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Projected regional changes in mean and extreme precipitation over Africa in CMIP6 models

V Bobde[1], A A Akinsanola[1,2,*], A H Folorunsho[3], A A Adebiyi[4] and O E Adeyeri[5,6]

1 Department of Earth and Environmental Sciences, University of Illinois Chicago, Chicago, IL, United States of America
2 Environmental Science Division, Argonne National Laboratory, Lemont, IL, United States of America
3 Department of Environmental Sciences, Baylor University, Waco, TX, United States of America
4 Life and Environmental Sciences, University of California Merced, Merced, CA, United States of America
5 Low-Carbon and Climate Impact Research Centre, School of Energy and Environment, City University of Hong Kong, Kowloon, Hong Kong Special Administrative Region of China, People's Republic of China
6 Australian Rivers Institute, Griffith University, Nathan, Queensland 4111, Australia
* Author to whom any correspondence should be addressed.

E-mail: aakinsan@uic.edu

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Abstract

Precipitation plays a crucial role in Africa's agriculture, water resources, and economic stability, and assessing its potential changes under future warming is important. In this study, we demonstrate that the latest generation of coupled climate models (CMIP6) robustly project substantial wetting over western, central, and eastern Africa. In contrast, southern Africa and Madagascar tend toward future drying. Under shared socioeconomic pathways (defined by Shared Socioeconomic Pathways SSP2-4.5 and SSP5-8.5), our results suggest that most parts of Africa, except for southern Africa and Madagascar, will experience very wet years five times more often in 2050–2100, according to the multi-model median. Conversely, southern Africa and Madagascar will experience very dry years twice as often by the end of the 21st century. Furthermore, we find that the increasing risk of extreme annual rainfall is accompanied by a shift toward days with heavier rainfall. Our findings provide important insights into inter-hemispheric changes in precipitation characteristics under future warming and underscore the need for serious mitigation and adaptation strategies.

1. Introduction

Extreme weather and climate events, such as floods, droughts, cyclones, and heatwaves, may have vast economic and environmental impacts, as their occurrence can negatively affect public health, lead to ecological loss, and cause large-scale destruction of infrastructure (Meehl *et al* 2000, Ummenhofer and Meehl 2017, Rogelj *et al* 2018). Despite scientific efforts within the last decade at regional and global scales to understand the frequency and variability of these extreme events, there remains a dearth of knowledge, particularly over the entire African continent. Nevertheless, some studies have documented changes in extreme weather events over specific regions, including western Africa (Sylla *et al* 2016, Akinsanola and Zhou 2018a, 2018b, Akinsanola *et al* 2020, Monerie *et al* 2020, Klutse *et al* 2021, Diba *et al* 2022), eastern Africa (Souverijns *et al* 2016, Ongoma and Chen 2016, Ongoma *et al* 2017), and southern Africa (Dube *et al* 2021, Lim *et al* 2021, McBride *et al* 2022). Despite the regional focus of these studies, there is still limited evidence in the literature about the overall impacts of the changes in extreme events over the whole continent, which may result from the complex inter-relationship of many weather drivers that could span both the Northern and Southern Hemispheres.

Africa, the second largest continent by size, with a population of 1.4 billion, accounted for just 2.84% of the world's gross domestic product in 2021 (Statistical Times 2021, United Nations 2023). The economic sector in Africa is dominated by rainfed agriculture, mining, and manufacturing, with the agriculture sector employing over 60% of the population (FAO 2021). Due to the sensitivity of these sectors to changes in temperature and precipitation, the increasing frequency of extreme weather events is expected to have huge socioeconomic consequences in the region. For example, small changes in precipitation can lead to a drastic decrease in yields and affect the physiological development of native crops in the region (Lobell *et al* 2008, Thornton *et al* 2011). Moreover, mining activities in mineral-rich regions like Zambia, the Democratic Republic of the Congo, and Ghana heavily depend on water for production and cooling (Amankwah and Anim-Sackey 2003, Lungu 2008). Induced climate change impacts on water availability and variability in precipitation patterns may further affect the operational demand in these sectors and, in turn, critically affect the economy. For example, Ngepah *et al* (2022) reported there will be an estimated loss of up to $2.48 billion for the South African economy by 2050 due to climate change. Furthermore, extreme events like flooding, cyclones, and excessive fog have compounded environmental challenges in the mining industry (Aleke and Nhamo 2016). More evidently, many studies have shown the effects of severe flooding and droughts on reduced agricultural production (Anyamba *et al* 2014, Serdeczny *et al* 2016). The African economy is largely vulnerable to climate change extremes based on its dependence on rainfed agriculture and mining activities. A robust projection of precipitation extremes and their possible impacts on the continent is therefore critical.

Under the coordination of the World Climate Research Programme (WCRP), the Coupled Model Intercomparison Project (CMIP) has significantly improved our understanding of climate variability and change with constant improvements in microphysical parameterization and spatial resolution (Covey *et al* 2003, Taylor *et al* 2012, Eyring *et al* 2016, Simpkins 2017). Previous versions of CMIP (e.g. CMIP3 and CMIP5) global climate models (GCMs) have been widely used in Africa to understand changes in means and extremes in historical and future contexts under several climate scenarios (Haensler *et al* 2013, Vizy *et al* 2013). Despite the robust projections over subregional Africa from these CMIP datasets, uncertainties still arise from the biases of these models, which may further undermine their reliability in developing climate adaptation strategies (Ukkola *et al* 2018). The outputs of the most recent phase of CMIP (CMIP6) provide an opportunity for improved understanding of the future climate. CMIP6 model improvements include updates to deep convective schemes, cloud microphysics, aerosol contributions to cloud formation, and higher model resolution (Eyring *et al* 2016); which have slightly reduced model bias in capturing precipitation characteristics (Kim *et al* 2020, Akinsanola *et al* 2021). Several studies have adopted CMIP5 and CMIP6 GCMs over subregional Africa to examine the variability and seasonal shifts in climate events as well as the frequency of extreme events under a changing climate. Results from these future projections show that temperature and precipitation will increase significantly under different climate scenarios in the 21st century (Akinsanola and Zhou 2018a, Almazroui *et al* 2020, Cook *et al* 2020, Ukkola *et al* 2020, Ayugi *et al* 2021). Precipitation-dependent climate change indicators have also been examined across different African subregions. Existing studies based on CMIP6 models have shown a projected increase in flood and drought tendencies over eastern Africa under extreme climate scenario pathways (Ayugi *et al* 2021). In northern and southern Africa, robust evidence shows a decline in future precipitation under a changing climate (Almazroui *et al* 2020, Majdi *et al* 2022). Extreme precipitation over regions in western and central Africa is also projected to increase and is linked to the intensification of floods in the region (Akinsanola and Zhou 2018c, Almazroui *et al* 2020). However, there is limited understanding of how 'wet or very wet' or 'dry or very dry' climate-induced changes would transition and intensify, especially on a subregional basis across the African continent.

In this study, we use the outputs of 19 CMIP6 models to quantify the changes in annual precipitation characteristics over the African continent and investigate how these changes vary from one subregion to another. Specifically, we assess the spatial changes and regional temporal evolution of the mean and extreme precipitation. The findings presented herein provide insights into inter-hemispheric changes in annual precipitation characteristics over the entire African continent.

2. Data and methodology

In this study, we used the simulated daily precipitation from 19 CMIP6 simulations (Eyring *et al* 2016) (see table S1) that were available at the time of this analysis to assess the impact of global warming on annual precipitation characteristics over the African continent. For each model, we use the first realization ('r1i1p1f1') for both the historical and future projection for 'middle of the road' and 'fossil-fuel development' emissions scenarios (Shared Socio-economic Pathways SSP2-4.5 and SSP5-8.5; O'Neill *et al* 2017). To compute the changes in the number of very wet and very dry years, a preceding 50 year running window is used, from 1950 to 2099. Therefore, the historical and projected future simulations cover 1901–2014 and 2015–2100, respectively.

We use the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and Climate Prediction Center (CPC) gridded daily precipitation datasets to evaluate model skill in simulating precipitation characteristics from 1985 to

2014. CHIRPS is a blended dataset that incorporates multiple satellite and station datasets (Funk *et al* 2015). It is a quasi-global (50° S–50° N, 180° E–180° W) land-only precipitation dataset available at a resolution of 0.05° × 0.05° at a daily timescale from 1981 to the near present. The CPC dataset is a gauge-based gridded global precipitation dataset available over land at a resolution of 0.5° × 0.5° at a daily timescale from 1979 to the near present (Chen *et al* 2008). We choose the reference period of 1985–2014 for consistency among all datasets. To facilitate intercomparison of results and calculation of the multi-model ensemble mean in the case of CMIP6, all datasets are regridded to a common grid of 2.81° × 2.81° (latitude × longitude) using first-order conservative remapping, which is implemented in the Climate Data Operators (https://code.mpimet.mpg.de/projects/cdo). The ensemble mean of all CMIP6 simulations (EnsMean) is used herein to reduce the systematic biases present in individual model members (Akinsanola and Zhou 2018c). All calculations are done for individual models before averaging for the ensemble mean. All the analyses and calculations presented herein are for the annual period (January–December) and are integrated over the African continent and further assessed over the subregions defined in the Intergovernmental Panel on Climate Change Working Group I reference regions (Iturbide *et al* 2020). The eight subregions in Africa are Sahara (SAH), West Africa (WAF), Central Africa (CAF), North Eastern Africa (NEAF), South Eastern Africa (SEAF), West Southern Africa (WSAF), East Southern Africa (ESAF), and Madagascar (MDG) (figure S1). We focus on the annual period because some subregions span both hemispheres. Furthermore, to compensate for potential errors due to changes in area with latitude, we adopt a weighted area-average approach for subregional analysis. The projected changes are computed by comparing the 50 year time slice from the projection (2050–2099) to the historical period (1965–2014). The 50 year period chosen provides a robust basis for statistical comparison during the second half of the 20th century and the second half of the 21st century.

Three extreme indices defined by the Expert Team on Climate Change Detection and Indices (Klein *et al* 2009, Zhang *et al* 2011) (ETCCDI; see table S2 and more details at http://etccdi.pacificclimate.org/indices_def.shtml) are used as indicators for dry and wet extreme precipitation, including consecutive dry days (CDD), maximum consecutive 5 day precipitation (RX5day), and heavy precipitation days (R10mm). These non-parametric indices describe moderate extremes with a recurrence time of at most a year and are calculated from daily precipitation. To focus more specifically on extreme periods, we define a very wet (very dry) year if the annual precipitation exceeds (is below) the 90th percentile (10th percentile) precipitation value during the historical period. To account for errors due to changes in grid box size with latitude, area-averaged rainfall is calculated before computing the threshold for each subregion and for all of Africa. Broad spatial assessment and several summary statistics are used to evaluate the models, including percentage bias, normalized root mean square error (NRMSE), pattern correlation coefficient (PCC), and Taylor skill score (TSS), all expressed in equations (1)–(4).

$$\%\mathrm{BIAS} = \frac{\sum_{i=1}^{n}(M_i - O_i)}{\sum_{i=1}^{n} O_i} \times 100 \qquad (1)$$

$$\mathrm{NRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - O_i)^2}}{\frac{1}{n}\sum_{i=1}^{n} O_i} \qquad (2)$$

$$\mathrm{PCC}(M,O) = \frac{\mathrm{Cov}(M,O)}{\sqrt{\mathrm{Var}(M)\,\mathrm{Var}(O)}} \qquad (3)$$

$$\mathrm{TSS} = \frac{4(1+\mathrm{PCC})^2}{\left(\frac{\sigma_M}{\sigma_O} + \frac{\sigma_O}{\sigma_M}\right)^2 (1+\mathrm{PCC}_0)^2} \qquad (4)$$

where M and O represent the model and observation means; Cov and Var denote covariance and variance, respectively; n is the number of observations; σ is the standard deviation, and PCC_0 is the maximum attainable PCC set to 1. The TSS has values ranging from 0 to 1, corresponding to no match or a perfect match between the model and observations. Several studies have used TSS to assess model performance (e.g. Faye and Akinsanola 2021, Li *et al* 2022).

3. Results and discussion

3.1. Representation of annual mean and extreme precipitation

We evaluate the ability of the CMIP6 models to reproduce the annual mean precipitation and extreme precipitation indices by comparing the model results to two gridded observations (CPC and CHIRPS) and the results presented in figure 1 for the ensemble mean (EnsMean) and figures S2–S6 for the individual models. Specifically, we examine indices such as CDD, which represents the number of CDDs with precipitation less than 1 mm; RX5day, which represents the highest total precipitation of five consecutive days in the time period; R10mm, which represents the number of days with precipitation exceeding 10 mm; and right tail (99th percentile minus 90th percentile precipitation), which represents very heavy precipitation. Across all the precipitation characteristics evaluated herein, EnsMean shows good agreement with the observations (figure 1), although there is more consistency between EnsMean and CHIRPS than with CPC, albeit with noticeable spatial bias. Numerous studies have similarly found that CHIRPS performs significantly better over most of Africa (Gebrechorkos

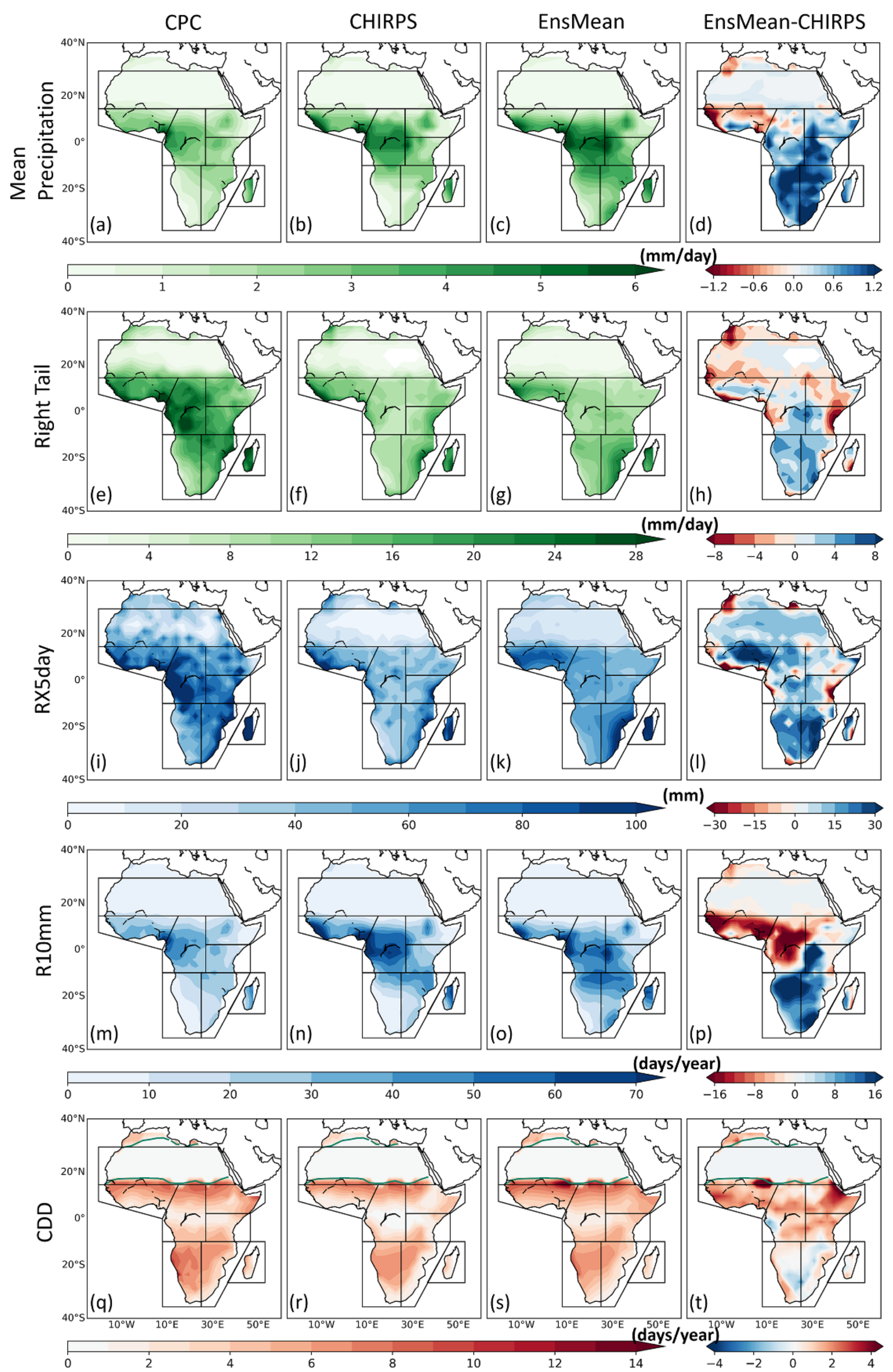

Figure 1. Annual mean (a)–(d) and extremes [Right Tail (e)–(h), RX5day (i)–(l), R10mm (m)–(p), and CDD (q)–(t)] precipitation from (left)–(right) CPC, CHIRPS, EnsMean, and EnsMean bias relative to CHIRPS over the period of 1985–2014. CDD values over the Sahara are masked out using a threshold of <0.3 mm d^{-1} mean precipitation of EnsMean (green contour line), considering the region is predominantly dry and exhibits very high values that spatially suppress the signals from other subregions.

et al 2018, Kouakou *et al* 2023, Mekonnen *et al* 2023). The signs and magnitude of these noticeable biases in EnsMean vary significantly across different subregions. For instance, EnsMean overestimates the annual mean precipitation in the Southern Hemisphere. In the Northern Hemisphere, we find an underestimation over most of western Africa except parts of the Guinea coast, where a slight overestimation is evident. A slight overestimation is also evident in eastern and central Africa (figure 1(d)). A similar pattern of bias is also generally evident in extreme right-tail (i.e. 99th percentile minus 90th percentile) precipitation except for eastern Africa, where an overestimation is evident (figure 1(h)).

Also, EnsMean grossly overestimates RX5day over the whole African continent (figure 1(l)), whereas R10mm is overestimated over west and east southern Africa and southeastern Africa and underestimated over western and central Africa (figure 1(p)). We mask out the CDD values over the Sahara using a threshold of <0.3 mm d^{-1} mean precipitation of EnsMean, considering the region is predominantly dry and exhibits very high values that spatially suppress the signals from other subregions (figures 1(q)–(t)). Nevertheless, CDD is generally overestimated over most subregions except parts of South Africa, where a slight underestimation is evident (figure 1(t)). The biases exhibited by the individual models are generally consistent with EnsMean (figures S2–S6), although with a higher magnitude. For instance, CanESM5 and MIROC6 grossly overestimate the mean annual precipitation and the wet extreme indices over most parts of Africa. We further assess the models' ability to capture the spatial annual trends of precipitation characteristics by comparing them with CHIRPS observations (figure S7). Apart from the Sahara and parts of some other subregions, where the individual model agreement with the CHIRPS precipitation trend is low (figures S7(c), (f), (i), (l) and (o)), more than 60% of the CMIP6 models reasonably capture the spatial trend of the mean and extreme precipitation across most subregions.

Aside from the climatological and trend assessment of the spatial pattern of precipitation characteristics, we also use various descriptive statistical measures described in equations (1)–(4) to assess the simulated precipitation accuracy relative to the two gridded observation datasets, with results presented in figures S8 and S9. Generally, a low percentage bias and NRMSE with high PCC and TSS are desirable. All CMIP6 models have a high PCC ~ 0.9 and TSS ~ 0.7, relative to both CHIRPS and CPC observations. The percentage bias and NRMSE are lower for CHRIPS than for CPC. This implies that the models are more closely related to CHIRPS than to CPC. In general, the characteristics of annual precipitation over Africa are reasonably reproduced by the CMIP6 models; thus, a discussion of annual rainfall over Africa using EnsMean is credible.

3.2. Projected changes in annual mean and extreme precipitation

The projected changes in annual mean and extreme precipitation over Africa under the SSP2-4.5 and SSP5-8.5 scenarios are shown in figure 2 and summarized in table 1. EnsMean shows a slight decrease in annual mean rainfall over southern Africa, with values reaching up to -0.2 mm d^{-1} in both scenarios (figures 2(a) and (b)). In contrast, there is an increase in the annual mean rainfall over central, western, and eastern Africa, reaching 1.0 mm d^{-1} in the SSP5-8.5 scenario and about 0.3 mm d^{-1} in SSP2-4.5.

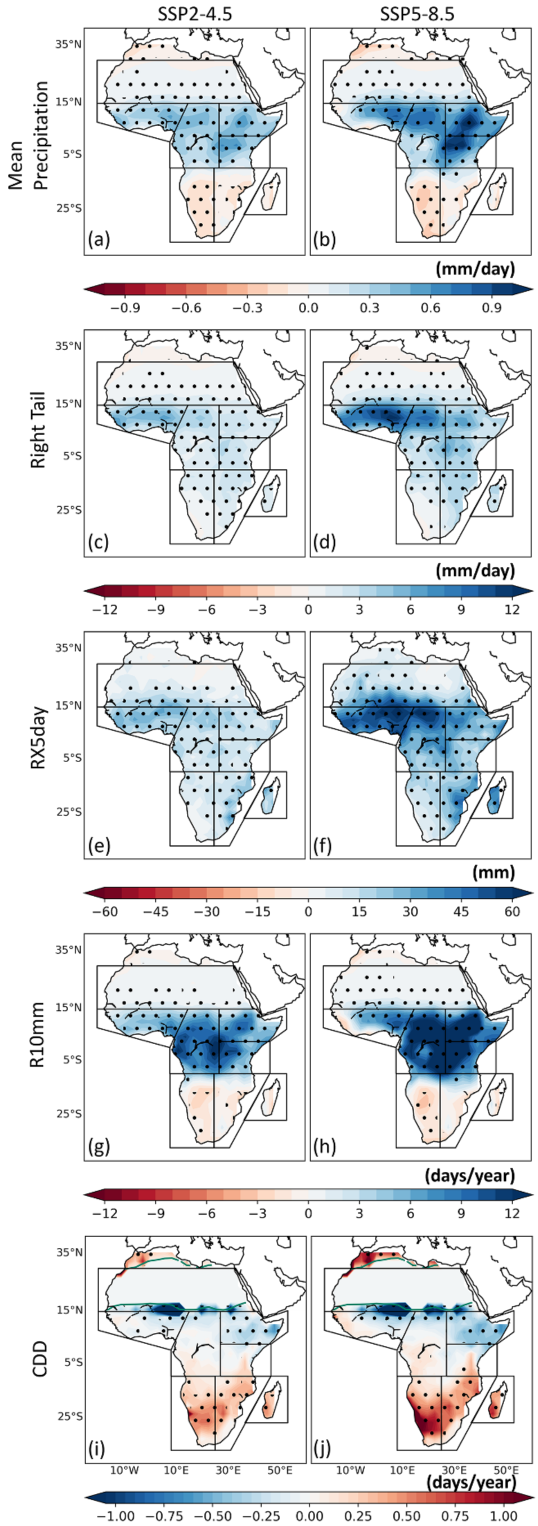

Figure 2. Projected changes in (a), (b) mean precipitation, (c), (d) right tail, (e), (f) RX5day, (g), (h) R10mm, and (i), (j) CDD for (a), (c), (e), (f), (i) SSP2-4.5 and (b), (d), (f), (h), (j) SSP5-8.5 in the future (2050–2099) compared to the historical period (1965–2014). Stippling indicates where at least 70% (14/19) of models agree on the sign of the change in EnsMean. CDD values over the Sahara are masked out using a threshold of <0.3 mm d^{-1} mean precipitation of EnsMean (green contour line).

The projected changes in heavy precipitation events (R10mm) are similar to those of annual rainfall; southern Africa is expected to have fewer days with

Table 1. Summary of projected changes in mean and extreme precipitation across all subregions of Africa.

	Mean precipitation	Right Tail	RX5day	R10mm	CDD
SAH	Robust slight increase	Slight increase	Slight increase	Slight increase	Changes are masked
WAF	Robust increase	Robust large increase	Robust large increase	Robust increase	Slight decrease
CAF	Robust increase	Robust increase	Robust increase	Robust large increase	No change
NEAF	Robust large increase	Robust increase	Robust increase	Robust large increase	Robust slight decrease
SEAF	Robust large increase	Robust increase	Robust increase	Robust large increase	No change
WASF	Robust decrease	Slight increase	Robust increase	Robust slight decrease	Robust large increase
ESAF	Slight decrease	Slight increase	Robust increase	Slight decrease	Robust large increase
MDG	Slight decrease	Robust slight increase	Robust increase	Slight decrease	Robust large increase

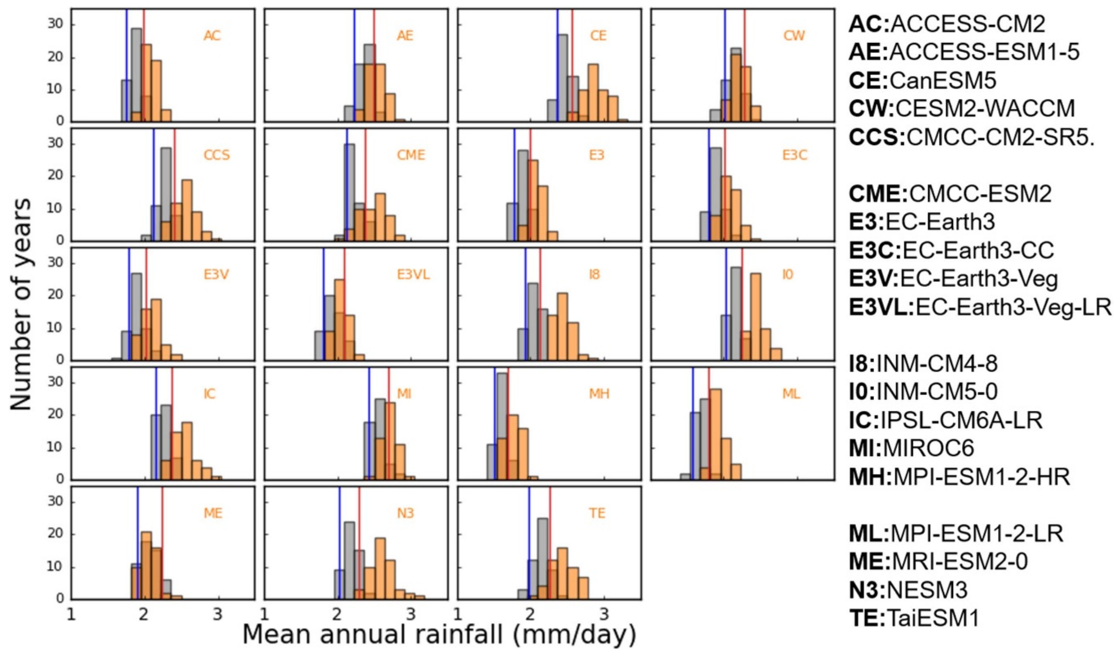

Figure 3. Mean annual precipitation distribution over Africa between the historical period (1965–2014) and future period (2050–2099). The historical precipitation distribution is represented in gray, and yellow bars represent model distribution for the SSP5-8.5 scenario. The red line marks the 90th percentile threshold for wet years and the blue line represents the 10th percentile threshold for dry years in the historical period.

heavy precipitation, while central, eastern, and western Africa will experience a huge increase in the number of events (figures 2(g) and (h)). Similarly, right-tail events are projected to increase south of 17°N (figures 2(e) and (f)), while RX5day increases are evident over the entire continent, with maximum values over western and central Africa and Madagascar (figures 2(e) and (f)). Interestingly, the tendency for drying conditions over the Sahara region is expected to significantly reduce as CDD is projected to decrease in both the SSP2-4.5 and SSP5-8.5 scenarios as the mean precipitation increases. Southern Africa and Madagascar exhibit a projected increase in CDD with high model agreement, while western, central, and eastern Africa have minor changes in CDD (figures 2(i) and (j)). For most parts of Africa, more than 70% of the models agree on the sign of the change in EnsMean, except for some parts of the Sahara, where the projected change has considerable uncertainty. Overall, the projected changes in annual mean and extreme precipitation are quite robust; aside from the consistency across both scenarios in EnsMean, the results from the individual model projections are broadly consistent, although the magnitude of change varies across models (figure not shown).

To better understand the changes in precipitation between the historical period (1965–2014) and the second half of the 21st century (2050–2099), we analyze the distribution of the annual mean precipitation for both scenarios (figures 3 and S10). The 90th percentile (10th percentile) of the historical period is the very wet (very dry) year threshold, indicating that five wet years have exceeded (are below) the wet threshold (dry threshold) in the 50 year historical period. For the future (2050–2099), precipitation distribution is generally shifted toward the right (i.e. wetting), with more years exceeding the very wet threshold. The shift is largely evident under SSP5-8.5, as most of the distribution has shifted to the right 90th percentile. SSP2-4.5 exhibits a similar distribution but to a lesser extent. Accordingly, dry years are projected to be less

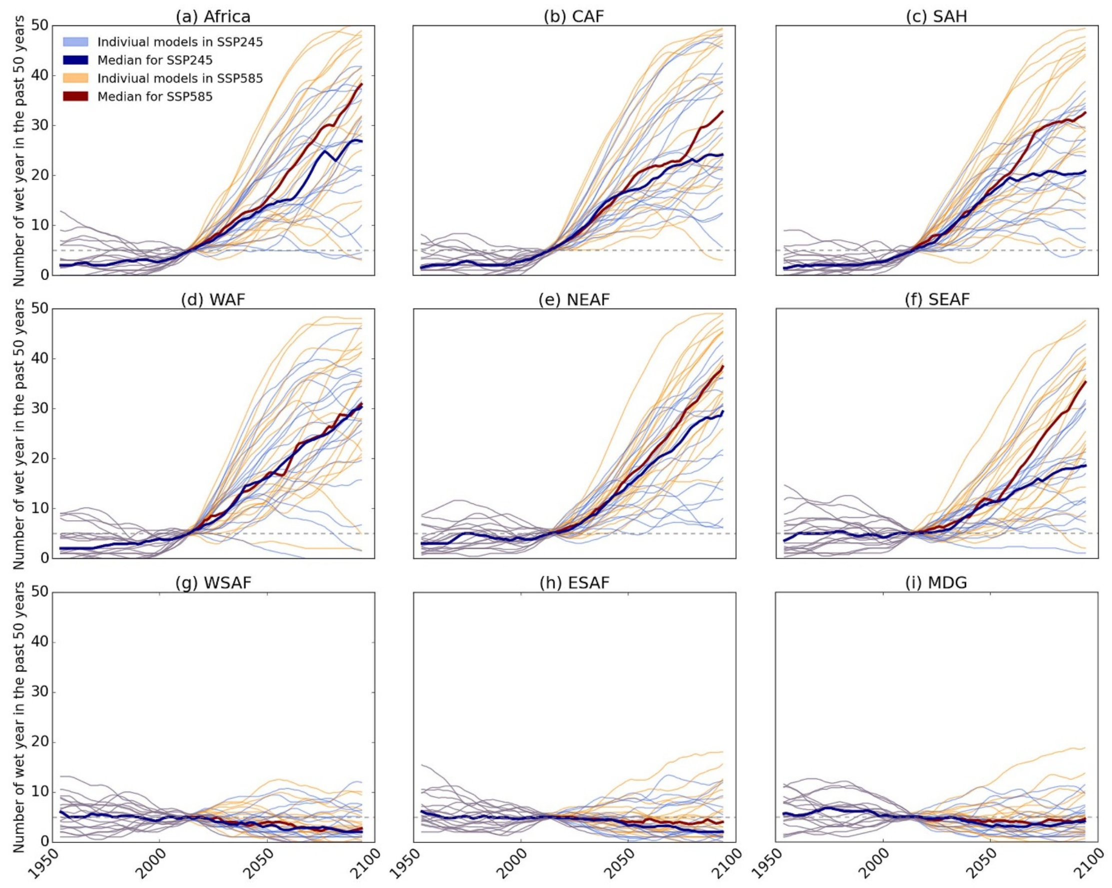

Figure 4. Time evolution of the number of wet years over different regions: (a) Africa, (b) Central Africa (CAF), (c) Sahara (SAH), (d) Western Africa (WAF), (e) North Eastern Africa (NEAF), (f) South Eastern Africa (SEAF), (g) West Southern Africa (WSAF), (h) East Southern Africa (ESAF), and (i) Madagascar (MDG). Number of wet years in the preceding 50 years is plotted and smoothed using 10-year running means from 1950 to 2100. Red (dark blue) lines represent the median of models for SSP5-8.5 (SSP2-4.5). Orange (blue) lines represent the individual models in SSP5-8.5 (SSP2-4.5). The horizontal dotted gray line marks the reference of 5 of 50 year wet years based on the 90th percentile value in the historical period (1965–2014).

frequent in the 21st century (taking into account only rainfall; we acknowledge that the role of evaporation is also crucial for water availability, but this is outside this study's focus). Most subregions (e.g. central Africa, Sahara, western Africa, eastern Africa) are similarly shifted to the right in the precipitation distribution, suggesting more wet years in the future for SSP2-4.5 (figures S11–S15) and SSP5-8.5 (figures S19–S23). On the other hand, southern Africa exhibits an obvious left shift in the distribution, implying that more years will become very dry in the future (figures S16–S17 and S24–S25). Considerable spread dominates Madagascar (figures S18 and S26).

Furthermore, the temporal evolution toward more extremely wet or dry years is presented in figures 4 and 6 using the defined threshold. Historical data from 1901 to 2014 are merged with future data from 2015 to 2099 to calculate the temporal evolution. Each point on the plot represents the number of wet/dry years within a 50 year window (computed backward in time). For example, for the year 1950, the corresponding window is from 1901 to 1950. There is a constant increase in the number of years transitioning to very wet years over Africa based on the model median, except for the SSP2-4.5 scenario, which sees a small dip around 2080 and then rises (figure 4(a)). We find that at the end of the 21st century, more than 25 of 50 years in the future will cross the very wet year threshold for SSP5-8.5 and SSP2-4.5. The overall projected increase is larger for SSP5-8.5. More evidently, the central, northeastern, and southeastern African subregions show a clear increasing trend in the number of wet years (figures 4(b), (e) and (f)), although it accelerates non-linearly and depends on the climate scenario. For the Sahara subregion (figure 4(c)), projections from SSP2-4.5 suggest a steady state in the number of wet years after 2050. This year marks the divergence between the two scenarios, as SSP5-8.5 significantly increases toward the end of the 21st century. Over western Africa (figure 4(d)), a steady increase is evident across both scenarios, with very little deviation in the model median. For both scenarios, southern Africa (WSAF and ESAF) and Madagascar exhibit a slight decline or steady state in the number of wet years throughout the 21st century (figures 4(g)–(i)). The circular bar plots in figure 5 summarize the changes in the wet extreme by looking at the number of wet years between 2050 and 2099.

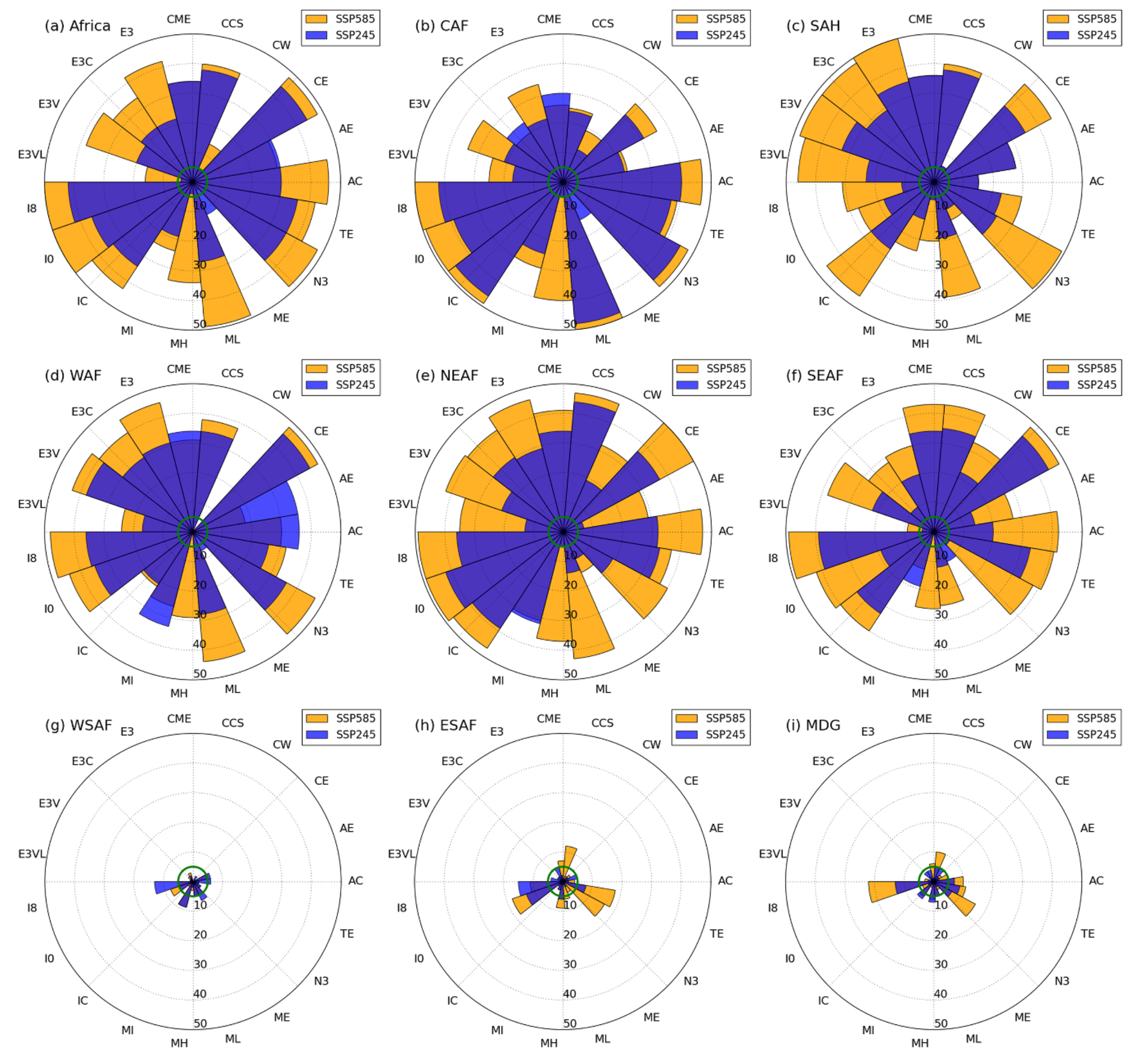

Figure 5. Number of wet years in the latter half of the 21st century (2050–2099) over (a) Africa, (b) CAF, (c) SAH, (d) WAF, (e) NEAF, (f) SEAF, (g) WSAF, (h) ESAF, and (i) MDG. The green circle represents 5 of 50 years, which is the number of years in the historical period (1965–2014) above the 90th percentile threshold. The yellow (blue) bars represent the SSP5-8.5 (SSP2-4.5) scenario.

Over the entire continent of Africa, as well as the CAF, SAH, WAF, NEAF, and SEAF subregions, most models have values of over 25 (∼20) years for SSP5-8.5 (SSP2-4.5).

The temporal evolution and circular bar plots for the dry threshold are displayed in figures 6 and 7, respectively. The overall results are consistent with the wet year tendency, as very dry years are projected to decline compared to the baseline period. By implication, at the end of the 21st century, only a few years will receive precipitation less than the 10th percentile of the baseline period. Similarly, CAF, WAF, NEAF, SEAF, and SAH are projected to have the least drying tendencies. In contrast, an increasing trend in the number of dry years is projected for WSAF, ESAF, and MDG from around the year 2020 toward the end of the century (figures 6(g)–(i)). For these three subregions, SSP2-4.5 and SSP5-8.5 show that the frequency of dry years will double by the end of the 21st century except over WSAF in SSP5-8.5, which is expected to triple.

4. Discussion and summary

In this study, we use nineteen CMIP6 models to investigate future changes in annual precipitation characteristics over the African continent and its subregions. The projections are based on the ensemble mean of all the models (EnsMean), which minimizes spatial bias associated with individual models and provides robust evidence for future climate. Nevertheless, there are observable biases in the models for different indices. These discrepancies may be attributable to various land surface schemes, the parameterization and model representation of vegetation (Di Virgilio *et al* 2022) and orography (Ehret *et al* 2012), unrealistic large-scale variability (Eden *et al* 2012, Adeyeri *et al* 2020, Dieng *et al* 2022), and contrasting internal variability across climate models and observations (Maraun 2012, Adeyeri *et al* 2022). Specifically, some models from the same institutes (e.g. EC-Earth Consortium, Institute for Numerical Mathematics) perform relatively similarly in several

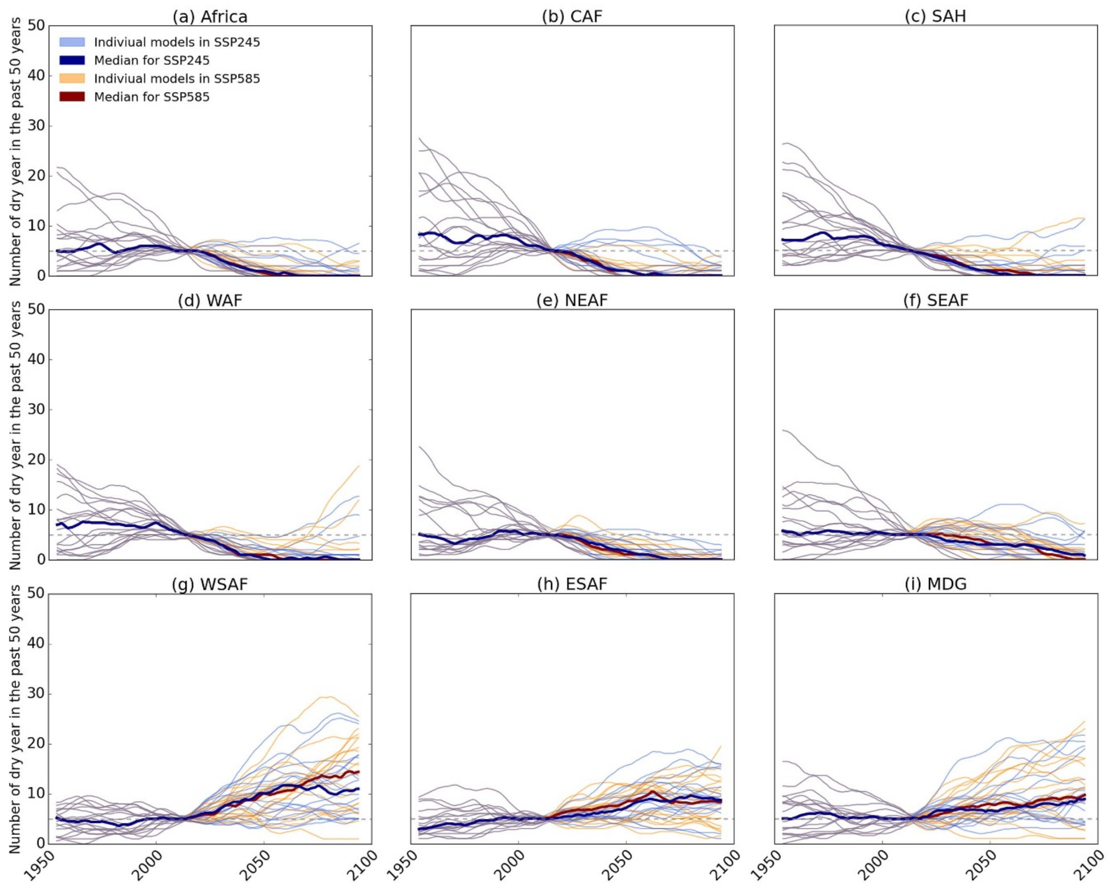

Figure 6. Time evolution of the number of dry years over different regions: (a) Africa, (b) Central Africa (CAF), (c) Sahara (SAH), (d) Western Africa (WAF), (e) North Eastern Africa (NEAF), (f) South Eastern Africa (SEAF), (g) West Southern Africa (WSAF), (h) East Southern Africa (ESAF), and (i) Madagascar (MDG). Number of wet years in the preceding 50 years is plotted and smoothed using 10 year running means from 1950 to 2100. Red (dark blue) lines represent the median of models for SSP5-8.5 (SSP2-4.5). Orange (blue) lines represent the individual models in SSP5-8.5 (SSP2-4.5). The horizontal dotted gray line marks the reference of 5 of 50 year wet years based on the 10th percentile value in the historical period (1965–2014).

African regions. This could be attributed to model interdependence (Srivastava *et al* 2020, Adeyeri *et al* 2022, Di Virgilio *et al* 2022).

As summarized in table 1, we find contrasting variation in the projected annual precipitation over Africa. Specifically, projected intensification in annual mean precipitation is evident over northern, western, central, and eastern Africa, while southern Africa is projected to become dry. Consequently, our findings show an increased intensity of wet precipitation extremes (RX5day and R10mm) over most subregions of Africa, except for southern Africa and Madagascar, where heavy precipitation days (R10mm) are expected to decrease. For most subregions, the precipitation distribution is generally shifted toward very wet conditions, with more years exceeding the 90th percentile threshold (i.e. very wet). Nevertheless, with the observed projected negative change [i.e. future reduction in annual rainfall, decreasing heavy precipitation events (R10mm), and projected increase in the number of years below the 10th percentile threshold (very dry)] over southern Africa, we expect an intensification of dry conditions. Madagascar will experience a decrease in precipitation throughout the 21st century, causing more meteorological drought-like conditions. This is consistent with the findings of Abiodun *et al* (2017), who reported a future increase in dry periods and a decrease in rainy days over South Africa. Similarly, Shongwe *et al* (2009) reported a rise in the severity of dry extremes in southwestern Africa.

In addition, particularly over the Sahel, we find a projected increase in annual mean precipitation. Furthermore, future precipitation events, particularly in western, eastern, and central Africa, will be more intense due to the projected positive shift. Overall, under global warming, southern Africa will get dryer while most parts of Africa will get wetter, and both SSP2-4.5 and SSP5-8.5 exhibit consistent and robust signs of change.

The projected changes herein would substantially impact the well-being and livelihood of many African subregions due to the continent's low adaptive capacity. The increasing dry extremes in southern regions may exacerbate drought risk (Lehner *et al* 2017). Moreover, as the climate continues to warm, the impacts of drought on the water supply

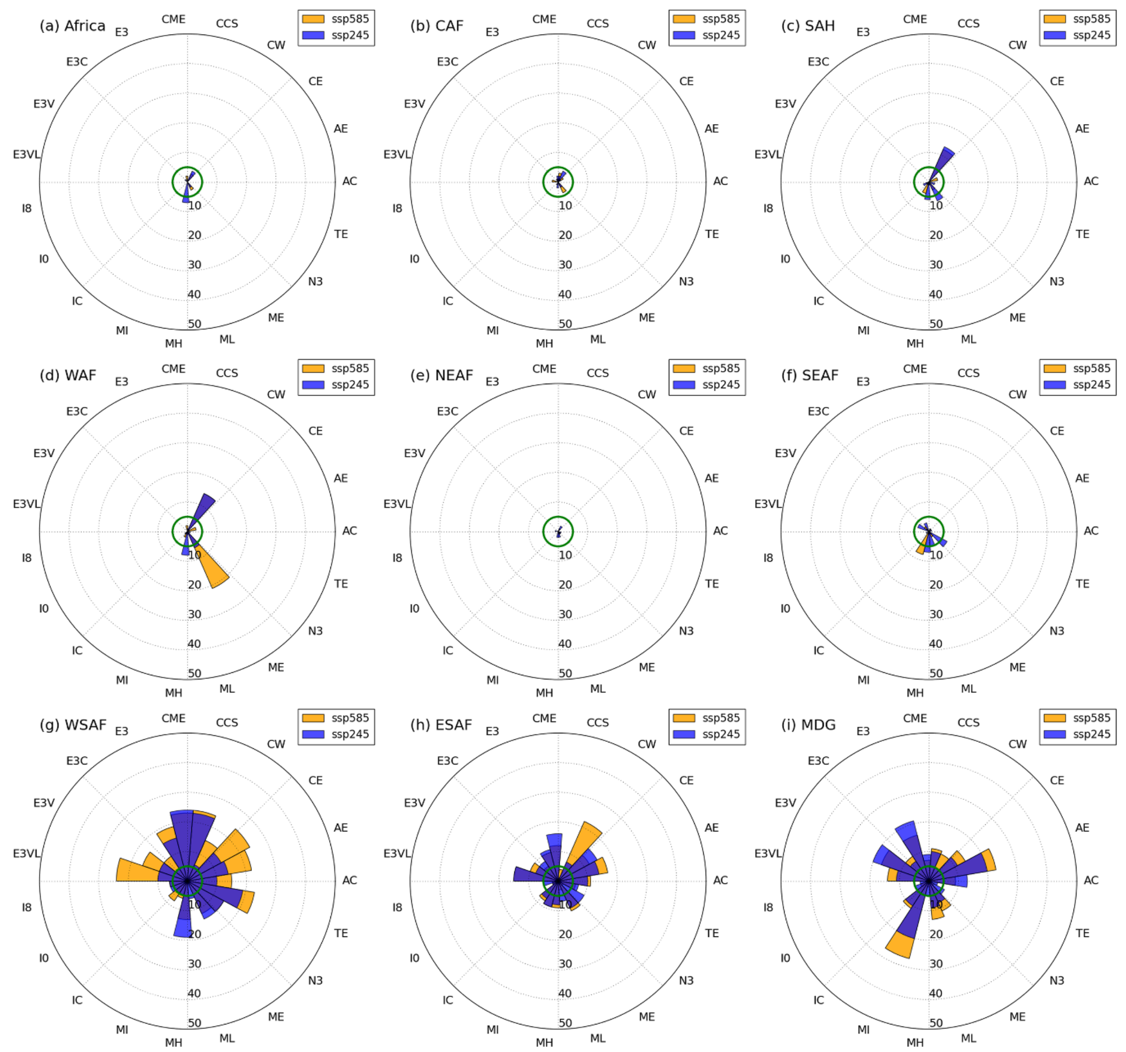

Figure 7. Number of dry years in the latter half of the 21st century (2050–2099) over (a) Africa, (b) CAF, (c) SAH, (d) WAF, (e) NEAF, (f) SEAF, (g) WSAF, (h) ESAF, and (i) MDG. The green circle represents 5 of 50 years, which is the number of years in the historical period (1965–2014) above the 10th percentile threshold. The yellow (blue) bars represent the SSP5-8.5 (SSP2-4.5) scenario.

and demand of both natural ecosystems and human populations are likely to intensify (Adeyeri *et al* 2022), thereby triggering inter-regional conflicts and forced migration. The anticipated wet extremes with potentially increasing flood tendencies in most subregions, including the Sahel and Sahara, may have devastating impacts due to the region's vulnerability and low preparedness (Grasham *et al* 2019). On the other hand, future increases in precipitation would benefit many subregions due to increasing water availability, leading to higher agricultural productivity and less dependence on groundwater. However, this could also intensify soil erosion and nutrient leaching, leading to loss of life and plant failure, respectively. Also, the hydroelectric power generation sector in most subregions would significantly benefit from increased rainfall, as hydroelectric dams would be replenished faster, generating enough power to drive the turbines. Nevertheless, we strongly emphasize the need for improved infrastructure, such as good drainage systems and large-capacity dams, as projected increases in rainfall are expected to further affect subregions that are most susceptible to flooding. Specifically, the release of water from dams following surplus rainfall could devastate the downstream population, destroying lives, livestock, and settlements. Therefore, the importance of proper mitigation policies to avert the devastating effect of extreme events, particularly at the local scale, cannot be overemphasized. Additionally, implementing techniques such as water harvesting, mulching, zero tillage farming, and proper land use and land cover management can effectively mitigate climate change impacts on the environment (Nhemachena *et al* 2020). Overall, future sustainable management plans are critical to addressing region-specific extreme conditions through social infrastructure, climate resilience, and adaptation policies, as well as greenhouse gas mitigation strategies.

Data availability statement

The data that support the findings of this study are openly available at the following URL: CMIP6 data are publicly available through the Earth System Grid Federation at http://esgf.llnl.gov/. The daily CHIRPS observation dataset is provided by the Climate Hazards Center at the University of California, Santa Barbara, and can be accessed at www.chc.ucsb.edu/data/chirps. Similarly, the daily CPC observation dataset is provided by the National Oceanic and Atmospheric Administration. It can be accessed at https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html. The derived data generated for the study are available from the corresponding author upon reasonable request.

Code availability

All analyses and figures are computed and drawn using Python version 3.10.8 (www.python.org/). The code used for the analysis in this study is available upon request from the corresponding author.

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Conflict of interest

All authors declare no competing interests.

ORCID iDs

V Bobde https://orcid.org/0000-0002-3140-2315
A A Akinsanola https://orcid.org/0000-0002-0192-0082
A H Folorunsho https://orcid.org/0000-0002-6039-8730
A A Adebiyi https://orcid.org/0000-0001-7091-6872
O E Adeyeri https://orcid.org/0000-0002-9735-0677

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