Larger Future Intensification of Rainfall in the West African Sahel in a Convection-Permitting Model

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Abstract  Monsoon rainfall in West Africa mostly comes from mesoscale convective systems, which are not well represented by standard convection-parameterized regional climate models (RCMs). We use a 4.5 km resolution convection-permitting RCM (CP4A) which has a good representation of these processes in the Sahel. By comparing the climate change signals of CP4A and a standard RCM (R25), we find that changes in mean rainfall and wet-day frequency are linearly related. However, rainfall intensity changes are independent. Intensification of rainfall is larger in CP4A and happens in regions of both increasing and decreasing mean rainfall. Rainfall from extreme events increases by a factor of 5 to 10 in CP4A, compared to 2 to 3 in R25. CP4A also shows larger changes in intraseasonal rainfall variability, dry spells, and short and long duration extreme rainfall than R25, all of which are relevant for hydrology and agriculture.

1. Introduction

Sub-Saharan Africa has a large proportion of people living below the poverty line, who rely mostly on rainfed agriculture (World Bank, 2018). The risks posed by climate change are high in this region, with vulnerabilities associated with increased water stress and alterations to the magnitude and frequency of extreme events (Maxwell, 2010; Parry et al., 2007).

Warming in the Sahel could reach 6 °C in the RCP8.5 concentration scenario (Vizy et al., 2013). CMIP5 GCMs show that the response of rainfall to this warming in West Africa will likely be large in terms of magnitude and affected area (Chadwick et al., 2015) but future mean changes diverge substantially between models (Chadwick et al., 2015; Dosio & Panitz, 2016; Monerie et al., 2012; Rowell et al., 2016). Underlying this, however, there is a robust signal of increasing intensity but decreasing frequency of wet days across models (Déqué et al., 2017; Sylla et al., 2015). Considering intense daily rainfall events, Diallo et al. (2016), Egbehiyi (2016), Abiodun et al. (2017), and Akinsanola and Zhou (2018) have shown an expected increase in the frequency and intensity of heavy rainfall events with future warming. However, this change is not robust or is uncertain in the CORDEX multimodel ensemble (Dosio et al., 2019).

End users need information on changes in climate extremes (Maraun et al., 2010). In West Africa, extreme rainfall often results from Mesoscale Convective Systems (MCSs) (e.g., Engel et al., 2017a). However, only large-scale MCSs are resolved by convection-parameterized models at about 25 km resolution (Vellinga et al., 2015). Indeed, standard regional climate models (RCMs) typically have an incorrect simulation of the diurnal cycle of precipitation (Nikulin et al., 2012) and produce too much low-intensity (<10 mm/day) and high-intensity (>80 mm/day) precipitation (Dosio et al., 2015). RCMs’ ability to represent extreme precipitation is highly dependent on their convective scheme (Klutse et al., 2016). Higher resolution convection-permitting regional climate models (CPRCMs) are more successful at representing MCSs and the diurnal cycle of convection and provide a more realistic representation of precipitation extremes (Birch et al., 2014; Marsham et al., 2013; Maurer et al., 2017; Prein et al., 2015). They also improve the whole precipitation distribution where these processes represent a large share of total precipitation (e.g., Mediterranean, Berthou et al., 2018; United States, Prein et al., 2017; West Africa, Berthou et al., 2019; and East Africa, Finney et al., 2019).

CPRCMs further provide useful information on the climate change signal at the subdaily timescales in mid-latitude regions (Kendon et al., 2017). The CPRCM used in the present study (CP4A, described in section 2) has a much better precipitation distribution at all timescales in West Africa compared to a standard resolution RCM with parameterized convection (R25) (Berthou et al., 2019). Regarding their climate change signal in rainfall on an Africa-wide scale, CP4A and R25 have similar mean changes, but CP4A shows a greater
future increase in the length of dry spells and in intense subdaily rainfall compared with R25 (Kendon et al., 2019). This is especially true in West Africa. Therefore, it is important to quantify these changes at the subregional scale and with specific user-relevant metrics. Hence, we have investigated different aspects of changes in intraseasonal rainfall variability while a companion study is studying changes in temperature, season length, and monsoon onset (R. Fitzpatrick, personal communication). We have compared how the climate change signal differs between the two models (R25 and CP4A) to identify the potential uncertainties linked with using only convection-parameterized RCMs and GCMs for climate change studies in West Africa.

