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The Plausibility of September–November Congo Basin Rainfall Change in Coupled Climate Models

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Key Points:
- The magnitude and distribution of Congo Basin future rainfall change varies across coupled models
- Process-based model evaluation can help to identify the plausibility of rainfall projections in the absence of observational data
- Historical model biases in the African Easterly Jets affect the magnitude of future rainfall change in the east Congo Basin

Supporting Information:
- Supporting Information S1

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Abstract As one of three global hot spots of tropical convection, potential future changes to the Congo Basin climate system will have regional and tropics-wide implications. However, the latest generation of climate models from the Coupled Model Intercomparison Project 5 disagree on the sign and magnitude of future change and diverge in their estimation of the historical rainfall climatology. This study assesses the plausibility of different signals of future rainfall change by examining the processes relating to rainfall projections in samples of historically wet or dry models during the September–November rainy season. In the west Congo Basin, there are no significant differences in rainfall change projections in models that are historically wet or dry. Both composites feature wetting in the north (up to 1.8 mm/day) and drying in the south, associated with enhanced tropical Atlantic sea surface temperatures, increased evaporation, and enhanced low-level moisture flux into the basin. In the east Congo Basin, there is greater evidence that differences in model historical climatologies has an influence on the magnitude of future rainfall change. Historically wet models project significant wetting in the northeast (1.19 mm/day) associated with a weakened northern component of the African Easterly Jet (AEJ) and enhanced moisture convergence. Dry models do not capture the structure of the AEJs in the historical period, and so changes to the AEJs under warming do not produce the same wetting pattern. The analysis therefore casts doubt on the plausibility of the driest rainfall change signals in the east Congo Basin.

1. Introduction

The continent of Africa is particularly vulnerable to climate change (Niang et al., 2014). Temperatures over Africa have been increasing at more than double that of global mean increases (Engelbrecht et al., 2015), and future warming over the African tropics exceeds the global average (greater than 1.4 K per 1 K of global mean warming) in projections from multiple climate model data sets (James et al., 2013). Combined with the region's low adaptive capacity and reliance on rain-fed agriculture, such changes may amplify existing stressors (Niang et al., 2014). In recent years, there has been increased scientific interest in both the physical mechanisms and the impacts of climate change over Africa, a region that has historically received limited scientific attention (Farnsworth et al., 2011; Rachel James et al., 2018; Washington et al., 2006). Research into climate change in the continent has focused predominantly on the subregions of West Africa and the Sahel (e.g., Biasutti & Sobel, 2009; Cook & Vizy, 2006; Hoerling et al., 2006; James et al., 2015; Vizy et al., 2013), East Africa (e.g., Hirons & Turner, 2018; Kent et al., 2015; Shongwe et al., 2011), and southern Africa (e.g., Kay & Washington, 2008; Lazenby et al., 2018; Shongwe et al., 2009) and has led to an improved understanding of the climate systems and projections in these areas.

Despite this progress, there remains a dearth of scientific research into the historical and future climate in the Congo Basin (James & Washington, 2013; Washington et al., 2006), the convective core of the continent and one of the three wettest places on Earth, alongside the Amazon Basin and Maritime Continent (Webster, 1983). This is likely due to the scarcity of recent observational data in this region, which has severely limited our understanding of the Congo Basin's climatology and climate variability (Washington et al., 2006; Washington et al., 2013). Data scarcity has severe implications for the evaluation of climate models, the tools used to predict and diagnose future climate changes. Without temporally and spatially homogenous observational data, it is difficult to test models' capabilities, and this may be one reason different models diverge significantly in their representation of historical climatology. A consequence of this is that the response of rainfall to warming across models is superimposed on vastly different basic states (Creese & Washington, 2016; Washington et al., 2013). Unsurprisingly, there is uncertainty in both the sign and magnitude of future change in rainfall in the Congo Basin across various global and regional climate models (Aloysius et al., 2016; Haensler et al., 2013; Pokam et al., 2018). Changes to rainfall amounts and seasonality have the potential to impact agricultural output and hydroelectricity, both of which are important for local and national economies in Congo Basin countries (CKDN, 2014; Hamududu & Killingtveit, 2012; Pereira, 2017). In addition, changes in rainfall have the potential to affect the boundaries of the Congo rainforest, the second largest above-ground carbon store in the world after the Amazon rainforest (Baccini et al., 2012; Malhi et al., 2013). It is therefore imperative that uncertainty in the climate response in this region is reduced, so that decision makers have the most robust evidence available for policy decisions.

1.1. Regionally Focused Process-Based Assessments

Regionally focused process-based assessments have emerged as a method for characterizing and differentiating among climate models, particularly where there is disagreement among models, or between models and observations (e.g., Cook & Vizy, 2006; James et al., 2015; Pinto et al., 2018; Seth et al., 2013). Models are assessed on their ability to represent processes that relate to rainfall; for example, low-level winds, jets, and overturning cells. This can be used to help determine the credibility of models in the absence of observational data. For example, James et al. (2015) assess the plausibility of model projections of change in West Africa via a comparison with known processes that drive rainfall variability in the historical period. They find that the processes associated with a strong drying signal in the future are not observed in the reanalysis data, casting doubt on the credibility of the drying signal.

Such approaches have also been used previously to assess modeled historical climatology in the Congo Basin. Creese and Washington (2016) analyze a sample of CMIP5 models and find that model rainfall is strongly related to the strength and pattern of low-level circulation, in particular the amount of water vapor entering the basin through specific boundaries. Creese and Washington (2018) further this analysis in the September–November (SON) rainy season, finding that the processes relating to relative model wetness in the west and east of the basin are distinct during this season. Their analysis shows that that models which are extremely wet in the west Congo Basin tend to have larger tropical Atlantic sea surface temperature (SST) biases than drier models. The study links the enhanced SSTs to higher rainfall via a chain of processes: warmer SSTs lead to enhanced evaporation in the Gulf of Guinea and associated enhanced low-level westerlies, which lead to enhanced local convection over the west Congo Basin, and thus enhanced rainfall. Given that the SST bias in coupled models is well established (e.g., Richter et al., 2014; Wang et al., 2014), identifying this link to rainfall casts doubt on extremely wet models, as their high rainfall appears to be in part caused by a spurious set of processes. In the east Congo Basin, the study finds that tropical Atlantic SST biases are not a significant differentiator between wet and dry models. Instead, wetter models feature stronger 925hPa westerly moisture flux and more poleward African Easterly Jets (AEJs) than dry models. This analysis highlighted the importance of approaching the east and west Congo Basin subdomains separately during SON, as the processes of importance differ within each subdomain.

The process-based assessment conducted by Creese and Washington (2018) led to a better understanding of why model climatologies diverge in the east and west subdomains in the Congo Basin, and in particular questioned the credibility of models that have large Atlantic SST biases and are wet in the west of the basin. In this paper, we extend the process-based analysis to future rainfall changes within the same groups of models (wet and dry in the east and west subdomains during SON) in order to establish whether categorizing models by their historical climatology results in different future rainfall signals. This may provide important insights into the plausibility of different rainfall change signals in the Congo Basin.

1.2. Climate Change in the Congo Basin

There are a small number of studies that have investigated the range of model projections of rainfall change in the Congo Basin across multimodel ensembles. Analyses of multiple projections from CMIP3, CMIP5, and CORDEX has found that the annual multimodel mean of these data sets projects a slight wetting over the basin in the future, though these changes are not large (Haensler et al., 2013). Similarly, Aloysius et al. (2016) find precipitation increases in CMIP5 models of only 2.4% and 2.8% by the end of the century under Representative Concentration Pathway (RCP) 4.5 and RCP8.5, respectively. However, the range of precipitation change among models varies between −9% and 27%. It is interesting to note that analysis of rainfall and hydrological data over recent decades has identified a drying trend over the Congo Basin (e.g., Diem et al., 2014; Malhi & Wright, 2004; Yin & Gruber, 2010), which contrasts with mean projections of wetting in model ensembles.

There may also be differences in the projected signal between global (GCMs) and regional climate models (RCMs); analysis of projected rainfall changes under 1.5°C and 2°C warming suggests that while GCMs tend to show increases in rainfall in this region, RCMs show an equal number of positive and negative changes (Pokam et al., 2018). In addition, all three studies find spatial patterns of rainfall change much less consistent among models, with Aloysius et al. (2016) noting in particular large variations in projected changes in the north and eastern parts of the region.

A process-based assessment has also been used in this region; James et al. (2013) evaluate rainfall changes in the Congo Basin in CMIP3 and two perturbed physics ensembles, before examining the atmospheric dynamics associated with different rainfall signals. They find the majority of models project drying in the west of the basin in all seasons (particularly during SON), which is associated with enhanced subsidence and a shift in the zonal circulation. They highlight that differences in models' preindustrial climatologies may influence their response to warming and conclude that further work is required to assess the plausibility of such changes.

1.3. Tropical Rainfall Change

As one of three core convective hot spots on the planet, changes in the Congo Basin will occur within the context of tropics-wide change. A number of mechanisms have been proposed which, in combination, could help to explain rainfall changes across the tropics. Global atmospheric water content will increase under warming, in line with Clausius-Clapeyron scaling (~7% K^{-1}), which could result in a "wet-gets-wetter" pattern of rainfall change, where convection, and thus rainfall, increases in areas of climatologically high rainfall and decreases in climatologically dry regions (Chou & Neelin, 2004; Chou et al., 2009; Held & Soden, 2006). This is likely to be offset at least in part by a weakening of the overturning circulation (Chadwick et al., 2013; Held & Soden, 2006; Ma & Xie, 2013; Ma et al., 2012; Vecchi et al., 2006) but can explain some of the changes observed and modeled at large spatial scales (Allan, 2012; Allan et al., 2010; Durack et al., 2012; Seager et al., 2010).

Chadwick et al.'s (2013) analysis finds that the wet-gets-wetter mechanism does not explain most of the rainfall change in the tropics, and they suggest that dynamical mechanisms of change may play a larger role, including shifts in the location of convection and alterations to the circulation. Patterns of SST change are also likely to influence the locations where rainfall increases and decreases occur ("warm-gets-wetter"). This has been found to be particularly influential over tropical oceans (Huang et al., 2013; Xie et al., 2010) but may also influence land areas via teleconnections (e.g., Biasutti & Sobel, 2009; Brown et al., 2016; Rowell & Chadwick, 2018). In East Africa, for example, Rowell and Chadwick (2018) find that differences in rainfall in CMIP5 models in part relate to their representation of SST pattern change and over central and southern Africa; Lazenby et al. (2018) find that the distinct pattern of northern regions wetting and southern regions drying during October to December is mostly associated with dynamic mechanisms of change, such as changes in the Indian Ocean SST gradient. In addition to the dynamic and thermodynamic changes associated with a warming atmosphere, there is also likely to be changes associated with the plant physiological effect (the narrowing of plant stomata under increased CO_2 concentrations), which may result in reduced evaporation over tropical forests the future, with associated implications for rainfall (Kooperman et al., 2018; Richardson et al., 2018). The extent to which this effect will influence rainfall patterns over the Congo rainforest is as yet unclear, particularly as recent analysis by Nicholson (2017) identifies weak subsidence over the Congo region below 700 hPa, which might limit the impact that reduced evaporation has on rainfall change over the Congo Basin.

