., Nair, V., and Giuliani, G.: RegCM4: model description and preliminary tests over multiple CORDEX domains, Climate Research, 52, 7-29, 2012.
Grell, G. A.: Prognostic evaluation of assumptions used by cumulus parameterizations, Monthly Weather Review, 121, 764-787, 1993.
Grell, G. A., Dudhia, J., and Stauffer, D. R.: A description of the fifth-generation Penn State/NCAR mesoscale model (MM5), 1994.
Hoerling, M., Hurrell, J., Eischeid, J., and Phillips, A.: Detection and attribution of twentieth-century northern and southern African rainfall change, Journal of climate, 19, 3989-4008, 2006.
Holtslag, A., De Bruijn, E., and Pan, H.: A high resolution air mass transformation model for short-range weather forecasting, Monthly Weather Review, 118, 1561-1575, 1990.
Huang, J., Zhai, J., Jiang, T., Wang, Y., Li, X., Wang, R., Xiong, M., Su, B., and Fischer, T.: Analysis of future drought characteristics in China using the regional climate model CCLM, Climate dynamics, 50, 507-525, 2018.
Hulme, M., Doherty, R., Ngara, T., New, M., and Lister, D.: African climate change: 1900-2100, Climate research, 17, 145-168, 2001.
Kamga, A. F., Jenkins, G. S., Gaye, A. T., Garba, A., Sarr, A., and Adedoyin, A.: Evaluating the National Center for Atmospheric Research climate system model over West Africa: Present- day and the 21st century A1 scenario, Journal of Geophysical Research: Atmospheres, 110, 2005.
Kay, J., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J., Bates, S., Danabasoglu, G., and Edwards, J.: The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability, Bulletin of the American Meteorological Society, 96, 1333-1349, 2015.
Kiehl, T., Hack, J., Bonan, B., Boville, A., Briegleb, P., Williamson, L., and Rasch, J.: Description of the NCAR community climate model (CCM3), 1996.
Kim, Y., and Wang, G.: Impact of vegetation feedback on the response of precipitation to antecedent soil moisture anomalies over North America, Journal of Hydrometeorology, 8, 534-550, 2007.

Deleted:
Deleted:

Kumar, S. V., Peters-Lidard, C. D., Eastman, J. L., and Tao, W.-K.: An integrated high-resolution hydrometeorological modeling testbed using LIS and WRF, Environmental Modelling & Software, 23, 169-181, 2008.
Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence, P. J., Zeng, X., Yang, Z. L., Levis, S., and Sakaguchi, K.: Parameterization improvements and functional and structural advances in version 4 of the Community Land Model, Journal of Advances in Modeling Earth Systems, 3, 2011.
Li, W.-G., Yi, X., Hou, M.-T., Chen, H.-L., and Chen, Z.-L.: Standardized precipitation evapotranspiration index shows drought trends in China, Chinese Journal of Eco-Agriculture, 20, 643-649, 2012a.
Li, W., Hou, M., Chen, H., and Chen, X.: Study on drought trend in south China based on standardized precipitation evapotranspiration index, Journal of Natural Disasters, 21, 84-90, 2012b.
Lorenzo-Lacruz, J., Vicente-Serrano, S. M., López-Moreno, J. I., Beguería, S., García-Ruiz, J. M., and Cuadrat, J. M.: The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain), Journal of Hydrology, 386, 13-26, 2010.
Maynard, K., Royer, J.-F., and Chauvin, F.: Impact of greenhouse warming on the West African summer monsoon, Climate Dynamics, 19, 499-514, 2002.
McEvoy, D. J., Huntington, J. L., Abatzoglou, J. T., and Edwards, L. M.: An evaluation of multiscalar drought indices in Nevada and eastern California, Earth Interactions, 16, 1-18, 2012.
McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales, Proceedings of the 8th Conference on Applied Climatology, 1993, 179-183,
McVicar, T. R., Roderick, M. L., Donohue, R. J., Li, L. T., Van Niel, T. G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., and Mahowald, N. M.: Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation, Journal of Hydrology, 416, 182-205, 2012.
Oleson, K. W., Lawrence, D. M., Gordon, B., Flanner, M. G., Kluzek, E., Peter, J., Levis, S., Swenson, S. C., Thornton, E., and Feddema, J.: Technical description of version 4.0 of the Community Land Model (CLM), 2010.
Paeth, H., Hall, N. M., Gaertner, M. A., Alonso, M. D., Moumouni, S., Polcher, J., Ruti, P. M., Fink, A. H., Gosset, M., and Lebel, T.: Progress in regional downscaling of West African precipitation, Atmospheric science letters, 12, 75-82, 2011.
Pal, J. S., Small, E. E., and Eltahir, E. A.: Simulation of regional- scale water and energy budgets: Representation of subgrid cloud and precipitation processes within RegCM, Journal of Geophysical Research: Atmospheres, 105, 29579-29594, 2000.
Palmer, W. C.: Meteorological drought. Research Paper No. 45. Washington, DC: US Department of Commerce, Weather Bureau, 59, 1965.
Patricola, C., and Cook, K. H.: Atmosphere/vegetation feedbacks: A mechanism for abrupt climate change over northern Africa, Journal of Geophysical Research: Atmospheres, 113, 2008.
Patricola, C. M., and Cook, K. H.: Northern African climate at the end of the twenty-first century: an integrated application of regional and global climate models, Climate Dynamics, 35, 193-212, 2010.