Methods are explained in section 2, changes in daily precipitation statistics are shown in section 3.1, and subdaily precipitation changes are shown in section 3.2. Finally, we investigate changes in user-relevant metrics in section 3.3.

2. Methods

2.1. Simulations

A brief summary of the simulation setup is given here as a detailed description is available in Stratton et al. (2018) and Kendon et al. (2019).

We compare two pairs (present/future) of 10-year regional climate simulations using the Met Office Unified Model (Walters et al., 2017) run over a pan-African domain (45S–39N; 24W–56E):

1. R25—a convection-parameterized model of 26 × 39 km resolution at the equator (0.234° × 0.351°).
2. CP4A—a convection-permitting model of 4.5 × 4.5 km resolution at the equator (0.0405° × 0.0405°).

It does not include any convection parameterization: The model dynamics together with the microphysics scheme explicitly represent precipitation.

The regional R25 simulation was run with a near-identical setup to CP4A, except the resolution difference and the use of convective parameterization (Stratton et al., 2018).

Lateral boundary conditions were provided by a global model with the same resolution as R25 (~25 km). The present global run uses observed SSTs (Reynolds et al., 2007) between 1997 and 2006. The future global run is similar to the present run but uses modified SSTs and greenhouse gas concentrations appropriate for the end of the century under the IPCC Representative Concentration pathway RCP8.5. In particular, the future SSTs are the sum of the observed SSTs and the climatological average SST change between 1975–2005 and 2085–2115 in a HadGEM2-ES RCP8.5 simulation (Jones et al., 2011).

This approach is similar to that of the UPScale project (Mizielinski et al., 2014). Figure 1 of Mizielinski et al. (2014) shows the delta SST applied to the simulation for JJA, with a larger warming in the northern hemisphere compared to the southern hemisphere and a larger warming in the equatorial current (+4–5 °C) than in the subtropical gyres (+2–3 °C).

2.2. Observations

CMORPHv1-CRT is the latest release of the Climate Prediction Center morphing technique (CMORPH) (Xie et al., 2017). Correction against gauges over land is substantial in this version: CMORPH is very comparable to ground observations in 1 km × 1 km subregions of Niger, Mali, and Benin (section 6.1.2 and Figures 11a, 11c, and 11e of Berthou et al., 2019). However, this correction introduces a discrepancy with other data sets in the Guinea mountain region (Berthou et al., 2019). The Tropical Rainfall Measuring Mission 3B42v7 (TRMM, 2011) has better mean rainfall amounts in this region (Figure 7 and section 3.2 of Berthou et al., 2019), although it tends to overestimate strong rainfall and underestimate weak rainfall in other regions (Tian et al., 2010; Berthou et al., 2019). Based on this, we chose to use CMORPH in central Sahel and TRMM in western Sahel as reference data sets. Ten years (1998–2007) were used on a 3-hourly timescale and a 0.25° grid in the present study.

2.3. Percentile-Based Metrics

CP4A, R25, and CMORPH are conservatively regridded to TRMM grid (0.25°), as advised by Chen and Dai (2018). Wet days are defined using a percentile threshold, which takes into account the fact that R25 has a lot of weak intensity events (Berthou et al., 2019). In particular, a wet day is considered as a day above the all-day 65th percentile, and a wet hour is above the all-hour 90th (values for each data set are given in supporting information Table S1). These wet-value percentiles are calculated for July to September during the wet season in the Sudano-Sahelian zone (SSZ) from 9N to 15N and 8W to 5E. User-relevant metrics also based on these percentile values are defined in section 3.3.
3. Results

3.1. Greater Changes in Rainfall Occurrence and Intensity in the Convection-Permitting Model

Figure 1a shows the mean changes for R25 in July to September: a wetter central Sahel, a drier western Sahel, and a drier Guinea coast. The north/south dipole is linked with a strengthening of the low-level monsoon flow leading to a northward shift, as shown in Figures S1e and S1f, as in James et al. (2015). The western Sahel drying is linked with upper-level air subsidence (Figures S1a and S1b) and low-level moisture stagnation in this region (Figures S2c–S2f) (Diallo et al., 2016; James et al., 2015; Monerie et al., 2012). The temperature (Figures S2a and S2b) and low-level circulation changes (Figures S1e and S1f) are also compatible with a strengthening of the Sahara heat low (Figures S2a and S2b) (Lavaysse et al., 2016).