1.4. Aims

The aim of the paper is to ascertain whether the plausibility of future climate projections can be established in the Congo Basin based on the performance of models in the historical period. We will do this by investigating whether the processes linked to the extremely wet or dry rainfall climatologies in models in the present day, as identified by Creese and Washington (2018), have a bearing on the magnitude or sign of future rainfall change in those models. The paper focuses on the SON rainy season, which has some of the largest historical differences in mean rainfall among models and which Creese and Washington (2018) linked to the representation of important regional processes such as the AEJs and the tropical Atlantic SST bias. The paper proceeds through answering three key questions:

Table 1
CMIP5 Models Used in This Study

Model	Institute	Reference
ACCESS1-3	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology Australia (CSIRO-BOM)	Collier and Uhe (2012)
bcc-csm1-1	Beijing Climate Centre (BCC)	Wu et al. (2013)
CCSM4	National Centre for Atmospheric Research (NCAR)	Gent et al. (2011)
CESM1-CAM5	National Centre for Atmospheric Research (NCAR)	Neale et al. (2012)
CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici (CMCC)	Scoccimarro et al. (2011)
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (CNRM-CERFACS)	Voldoire et al. (2011)
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence (CSIRO-QCCCE)	Jeffrey et al. (2013)
EC-EARTH	EC-Earth Consortium: European Centre for Medium-Range Weather Forecasts (ECMWF) and other European institutes	Hazeleger et al. (2010)
FGOALS-g2	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) and Institute of Atmospheric Physics (IAP)	Li et al. (2013)
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory (NOAA GFDL)	Donner et al. (2011)
GISS-E2-R	NASA Goddard Institute for Space Studies (GISS)	Schmidt et al. (2014)
HadGEM2-ES	Met Office Hadley Centre (MOHC)	Jones et al. (2011)
IPSL-CM5A-MR	Institut Pierre-Simon Laplace (IPSL)	Dufresne et al. (2013)
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC)	Watanabe et al. (2010)
MPI-ESM-LR	Max-Planck-Institut für Meteorologie (MPI-M)	Marsland et al. (2003)
MRI-CGCM3	Meteorological Research Institute (MRI)	Yukimoto et al. (2012)
NorESM1-M	Norwegian Climate Centre (NCC)	(Bentsen et al., 2013)

1. What is the range of Congo Basin rainfall changes across models in SON, both in terms of magnitude and spatial distribution?
2. Do models with relatively wet or dry historical climatologies in the east or west Congo Basin during SON feature significantly different rainfall signals at the end of the 21st century?
3. What are the physical processes related to rainfall change in the models with wet or dry historical climatologies, and based on previous assessment of the credibility of the model composites, can we determine whether some models produce more plausible future projections than others?

This paper is structured as follows. The data and methods used are outlined in section 2. Section 3 will assess the broadscale rainfall changes that occur across models in the SON season, including the magnitude and distribution of rainfall change. Section 4 will then identify the processes associated with rainfall change in the west Congo Basin composites defined above. The analysis is repeated in section 5 for the east Congo Basin composites. Section 6 will discuss the results and summary.

2. Data and Methods

Coupled model data are taken from the latest Coupled Model Intercomparison Project (CMIP5), which comprises models from different modeling centers that have committed to running the same suite of experiments (Taylor et al., 2012). As this study builds on the analysis of coupled model climatology by Creese and Washington (2018), the same sample of 17 models is used for analysis (Table 1). These models represent the full spectrum of wet to dry over the Congo Basin and contain the required variables for analysis. Data are used from the historical (coupled) experiment and the RCP8.5 future experiment, which represents 8.5 W/m^2 of global net radiative forcing by 2100 (van Vuuren et al., 2011). This level of forcing is consistent with a "business-as-usual" approach to climate mitigation.

Analysis is conducted separately on the eastern (22°E to 35°E, 10°S to 10°N) and western (8°E and 21°E, 10°S to 10°N) subdomains, following Creese and Washington (2018). Long term means of the historical (1979–2005) and future (2074–2100) periods are calculated over the above domains. The future-minus-present rainfall signal is denoted throughout as ΔP. The four wettest and four driest models in each subdomain are selected for use in composite analysis and are indicated in Figure 1. These are the same models

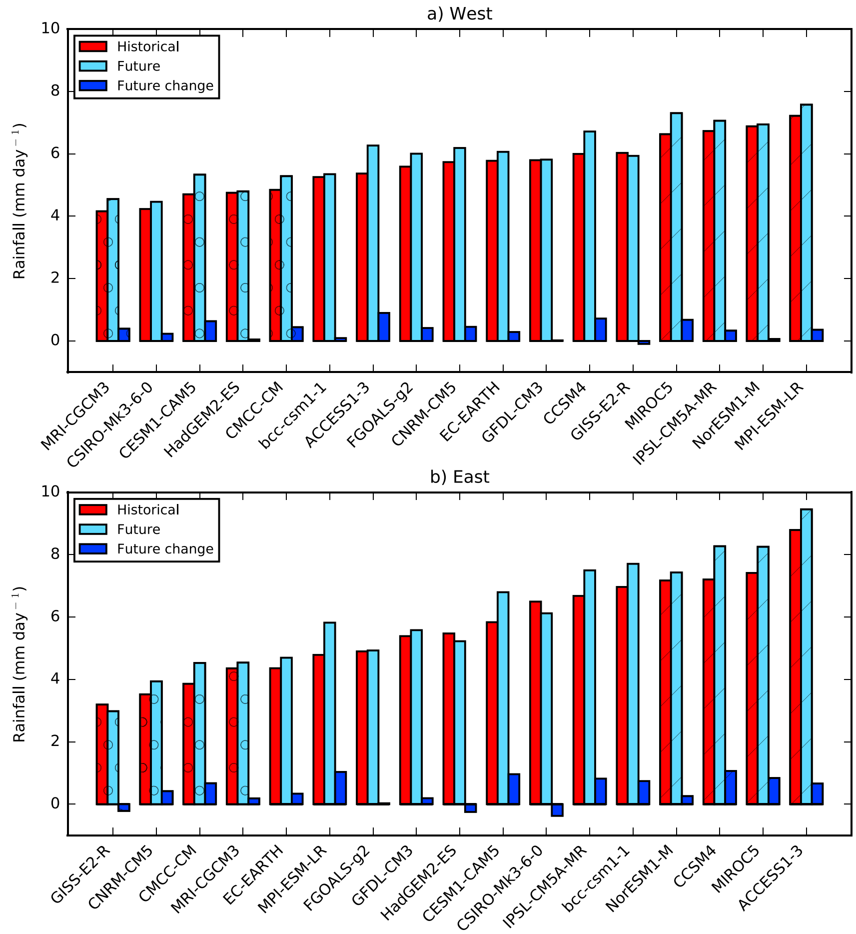

Figure 1. Long-term mean September–November rainfall (mm/day) in individual CMIP5 models in (a) the west Congo Basin (8°E to 21°E, 10°S to 10°N) and (b) east Congo Basin (22°E to 35°E, 10°S to 10°N), in the historical period (1979–2005; red), the future period (2074–2100; light blue), and the 2074–2100 minus 1979–2005 (ΔP; dark blue). Ordered by mean historical rainfall values (low to high). Models used in the wet (dry) composites are denoted by hatching (stipples). CSIRO-Mk3-6-0 is excluded from the dry composite (as in Creese & Washington, 2018) due to the opposite signal of the historical sea surface temperature bias.

used by Creese and Washington (2018) as one aim of this paper is to understand if categorizing models in this way, with an understanding of the plausibility of their climatologies, can give insights into their rainfall change signal and pattern. Long-term means of the historical (1979–2005) and future (2074–2100) periods are calculated over the above domains. The future-minus-present rainfall in the wet and dry composites is denoted as ΔP_{wet} and ΔP_{dry}, respectively.

3. Rainfall Changes in SON

Figure 1 shows that in both the east and west Congo Basin subdomains, models that are currently relatively wet compared to the suite of models remain so in the future, as do models that are currently dry. Historical and future mean basin rainfall are strongly positively correlated across models in both the west ($r = 0.96$, $p < 0.000001$) and east ($r = 0.97$, $p \leq 0.000001$) of the basin during SON and indeed in all other seasons. This suggests that some of the processes controlling rainfall magnitude and distribution in the historical period may continue to play a role in the future and may account for any differences in the rainfall change (ΔP) signal found among the wet and dry composites. This hypothesis will be explored in sections 4 and 5. Understanding the role of the underlying climatology in determining future change will be particularly important, as the differences between model climatological rainfall are much greater than the values of

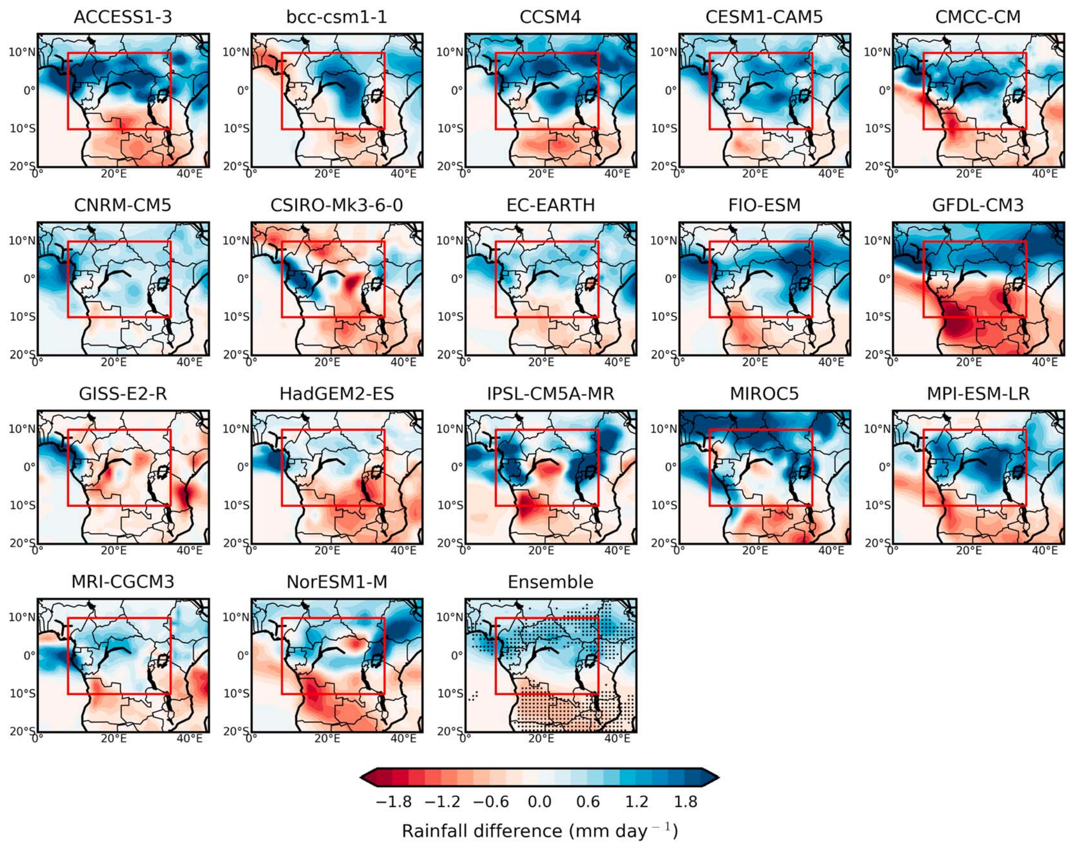

Figure 2. Future (2074–2100) minus historical (1979–2005) long-term mean rainfall (Δ*P*; mm/day) in individual CMIP5 models. Stipples in the ensemble mean plot show grid boxes where 14 out of 17 models agree on the sign of change. The red box indicates the whole Congo Basin domain (8°E to 35°E, 10°S to 10°N)

Δ*P* that are being projected in this region (Figure 1, dark blue bars). Figure 1 also shows that historical rainfall is not correlated with the change in rainfall in either subdomain across the suite of models.

Spatial patterns of Δ*P* in individual models and the ensemble mean in SON are shown in Figure 2. Across the annual cycle (not shown) there is some evidence of a north-south pattern of future-minus-present rainfall (Δ*P*) over Africa, where northern areas get wetter and southern areas get drier under RCP8.5 forcing. In SON the north-south pattern of Δ*P* is most clear, and the majority of models agree on the direction of Δ*P* changes broadly between 0° and 10°N and 10°S and 25°S. However, in the south Congo Basin (between 0 and 10°S) there is little agreement on the sign of change. This suggests that models disagree on the precise location of the change between the wetting and drying zones. While some show distinct north/south divisions (e.g., GFDL-CM3 and MPI-ESM-LR), others exhibit less regular distributions of rainfall change (e.g., CSIRO-Mk3-6-0 and IPSL-CM5A-MR). It is also evident that even among models with a clear north-south divide, the latitude of the change from wetting to drying varies; for example, in GFDL-CM3, this change occurs near the equator, whereas in MPI-ESM-LR, it occurs closer to 10°S. This implies that while the overall north-south pattern across Africa is common across the majority of models, processes controlling rainfall change at more local scales within the basin may not be consistent among models.