Deleted:
Deleted:

Paulo, A., Rosa, R., and Pereira, L.: Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal, Natural Hazards and Earth System Sciences, 12, 1481-1491, 2012.
Roehrig, R., Bouniol, D., Guichard, F., Hourdin, F., and Redelsperger, J.-L.: The present and future of the West African monsoon: A process-oriented assessment of CMIP5 simulations along the AMMA transect, Journal of Climate, 26, 6471-6505, 2013.
Smith, B., Samuelsson, P., Wramneby, A., and Rummukainen, M.: A model of the coupled dynamics of climate, vegetation and terrestrial ecosystem biogeochemistry for regional applications, Tellus a: Dynamic Meteorology and Oceanography, 63, 87-106, 2011.
Saini, R., Wang, G., Yu, M., and Kim, J.: Comparison of RCM and GCM projections of boreal summer precipitation over Africa, Journal of Geophysical Research: Atmospheres, 120, 3679-3699, 2015.
Sohn, S. J., Ahn, J. B., and Tam, C. Y.: Six month–lead downscaling prediction of winter to spring drought in South Korea based on a multimodel ensemble, Geophysical Research Letters, 40, 579-583, 2013.
Solmon, F., Giorgi, F., and Liousse, C.: Aerosol modelling for regional climate studies: application to anthropogenic particles and evaluation over a European/African domain, Tellus B: Chemical and Physical Meteorology, 58, 51-72, 2006.
Spinoni, J., Antofie, T., Barbosa, P., Bihari, Z., Lakatos, M., Szalai, S., Szentimrey, T., and Vogt, J.: An overview of drought events in the Carpathian Region in 1961–2010, Advances in Science and Research, 10, 21-32, 2013.
Team, G. G. A. M. D., Anderson, J. L., Balaji, V., Broccoli, A. J., Cooke, W. F., Delworth, T. L., Dixon, K. W., Donner, L. J., Dunne, K. A., and Freidenreich, S. M.: The new GFDL global atmosphere and land model AM2–LM2: Evaluation with prescribed SST simulations, Journal of Climate, 17, 4641-4673, 2004.
Tiedtke, M.: A comprehensive mass flux scheme for cumulus parameterization in large-scale models, Monthly Weather Review, 117, 1779-1800, 1989.
Van der Schrier, G., Jones, P., and Briffa, K.: The sensitivity of the PDSI to the Thornthwaite and Penman- Monteith parameterizations for potential evapotranspiration, Journal of Geophysical Research: Atmospheres, 116, 2011.
Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index, Journal of climate, 23, 1696-1718, 2010a.
Wang, G., and Eltahir, E. A.: Ecosystem dynamics and the Sahel drought, Geophysical Research Letters, 27, 795-798, 2000.
Wang, G., Yu, M., Pal, J. S., Mei, R., Bonan, G. B., Levis, S., and Thornton, P. E.: On the development of a coupled regional climate–vegetation model RCM–CLM–CN–DV and its validation in Tropical Africa, Climate dynamics, 46, 515-539, 2016.
Watanabe, S., Hajima, T., Sudo, K., Nagashima, T., Takemura, T., Okajima, H., Nozawa, T., Kawase, H., Abe, M., and Yokohata, T.: MIROC-ESM: model description and basic results of CMIP5-20c3m experiments, Geoscientific Model Development Discussions, 4, 1063-1128, 2011.

Deleted: Spinoni, J., Naumann, G., Carrao, H., Barbosa, P., and Vogt, J.: World drought frequency, duration, and severity for 1951–2010, International Journal of Climatology, 34, 2792-2804, 2014.