CP4A mean changes (Figure 1b) have a relatively similar pattern to R25 (Pearson correlation coefficient $R = 0.75$). CP4A shows a smaller increase (spatial slope of 0.85), which comes from a larger reduction in the wet-day frequency in CP4A (Figures 1d–1f). Frequency is reduced by 10% to 30% in central Sahel and 30–70% in a large part of western Sahel and the Guinea coast in CP4A, whereas any significant frequency reduction is confined to western and southern areas in R25. Similarly, the increase in maximum consecutive dry days and the decrease in maximum consecutive wet days are more extensive in CP4A (Figure S3). The spatial relationship between R25 and CP4A is also significant for the frequency ($R = 0.83$). The slope (0.60) and intersect (~24%) indicate stronger reduction of frequency in CP4A: Typically, a 50% increase in wet-day frequency in R25 is translated to no change in CP4A, and a 100% increase in R25 corresponds to only 40% increase in CP4A.

As found in previous studies (e.g., Déqué et al., 2017; Sylla et al., 2015), the wet-day intensity (also called Simple Daily Intensity Index, which is the mean rainfall falling during wet days) is increased in both models (Figures 1g–1i). The main difference is a larger intensification of rainfall in CP4A, with an increase of 25% to 75% in most areas, compared to 10% to 50% in R25. There is no spatial relationship between the two models, but most points are centered around a 25% increase in R25, corresponding to a 50% increase in CP4A. The
Figure 2. Changes in the 3-hourly precipitation contribution to the mean (precipitation frequency × bin intensity), with exponential bins for three regions (Figure S5). Present-day distributions are the thin lines, and the filled lines are future changes for R25 and CP4A. Percentage changes at the bottom of each panel are indicated for (left) first tercile of the contribution to mean precipitation, (middle left) second tercile, (middle right) third tercile, and (right) total precipitation above the 99.99th percentile.

Increase in maximum daily (RX1) and 5-day rainfall (RX5) is also uncorrelated, but of similar intensity in both models (Figure S4). In section 3.2, we provide an explanation of these differences based on recent literature.

Note that these results are similar when using percentile thresholds or a fixed threshold of 1 mm/day to define wet days (not shown).

3.2. Intensification of Rainfall Is Larger at Convection-Permitting Resolution

Figure 2 shows the 3-hourly precipitation distribution in terms of the actual contribution from different intensity bins to mean precipitation, in the same way as Klingaman et al. (2017) but using exponential bins (Figure S5). To calculate the contribution to mean precipitation, each bin frequency is multiplied by its average rate. This way, mean precipitation is split between precipitation contribution of different rates. Because of the logarithmic scale on the x axis, the area under the curve is directly proportional to the mean.

Figure 2 shows TRMM or CMORPH as reference, depending on their performance: CMORPH distribution agrees better with rain gauges in SSZ and NSA, whereas TRMM has better total rainfall in the Guinean highlands and Senegal regions (Berthou et al., 2019). This choice is based on previous analysis, summed up in section 2.2. CP4A has a much better intensity distribution than R25, which has a flatter distribution centered on lower precipitation rates. CP4A is best in northern Sahel (NSA), but it overestimates intense precipitation and underestimates weaker rainfall rates in the SSZ. CP4A therefore potentially provides a better, but upper-limit, estimation of rainfall intensity.

Regarding future changes, Figure 2 reiterates that rainfall intensification is projected in all regions in both models but that it is larger in CP4A, especially in regions getting wetter. In NSA and SSZ, mean rainfall increases since the positive shaded area is larger than the negative one. The opposite is true in SEN. In the following, we refer to light, moderate, and intense precipitation rates as the first, second, and third terciles of the present-day distribution (delineated by vertical bars in Figure 2). In SEN (Figure 2c), models agree that the decrease in mean precipitation is due to a 35% to 47% decrease in light and moderate rainfall, as intense rainfall actually increases by 6–16%. In NSA (Figure 2b), the mean increase comes from an increased
Figure 3. Frequency of different types of events for CP4A (orange) and R25 (blue) for present (darker color) or future (lighter color) for SEN and SSZ land-only regions as defined in Figure 2. Definitions of events are given in panel (c) and percentile values in Table S1. Units are written on the graphs, as they can differ between metrics. Significance at the 1% level is assessed using the bootstrapping method explained in the supporting information.