4. Rainfall Change Mechanisms in the West Congo Basin

This section will assess whether categorizing models as climatologically (in the historical period) wet or dry in the east and west Congo Basin (as in Creese & Washington, 2018) provides insight into the processes controlling rainfall change over the Congo Basin in such models and, by extension, the plausibility of such rainfall changes.

4.1. Rainfall Change

The rainfall distribution in the historical and future period, for both wet and dry composites, is shown in Figure 3. In the historical period, wet models are on average 2.2 mm/day wetter than dry models over the

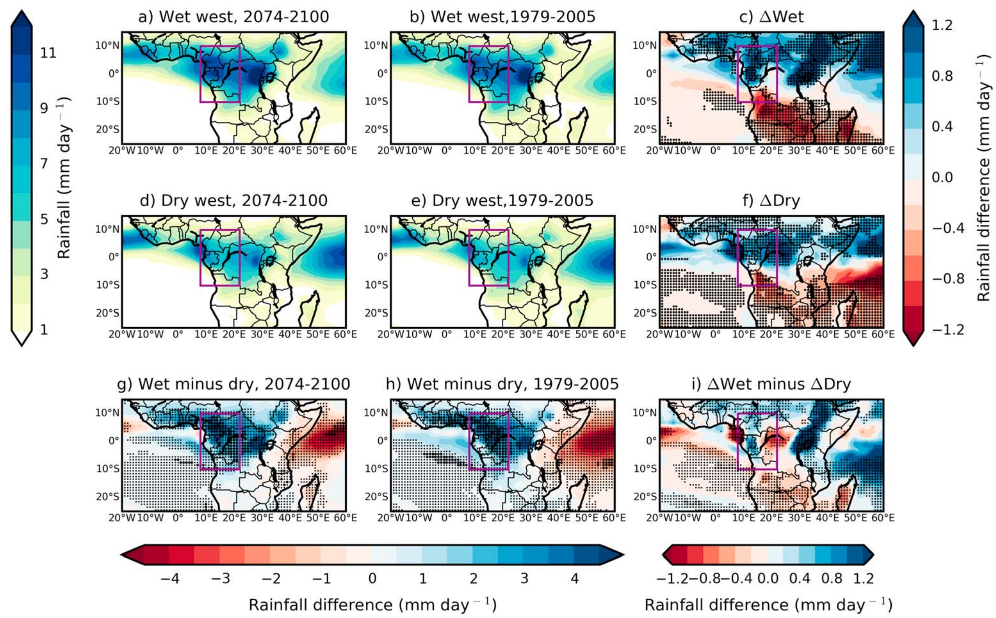

Figure 3. Long-term mean September–November rainfall (mm/day) in the west Congo Basin wet composite (top row) and dry composite (middle row) in (a, d) 2074–2100; (b, e) 1979–2005; and (c, f) 2074–2100 minus 1979–2005 (ΔP); (g) 2074–2100 wet-minus-dry composite; (h) 1979–2005 wet-minus-dry composite; and (i) wet ΔP minus dry ΔP. Stipples in (c) and (f) indicate where all four models in the composite agree on the sign of change. Stipples in (g–i) occur at grid boxes where (1) all wettest composite values are larger or smaller than all driest composite values (large) and (2) all wettest (driest) composite values are greater or smaller than the driest (wettest) composite mean (small). The purple box indicates the location of the west Congo Basin domain.

west Congo Basin domain (Figure 3h). The wet-minus-dry difference of future simulations of the composites is very similar to the historical simulations (Figure 3g), showing that the broad pattern of mean rainfall in models remain similar in the future climatology. For example, in the historical period in the west wet composite, there are two regions of high rainfall; one in the east of the basin and one near the Atlantic coast (Figure 3b). This pattern does not change significantly in the future period (Figure 3a). This is also the case in individual models: the rainfall distribution (which Creese and Washington (2016, 2018) found varied significantly among models) does not change significantly in the future simulation of that model (not shown).

Of interest to this paper is the pattern of ΔP in the wet composite (ΔP_{wet}, Figure 3c) and dry composite (ΔP_{dry}, Figure 3f) and the difference between the two (ΔP_{wet} minus ΔP_{dry}, Figure 3i). Both wet and dry models show similar patterns of rainfall change; as in the ensemble mean, there is a north-south pattern of wetting and drying. In both composites, the wetting is north of the equator, but in dry models, the region of wetting covers a larger area. Both composites also feature drying to the south of the Congo Basin domain, with a small incursion of robust drying into the domain along the Atlantic coast.

Figure 3i shows that there are some differences between ΔP_{wet} and ΔP_{dry}. Wet models feature greater wetting in the center of the west Congo Basin domain, whereas dry models feature greater wetting at the western and eastern boundaries of the domain. However, for a large portion of the domain, there is no clear or significant difference between ΔP_{wet} and ΔP_{dry}. This suggests that in this subdomain during SON, whether or not a model is historically extremely wet or dry does not have a large impact on the ΔP signal for parts of the basin.

The following section attempts to elucidate the plausibility of these projected changes in rainfall.

4.2. Processes Associated With Rainfall Change

Creese and Washington (2018) identified the following processes that help to explain the differences between historically wet and dry models in the west Congo Basin:

1. Models that are wetter tend to have higher SST biases in the tropical east Atlantic Ocean.
2. Evaporation and low-level westerlies are stronger over this region.

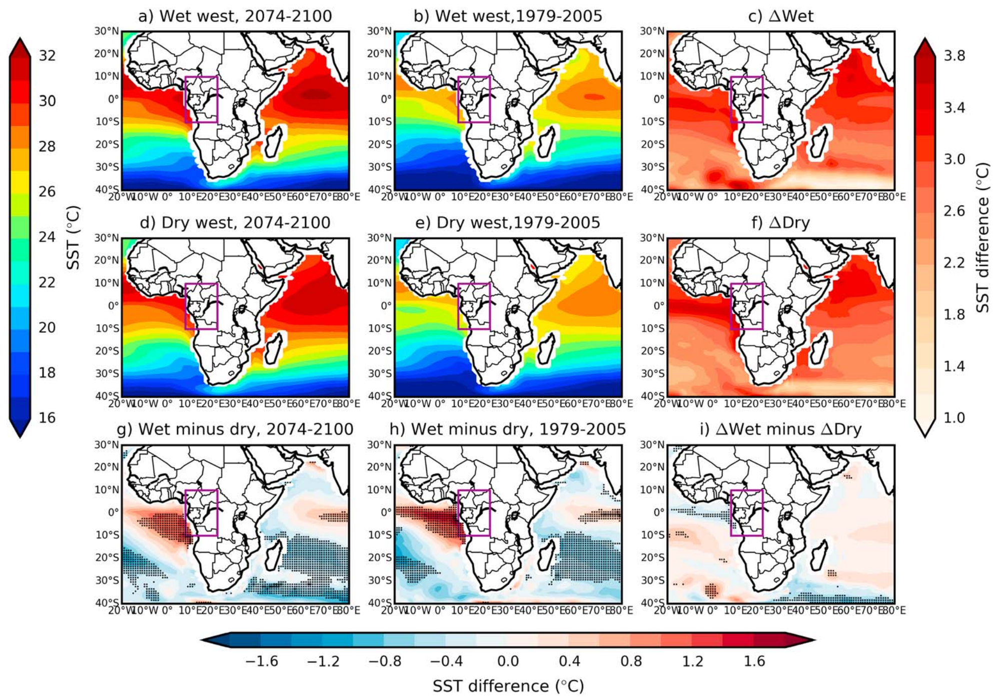

Figure 4. Long-term mean September–November sea surface temperature (SST; °C) in the west Congo Basin wet composite (top row) and dry composite (middle row) in (a, d) 2074–2100; (b, e) 1979–2005; and (c, f) 2074–2100 minus 1979–2005 (ΔSST); (g) 2074–2100 wet-minus-dry composite; (h) 1979–2005 wet-minus-dry composite; and (i) wet ΔSST minus dry ΔSST. Stipples in (g–i) as in Figure 3. The purple box indicates the location of the west Congo Basin domain.

3. The combination of enhanced evaporation and low-level wind transports moisture onto the west Congo Basin coast and contributes to a local enhancement of convection and rainfall.

Given the important role these processes play in determining rainfall amounts and patterns in the Congo Basin in the historical period, assessing how these processes change in models in the future is considered next.

4.2.1. SST

Most coupled models feature a large and persistent warm SST bias in the tropical east Atlantic Ocean (Wang et al., 2014), and this bias tends to be stronger in wet west Congo Basin models in the historical period (Creese & Washington, 2018; Figure 4h). Both wet and dry models feature positive SST change (ΔSST) across both the Atlantic and Indian Oceans (Figures 4c and 4f). Both composites feature particularly strong warming over the tropical east Atlantic, in the region of the historical SST bias. The pattern of ΔSST is broadly similar between the wet and dry composite; the only robust region of difference is a small area in the tropical east Atlantic where dry models warm slightly more than wet models (Figure 4i). As in the processes identified in the historical period, warmer SSTs in both composites are also associated with enhanced evaporation over this region; this is also slightly greater in dry models than wet model, fitting with the greater ΔSST (supporting information Figure S1).

The enhanced SST and evaporation in the future could therefore explain some of the wetting in this region in both composites and may explain the enhanced wetting in dry models compared to wet models along the coasts of Gabon and Cameroon. It does not however explain the greater wetting wet models experience in the center of the western subdomain. It is also noteworthy that the positive ΔSST signal is in a region of historically large positive SST biases (of more than 4 K in some models), and so changes in SST under future warming build on an already significant bias.

4.2.2. Low-Level Moisture Flux

Previous work has identified low-level moisture flux (qflux) as an important influence on model wetness, particularly in the form of low-level westerlies during SON (W. Pokam et al., 2014). Both wet and dry models feature increases in low-level (925 hPa) westerly qflux into the basin in the future (Figure 5), with no

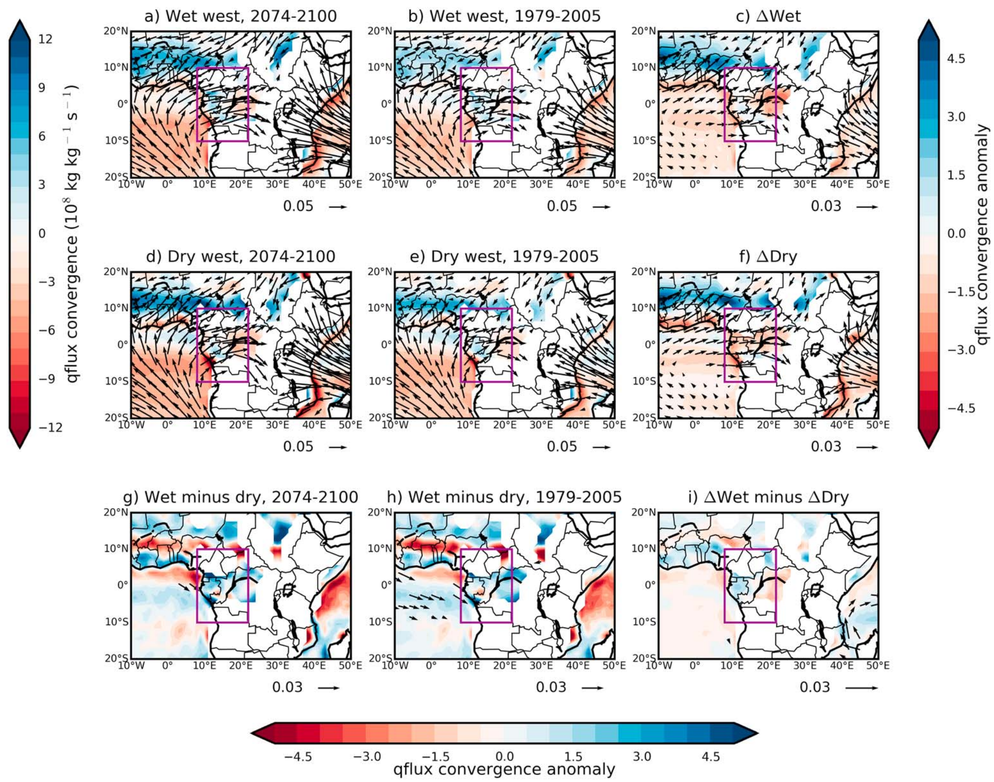

Figure 5. Long-term mean September–November qflux convergence (10^{-8} kg·kg^{-1}·s^{-1}; shaded) and qflux (kg·kg^{-1}·m·s^{-1}; vectors) at 925 hPa in the west Congo Basin wet composite (top row) and dry composite (middle row) in (a, d) 2074–2100; (b, e) 1979–2005; and (c, f) 2074–2100 minus 1979–2005; (g) 2074–2100 wet-minus-dry composite; (h) 1979–2005 wet-minus-dry composite; and (i) wet change minus dry change. Vectors in (c) and (f) indicate where all four models in the composite agree on the sign of change. Vectors in (g–i) occur at grid boxes where all wettest composite values are larger or smaller than all driest composite values. The red box indicates the location of the west Congo Basin domain.