Deleted: and Alo, C. A.: Changes in precipitation seasonality in West Africa predicted by RegCM3 and the impact of dynamic vegetation feedback, International Journal of Geophysics, 2012, 2012. ... [19]

Deleted:

Deleted:

Wramneby, A., Smith, B., and Samuelsson, P.: Hot spots of vegetation- climate feedbacks under future greenhouse forcing in Europe, Journal of Geophysical Research: Atmospheres, 115, 2010.

Wu, M., Schurgers, G., Rummukainen, M., Smith, B., Samuelsson, P., Jansson, C., Siltberg, J., and May, W.: Vegetation-climate feedbacks modulate rainfall patterns in Africa under future climate change, Earth System Dynamics, 7, 627-647, 2016.

Xue, Y., Boone, A., and Taylor, C. M.: Review of recent developments and the future prospective in West African atmosphere/land interaction studies, International Journal of Geophysics, 2012, 2012.

Yu, M., Li, Q., Hayes, M. J., Svoboda, M. D., and Heim, R. R.: Are droughts becoming more frequent or severe in China based on the standardized precipitation evapotranspiration index: 1951–2010?, International Journal of Climatology, 34, 545-558, 2014a.

Yu, M., Wang, G., Parr, D., and Ahmed, K. F.: Future changes of the terrestrial ecosystem based on a dynamic vegetation model driven with RCP8. 5 climate projections from 19 GCMs, Climatic change, 127, 257-271, 2014b.

Yu, M., Wang, G., and Pal, J. S.: Effects of vegetation feedback on future climate change over West Africa, Climate dynamics, 46, 3669-3688, 2016.

Zakey, A., Solmon, F., and Giorgi, F.: Implementation and testing of a desert dust module in a regional climate model, Atmospheric Chemistry and Physics, 6, 4687-4704, 2006.

Zakey, A., Giorgi, F., and Bi, X.: Modeling of sea salt in a regional climate model: Fluxes and radiative forcing, Journal of Geophysical Research: Atmospheres, 113, 2008.

Zeng, X., Zhao, M., and Dickinson, R. E.: Intercomparison of bulk aerodynamic algorithms for the computation of sea surface fluxes using TOGA COARE and TAO data, Journal of Climate, 11, 2628-2644, 1998.

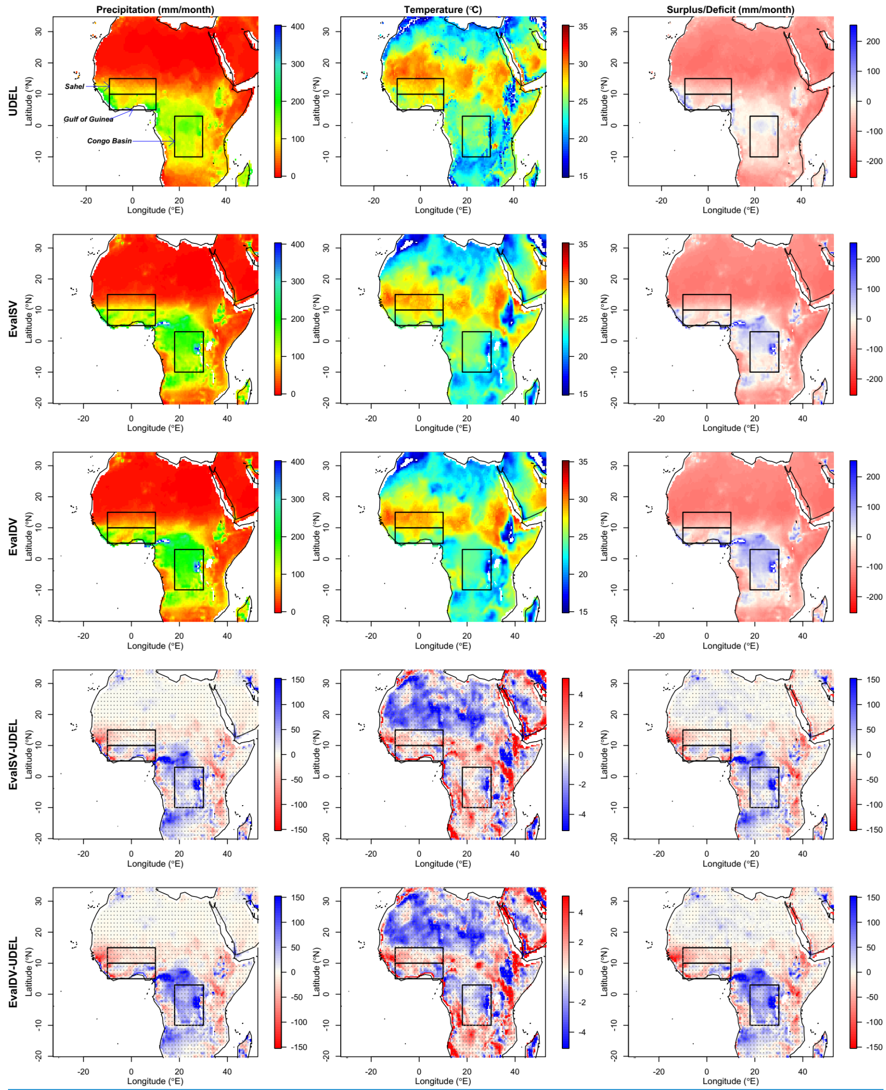
Zhang, W., Jansson, C., Miller, P. A., Smith, B., and Samuelsson, P.: Biogeophysical feedbacks enhance the Arctic terrestrial carbon sink in regional Earth system dynamics, Biogeosciences, 11, 5503-5519, 2014.