3.3. High Impact Events Could Occur More Often in the Future

The future shift of the precipitation distribution to higher intensities contributing to mean rainfall could have strong consequences on hydrology and agriculture. In this section, we provide a sample of metrics based on daily and subdaily intraseasonal rainfall variability. The definition of these metrics (hereafter and in Figure 3c) is based on a consultation with stakeholders (Rowell et al., 2015) and is specific to the SSZ. Two regions with different mean changes in this climatic zone are used: SEN and SSZ (defined in Figure 2a).

Contribution of intense rainfall, but models disagree on the magnitude: CP4A projects a doubling of this contribution while R25 shows a smaller increase of 53%. In SSZ, where mean changes are also positive, CP4A projects a larger decrease in light and moderate rainfall (28% and 9%) which is offset by a doubling of intense rainfall. These changes are larger than in R25.

Models disagree most on the changes in extreme rainfall contribution (above the 99.99th percentile of all hours, about 15 to 25 mm/hr). In the present-day simulations, these extreme events contribute 1% to 2% of mean rainfall. CP4A projects a factor of 5 to 10 increase for extreme rain, while R25 projects a doubling or tripling. Precipitation above the present-day 99.99th percentile becomes a significant contributor to the future mean: 9% to 12% in CP4A and 2% to 5% in R25.

These results are consistent with the Sahel-wide estimation by Kendon et al. (2019), who used the same models. Kendon et al. (2019) showed that the decrease in light/moderate precipitation was linked with a future increase in convective inhibition: The number of profiles able to support convection from the surface layer during the day decreased, in agreement with Dai et al. (2017) and Rasmussen et al. (2017). Moreover, Kendon et al. (2019) also showed that changes in extreme precipitation were largely explicable in terms of increasing atmospheric moisture with warming. Nevertheless, they suggest that widespread super Clausius-Clapeyron scaling in CP4A indicates that other processes may also play a role. For example, increased wind shear favors the mesoscale organization of convection, and this has led to a recent intensification of extreme Sahel storms (Taylor et al., 2017).

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Sensitivity tests to the precise thresholds used were performed and discussed briefly at the end of this section.

1. Efficient moderate rain (April to July). Short periods of intraseasonal drought can have strong effects on crop growth, especially after sowing or around 40 days later at the flowering stage (Laux et al., 2009; Rockström & De Rouw, 1997). We use moderate rain spells (≥20–100 mm of accumulated rainfall in less than 7 days consecutive wet days—with isolated dry days allowed) not followed by a 10-day (or longer) dry spell.

2. Moderate rain + dry spell (April to July). It is also a moderate rain spell (see above) but which is followed by a dry spell of at least 10 days.

3. The number of intense days (>30 mm/day) (July to September) is important for agriculture, as it can enhance soil erosion and nutrient leaching.

4. Short and intense (July to September) subdaily rainfall can lead to flash floods with devastating effects (Engel et al., 2017b). We provide the number of wet spells lasting 9 hr or less and accumulating more than 75 mm of rainfall.

5. Long and intense wet spells (July to September) last at least 7 days with high cumulative rainfall (>100 mm). Wet spells are defined as consecutive days/hours of rainfall above the wet-day/hour definition threshold (Table S1). Single dry days are allowed during a wet spell to allow for some intermittency.

6. Dry spells (July to September) are defined as the ratio of days belonging to long dry spells within a season to the season length. A long dry spell is a period longer than 10 days without rainfall or with isolated weak rainy days (less than 3 mm).

It is important to note that these thresholds are mostly valid for the SSZ and that we translate these to a percentile threshold using the observations. These percentile thresholds are then used for the models (Figure 3c and Table S1) and in the sensitivity tests discussed later.

Figure S4 shows an evaluation of these metrics using actual thresholds as described above. CP4A represents all metrics except long-lasting wet spells better than R25 (Figure S6). We note that good historical performance is not a sufficient condition for reliable future projections. In particular, an understanding of the local and remote drivers of future change is also important. Further work is needed to understand these drivers and then find relevant ways to assess the reliability of their representation in CP4A; this is beyond the scope of this study.