significant difference in the pattern of qflux change (Δqflux) between the two composites (Figure 5i). Both composites feature generally enhanced convergence to the north of the domain, colocated with the broad region of wetting in all models. Despite broadscale similarities, there are some differences in the pattern of qflux convergence over the western subdomain between the two composites. Wet models feature an enhancement of moisture flux convergence in the west of the subdomain (over Gabon) in the future, whereas dry models feature a weakening. This colocates with the region of increased rainfall in wet models compared to dry models (Figure 3i). Both composites also feature enhanced moisture flux divergence in the east of the subdomain in the future. This is weaker in dry models, coinciding with where dry models feature greater rainfall increases than wet models. These findings suggest that local patterns of low-level convergence may relate to spatial differences in ΔP between the composites but that the overall low-level moisture circulation is not significantly different between wet and dry models.

4.2.3. Overturning Circulation

In the historical period during SON, stronger low-level moisture flux and enhanced evaporation are associated with enhanced convection in wet models in the west Congo Basin. It is hypothesized that the wetting signal in both composites may therefore be linked to increased local uplift. Figure 6 shows the zonal cross section of omega (Ω) near the equator, where a zonal overturning circulation is present in the climatology of both composites, and the change in omega (ΔΩ) signal. Somewhat surprisingly, in both composites, uplift weakens in the future, though the sign of change across composite members is not consistent throughout the column (Figures 6c and 6f). This weakening is greater in wet models than dry models. In both wet and dry models, there is a decrease in subsidence above 600 hPa between 35° and 40°E, over East Africa. The pattern of decreased uplift over the west Congo Basin is reduced slightly in the north of the domain (0°–10°N; supporting information Figure S2), which features mean wetting and increases in

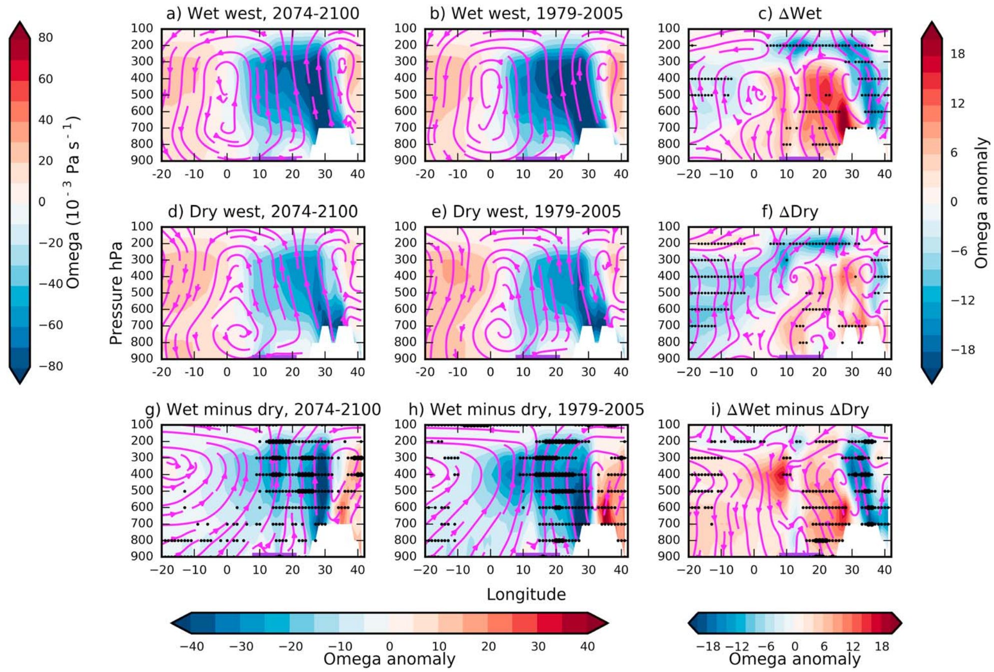

Figure 6. Long-term mean September–November omega (10^{-3} Pa/s; shaded) averaged between 3°S and 3°N and divergent component of zonal wind (m/s) and omega (10^{-3} Pa/s streamlines), in the west Congo Basin wet composite (top row) and dry composite (middle row) in (a, d) 2074–2100; (b, e) 1979–2005; and (c, f) 2074–2100 minus 1979–2005; (g) 2074–2100 wet-minus-dry composite; (h) 1979–2005 wet-minus-dry composite; and (i) wet change minus dry change. Areas with high topography in models are masked (white). The purple box shows the extent of the west Congo Basin domain (8°E to 21°E). Stipples as in Figure 3 and refer to omega values.

the south (5°–10°S; supporting information Figure S3), where both composites feature mean drying over land. In the south, the decrease in uplift cooccurs with reductions in subsidence over the coastline and tropical Atlantic, indicating that the zonal overturning circulation weakens in the future in both composites.

The general overturning circulation is expected to weaken under warming, and these results suggest that, particularly in the historically wet models, a local weakening of the overturning circulation is present despite wetting. Figure 7 shows how the changes in Ω at 500 hPa map on to changes in rainfall across the annual cycle in the composites. In both the future and historical climatology, the latitudinal location of rainfall throughout the annual cycle maps reasonably well onto the latitudinal location of negative omega. However, when comparing the ΔΩ and ΔP patterns, it is clear there is some displacement of the two variables in the future (Figures 7c and 7f). In both composites, there is a clear pattern of positive ΔΩ (i.e., reduced uplift) throughout the annual cycle, following approximately the north-south trajectory of the rain band. Changes in rainfall, however, are displaced from this band; wetting tends to occur on the northern flank of the region of positive ΔΩ and drying occurs on the southern flank. This pattern is strongest between July and December in both composites. These results suggest the localized reduction in uplift over the central Congo Basin is part of a larger pattern whereby the zone of maximum convection is shifted northward.

Despite the local reduction in uplift, both composites feature wetting in the northwest domain. This may be related to changes in the frequency distribution of daily rainfall, as shown in Figure 8. In the future in the wet composites that feature greater reductions in uplift, the distribution of daily rainfall is flatter and wider, showing an increase in both wet and dry days in the future. This is despite a clear shift toward less negative daily omega values in the future in the wet composite (supporting information Figure S4). The increase in rainfall over the northwest domain is thus likely to be the result of increases in specific humidity (q) that are sufficient to overcome the slight decreases in uplift. Increased q could in turn be a result of thermodynamic mechanisms (e.g., increased q as the atmosphere warms) or a combination of thermodynamic and dynamic mechanisms (e.g., enhanced qflux into the basin, as shown in Figure 5).

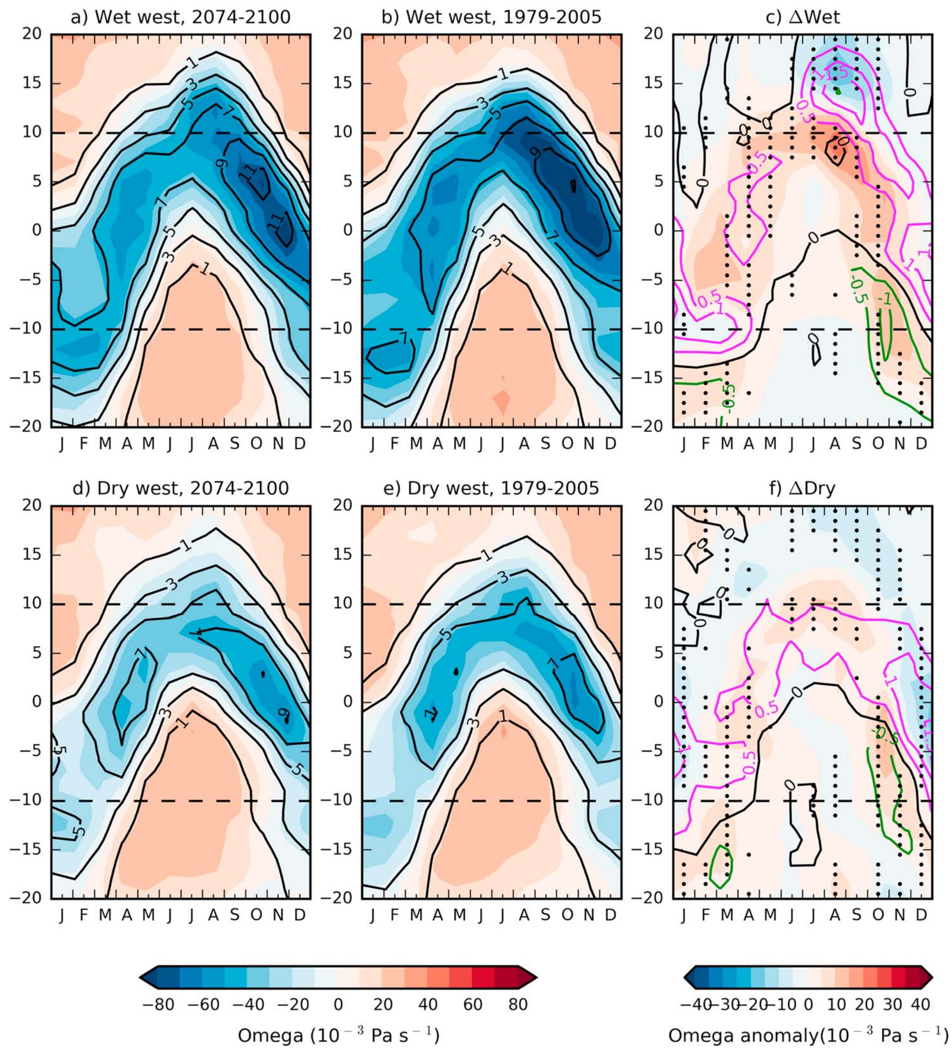

Figure 7. Annual cycle of long-term mean omega at 500 hPa (10^{-3} Pa/s; shaded) and rainfall (mm/day; contours), averaged between 8°E and 21°E in the west Congo Basin wet composite (top row) and dry composite (middle row) in (a, d) 2074–2100; (b, e) 1979–2005; and (c, f) 2074–2100 minus 1979–2005. Stipples as in Figure 3 and refer to omega values. Dashed lines indicate the northern and southern boundaries of the domain. Pink (green) contours in (c) and (f) show positive (negative) rainfall change; the zero contour is black.