Zhou, S., Williams, A. P., Berg, A. M., Cook, B. I., Zhang, Y., Hagemann, S., Lorenz, R., Seneviratne, S. I., and Gentine, P.: Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity, Proceedings of the National Academy of Sciences, 201904955, 2019.

Deleted: Page Break

Deleted:

Deleted:



Deleted:

Deleted:

Figure 1. Averages of precipitation (left column), air temperature (middle column) and precipitation surplus/deficit (right column) from 1989–2008 using datasets from the University of Delaware (UDEL; top row), evaluation run with SV (EvalSV; second row), the difference between EvalSV and UDEL (EvalSV-UDEL; third row), evaluation run with DV (EvalDV; fourth row) and the difference between EvalDV and UDEL (EvalDV-UDEL; bottom row). The boxes with the dashed lines show three focal regions of Sahel, Gulf of Guinea and the Congo Basin. Doted region shows areas passing the two-tailed confidence level with α=0.01.

Deleted: Observed averages

Deleted: (a)

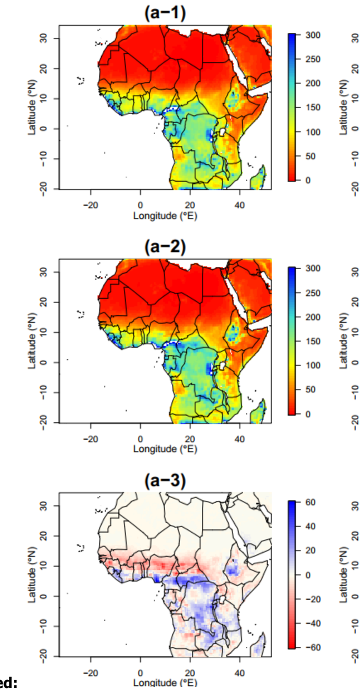
Deleted: mm/month) and (b)

Deleted: °C

Moved down [6]: 1981–2000

Deleted: , and (c) derived precipitation deficit/surplus (mm/month). In (a), the

Deleted: Page Break



Deleted:

Deleted:

Deleted:

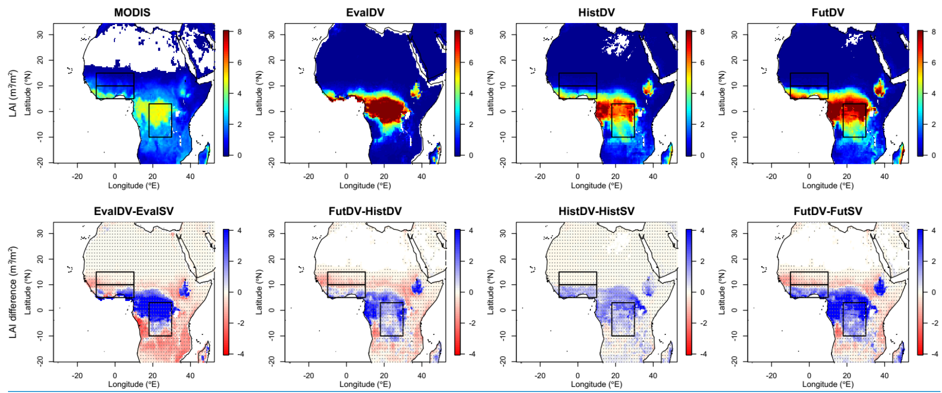


Figure 2. Averages of leaf area index (LAI) from observation (MODIS), which is used for SV runs (EvalSV, HistSV and FutSV) and simulated in DV for evaluation run and experiment ensemble runs (EavlDV, HistDV and FutDV) in the first row, and their LAI differences in the second row. Doted regions show areas passing the two-tailed confidence level with α=0.01.