Future changes are strongly dependent on resolution and the representation of convection. In SEN, where mean precipitation changes are negative, both models agree on the sign of changes for all metrics, but the amplitude of the change is larger in CP4A for all metrics. In SSZ, where mean precipitation changes are positive, the changes differ in sign for three out of five metrics (dry spells, long, and intense wet spells, moderate rain followed by a dry spell).

In the SEN region, mean rainfall decreases by 27% in CP4A and 21% in R25 in July to September. At the start of the wet season (April-July), long dry spells follow moderate wet spells in about 50% of the cases in the future in CP4A (40% in R25) compared to 20% in the present climate. The number of days belonging to long dry spells in July to September increases by 20% in R25 and 76% in CP4A and rare long and intense rainfall events decrease by 83% (CP4A) and 63% (R25). The number of intense days is stable in R25 and decreases by 20% in CP4A. However, rarer short and intense subdaily rainfall occurrence increases in both models, again with a stronger amplitude (66%) in CP4A (16% in R25).

In the SSZ region, mean rainfall increases by 22% in CP4A and 30% in R25. At the start of the wet season, efficient moderate rainfall increases in both models by 29% (CP4A) and 20% (R25). However, long dry spells following moderate rainfall more than doubles in CP4A but halves in R25. In peak season, the number of days belonging to long dry spells increases in CP4A (+69%) and decreases in R25 (−28%), which is a major difference between the two models. The models agree on the increase in the number of intense days (+57% to 79%). We note that this trend is of comparable magnitude (=1 more event every 30 years at each grid point) to the recent trend between the 1980s and 2010s reported in Panthou et al. (2014) (their extreme day definition is comparable to our intense day definition). Regarding more extreme metrics, CP4A increases more dramatically the number of short and intense subdaily rainfall events (by a factor 4 against 2.5 in R25). Although not directly comparable with the definitions of Taylor et al. (2017) since they use cloud-top temperatures, an extrapolation of the tripling that they found over 35 years to the end of the century would...
mean a doubling of the number of events compared to the most recent period. This is close to R25, and CP4A suggests a larger increase than this recent trend. Finally, CP4A decreases the number of long and intense rainfall events by 54% while R25 increases them by 28%.

Sensitivity tests to the metric definitions have been performed (Figures S7–S10). They show that the conclusions are robust to the definition for all metrics. Nevertheless, the conclusions are sensitive to the threshold for short and intense subdaily rainfall (Figure S5), but they remain true (CP4A shows larger increases than R25) above the 1.5 × 99.9th percentile (at least 75 mm in less than 9 hr in CMORPH). The amplitude of changes increases in CP4A when the threshold level is raised, whereas it stays stable in R25. Using actual thresholds from CMORPH (75 mm), CP4A has a comparable increase to R25, partly because it corresponds to a lower percentile in CP4A and higher percentile in R25.

4. Discussion and Conclusion

Convection-permitting modeling (CP4A) drastically improves the distribution of precipitation over the Sahel (Berthou et al., 2019). This is in part due to a better representation of the life cycles and direction of propagation of MCSs compared to the RCM at 25 km with parameterized convection (R25) (Crook et al., 2019). This study is based on only one scenario and realization, but we have compared how the climate change signal differs between the two models to identify the potential uncertainties linked with using only convection-parameterized RCMs and GCMs for climate change studies in West Africa.

We find a linear scaling relationship between the climate change signal in CP4A and in R25 for mean precipitation and wet-day frequency (Figure 1). CP4A tends to have a drier signal than R25, because of a widespread decrease in wet-day frequency, even in areas where mean rainfall increases. It may be possible to adjust the outputs of a parameterized model in mean and wet-day frequency, but this requires further assessment of the scaling relationship with other models. The increase in wet-day intensity is generally twice as strong in CP4A, but it cannot be linearly related with the changes in R25.