5. Rainfall Change Mechanisms in the East Congo Basin

5.1. Rainfall Change

Rainfall changes over the east Congo Basin for the wet and dry composites are shown in Figure 9. In the historical period, models in the wet composite are on average more than twice as wet as those in the dry composite, with the largest differences in the interior of the continent. The difference between wet and dry models increases in the future climatology, particularly in the north of the domain (Figure 9g). Wet models feature a robust and positive ΔP signal in the future (Figure 9c), while the dry models feature weak wetting over this domain, with very little agreement on the sign of change (Figure 9f). Figure 9i quantifies the difference in ΔP between the composites, showing that wet models experience significantly higher wetting than dry models in the east near the equator and in the north of the subdomain. This may indicate a "wettest-models-get-wetter" response across models, whereby rainfall increases most in models with historically high rainfall. Figure 9i also suggests that the strength of the north wetting/south drying pattern (observed across the majority of models in Figure 2) is stronger in wet models than dry models. Correlation analysis of the contrast in ΔP magnitude between wetting and drying grid boxes over the subdomain and the historical

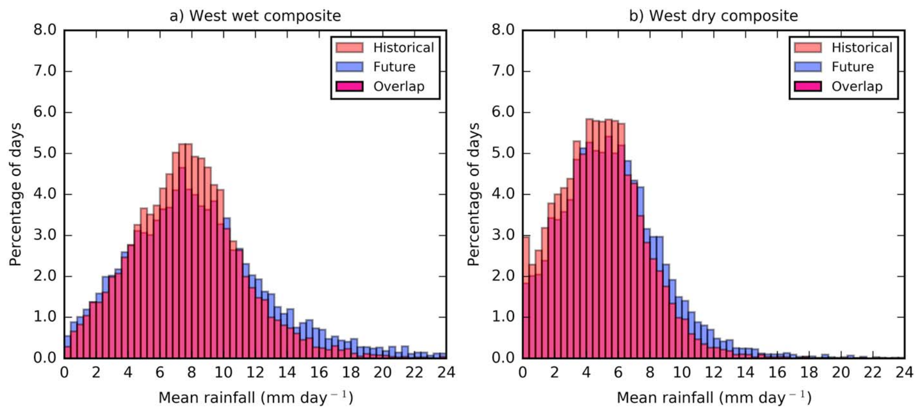

Figure 8. Frequency distribution of daily rainfall (mm/day) in all September–November days in the northwest of the basin (8°E to 21°E, 0° to 10°N) in all composite member models in (a) the west Congo Basin wet composite and (b) the dry composite, between 2074 and 2100 (blue) and 1979–2005 (orange). Pink denotes overlap between the orange and blue distributions.

rainfall across models concurs, returning an r value of 0.67 ($p = 0.003$) for the east Congo Basin (supporting information Figure S5).

These results suggest that categorizing the models on their historical climatology in the two sets of models has an impact on both the pattern and magnitude of the future rainfall change signal in this region. The following section will therefore examine future changes in the processes known to relate to model wetness in the historical period to determine whether they relate to model differences in the ΔP signal in this region.

5.2. Processes Associated With Rainfall Change

The following processes have previously been found to be related to climatological rainfall differences across models in the east Congo Basin (Creese & Washington, 2018):

1. Models that are wetter tend to have stronger low-level westerlies from the tropical Atlantic, associated with a stronger South Atlantic High (SAH).

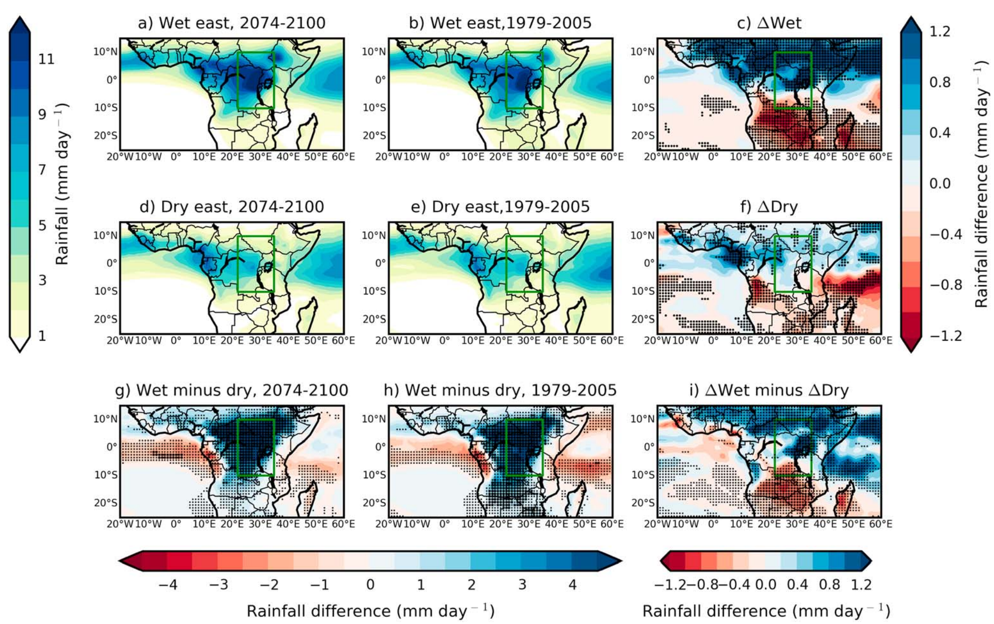

Figure 9. As in Figure 3 but for the east Congo Basin composites. The green box indicates the location of the east Congo Basin domain.

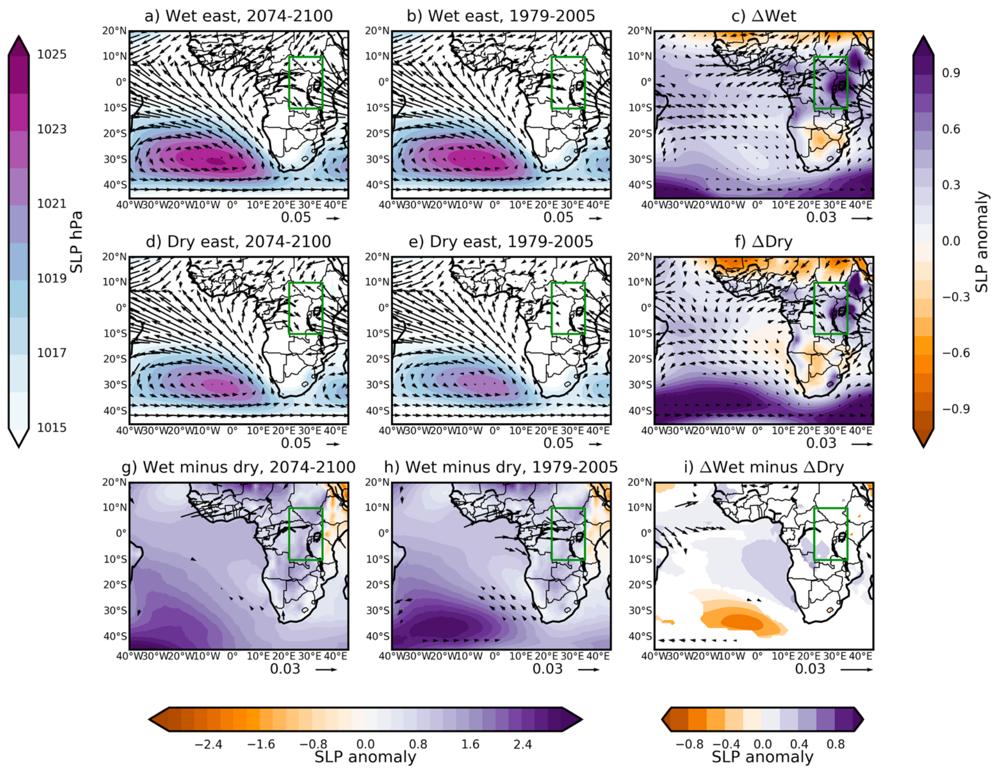

Figure 10. Long-term mean September–November sea-level pressure (hPa; shaded) and qflux at 925 hPa (kg·kg^{-1}·m·s^{-1}; vectors) in the west Congo Basin wet composite (top row) and dry composite (middle row) in (a, d) 2074–2100; (b, e) 1979–2005; and (c, f) 2074–2100 minus 1979–2005; (g) 2074–2100 wet-minus-dry composite; (h) 1979–2005 wet-minus-dry composite; and (i) wet change minus dry change. Vectors as in Figure 5. Sea-level pressure (SLP) shading is only shown at grid boxes in (i) when the values in all wet models are greater than the values in all dry models or all the values in all dry models are greater than the values in all wet models.

2. The low-level westerlies form the lower branch of a stronger zonally overturning circulation between the Atlantic and Congo Basin, such that wet models have enhanced convection over land and subsidence over the ocean.
3. Wet models also have a weaker and more poleward northern branch of the AEJ, while dry models have a stronger and more equatorward jet. The stronger jet in dry models may act to export moisture out of the basin through the western boundary and suppress rainfall.

The extent to which these processes relate to rainfall changes in the east Congo Basin is assessed below.

5.2.1. Low-level Westerlies and SAH

As in the west composites, low-level westerly qflux into the basin increases in the future in both the wet and dry composites (Figures 10c and 10f). There is also an increase in south easterly flow in the south tropical Atlantic, along the northeastern flank of the SAH. Sea-level pressure increases slightly across the Atlantic in the future, with the largest increases south of 30°S, suggesting a southward expansion of the high-pressure cell, which is consistent with the observed and theorized poleward expansion of the Hadley cell under warming (Held & Hou, 1980; Hu & Fu, 2007). However, there are few significant differences in both fields between the wet and dry models. The strength of the increase in 925-hPa westerly qflux is not significantly different between the two composites nor are there other low-level circulation differences. The dry models do feature a greater increase in the strength of the southern flank of the SAH than wet models; however, this does not cooccur with greater westerly qflux or greater wetting in the east Congo Basin domain. Thus, while changes in both variables may contribute to wetting in both composites, they are not the dominant processes differentiating between the ΔP_{wet} and ΔP_{dry} signals.

5.2.2. Overturning Circulation

In the historical period, wet models feature a stronger zonal overturning circulation near the equator between the Atlantic and the Congo Basin (Figure 11h), as well as enhanced uplift over the Maritime

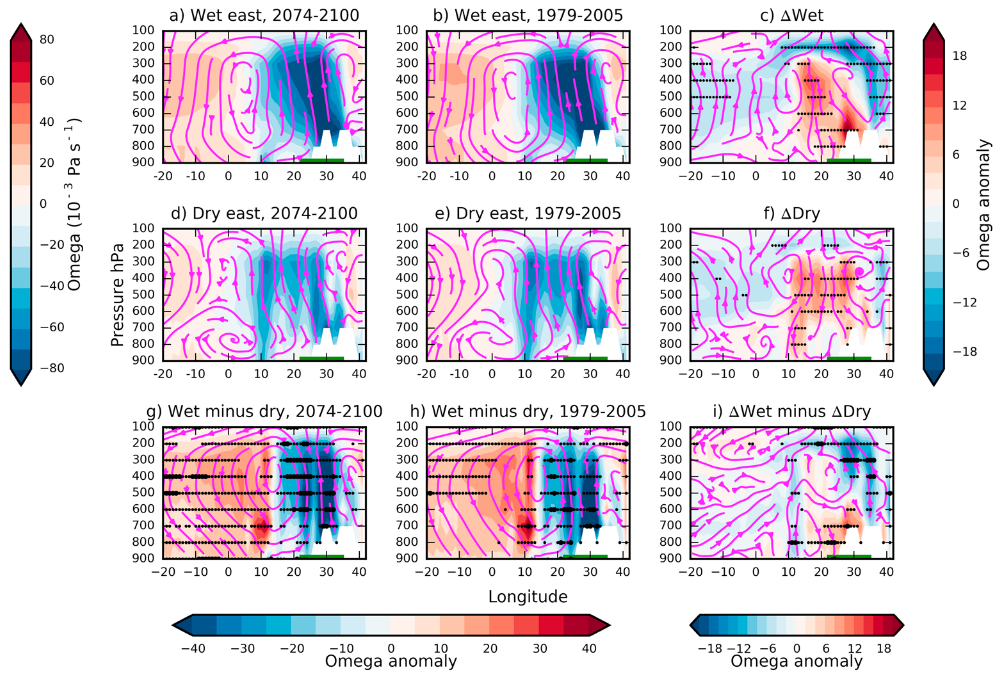

Figure 11. As in Figure 6 but for the east Congo Basin composites. The green box indicates the location of the east Congo Basin domain.

Continent and subsidence over the East African coast. This wet-minus-dry pattern is very similar in the future (Figure 11g), suggesting that this process is still important for maintaining relatively wet or dry future climatologies. However, as in the west composites, both wet and dry composites feature a decrease in uplift in the future over the region of climatological uplift, and anomalous uplift over the region of climatological subsidence (east of 30°E; Figures 11c and 11f). In wet models, this decrease is confined to a narrower portion of the column (~15–30°E) than in dry models. This is also evident in the north of the domain (0°–10°N, supporting information Figure S6). There is anomalous uplift in the wet composite compared to the dry composite in the east of the domain above 500 hPa, which may contribute to increased wetting in the wet models. However, there is limited evidence that differences in the zonal overturning circulation between the composites account for the rainfall change differences.

Given the north wetting/south drying pattern observed in Figure 9, there may also be latitudinal differences in convection and subsidence that relate to rainfall. The annual cycle by latitude of Ω at 500 hPa and rainfall are shown in Figure 12. Uplift decreases in the core region of convection throughout the year but increases to the north of the historical band of omega between July and December. As in the west composites, increased (decreased) rainfall does not exactly map onto increased (decreased) uplift: positive rainfall changes occur on the northern flank of the region of omega decreases, while negative rainfall changes occur on to the southern flank.

Figures 11 and 12 show that rainfall increases are occurring in a region with uncertain changes in omega, both throughout the atmospheric column and latitudinally. The fact that increases in rainfall cooccur with slight decreases in convection, particularly in wet models, suggests that there may be other processes in wet models that are able to contribute to increases in rainfall despite weakened uplift, for example, increased moisture supply or convergence. In dry models, there is a greater reduction in uplift in the east of the domain than in wet models, which may contribute to suppression of rainfall increases. Figures 11 and 12 may also suggest that the processes that contribute to enhanced rainfall in spite of weakened uplift are not present in the dry models.

5.2.3. The 700-hPa qflux and the AEJs

Creese and Washington (2018) found that 700 hPa wind and qflux were important differentiators between historically wet and dry models in the east Congo Basin. Figure 13 shows the 700 hPa qflux and qflux convergence fields for the wet and dry composites. Both wet and dry models feature an increase in qflux

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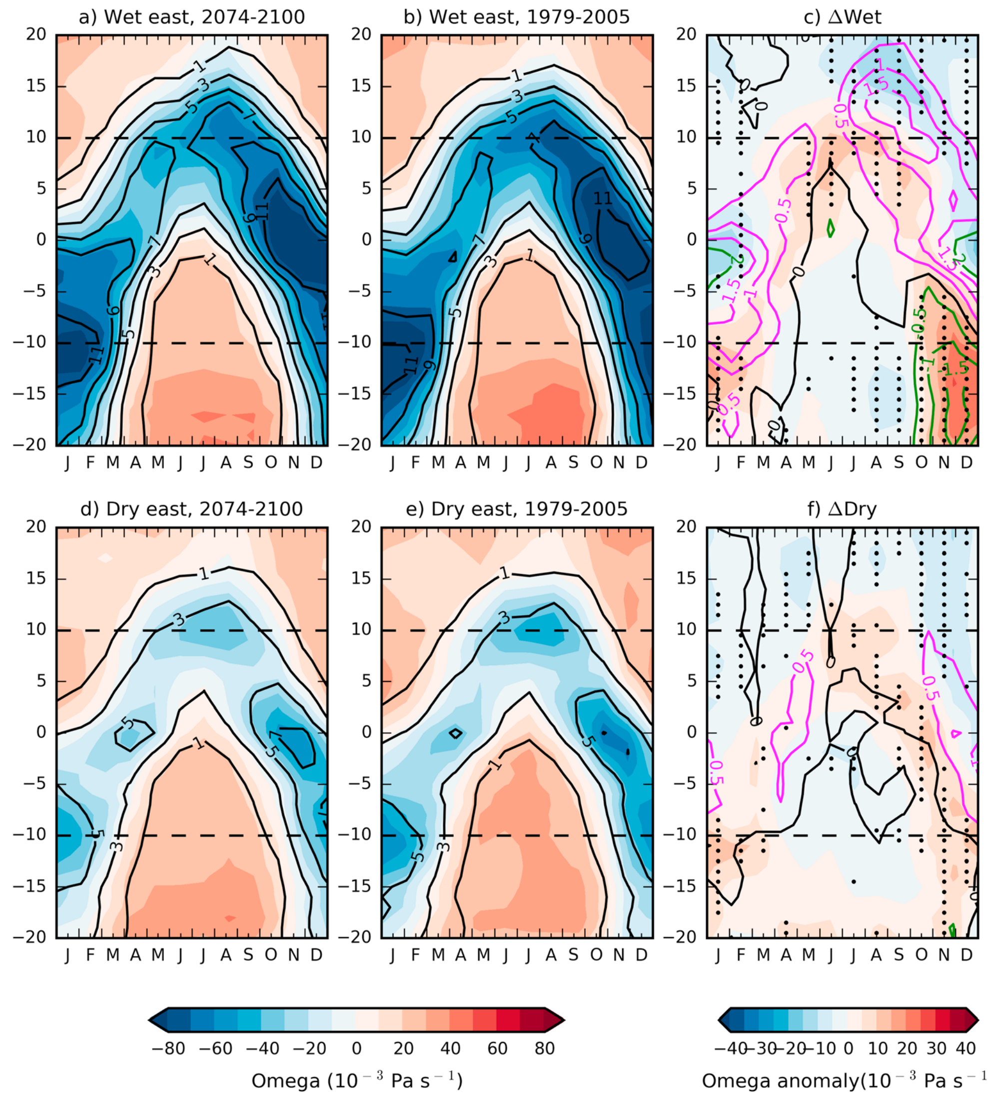

Figure 12. As in Figure 7 but for the east Congo Basin composites. Dashed lines indicate the northern and southern boundaries of the domain.

divergence in the south of the subdomain, possibly associated with enhanced southeasterly qflux from the Indian Ocean, which becomes more meridional in future. The increase in strength of the southeasterly qflux is not significantly different between the wet composite and dry composite (Figure 13i). Near the equator, where wet models feature anomalous wetting in the future compare to dry models, wet models also feature anomalously enhanced qflux convergence. Dry models feature enhanced qflux convergence further north in the subdomain and enhanced northeasterly qflux into the basin across the northern border. Increased northeasterly qflux in dry models across the north of the domain (Figure 13f) is not present in the wet models (Figure 13c); this is the dominant difference between wet and dry models in their future change signal.

Changes in the strength and location of the northeasterly and southeasterly qflux into the basin are suggestive of changes in the strength and structure of the AEJs. Creese and Washington (2018) found that historically wet models feature two distinct AEJs during SON, as seen in observations, with a clear separation between them near the equator. Conversely, dry models feature one, strong jet, centered just north of the equator. Figure 14 shows the latitudinal structure of the zonal wind (u) and future changes (Δu) between composites. In both composites, there is a weakening of the easterlies between 0 and 10°N and a strengthening of the easterlies/weakening of the westerlies centered near 20°N and 20°S. Despite

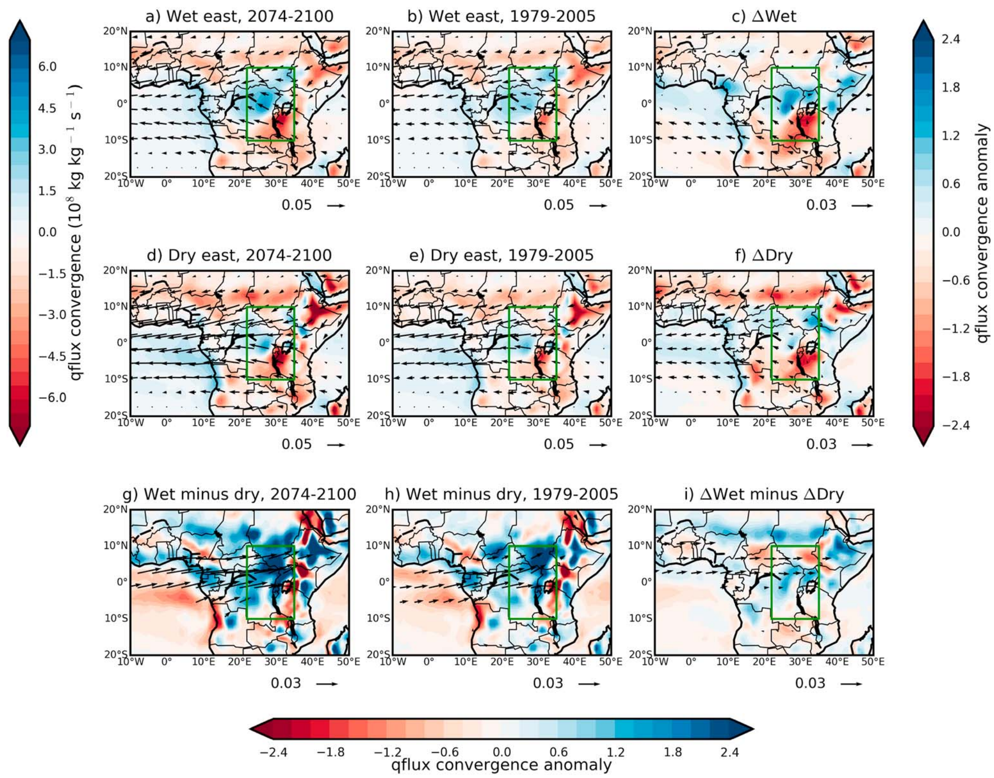

Figure 13. As in Figure 5 but for the east Congo Basin composites at 700 hPa. The green box indicates the location of the east Congo Basin domain.

similarities in the latitudinal pattern of zonal wind change, there are large differences in strength of this pattern between wet models and dry models. In wet models, the AEJ-N at around 10°N weakens significantly more than in dry models. Combined with the more meridional direction of the 700-hPa southeasterly qflux (Figure 13c), this weakening may account for some of the increases in convergence in the north of the subdomain, which may contribute to increased wetting. In the dry composites, changes in the zonal wind field are much smaller; the AEJ-N only weakens slightly, and there are few significant changes south of the equator.

The difference in Δu between the wet and dry composites (Figure 14i) is very similar to the historical wet-minus-dry difference (Figure 14h). This suggests that the process causing differential wetting between the composites is similar to that causing wetness/dryness in the historical period; namely, a relatively stronger and more equatorward AEJ-N in dry models compared to wet models. Despite the fact that dry models feature some weakening of the AEJ-N, it is of much smaller magnitude than in the wet models and does not correct for the equatorward bias of the jets. This indicates that the future changes experienced by models may be influenced by their underlying base climatology. In the case of the dry models, this means that the equatorward location and enhanced strength of the jet in the mean state of the climatology dominates over mechanisms, which may contribute to wetting in the future, such as enhanced moisture supply or the northward shift in convection. The equatorward jet structure instead continues to remove moisture from the basin through the western boundary, resulting in only a weak wetting signal in dry models. As the structure of the AEJs in dry models is inconsistent with reanalysis estimates of the circulation, there is cause to question the plausibility of the weak wetting signal in the dry composite.