Deleted: Averages of simulated (a) precipitation (mm/month), (b) temperature (°C), and (c) derived precipitation surplus/deficit (mm/month) from 1) SV ensembles, 2) DV ensembles, and 3) the difference between DV and SV ensembles for the historical period of 1981–2000. ... [20]

Deleted: (a)

Deleted: (b)

Deleted: ensembles for historical period (1981–2000)

Deleted: (c)

Deleted: (DV-SV). And, we

Deleted: (d)

Deleted:

Deleted:

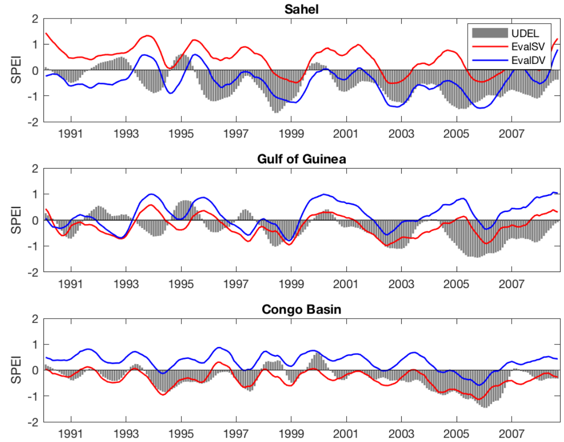


Figure 3. Six-month moving averages of monthly SPEIs of observations (UDEL), EvalSV and EvalDV over three regions of the Sahel, the Gulf of Guinea, and the Congo Basin in 1989-2008. SPEI for UDEL is calibrated with the data from 1959-2008 (50 years).

Deleted:

Deleted:

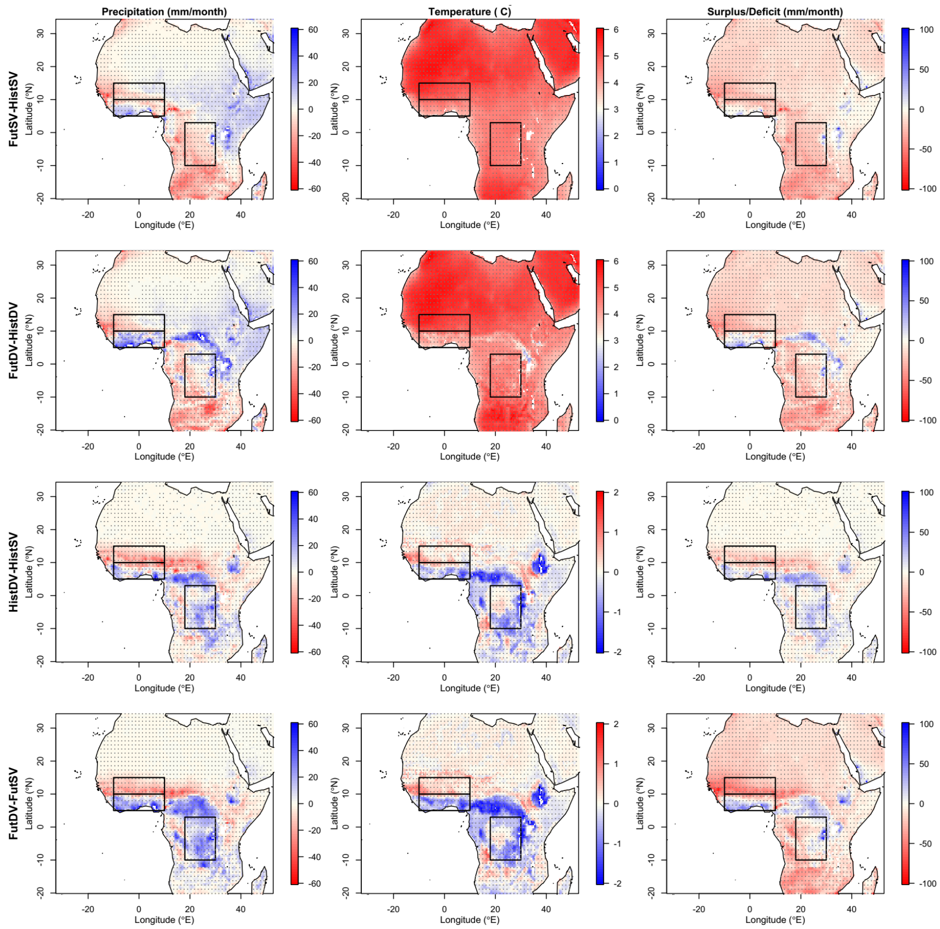


Figure 4. Difference in precipitation (mm/month) (left column), air temperature (°vC) (middle column), and precipitation surplus/deficit (mm/month) (right column) between different experimental simulations (HistSV, HistDV, FutSV and FutDV). Doted region shows areas passing the two-tailed confidence level with α=0.01.

Moved (insertion) [7]

Deleted:

Deleted:

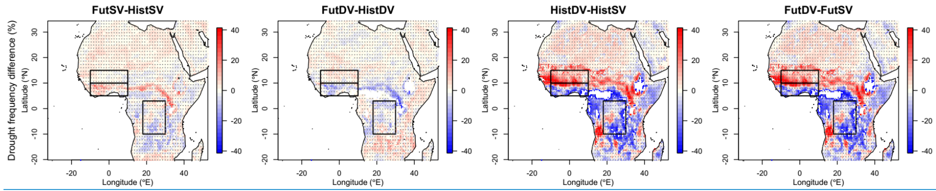


Figure 5. Difference of drought frequencies between different experimental simulations (HistSV, HistDV, FutSV and FutDV). Drought frequency is defined for events with an SPEI less than -1. Doted region shows areas passing the two-tailed confidence level with α=0.01.

Moved (insertion) [8]

Moved up [7]: **Figure 4.**

Deleted: difference between future (2081-2100) and historical periods in DV, (e) averages of simulated LAI in DV ensembles for future period and (f) the difference between DV and SV in the future period.

Page Break

... [21]

Deleted: the DV and the SV ensembles (a) for the historical period (1981-2000)

Deleted: (d) for the future period (2081-2100). Differences between the future and historical periods (future-historical) for (b) SV ensembles and (c) DV ensembles.

Deleted:

Deleted:

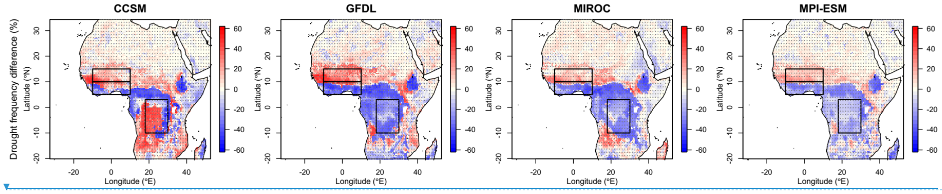
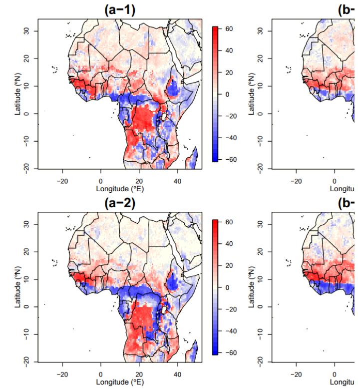


Figure 6. Difference of drought frequencies between the DV and the SV ensembles for the future period (2081-2100) (FutDV-FutSV) from the ensemble members with different LBCs of CCSM, GFDL, MIROC and MPI-ESM. Drought frequency is defined for events with an SPEI less than -1. Doted region shows areas passing the two-tailed confidence level with α=0.01.



Deleted:

Moved (insertion) [9]

Moved up [8]: **Figure 5.**

Deleted: (1) for the historical period (1981-2000) and (2)

Deleted: (a)

Deleted: (b)

Deleted: (c)

Deleted: (d)

Deleted:

Deleted:

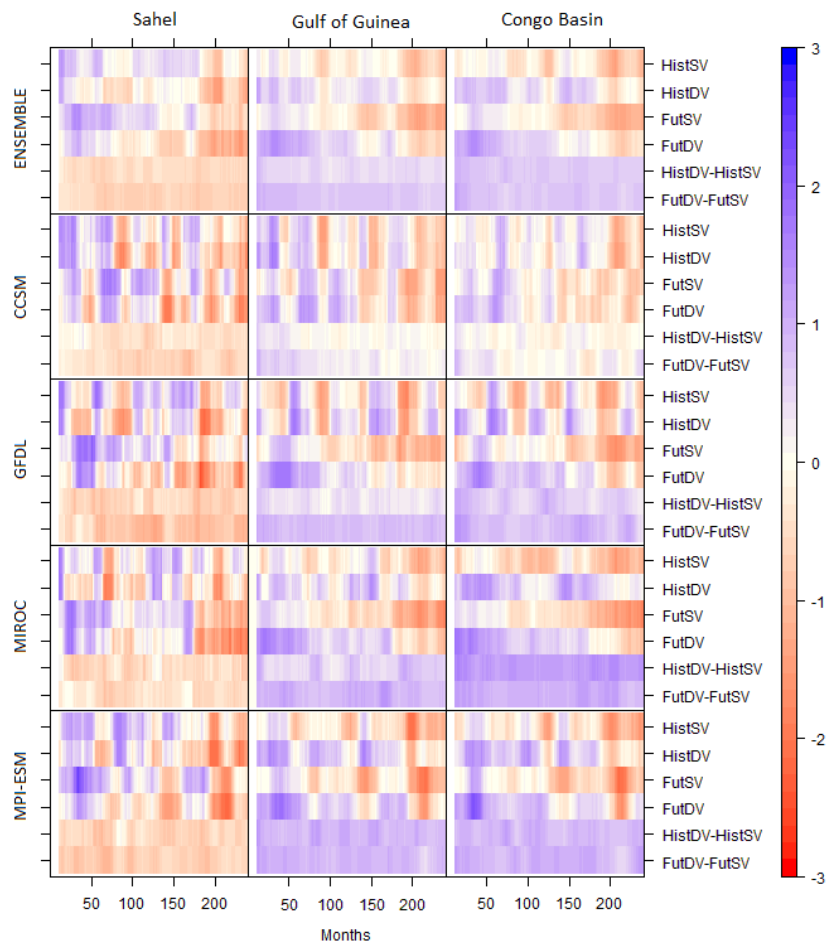
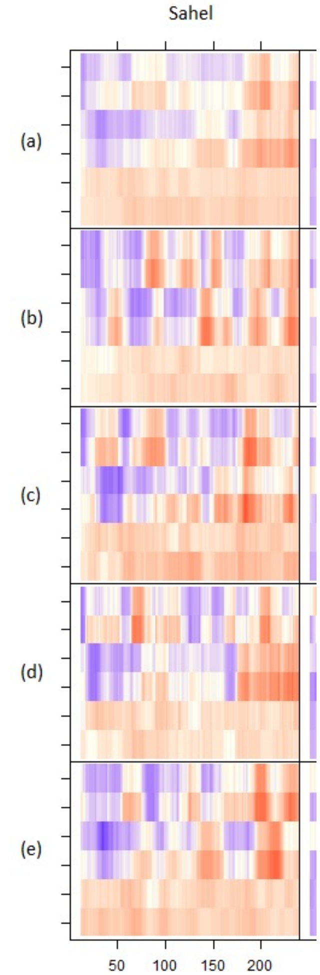


Figure 7. Monthly SPEI averaged for three regions of the Sahel (left column), the Gulf of Guinea (middle column), and the Congo Basin (right column) in ensembles and the individual member of experimental runs (HistSV, HistDV, FutSV and FutDV) with different LBCs of CCSM, GFDL, MIROC and MPI-ESM.

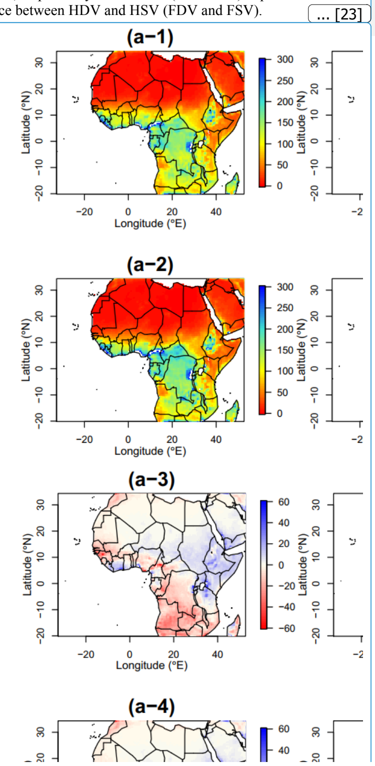


Deleted:

Moved up [9]: Figure 6.