CP4A shows a stronger decrease in the lowest precipitation rates in regions getting wetter. It also shows a much stronger increase (5–10 times) of precipitation contribution above the 99.9th percentile (15–25 mm/hr), which accounts for a significant portion of mean precipitation in the future (9–12% in the future against 1–2% in the present day), whereas it only doubles in R25. Using the same simulations, Kendon et al. (2019) explain that greater convective inhibition in the future inhibits the smaller-scale diurnal-cycle convection, inducing longer dry spells. Greater moisture content in the atmosphere also leads to heavier extreme rainfall events. The convection-permitting model is able to generate more intense extreme rainfall than R25, along with a greater reduction in lighter rainfall, notably associated with further reductions in diurnal convection (Kendon et al., 2019).

R25 underestimates changes in impact-relevant metrics of intraseasonal precipitation variability, especially in subregions of the Sahel getting more rainfall in the future. Indeed, we compared the future projected changes of several metrics relevant for hydrology and agriculture in the SSZ of West Africa. CP4A generally represents the metrics better than R25 and simulates larger amplitude changes for most metrics and regions. CP4A agrees with R25 on the sign of changes in western Sahel (SEN), which is getting drier, but not in central Sahel (SSZ), which is getting wetter. Some impact studies use monthly mean changes imposed on present-day observed precipitation variability to assess climate change impacts on agriculture and hydrology (Roudier et al., 2011; Sultan et al., 2014; Stanzel et al., 2018). However, we have shown that intraseasonal rainfall variability may change more significantly with climate change than previously thought (Guan et al., 2015). This should be taken into account in impact models.

Although mean changes in precipitation with climate change in West Africa remain challenging to predict, our study confirms with a convection-permitting climate model that precipitation will likely become about 1.5 times as intense as currently experienced, with the number of days falling in long dry spells increasing by about 70% in an RCP8.5 scenario. This model also suggests that increases in intense rainfall days in central Sahel may continue at a similar pace compared to the last 35 years (Panthou et al., 2014), but the trend in extreme subdaily rainfall occurrence (Taylor et al., 2017) may increase. The results that the future intensification of rainfall in CP4A is larger than in R25 call for convection-permitting model intercomparison studies over this region, where the representation of convection is key.
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Mizielinski, M. S., Roberts, M. J., Vidale, P. L., Schiemann, R., Demory, M.-E., Strachan, J., et al. (2014). High-resolution global climate modelling: The UPScale project, a large-simulation campaign. *Geoscientific Model Development*, 7(4), 1629–1640. https://doi.org/10.5194/gmd-7-1629-2014

Monerie, P.-A., Fontaine, B., & Roucou, P. (2012). Expected future changes in the African monsoon between 2030 and 2070 using some CMIP3 and CMIP5 models under a medium-low RCP scenario. *Journal of Geophysical Research*, 117, D16111. https://doi.org/10.1029/2012JD017510

Nikulin, G., Jones, C., Giorgi, F., Astrar, G., Büchner, M., Cerezo-Mota, R., et al. (2012). Precipitation climatology in an ensemble of CORDEX-Africa regional climate simulations. *Journal of Climate*, 25(18), 6057–6078. https://doi.org/10.1175/JCLI-D-11-00375.1

Panthou, G., Vischel, T., & Lebel, T. (2014). Recent trends in the regime of extreme rainfall in the Central Sahel. *International Journal of Climatology*, 34(15), 3998–4006. https://doi.org/10.1002/joc.3984

Parry, M., Parry, M. L., Canziani, O., Palutikof, J., De Linden, P., & Hanson, C. (2007). *Climate change 2007—Impacts, adaptation and vulnerability: Working Group II contribution to the fourth assessment report of the IPCC*, vol. 4. United Kingdom and New York, NY, USA: Cambridge University Press.

Prein, A. F., Langhans, W., Fosser, G., Ferrone, A., Ban, N., Goergen, K., et al. (2015). A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges. *Reviews of Geophysics*, 53, 323–361. https://doi.org/10.1002/2014RG000475

Prein, A. F., Liu, C., Ikeda, K., Bullock, R., Rasmussen, R. M., Holland, G. J., & Clark, M. (2017). Simulating North American mesoscale convective systems with a convection-permitting climate model. *Climate Dynamics*, 1–16. https://doi.org/10.1007/s00382-017-3993-2

Rasmussen, K. L., Prein, A. F., Rasmussen, R. M., Ikeda, K., & Liu, C. (2017). Changes in the convective population and thermodynamic environments in convection-permitting regional climate simulations over the United States (pp. 1–26). https://doi.org/10.1007/s00382-017-4000-7

Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., & Schlax, M. G. (2007). Daily high-resolution blended analyses for sea surface temperature. *Journal of Climate*, 20, 5473–5496.

Rowell, A. D., Parker, D., Kane, N., Affholder, F., Bell, V., Challinor, A., et al. (2015). Initial lists of AMMA-2050 user-relevant climate metrics (1).

Rowell, D. P., Senior, C. A., Vellinga, M., & Graham, R. J. (2016). Can climate projection uncertainty be constrained over Africa using metrics of contemporary performance? *Climatic Change*, 134(4), 621–633. https://doi.org/10.1007/s10584-015-1554-4

Stanzel, P., Kling, H., & Bauer, H. (2018). Climate change impact on West African rivers under an ensemble of CORDEX climate projections. *Climate Services*, 11, 36–48. https://doi.org/10.1016/j.cliserv.2018.05.003

Stratton, R. A., Vosper, S. B., Folwell, S. S., Boutle, I. A., Earnshaw, D., Kendon, E., et al. (2018). A pan-Africa convection-permitting regional climate simulation with the Met Office Unified Model: CP4-Africa. *Journal of Climate*, 31, 3485–3508. https://doi.org/10.1175/JCLI-D-17-0503.1

Sultan, B., Guan, K., Kourmessi, M., Biasutti, M., Piani, C., Hammer, G. L., et al. (2014). Robust features of future climate change impacts on sorghum yields in West Africa. *Environmental Research Letters*, 10(4), 006.

Sylla, M. B., Giorgi, F., Pal, J. S., Gibba, P., Kebe, I., & Nikiema, M. (2015). Projected changes in the annual cycle of high-intensity precipitation events over West Africa for the late twenty-first century. *Journal of Climate*, 28(16), 6475–6488. https://doi.org/10.1175/JCLI-D-14-00854.1

Taylor, C. M., Beloucif, N., Guichard, F., Parker, D., Vischel, T., Bock, O., & Gallois, G. (2017). Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, 544, 475.

Tian, Y., Peters-Lidard, C. D., & Eylander, J. B. (2010). Real-time bias reduction for satellite-based precipitation estimates. *Journal of Hydrometeorology*, 11, 1275–1285. https://doi.org/10.1175/2010JHM1246.1

Tropical Rainfall Measuring Mission (TRMM) (2011). TRMM (TMPA) rainfall estimate L3.3 hour 0.25 degree x 0.25 degree v7: Greenbelt, MD.

Vellinga, M., Roberts, M., Vidale, P. L., Mizielinski, M. S., Demory, M.-E., Schiemann, R., et al. (2015). Sahel decadal rainfall variability and the role of model horizontal resolution. *Geophysical Research Letters*, 43, 326–333. https://doi.org/10.1002/2015GL066690

Vizy, E. K., Cook, R. H., Crétat, J., & Neupane, N. (2013). Projections of a wetter Sahel in the twenty-first century from global and regional models. *Journal of Climate*, 26(13), 4664–4687. https://doi.org/10.1175/JCLI-D-12-00533.1

Walters, D., Baran, A., Boutle, I., Brooks, M., Earnshaw, P., Edwards, J., et al. (2017). The Met Office Unified Model Global Atmosphere 7.0/7.1 and JULES Global Land 7.0 configurations. *Geoscientific Model Development Discussions*, 12, 1909–1963. https://doi.org/10.5194/gmd-2017-291

Wilks, D. S. (2016). The stippling shows statistically significant grid points: How research results are routinely overstated and overinterpreted, and what to do about it. *Bulletin of the American Meteorological Society*, 97(12), 2263–2273. https://doi.org/10.1175/BAMS-D-15-00267.1

World Bank. (2018). Regional dashboard: Poverty and equity in Sub-Saharan Africa.

Xie, P., Joyce, R., Wu, S., Yoo, S.-H., Yarosh, Y., Sun, F., & Lin, R. (2017). Reprocessed, bias-corrected CMORPH global high-resolution precipitation estimates from 1998. *Journal of Hydrometeorology*, 18(6), 1617–1641. https://doi.org/10.1175/JHM-D-16-0168.1