6. Discussion and Summary

While previous research has indicated that ensemble mean changes in Congo Basin rainfall are relatively small (Aloysius et al., 2016; Haensler et al., 2013), there remain differences in both the sign and magnitude of rainfall changes across coupled models. There has been little research to date on the plausibility of these

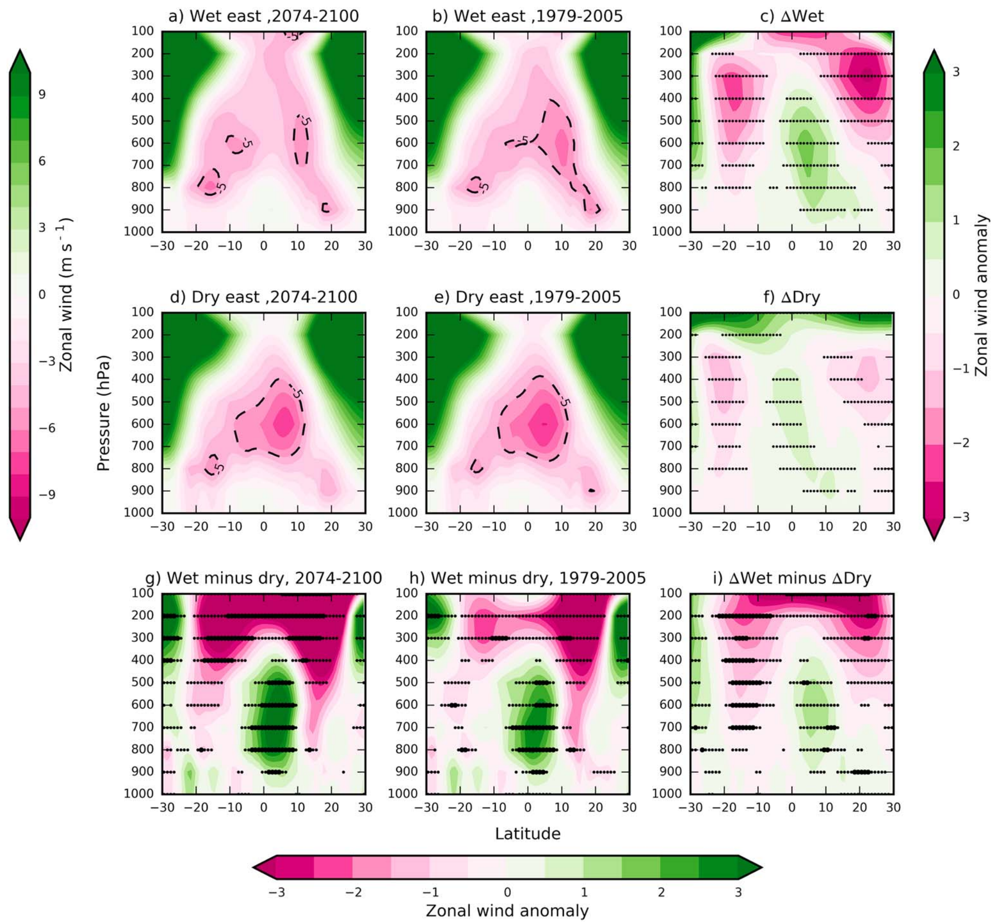

Figure 14. Latitude-height cross section of zonal wind averaged across 26–30°E (m/s; shaded) and location of −5-m/s contour in the east Congo Basin wet composite (top row) and dry composite (middle row) in (a, d) 2074–2100; (b, e) 1979–2005; and (c, f) 2074–2100 minus 1979–2005; (g) 2074–2100 wet-minus-dry composite; (h) 1979–2005 wet-minus-dry composite; and (i) wet change minus dry change. Stipples as in Figure 3.

varying signals, especially in terms of the spatial patterns of change. This paper used a process-based framework to identify the mechanisms associated with rainfall change in subsets of models that have historically wet or dry climatologies, in order to assess the credibility of these rainfall signals.

6.1. Magnitude and Patterns of Rainfall Change Across Models

Under a high emissions experiment (RCP8.5), the majority of coupled models in our sample feature slight wetting in the future, in both the east (average wetting 0.43 mm/day) and west (average wetting 0.35 mm/day) Congo Basin (Figure 1). These changes are generally low magnitude compared to the mean historical rainfall in individual models. Nevertheless, there are still differences among models in both the sign and magnitude of the change. In the east of the basin, three models feature mean drying in the future, while the remaining models feature wetting. Given that ΔP is relatively small, models that are relatively wet or dry in the historical period remain so in the future period (Figure 1). In addition, the distribution of rainfall in individual models remains similar in the future climatology; models which have rainfall maxima in the east or west continue to do so in the future. Creese and Washington (2018) used a process-based assessment to identify chains of processes, predominantly related to moisture flux and low-level circulation, which differentiate between the extremely wet and dry models in the historical period. This paper hypothesizes that differences in model representation of these processes in the historical period may translate into differences in the rainfall change pattern and signal simulated by that model.

In terms of the spatial distribution of Δ*P*, most models simulate a broadly similar pattern of wetting in the north Congo Basin and beyond and drying to the south of the basin (Figure 3). This has been identified in coupled models over the broader African region by Lazenby et al. (2018) and is hypothesized to relate to shifts in the location of convection under warming as a result of patterns of tropical SST warming and changes in circulation. Despite agreement in the broad pattern, the latitude at which wetting switches to drying is not consistent among all models, resulting in disagreement in the signal of change in the south of the basin (Figure 2). Further, the magnitude of the northern wetting and southern drying can differ by several millimeters per day between models.

There is some evidence that the north-south divide is related to shifts in the latitudinal location of the tropical rain belt across the annual cycle. The northern region of wetting reaches its southernmost position in DJF and northernmost position in JJA, mapping broadly onto the north-south oscillation of the climatological rain belt. The north-south pattern is therefore suggestive of either a delay in the southward movement of the rain belt or a cessation of the movement of the rainfall band further north compared with the historical period. Figures 7 and 12 indicate that it is the latter; during SON, positive Δ*P* values are anomalously northward in the future compared to the historical period, and during DJF, there is enhanced drying over southern Africa as the rain belt does not traverse as far south. The potential regional processes that may relate to this shift, including changes in vertical motion, are discussed further below, with reference to the west and east composites.

6.2. Rainfall Change in the West Composites

Coupled models in the Congo Basin produce a wide spectrum of historical rainfall climatologies, which are related to different models' representations of circulation processes in the wider region (Creese & Washington, 2016, 2018). Previous research by the authors has also indicated that the processes most strongly related to the intermodel spread in rainfall differ between the west and east of the basin. The aims of the latter part of this paper were thus twofold. First, does categorizing a model by its historical climatology result in a different future rainfall signal? Given that some of the historical differences in climatology are related to known biases (for example, the tropical Atlantic SST bias), it is possible that changes in the future period build on these biases, resulting in different future rainfall signals across models. Second, are the future rainfall changes projected by models plausible based on our understanding of the processes related to those changes? This question is applicable whether the wet and dry model Δ*P* signals differ significantly or not.

In the west Congo Basin, both the wet and dry composites feature similar patterns and magnitudes of rainfall change in the future. Both feature some wetting in the north and drying in the south of the domain. Wet models tend to feature greater wetting over land in the west of the domain, and dry models feature more wetting over the Gulf of Guinea, but these differences are small compared to the overall signal. This analysis suggests that, despite the significant differences in the rainfall climatology in the historical period between the extreme wet and dry models, these do not translate into large differences in the Δ*P* signal projected by those models. Figure 15 shows that excluding the spurious (wet) models from the total ensemble has little impact on the spread of Δ*P* values in the future. In the northwest domain, where wetting is more consistent, the spread of the interquartile range and the median value reduce slightly, but the range remains large. The results for the west Congo Basin, therefore, suggest that there is not a simple relationship between the strength of present day model biases and the magnitude of future change. However, comparison of the processes underlying the signal of change with those that drive present-day climatological differences in models could tell us something about the plausibility of the rainfall change signals across the suite of models.

In the future-minus-present analysis, both wet and dry composites feature an increase in SST generally across the tropics, with above-average increases in the tropical east Atlantic (>3 °C). This is the region where models feature present-day biases of up to 4 °C, and so any warming here is superimposed on top of an already too-warm base state. The SST warming is slightly higher in the dry composite than the wet composite, though only significantly so over a small area. Both composites also feature increased evaporation over this region; again, this is slightly greater in the dry models, coinciding with relatively larger increases in SSTs. Further, both wet and dry composites feature enhanced low-level westerly qflux into the basin from this region. This was also found to be a differentiating process between extremely wet and dry historical climatologies.

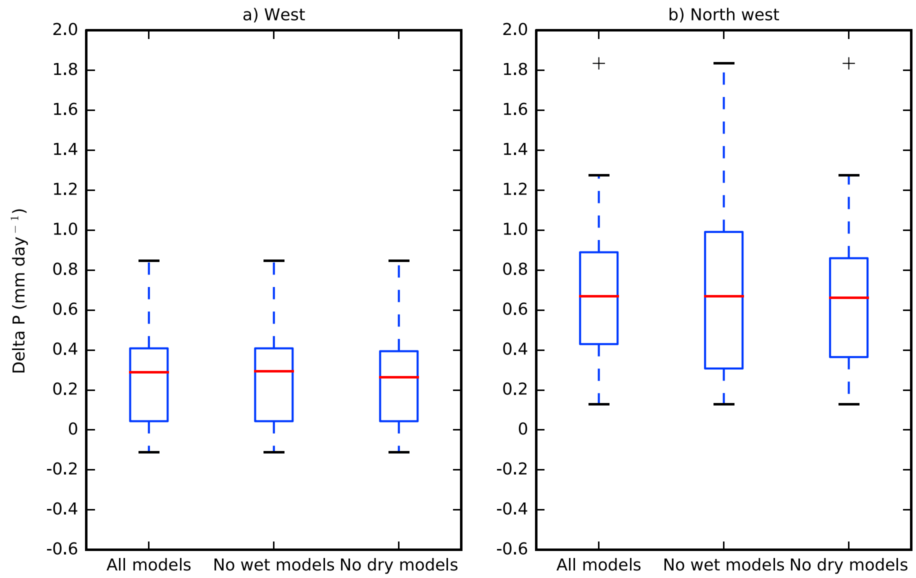

Figure 15. Box plot of 2074–2100 minus 1979–2005 long-term mean rainfall (mm/day; Δ*P*) averaged over (a) the west Congo Basin domain (8°E to 21°E, 10°S to 10°N) and (b) the northwest Congo Basin domain (8°E to 21°E, 0° to 10°N). The first box plot includes all models, the second excludes the wet composite models, and the third excludes the dry composite models.

That some of the same processes related to extreme model wetness in the historical period may be related to the future wetting signal in both composites is a cause for concern. While the "rich-gets-richer" mechanism of tropical rainfall change posits that the low-level moisture transport will increase into already-convective regions, this analysis also indicates that enhanced tropical Atlantic SSTs, and associated increases in evaporation, may also contribute to enhanced moisture transport within the low-level westerlies in the future. This potentially casts doubt on the magnitude of the positive Δ*P* signal in all models the northwest Congo Basin domain, as the processes related to wetting are building on known SST biases in the region. The Gulf of Guinea warm SST bias is present in all but one model in the sample, not just the historically wet models.

There is one element of the historical process chain that does not manifest in relation to the positive Δ*P* signal. In the historical period, enhanced model wetness is associated with a local increase in convection at the Atlantic coast, and it was hypothesized that greater evaporation over the too-warm Gulf of Guinea SSTs was contributing to a local enhancement of convection in this region. However, in the future experiment uplift decreases in both wet and dry models. This may be a local manifestation of the weakening of the overturning circulation under warming (Held & Soden, 2006; Vecchi & Soden, 2007). One explanation for wetting in the future despite decreased uplift is that the distribution of daily rainfall changes in the future. As Figure 8 shows, the distribution of daily rainfall flattens in the future, and in the wet composite, there are a greater number of both very wet and very dry days in the future. Further, the wetting in the northwest colocates with the northern edge of the area of decrease in upward motion (Figure 7), whereas the south of the domain, which features drying, is located with the core of the decrease in uplift. This indicates that in the north, the increased moisture supply into the basin is enough to counteract the slight decrease in uplift, resulting in a positive Δ*P* signal.

These results suggest that enhanced moisture from the tropical east Atlantic may be contributing to wetting in the west Congo Basin, despite decreases in subsidence. Given that this process builds on dubious historical SST biases, which are present in both composites, there is reason to be cautious about accepting the magnitude of the wet signal displayed in both composites. Analysis of the processes related to the long-term drying trend over equatorial Africa may support this hypothesis. Hua et al. (2016) analyze the circulation features associated with drying in reanalysis data between April and June and suggest that it may reflect the response of the large-scale circulation to relatively greater warming of west Pacific SSTs compared to the central Pacific SSTs. This differential SST warming has resulted in a westward extension of the tropical Walker circulation (e.g., Williams & Funk, 2011) and may have resulted in anomalous subsidence over equatorial Africa in recent decades. While in a different season, and highlighting SST anomalies in a different basin, these results indicate that observed patterns of SST change are likely to induce drying, rather than wetting, over the Congo Basin. A dedicated coupled model experiment with varying baseline SSTs upon which to apply the emissions forcings would be necessary to test this hypothesis. These results also suggest that reducing the Atlantic SST bias across coupled models should still be a priority for model developers, as it is difficult to make assessments of the likelihood of future wetting or drying while these biases persist. Recent work by Harlaß et al. (2018) has found that increased horizontal and vertical model resolution contributes to improvements in model representation of the tropical Atlantic climatology. Improving resolution may therefore be an important element of reducing this bias in future generations of coupled models.

6.3. Rainfall Change in the East Composites

In the east composites, categorizing models as historically wet or dry does result in significantly different patterns of ΔP, particularly in the northeast of the basin, where wet models feature an average rainfall increase 1.19 mm/day; more than twice the amount of wetting in dry models (0.43 mm/day). There is also evidence that the contrast between northern wetting and southern drying over the central African region is greater in wet models than dry models. The wettest-models-get-wetter response in the northeast is investigated with reference to the processes that differentiate wet and dry model climatologies in the historical period.

In the historical period, wet models feature a stronger SAH, which is related to stronger low-level southeasterlies in the south tropical Atlantic and stronger westerlies near the equator. This enhanced westerly flux constitutes the lower branch of a zonal overturning cell, bringing moisture into the east of the basin and contributing to greater convection. In the future-minus-present analysis, both wet and dry models feature enhanced southeasterly and southwesterly qflux in the Atlantic, alongside a strengthening of the southern flank of the SAH. However, there is no significant difference in this signal between wet and dry models, indicating that changes in these processes are not the dominant cause of differences in the composites' ΔP signals.

Further, as in the west composite models, models in the east feature a decrease in uplift in the future, despite wetting. Again, this could be explained by differences in the distribution of daily rainfall in the two periods; in the future, the distribution of rainfall on individual days flattens, with more very wet days in the future compared to the present (not shown). In terms of differences between the two composites, the decrease in upward motion is stronger in wet models near the surface, but stronger in dry models above 500 hPa, the core of convective activity, which could be related to enhanced wetting in wet models. Overall, the decrease in uplift in wet models despite significant wetting indicates that, as in the west composites, increases in q may be sufficient to enhance rainfall despite reduced convection. These increases in q may not be present in dry models.

While there are few differences between composites in the 925 hPa circulation and vertical motion, there are greater differences in the midlevel (700 hPa) moisture circulation (Figure 13). At 700 hPa, both composites feature enhanced qflux into the basin from the southeast. In wet models, this is more meridional in the future than in the historical period. In addition, dry models feature greater qflux from the northeast, whereas this flux does not change significantly in wet models. In both composites, these changes appear related to increase qflux convergence in the northeast of the basin and divergence in the south of the basin; this pattern is strongest in the wet models, possibly due to the more meridional orientation of the southeasterly feed contributing to enhanced convergence. The wet-minus-dry Δqflux pattern (Figure 13i) is similar to the historical wet-minus-dry pattern; wet models have weaker easterly qflux in the north of the basin than dry models. This suggests that the cause of the different ΔP signals in the composites is related to similar processes that produce relative wetness or dryness in the historical period.

In addition to the qflux circulation, there are significant differences between the wet and dry composites' simulations of the latitudinal structure of the zonal wind, in particular the location and strength of the AEJs (Figure 14). In the historical period, this is a key differentiator between wet and dry models, with wet models featuring a weaker and more equatorward AEJ-N, while dry models feature a stronger and more poleward AEJ-N. Analysis of reanalysis data from the European Centre for Medium Range Forecasting (ERA-Interim) suggests that wet models are closer to observations, as they produce two distinct AEJs, and

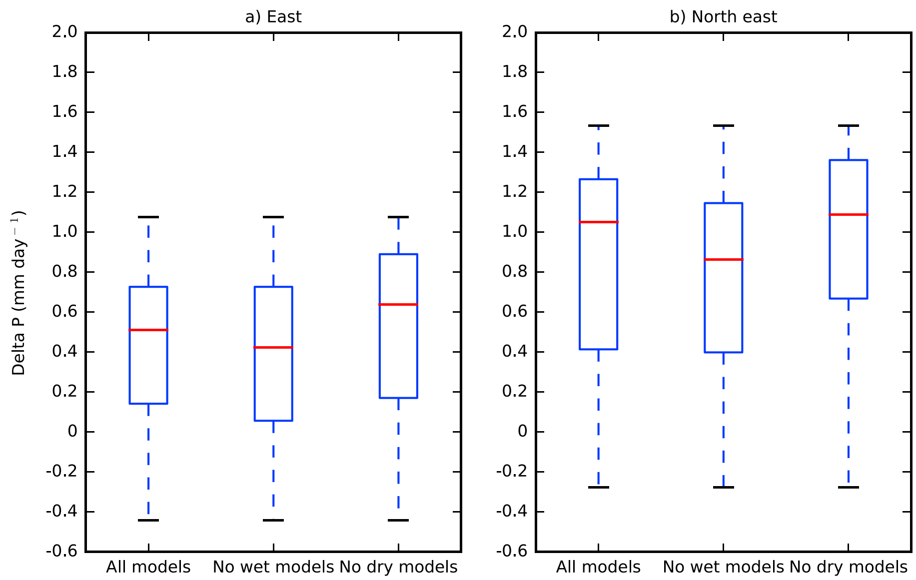

Figure 16. Box plot of 2074–2100 minus 1979–2005 long-term mean rainfall (mm/day; ΔP) averaged over (a) the east Congo Basin domain (22°E to 35°E, 10°S to 10°N) and (b) the northeast Congo Basin domain (22°E to 35°E, 0° to 10°N). The first box plot includes all models, the second excludes the wet composite models, and the third excludes the dry composite models.

therefore are possibly more plausible (Creese & Washington, 2018). In the future, the AEJ-N weakens in both composites; however, this weakening is stronger in the wet models (Figure 14i), which may account for enhanced convergence and thus enhanced wetting in the northeast Congo Basin domain.

As in the 700-hPa horizontal circulation, the wet-minus-dry Δu pattern (Figure 14i) is very similar to the historical wet-minus-dry pattern (Figure 14h). This suggests that differences in the ΔP signal between composites may be related to the same process differences in AEJ structure identified in the historical period. In wet models, the presence of two distinct and relatively weaker jets contributes to convergence and hence rainfall, where they meet. As the northern component weakens in the future and becomes more meridional, this convergence increases, resulting in wetting in the northeast Congo Basin. Conversely, in dry models, the strong, equatorward jet acts to remove moisture from the basin in the historical climatology, and the lack of distinction between the two jets reduces convergence between the two. In the future, despite some weakening of easterly flow near the equator in the atmospheric column (Figure 14), there is little increase in convergence, and the enhanced easterly qflux from both the northeast and southeast at 700 hPa acts to remove moisture from the basin. This finding indicates that the influence of the climatological AEJ structure in dry models dominates over any changes in the circulation in the future and acts to suppress significant rainfall change in this region.

This analysis suggests that biases in the historical period may influence the ΔP signal projected by models in the east of the basin and that removing models with such historical extremes could help reduce the range of uncertainty in the ΔP signal. Figure 16 quantifies the removal of both extremely wet and dry models on the ensemble spread. In the northeast of the domain, where wetting is most consistent across models, excluding extremely dry models does increase the upper quartile, median, and lower quartile values, as well as reducing the interquartile range. The overall range is substantially reduced (from 1.813 to 1.244 mm/day) if the CSIRO-Mk3-6-0 model is excluded from the analysis. This is the only model to exhibit mean drying in the northeast of the basin and has previously been identified as an outlier in the historical period (Creese & Washington, 2018). If we consider dry models to be untrustworthy due to their dubious representation of the AEJs, then this analysis indicates that greater wetting is a more likely response to warming. However, the overall range still includes both positive and negative ΔP signals, and so further work is needed to elucidate the plausibility of this response. These results also suggest that improving the climatological representation of the AEJs in future generations of coupled models may produce better constrained and more plausible future climate projections for this region.

7. Summary

This study used a process-based analysis to attempt to elucidate the influence of extreme historical climatologies on rainfall change in the future period and to identify the processes driving rainfall changes. In terms of changes in the Congo Basin, this study finds the following:

1. Rainfall changes in the Congo Basin across CMIP5 models are small compared to historical rainfall differences among models.
2. Rainfall increases in the north and decreases in the south of the Congo Basin across all models in SON; however, there are differences in the latitude of where the rainfall change signal switches from positive to negative.
3. The rainfall change signal in the west of the Congo Basin is not significantly different between wet and dry composites, suggesting that the rainfall response to forcing dominates over differences in the present day mean state.
4. In both wet and dry models in the west Congo Basin, the low-level circulation intensifies, which may be part of a rich-gets-richer response.
5. In both composites, SSTs increase in the tropical east Atlantic, a region which features positive SST biases in all composite members. There is also enhanced evaporation over the Gulf of Guinea and qflux into the basin.
6. As the SST increases build on a region of historical biases, the enhanced evaporation and qflux in the future may contribute to higher magnitude wetting than would be the case without the underlying bias in all models investigated. Further investigation is needed to test this hypothesis.
7. There are significant differences in the rainfall change signals between historically wet and dry models in the east Congo Basin. Wet models feature greater wetting than dry models, particularly in the northeast of the domain.
8. The differences in rainfall change between wet and dry composites in the east are related to changes in the AEJs. In the wet models, the AEJ-N weakens, contributing to enhanced convergence and rainfall. In dry models, the underlying equatorward AEJ structure dominates over changes to the circulation, continuing to export moisture away from the east Congo Basin and resulting in reduced wetting.
9. Given that the climatological structure of the AEJs in dry models is not reflected in reanalysis data, this casts doubt on the low magnitude wetting/ (or drying) signal projected in the dry composite models.
10. Improving model representations of the AEJs in the historical period should therefore be a key focus for model developers hoping to constraint future Central African rainfall changes.

In addition to understanding the processes related to rainfall change in the Congo Basin, this study also tested the hypothesis that a model's representation of processes in the historical period may impact its rainfall change signal in the future. The results in this regard were mixed. In the east Congo Basin, where the two composites (representing differing historical rainfall) feature different climatological structures of the same feature (the AEJs), the method was useful since the underlying differences related to the amplitude of the rainfall change signal. However, in the west Congo Basin, where all models share a similar bias (the tropical Atlantic SST bias), the approach was less successful. This suggests that a process-based approach may be most useful in cases where there are clear differences in the representation of the process between composites or where some feature biases and others do not. In cases where a similar bias exists in all models, sampling models across the rainfall spectrum is not helpful in constraining the range of rainfall change values.

In regions where biases are present across all models, such as the west Congo Basin, a different approach to process-based evaluation may therefore be required. This study sampled models from the extreme ends of the spectrum of historical rainfall; another approach is to sample instead on the representation of climatological processes in models. In the case of the west Congo Basin, this could involve examining models with the largest and smallest Atlantic SST biases, or strongest and weakest westerly moisture flux, to determine whether they produce different rainfall change signals. Another option is to sample based on rainfall change itself and identify the processes controlling rainfall change at the extreme ends of the rainfall change spectrum. Assessing the plausibility of changes in regionally important processes (and by extension rainfall) will require an understanding of which processes are important for controlling intermodel differences, and so the historical process-based assessments, as developed in Creese and Washington (2018), will remain a useful step in this method.

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