Moved (insertion) [10]

Deleted: ,…(left column), the Gulf of Guinea,…(middle column), and the Congo Basin (right column) in (a)…ensembles and the individual member of experimental runs (HistSV, HistDV, FutSV and FutDV) with different LBCs of (b) …CSM, (b) …FDL, (c) MIROC and (d) …PI-ESM. HSV and HDV (FSV and FDV) represent the historical (future) simulation without and with dynamic vegetation, respectively. HDV-HSV (FDV-FSV) depict the difference between HDV and HSV (FDV and FSV). ... [23]



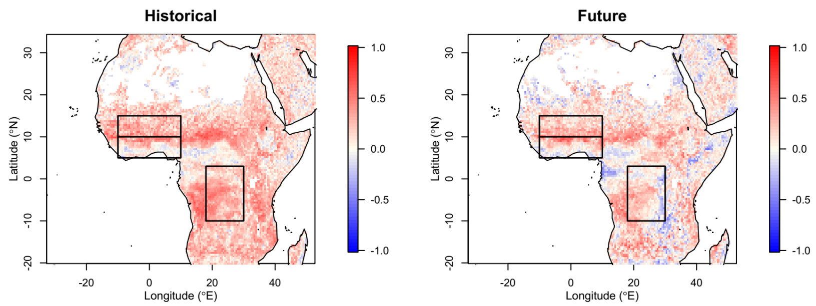


Figure 8. Spearman's rank correlation coefficient between annual minimum LAI and annual maximum SPEI from HistDV (1981-2000; left column) and FutDV (2081-2100; right column).

Moved up [10]: **Figure 7.**

Deleted: Averages of simulated (a) precipitation (mm/month) and (b) temperature (°C), and (c) derived precipitation surplus/deficit (mm/month) from 1) SV ensembles and 2) DV ensembles for the future period of 2081–2100. Their difference between future and historical periods (future-historical) for 3) SV ensembles and 4) DV ensembles are shown. The difference between DV and SV ensembles reflect the future period.

Page Break

... [24]

Deleted: the DV ensembles for (a) the historical

Deleted: (b) future

Deleted:) periods.

Deleted:

Deleted:

Table 1. Description of 18 different simulation setups

Periods	Evaluation (EvalSV, EvalDV)		1989–2008
	Experimental	Historical (HistSV, HistDV)	1981–2000
		Future (FutSV, FutDV)	2081–2100
Vegetation dynamics	DV		Dynamic Vegetation
	SV		Static Vegetation
Boundary conditions	Evaluation		ERA-Interim
	Experimental	CCSM	Community Earth System Model
		GFDL	Geophysical Fluid Dynamics Laboratory
		MIROC	Model for Interdisciplinary Research on Climate-Earth System Model
		MPI-ESM	Max Planck Institute Earth System Model

Deleted: 16

Deleted: (4 boundary conditions, 2 different vegetation dynamics and 2 different periods)

Deleted: CCSM

Moved down [13]: Community Earth System Model

Moved (insertion) [4]

Moved down [12]: Boundary conditions

Moved (insertion) [11]

Moved (insertion) [6]

Deleted: from different GCMs

Deleted: GFDL

Inserted Cells

Moved down [14]: Geophysical Fluid Dynamics Laboratory

Deleted: MIROC

Moved down [15]: Model for Interdisciplinary Research on Climate-Earth System Model

Deleted: MPI-ESM ... [25]

Moved down [16]: Max Planck Institute Earth System Model

Deleted: Historical

Deleted: 1981–2000

Deleted: Future

Moved (insertion) [5]

Deleted: 2081–2100

Moved (insertion) [13]

Inserted Cells

Moved (insertion) [12]

Moved (insertion) [14]

Moved up [11]: Periods

Moved (insertion) [15]

Moved (insertion) [16]

Deleted:

Deleted:

Deleted:

Table 2. Model parameterizations used in this study

Model's feature	Selected schemes
Boundary layer	Holtslag PBL (Holtslag et al., 1990)
Cumulus convection	Emanuel scheme (Emanuel, 1991)
Precipitation and cloud	Sub-grid Explicit Moisture Scheme (Pal et al., 2000)
Radiation	Community climate model 3 (Kiehl et al., 1996)
Dynamics	Mesoscale model 5 (Grell et al., 1994)
Ocean flux	Zeng scheme (Zeng et al.,1998)
Anthropogenic aerosols/ Interactive aerosols	Tracer model (Solmon et al., 2006; Zakey et al., 2006, 2008)
Land Surface	Community Land Model 4.5-CN-DV (Oleson et al., 2010, 2013; Wang et al., 2017)

Deleted:

Deleted: