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ADVANCES IN ATMOSPHERIC SCIENCES, 2025

• Review •

Modeling of Precipitation over Africa: Progress, Challenges, and Prospects※

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ABSTRACT

In recent years, there has been an increasing need for climate information across diverse sectors of society. This demand has arisen from the necessity to adapt to and mitigate the impacts of climate variability and change. Likewise, this period has seen a significant increase in our understanding of the physical processes and mechanisms that drive precipitation and its variability across different regions of Africa. By leveraging a large volume of climate model outputs, numerous studies have investigated the model representation of African precipitation as well as underlying physical processes. These studies have assessed whether the physical processes are well depicted and whether the models are fit for informing mitigation and adaptation strategies. This paper provides a review of the progress in precipitation simulation over

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Africa in state-of-the-science climate models and discusses the major issues and challenges that remain.

Key words: rainfall, monsoon, climate modeling, CORDEX, CMIP6, convection-permitting models

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Article Highlights:

- Recent advances in climate models have enhanced the understanding of African precipitation, but substantial biases still persist.
- These model biases are largely due to the misrepresentation of key physical processes.
- Advancements in convection-permitting models and dynamical downscaling techniques are crucial for improving precipitation representation, but addressing observational data gaps and developing local modeling capacity remain essential for improvement.

1. Introduction

Precipitation is one of the most important meteorological variables, as its characteristics (e.g., distribution, amount, frequency, intensity, and timing) influence freshwater availability and extreme hydroclimatic events such as drought and flooding. It can also significantly impact agricultural activities, hydropower generation, and the transmission of waterborne and vector-borne diseases (e.g., malaria, meningitis, cholera) (Dimitrova et al., 2022; Mbouna et al., 2023). Over Africa, precipitation is highly variable across a wide range of spatial and temporal scales (e.g., synoptic, intraseasonal, interannual, and decadal) (Sian et al., 2023). This complexity makes it difficult to accurately determine how it responds to large-scale climate changes (i.e., both natural and human-induced; Hoerling et al., 2006; Akinsanola et al., 2020). The continent's limited adaptive capacity and the dependence of its various economic sectors on rainfall increase its vulnerability to the impacts of climate variability (Trisos et al., 2022). In fact, studies have shown that increases in global mean surface temperature, attributed mainly to anthropogenic activity (Niang et al., 2014; IPCC, 2018, 2021), increase the risk of extreme precipitation events across Africa. Precipitation extremes, which manifest most frequently as costly drought and flooding events (Trisos et al., 2022), have been on the rise in recent decades in terms of their intensity, frequency, and spatial extent (Seneviratne et al., 2021; Bobde et al., 2024). For instance, in equatorial regions of eastern Africa, prolonged drought conditions were observed between 2020 and 2023 (UNHCR, 2023; Gudoshava et al., 2024), followed by flooding events in the subsequent seasons from March to May 2023 through March to May 2024. Thus, understanding the historical as well as the future characteristics of precipitation over the continent is critical for formulating and implementing effective adaptation and mitigation measures. Datasets of ground-based or space-borne observations, as well as reanalyses, provide valuable information to assess past and current climate, while climate models have complemented those products and made future climate projections possible. In this review, we highlight the progress and challenges in precipitation modeling over Africa. We further propose a strategy for overcoming the modeling challenges and gaps in understanding the relevant, underlying physical processes.

1.1. *Scope of review*

This review aims to assess the general status of climate modeling based on model performance in simulating precipitation over Africa and to highlight the progress, challenges, and prospects of these models. The findings of this review are intended to inform the community of model developers and users, as a more realistic simulation of African precipitation will be beneficial not only to them but also, and especially, to decision-makers. The review draws on the collective expertise of the CLIVAR/GEWEX Working Group on African Monsoons, including experts from academia, regional climate centers, and National Meteorological and Hydrological Services from southern, eastern, western, and central Africa. It aims to provide a comprehensive literature review of state-of-the-science precipitation modeling across Africa. In section 1.2, we extensively discuss the observational datasets used for model evaluations as well as for existing climate models. In section 2, we review the progress in precipitation simulation by region, considering the western, central, eastern, and southern parts of Africa in turn. Section 3 summarizes the challenges and prospects for modeling African precipitation, while section 4 provides a summary and conclusions.

1.2. *Observational datasets for model evaluations*

The ability of climate models to realistically represent the past and current climate is generally assessed by comparing model simulations with observations and/or reanalysis datasets. However, in most African countries, in-situ observation data networks are limited, and the quality of the available data further diminishes their reliability (James et al., 2018; Dinku, 2019; Nsabagwa et al., 2019; Trisos et al., 2022; Tzachor et al., 2023; Lamptey et al., 2024). Nicholson et al. (2012) noted that the available datasets have a short temporal coverage, with fewer than 20 stations across the continent that have data dating back to the 19th century. The lack of reliable historical observations hinders the comprehensive evaluation of climate models, especially in sub-Saharan Africa, where the dearth of station observational data is particularly acute (James et al., 2018; Otto et al., 2020; Arias et al., 2021). Nevertheless, there have been efforts to improve the quality of observations over the continent by installing Automatic Weather Stations (AWSs) as part of various local and international projects. Some examples include the Trans-African Hydrometeorological Observatory (TAHMO, van de Giesen et al., 2014), Fennec AWSs across the Sahara (Hobby et al., 2013), the AMMA-CATCH National Observation Service and Critical Zone Exploration Network (Galle et al., 2018), the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL, Salack et al., 2019) over West Africa, and the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL, Kaspar et al., 2015) over southern Africa. The World Meteorological Organization (WMO) is also enhancing and strengthening observational systems through development projects and initiatives such as the Systematic Observations Financing Facility (SOFF) (WMO, 2020; Kijazi et al., 2021; Santamaria et al., 2021). However, AWSs have their limitations, including cost (Shanko, 2015; Nsabagwa et al., 2019), lack of technical capacity to maintain them, and the need for security against theft and vandalization, especially in remote locations (Sabatini, 2017). Overall, reasons for the inaccessibility of station-based observational data include but are not limited to (1) the data not being available to the public (Alexander et al., 2006); (2) the existence of gaps within the time series of the data (Sun et al., 2018); (3) some large areas (e.g., Central Africa) not having stations at all (Hua et al., 2016; James et al., 2018; Nangombe et al., 2018). Instead of relying on scarce or non-free station-based observations, climate researchers have increasingly turned to multiple space-borne gridded observations, which are often merged and harmonized with in-situ measurements. These products are generally freely available to the public at regional or global levels (Alexander et al., 2006; Donat et al., 2013; Gehne et al., 2016; Akinsanola et al., 2017; Herold et al., 2017; Sun et al., 2018; Steinkopf and Engelbrecht, 2022). Utilizing multiple observational datasets helps to avoid the risks associated with depending on a single source, as these datasets can vary in consistency (Dosio et al., 2021a). Differences in gridded observational datasets may arise from different data generation algorithms, differences in the interpolation techniques and quality control schemes used, and the varying amount and quality of in-situ data they incorporate (Tapiador et al., 2017; Akinsanola et al., 2017). The in-situ observation data used in gridded observation products are often sourced from the National Meteorological and Hydrological Services, the WMO Global Telecommunication System platform, and other regional collection centers.

Various gridded observational datasets rely on different sets of source data. Some datasets use only data acquired from weather stations, like the University of East Anglia's Climatic Research Unit (CRU, Harris et al., 2014) and the Global Precipitation Climatology Centre dataset (GPCC, Schneider et al., 2015). The more common type of data uses a combination of satellite data and station-based observations: (1) the Climate Prediction Center Morphing Technique (CMORPH, Joyce et al., 2004), (2) the Integrated Multi-satellitE Retrievals for GPM (IMERG, Huffman et al., 2020), (3) the Tropical Applications of Meteorology using SATellite and gauge-based observations (TAMSAT, Tarnavsky et al., 2014), (4) the African Rainfall Climatology version 2 (ARC2, Novella and Thiaw, 2013), and (5) the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS, Funk et al., 2015). Other gridded observational datasets are combined with reanalysis data, such as the WATCH Forcing Data (WFD, Weedon et al., 2011), which combines daily statistics based on ERA-40 data (Uppala et al., 2005) with the monthly mean attributes of the GPCC and CRU datasets. Reanalysis datasets have become essential in climate research, offering comprehensive syntheses of historical data through advanced numerical models. These datasets are invaluable for understanding past climate conditions, validating models, and providing boundary conditions for impact models (Dee et al., 2011; Hersbach et al., 2020). Their growing accuracy, as evident in the latest generation of ECMWF reanalysis (ERA5), has enhanced the analysis of multivariate climate phenomena and has been crucial for both scientific research and practical decision-making (Hersbach et al., 2020). Scientists increasingly rely on reanalysis data to drive impact models and evaluate climate models, underscoring the need for continuous improvement (Pappenberger et al., 2015; Eyring et al., 2016). Recent comparisons, like those by Gbode et al. (2023) and Steinkopf and Engelbrecht (2022), demonstrate significant advancements in ERA5 over ERA-Interim, particularly in terms of reducing biases and improving resolution, which is critical for assessing the performance of high-resolution climate models. These improvements support more accurate climate adaptation and mitigation strategies.

The aforementioned large range of available data sources (although not exhaustive) allows researchers to work around the challenges of data scarcity. However, researchers must identify which data sources are best suited for evaluating model data. For example, the analysis of long-term precipitation trends has typically relied on limited data from sparse rainfall stations. (e.g., Nicholson et al., 2019). However, short-term rainfall statistics have benefited from satellite-derived data products such as CMORPH and IMERG, among others. Moreover, when the reliability of different datasets is uncertain, comparing the uncertainty of rainfall observations with modeled precipitation can better address this challenge. Researchers must be fully aware of the specific strengths and weaknesses of different observational products, as in some cases, even their long-term trends may differ (e.g., Maidment et al., 2015). Dosio et al. (2021a) demonstrated that the inter-product difference is highly region-dependent across Africa, with better agreement over the most well-observed regions. The regional dependence inherent to the reliability of rainfall observations continues to make climate model evaluation, and therefore development, a challenge.

1.3. *Existing climate models*

Despite the challenges posed by limited high-quality observations across many regions over extended periods, precipitation modeling for various African regions continues to advance. There is a pressing need for such research, as climate models are crucial for understanding regional climate change in the coming decades. Global climate models (GCMs), which operate on a planetary scale, are essential for projecting the future evolution of the global climate system and precipitation under various climate scenarios. However, GCMs often struggle to capture fine-scale processes. In contrast, regional climate models (RCMs), which are used at meso- and regional scales, offer higher resolution and more detailed insights when nested within a GCM over specific regions. Unfortunately, despite advancements in modeling over Africa, improvements in the accurate representation of precipitation patterns over Africa have been limited (Watterson et al., 2014; James et al., 2018). This finding is corroborated by the recent Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR), which highlights ongoing challenges in capturing the complex climatic processes in Africa (IPCC, 2021). Most GCMs struggle to accurately reproduce the climate at a regional level, in part due to their low spatial resolution, which makes it challenging to model important processes over Africa, including tropical convection, atmosphere-ocean coupling, land-surface coupling, strong horizontal temperature and pressure gradients, and orographic influences (Haarsma et al., 2016; James et al., 2018; IPCC, 2021). Therefore, individual model results have biases, and future projections have large uncertainties. To account for model uncertainties, multi-model ensembles are needed. The most well-known initiative to facilitate this is the Coupled Model Intercomparison Project (CMIP; https://www.wcrp-climate.org/wgcm-cmip) of the World Climate Research Programme (WCRP; http://www.wcrp-climate.org/), which was created in the mid-1990s, with model simulations covering both the twentieth- and twenty-first-century climate. The CMIP output has formed the scientific basis of numerous IPCC ARs. The project has evolved from phase 3 (CMIP3; Meehl et al., 2007) to phase 5 (CMIP5; Taylor et al., 2012), and now phase 6 (CMIP6; Eyring et al., 2016), yielding simulations used to prepare IPCC AR4, 5, and 6, respectively. Notably, the number of models and coupled climate system processes included in the CMIP models has been steadily increasing, along with their horizontal and vertical grid spacings (Smalley et al., 2023). Likewise, recent CMIP models have better representation of various Earth system processes (e.g., ice sheets and biogeochemical cycles) and improved cloud microphysics parameterizations.

Regional climate models (RCMs), on the other hand, are designed to explicitly simulate fine-scale processes in local regions or subregions of interest where GCMs are less useful, and they have been actively used for the last 20 years. However, RCM performance depends largely on the quality of the initial and lateral boundary conditions taken either from reanalysis ("perfect boundary") or GCMs through dynamical downscaling, as well as on the RCM's internal physics and parameterization. Dynamical downscaling of precipitation and other climate variables has gained popularity not just in Africa but across the globe following the growing need for regional- and finer-scale climate information for decision-makers. RCM experiments and analyses have been used in the COordinated Regional climate Downscaling EXperiment (CORDEX; Giorgi et al., 2009), an international research initiative of the WCRP. CORDEX seeks to bridge the gap between global climate modeling and the specific regional need for high-resolution, actionable climate data, particularly for regions like Africa where the impacts of climate change are expected to be severe and where detailed climate projections are crucial for effective adaptation strategies (Hewitson et al., 2012). Through the CORDEX initiative and the aforementioned CMIP project, the African continent received important research attention, leading to a better understanding of the impacts of climate variability and change (e.g., Mariotti et al., 2014; Dosio and Panitz, 2016; Gibba et al., 2019; Dosio et al., 2020, 2021b; Fotso-Kamga et al., 2020; Nonki et al., 2020; Tamoffo et al., 2022). Notably, numerous RCM studies have been conducted independently of the CORDEX protocol (i.e., using configurations different from those recommended by CORDEX and sometimes locally) (e.g., Sylla et al., 2010; Mariotti et al., 2011; Diallo et al., 2015). Most of these studies have used the Regional Climate Model (RegCM; Giorgi et al., 2012), developed and maintained by the Abdus Salam International Centre for Theoretical Physics (ICTP) in Italy, and the Weather Research and Forecasting Model (WRF; Skamarock et al., 2019) from the National Center for Atmospheric Research (NCAR). RegCM and WRF have received widespread use partly because both ICTP and NCAR offer their models openly as well as provide sustained support and maintenance for these models. In addition, there is strong community support for these models because they are made open-source by the corresponding institutions in charge of their development. Some studies have proposed a multi-model ensemble approach as a way to understand and minimize inconsistencies in model representations of African precipitation (e.g., Paeth et al., 2011; Diallo et al., 2012; Saini et al., 2015).

Another valuable dataset comes from the high-resolution convective-permitting simulations of the "CP4-Africa" project, which covers a comprehensive pan-African domain (Berthou et al., 2019). With an impressive horizontal resolution of 4.5 km, these simulations provide an in-depth understanding of the mechanisms driving African precipitation, with a particular focus on mesoscale convective systems. Similarly, the Dynamics of the Atmospheric general circulation Modeled on Non-hydrostatic Domains project (DYAMOND; Stevens et al., 2019) offers detailed insights into precipitation development at a fine spatial scale with its 5-km resolution, though it spans a shorter period of 40 days. The detailed temporal and spatial resolution of DYAMOND simulations complements the longer-term CP4-Africa data, allowing researchers to explore intricate fine-scale processes of precipitation.

In addition to the previously discussed models, significant advances have been made with the recent introduction of the High-Resolution Model Intercomparison Project (HighresMIP; Haarsma et al., 2016) and variable-resolution GCMs. HighresMIP evaluates the impact of increased resolution on climate simulations, and recent studies have highlighted its benefits in modeling regional precipitation over Africa (e.g., Ajibola and Afolayan, 2024; Samuel et al., 2024). Variable-resolution GCMs, which utilize adaptive grid refinement, can further enhance regional climate projections by more effectively allocating computational resources to areas with significant variability. This approach has been demonstrated in the work of Engelbrecht et al. (2011) and Maoyi and Abiodun (2022). Increased application of these models and their outputs will deepen our understanding of precipitation characteristics over Africa.

2. Progress in precipitation simulations over Africa in state-of-the-science climate models

2.1. *West Africa*

The subregion of West Africa is home to over 300 million people, bounded by the Sahara Desert to the north, Lake Chad to the east, the Gulf of Guinea to the south, and the Atlantic Ocean to the west. The region's vegetation zones exhibit a distinct east-west orientation, shaped by a gradient of decreasing precipitation from the Gulf of Guinea toward the Sahara. The topography of West Africa is marked by diverse landscapes, including coastal plains, inland plateaus, and prominent mountain ranges such as the Guinea Highlands and the Fouta Djallon (Fig. 1).

The rain-fed, agriculture-based economy of the region strongly depends on the West African Monsoon (WAM) system, which is responsible for more than 70% of the total annual precipitation received (Akinsanola et al., 2020). Hence, the variability and changes in WAM precipitation can potentially have a profound impact on the local population and the overall economy of the region. West Africa has also been identified as one of the areas that is most vulnerable to global warming due to its high exposure and low adaptive capacity (Barros et al., 2014; Akinsanola and Zhou, 2019a). This subregion is also known for its climate extremes (Nicholson, 2013), which have extensive socioeconomic impacts (Cornforth, 2012). One example is the well-known Sahelian drought in the 1970s and 1980s, which resulted in an extensive loss of life and property, leading to severe humanitarian crises (Timberlake, 1985). Therefore, a realistic representation of precipitation in West Africa in climate models is crucial for improving the adaptability of this region to climate change.

Seasonal precipitation is high over the coast of Guinea and decreases with latitude toward the Sahel, a semi-arid subregion between the humid equatorial rainforest and the Sahara Desert and between the Atlantic and Red Sea coasts of Africa. Most of the annual total precipitation in the Sahel comes from the summer monsoon and is associated with the meridional migration of a zonal rain band at ~5°–7°N in May–June before it "jumps" to a new location at ~10°–13°N in July–August (Sultan and Janicot, 2003; Sijikumar et al., 2006; Hagos and Cook, 2007). This meridional migration of the rain band is associated with changes in temperature following the maximum insolation over land, and a strengthening of the meridional cross-equatorial energy gradient (e.g., Nicholson, 2013; Ramel et al., 2006; Biasutti, 2019). The development of the cold tongue over the Gulf of Guinea also strongly contributes to the northward shift of the monsoon (e.g., Okumura and Xie, 2004) by strengthening the Saharan–tropical South Atlantic temperature gradient.

The structure of the monsoon is complex. Near the surface, the convergence of westerlies and northerlies is associated with intense precipitation and deep convection. North of this monsoon cell lies a shallower circulation associated with drier and weaker vertical ascent, with its northernmost edge called the "intertropical front" or "intertropical discontinuity" (Hall and Peyrillé, 2006; Hagos and Zhang, 2010). This shallow circulation is associated with the Saharan Heat Low (SHL), which in turn is associated with high surface temperature and low surface pressure, thus promoting a cyclonic low-level circulation that modulates the moisture flux. At higher altitudes, the circulation is affected by the African Easterly Jet (AEJ) at 600–700 hPa and the Tropical

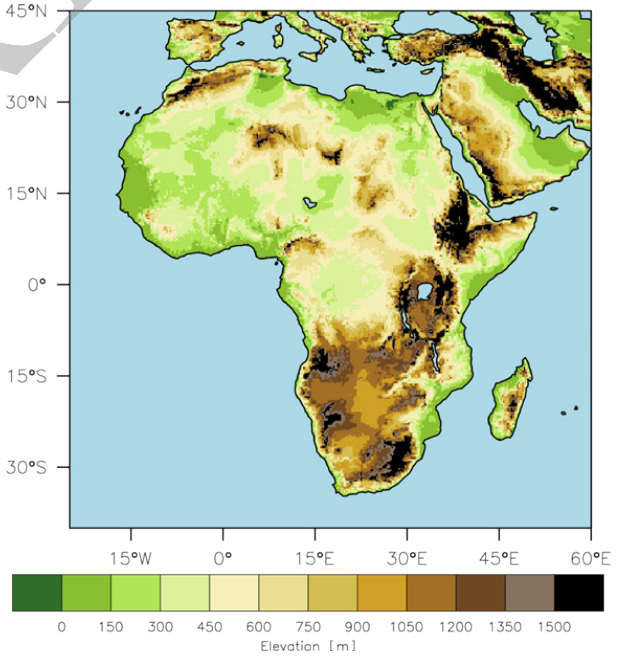

Fig. 1. Topography (elevation in meters) over Africa, derived from ETOPO1 data.

Easterly Jet at 150–200 hPa, with their cores centered around 15°N and 5°N in August, respectively (Nicholson, 2013; Akinsanola and Zhou, 2020). These mid-to-upper tropospheric jets interact with the monsoon circulation and are associated with meridional gradients in temperature and moisture over West Africa (Thorncroft and Blackburn, 1999) and elsewhere (e.g., the temperature of the Tibetan Plateau for the TEJ). A southward-shifted and strengthened AEJ is associated with a decrease in monsoon precipitation, while a strengthened TEJ is associated with a strengthened monsoon circulation (e.g., Grist and Nicholson, 2001), although the physical mechanism by which the jets influence the monsoon is not fully understood (Whittleston et al., 2017). The AEJ also serves as a waveguide for African Easterly Waves (AEWs), and the hydrodynamic instability of the AEJ can initiate and maintain AEWs (Diedhiou et al., 1999; Ocasio et al., 2020). The AEWs favor deep convection and are associated with mesoscale convective systems that bring most of the precipitation (Mathon et al., 2002; Gaye et al., 2005), causing extreme precipitation events (Crétat et al., 2015; Vellinga et al., 2016). Overall, variations in the WAM strength and location are due to variations in multiple factors, such as tropical and extratropical sea surface temperatures (SSTs) (e.g., Mohino et al., 2011), vegetation cover (Zeng et al., 1999), vegetation response to CO_2 (Skinner et al., 2017), anthropogenic aerosol emissions and greenhouse gas concentration (e.g., Monerie et al., 2022), and Arctic changes such as the Greenland ice sheet (Defrance et al., 2017), among others.

In recent decades, climate modeling in West Africa has received much attention and generated a series of research initiatives. These include the West African Monsoon Modeling and Evaluation (WAMME; Boone et al., 2010; Druyan et al., 2010; Xue et al., 2010; Hagos et al., 2014), African Monsoon Multidisciplinary Analyses and Ensembles-based Predictions of Climate Changes and Their Impacts (AMMA-ENSEMBLES; Van der Linden and Mitchell, 2009; Paeth et al., 2011; Diallo et al., 2012; Sylla et al., 2013), CORDEX initiative (Giorgi et al., 2009; Jones et al., 2011; Mariotti et al., 2014), AMMA Model Intercomparison Project (AMMA-MIP; Hourdin et al., 2010), CORDEX-CORE (Gutowski et al., 2016), AMMA Land-surface Model Intercomparison Project (ALMIP; Boone et al., 2009), and WAMME-II (Xue et al., 2016). Likewise, model outputs from all three phases of CMIP (Meehl et al., 2007; Taylor et al., 2012; Eyring et al., 2016; Gidden et al., 2019) have been analyzed over West Africa, albeit less than for some other regions globally. Amid these efforts, numerous studies have shown that ocean–atmosphere coupled models (e.g., CMIP6) systematically overestimate tropical South Atlantic SSTs (e.g., Hagos and Cook, 2009; Adeniyi et al., 2019; Richter and Tokinaha, 2020), leading to a shift of the monsoon circulation (e.g., Okumura and Xie, 2004), which results in overestimated precipitation over the Guinea coast and underestimated precipitation over the Sahel.

As a consequence, CMIP models, particularly Phase 6 models, underestimate summer mean precipitation over the Sahel (Monerie et al., 2020), implying that the monsoon system does not propagate far enough northward (Figs. 2a, b). This systematic dry bias over the Sahel is also associated with a cold (warm) bias over the Sahara (Atlantic cold tongue) (Richter et al., 2012; Roehrig et al., 2013; Monerie et al., 2017; Foltz et al., 2019). Dunning et al. (2017) showed that CMIP5 models do not capture the Little Dry Season over the Guinea coast following monsoon onset, which again implies that the latitudinal location of rainfall is too far south and that the monsoon does not propagate far enough northward. One can expect the new generation of models (CMIP6) to better simulate the WAM than the previous generation of models (CMIP5). However, Monerie et al. (2020) argue that the CMIP6 models do not perform better than the CMIP5 models; rather, they produce a larger dry bias over a large part of the Sahel (see also Figs 2a, b). In addition, Sow et al. (2020) and Dosio et al. (2021b) have shown that the CMIP5 and CMIP6 climate models have similar biases in their simulations of daily precipitation characteristics, such as precipitation intensity and extreme precipitation events.

Efforts have been made to understand biases in monsoon precipitation. Comparing fully coupled simulations with simulations with prescribed SSTs (AMIP-type simulations) represents a powerful approach for understanding the effects of biases in SSTs on the simulation of atmospheric processes and precipitation (Tamoffo et al., 2024b). Several studies have focused on analyzing AMIP simulations over West Africa (Roehrig et al., 2013; Niang et al., 2017; Adeniyi et al., 2019; Monerie et al., 2021; Adeniyi and Lin, 2022). AMIP models simulate both global monsoons and local Hadley circulations with less biases than coupled models (Toh et al., 2018). In fact, Adeniyi et al. (2019) found that AMIP models well capture the mean climatology and annual variability of precipitation over West Africa but with weak signals of the Multivariate El Niño–Southern Oscillation (ENSO) Index. Roehrig et al. (2013) documented a better performance of AMIP models in capturing the decadal variability of monsoon rainfall compared to the coupled models' underestimation over West Africa. In addition, the timing of the monsoon is better simulated when SST is prescribed (Dunning et al., 2018). These results show that biases in the simulation of SSTs have strong effects on the simulation of the precipitation mean state, variability, and seasonal cycle. Over land, the SHL was found to have strong biases in coupled CMIP5 models that were not as strong in uncoupled AMIP simulations (Dixon et al., 2017). These biases were found to be connected to biases in global energy transport and interhemispheric temperature gradients as well as to the monsoon circulation (Dixon et al., 2018, 2019). In addition, AMIP models are able to simulate the Madden-Julian Oscillation (MJO), and both Kelvin and Rossby wave signals in the zonal wind around the equator (15°S–15°N) that are comparable to observations, albeit with a weak MJO signal (Niang et al., 2017; Adeniyi and Lin, 2022). This is likely due, in part, to poorly resolved fine-scale processes and parameteriza-

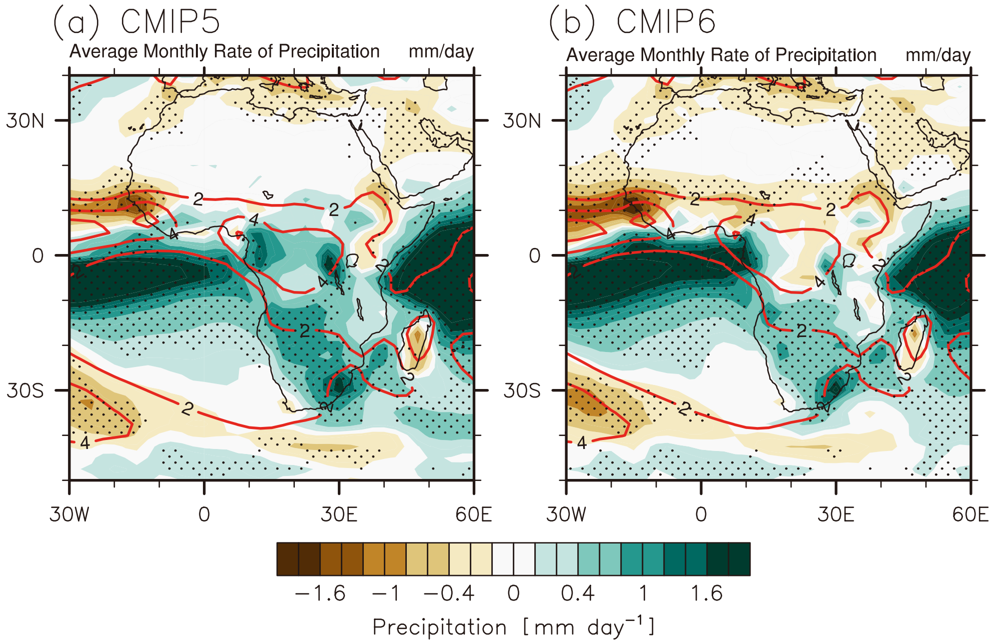

Fig. 2. Bias in annual mean precipitation (mm d^{-1}) for the (a) CMIP5 and (b) CMIP6 ensemble mean, relative to GPCC, over the period 1979–99. Stippling indicates that at least 70% of the models agree on the sign of the multi-model mean bias in precipitation. The red contours show the historical annual mean precipitation, averaged over the period 1960–99; 29 (41) CMIP5 (CMIP6) models were used.

tions at coarse model resolutions. These waves have been found to be important drivers of extreme precipitation across the Sahel (Peyrillé et al., 2023). Some of these issues with GCMs have been attributed to their coarse horizontal (100–200 km) and vertical resolutions, which result in precipitation being parameterized. This presents serious challenges for the simulation of mesoscale, local, and fine-scale processes that modulate the WAM system (Diallo et al., 2014, 2016; Mariotti et al., 2014; Vellinga et al., 2016; Dosio et al., 2021b). Numerous studies have assessed how using RCMs to dynamically downscale the results of either reanalyses (e.g., ERA-Interim or ERA5) or GCMs (e.g., CMIP5 or CMIP6) can improve the simulation of monsoon characteristics within the CORDEX framework (e.g., Diallo et al., 2012, 2014, 2016; Akinsanola et al., 2015; Dosio and Panitz, 2016; Klutse et al., 2016; Dieng et al., 2017; Akinsanola and Zhou, 2019b, 2019c; Akinsanola et al., 2020; Dosio et al., 2020). Some studies have reported an improvement in simulations of monthly mean and daily precipitation characteristics (e.g., Diallo et al., 2012; Klutse et al., 2016; Nikiema et al., 2017; Kebe et al., 2017; Gibba et al., 2019; Akinsanola and Zhou, 2019b, 2019c). However, downscaling to a finer horizontal grid of 50 km has not systematically improved the representation of WAM precipitation.

With the aim of addressing the limitations of the original CORDEX protocol and delivering simulations more suitable for global impact modeling, a new generation of higher-horizontal-resolution (~25 km) simulations was developed under the CORDEX-Coordinated Output for Regional Evaluations (CORDEX-CORE; Gutowski et al., 2016). CORDEX-CORE results are designated to be utilized jointly across the world for the study of regional climate processes and the analysis of the impact of climate change on different sectors, including vulnerability assessment and adaptation options (Giorgi et al., 2021). Some studies have already investigated the performance of the CORDEX-CORE RCMs over West Africa (Ashfaq et al., 2021; Dosio et al., 2021b; Gnitou et al., 2021; Ilori and Balogun, 2022; Olusegun et al., 2022) in simulating seasonal and annual precipitation, as well as circulation (Tamoffo et al., 2023a). Olusegun et al. (2022) documented the performance of CORDEX-CORE models in simulating the mean spatial pattern and seasonal cycle of daily precipitation characteristics over West Africa. They reported that although the models showed an overall good performance, model biases in both simulated precipitation spatial patterns and in the seasonal cycle timings of the daily indices were still evident. Gnitou et al. (2021) found that the added value of CORDEX-CORE precipitation is not homogeneous over key seasonal climate features. The authors argue that the precipitation deficiencies of the CORDEX-CORE models could be related to their representation of important processes within RCM models.

The limited ability of both GCMs and parameterized RCMs to simulate precipitation in West Africa suggests that even higher resolutions may be necessary, as in kilometer-scale convective permitting simulations, to realistically simulate regional climate variability and changes in the WAM. The coarse resolution of GCMs (from 50–200 km) and RCMs (from 10–50 km) requires the parameterization of subgrid-scale processes, including convection. These convective parameterizations have created challenges in accurately simulating precipitation associated with the WAM, leading to large uncertainty in climate change projections. The challenges of poor representation as well as that of parameterizations (Berthou et al., 2019; Wang et al., 2021) motivated the development of convective-permitting simulations over West Africa as part of the Cascade project (Pearson et al., 2014) and by Birch et al. (2014), and more recently over a pan-African domain in the “CP4-Africa” (CP4A) simulations emerging from the Future Climate for Africa (FCFA) program (Stratton et al., 2018; Kendon et al., 2019). These CP4A simulations were run using a 4.5-km grid spacing and included two decade-long runs for both present-day and future scenarios. Birch et al. (2014) illustrated the potential of convection-permitting models to improve the simulated monsoon circulation over West Africa. CP4A has illustrated further potential. For instance, compared to a coarser (25 km) model, CP4A more realistically captures monthly and hourly rainfall characteristics when compared to observations (Berthou et al., 2019; Kendon et al., 2019) (Fig. 4).

Higher-resolution simulations allow us to better understand the underlying mechanisms for changes and variability in the WAM. Though they have their limitations, convection-permitting models simulate more realistic convection over Africa (Kendon et al., 2019). Simulation of storms with a more realistic diurnal cycle, lifetime, and propagation direction, as well as a relatively improved spatial distribution, has been achieved with convection-permitting simulations (Crook et al., 2019). Likewise, Fitzpatrick et al. (2020) used CP4A output to study mesoscale convective systems (MCSs) embedded in the monsoon system, emphasizing the role of moisture in future extremes. However, due to the high computational cost of these simulations, only one realization is currently available for each time period. However, recent work by Klein et al. (2021) has created a framework for process-based precipitation scaling for CMIP models based on output from CP4A. Additional convection-permitting simulations across West Africa would provide further support for understanding these mechanisms and applying them to better constraining global model projections. The earlier discussed simulations produced by the DYAMOND project may also be helpful in improving our understanding of simulated precipitation uncertainty in CMIP5/CMIP6, and in CORDEX-CORE simulations.

Finally, in addition to model resolution and SST representation, external anthropogenic forcing has a strong impact on precipitation in West Africa. It has been shown, for instance, that past increases in the U.S. and European anthropogenic aerosol emissions partly drove the Sahel drought of the 1970s and 1980s, either through a weakened SHL or via the Walker circulation (Dong et al., 2014; Herman et al., 2020; Hirasawa et al., 2020, 2022; Marvel et al., 2020; Monerie et al., 2022). However, differences between models in simulating the effects of anthropogenic aerosols lead to uncertainty in simulations of the decadal to multi-decadal trends in WAM precipitation (Monerie et al., 2023). Understanding and better simulating the effect of external forcing represents another avenue for improving the simulation of the WAM for more skillful predictions.

2.2. *Central Africa*

Central Africa is a vulnerable region in which multiple biophysical, political, and socioeconomic stressors interact to constrain adaptive capacity. The economy of this region relies heavily on climate-sensitive sectors, including rainfed agriculture, forestry, hydroelectric power generation, and water resources (IPCC, 2018, 2021; King and Harrington, 2018). This region includes the Congo rainforest, the world's second-largest rainforest after the Amazon forest (Fisher et al., 2013; Dargie et al., 2017). The Congo rainforest plays a pivotal role in the climate system as one of the three most active convection regions on the planet, along with the Amazon and Indo-Pacific Maritime Continent (Washington et al., 2013). However, the drivers of regional climate in Central Africa remain largely understudied due to the scarcity of observational data (Williams et al., 2007; Jury and Mpeta, 2009). For instance, only three stations in the Democratic Republic of Congo participated in the Global Telecommunication System in 2013 (Todd and Washington, 2004; Washington et al., 2013). Furthermore, Washington et al. (2013) observed that of more than 50 measuring stations available in the region between the 1950s and 1980s, fewer than 10 were still operating in 2010.

The current understanding of the mechanisms controlling Central African climate is based in part on theories adapted from other regions. Until recently, rainfall seasonality over Central Africa was associated with the concept of the Inter-Tropical Convergence Zone (ITCZ), whose mechanisms do not match the regional circulation, as revealed by reanalysis data (Nicholson, 2018). Related to this ITCZ concept, seasons are defined as three months in length, a definition based on mid-latitude seasonality that is not suitable for the tropics (Bombardi et al., 2019). This mismatch may partly obscure some aspects of model performance, particularly in accurately characterizing the timing and intensity of the rainy season (Mba et al., 2022). Central Africa has long been described as having a bimodal annual precipitation cycle (Pokam et al., 2012; Nicholson and Dezfuli, 2013; Washington et al., 2013). However, a previous study by Liebmann et al. (2012) that analyzed the onset and end of the rainy season contradicted this classification. In fact, these authors argued that most regions in Africa exhibit a unimodal rainfall pattern, with the exception of some regions bordering the equator that display a bimodal rainfall cycle. A recent study by Cook and Vizy (2022) corroborated the earlier findings of Liebmann et al. (2012), demonstrating that the misconception that Central Africa exhibits a bimodal rainfall regime arises from an averaging approach that often combines regions on both sides of the equator. In fact, both the northern and southern hemispheres of Central Africa have unimodal rainfall patterns (Fig. 3), with each hemisphere serving as a moisture source for the other through convergent meridional circulation between the 850–500-hPa pressure levels. In the northern hemisphere, peak precipitation occurs from March to November, with a slight decrease in July and August, though the

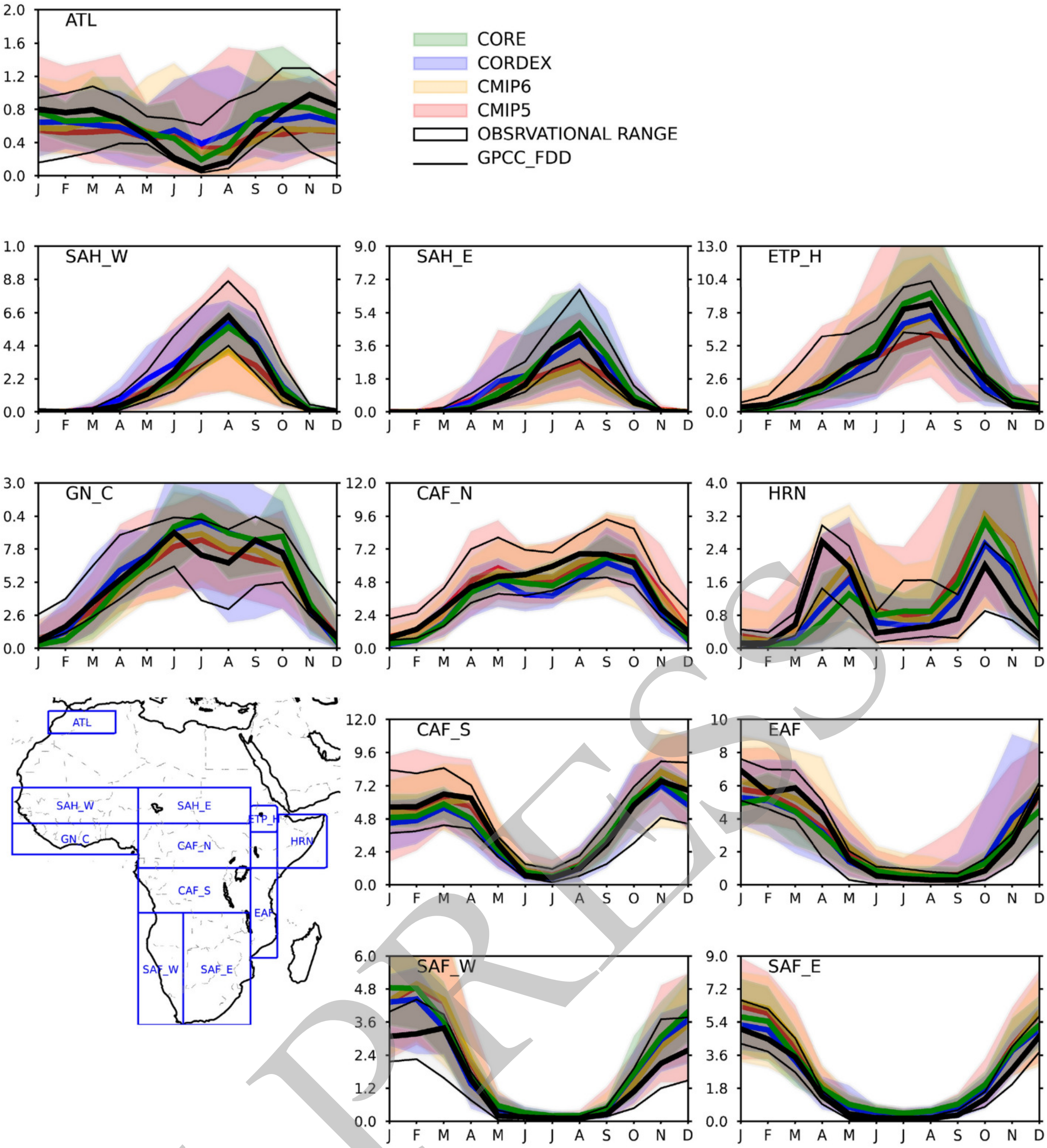

Fig. 3. Annual cycle of monthly averaged daily precipitation (mm d^{-1}) over the reference period (1981–2010) in the African subregions shown as blue boxes in the map. The thick black line represents the GPCC observed values, whereas the thin black lines show the range of a large ensemble of observational products, including reanalyses as well as satellite-based and gauge-based products. Colored lines and shaded areas show the ensemble mean and range of the different model ensembles, respectively. The figure is from Dosio et al. (2021b).

monthly frequency remains relatively high at 4 mm d^{-1}. Similarly, the southern hemisphere experiences a rainy season from October to May but with a delayed peak in November rather than October, as seen in the northern hemisphere, and a dry season from June to September.

The drivers of the Central African climate system span a wide range, encompassing local to large-scale factors and operating on sub-daily to multidecadal timescales. Soil moisture recycling has been identified as a significant factor contributing to precipitation variability, given the predominantly forested nature of the Congo Basin. In particular, studies by Pokam et al. (2012) and Dyer et al. (2017) have characterized annual recycling rates at approximately 38% and 25%, respectively. However, Crowhurst et al. (2021) have demonstrated that the mechanisms controlling evaporation can vary significantly from one time of year to another. Furthermore, there is still substantial uncertainty regarding the factors influencing evaporation in this region (Kenfack et al., 2023). Consis-

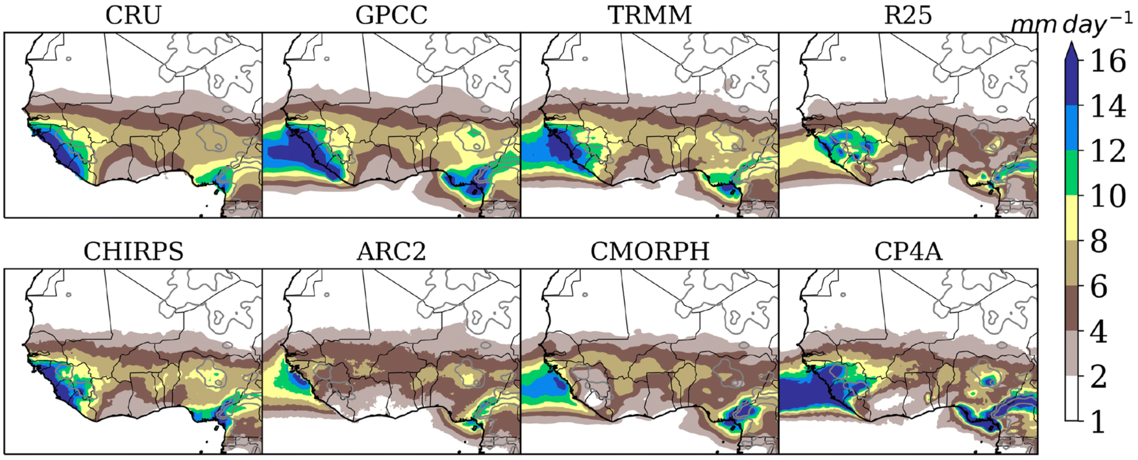

Fig. 4. Mean precipitation (mm d^{-1}) in JAS for different observed datasets, CRU, GPCC, TRMM, CHIRPS, ARC2, and CMORPH, and for a convection-permitting model (CP4A; at a 4.5 × 4.5-km horizontal resolution at the equator) and a convection parameterized model (R25; at a 26 × 39-km horizontal resolution at the equator). The average is computed over the period 1997–2006 (1998–2007) for CRU, GPCC, CHIRPS, ARC2, R25, and CP4A (TRMM and CMORPH). The figure is from Berthou et al. (2019).

tently and in agreement with Cook and Vizy (2022), these authors argued that the contribution of total evaporation remains minor in driving the seasonality of rainfall. The Walker- and Hadley-like circulations are also characteristic of the Central African climate system. The lower branch of the Walker-like cell generates low-level westerlies (Pokam et al., 2014; Cook and Vizy, 2016), which transport moisture from the eastern Atlantic Ocean to Central Africa. This moisture ascends over the highlands of the eastern Rift Valley, forming the upward branch of the Atlantic–Congo Basin overturning circulation. The presence of a distinct closed, counterclockwise, shallow zonal overturning cell known as the Congo Basin Cell over Central Africa was emphasized by Longandjo and Rouault (2020). Their research illustrated that the Congo Basin Cell facilitates the exchange of heat between the warm Central African landmass and the cold eastern equatorial Atlantic Ocean. This, in turn, results in a zonal surface pressure gradient between the warm Central African landmass and the cold eastern Atlantic Ocean. Consequently, the pressure gradient initiates a monsoon-like circulation, leading to mass convergence at the Congo Air Boundary (Howard and Washington, 2019), which fuels convection. A recent study by Munday et al. (2023) further highlighted the significant role of valleys within the 6,000-km-long East African Rift System (EARS) in supplying water vapor to Central Africa, thereby contributing to the moistening of the Congo Basin rainforest. In mid-tropospheric layers, similar to West Africa, the AEJ (wind speed >6 m s^{-1}) develops between 600 and 700 hPa. The northern component (AEJ-N) is present throughout the year, whereas the southern component (AEJ-S) is active only from August to November (Nicholson and Grist, 2003). AEJs result from meridional surface temperature gradients between the equator and subtropics. It has been demonstrated that the force and position of AEJ-N influence rainfall variability such that over the Sahel in West Africa, wet years feature a weaker and northward AEJ-N while dry years show the opposite pattern (Grist and Nicholson, 2001). Jackson et al. (2009) associated the increased activity of MCSs during September-October-November with activation of the AEJ-S at this time of year.

Because of the paucity of ground-based observations, climate models remain the main tools for studying climate over Central Africa. International climate research initiatives within the WCRP have brought more attention to this region. Climate models have been widely applied over Central Africa to assess seasonal and annual precipitation cycles. These assessments used individual ensemble members, the perturbed physics ensemble mean, and the ensemble mean of all members (James and Washington, 2013; James et al., 2014; Aloysius et al., 2016; Dunning et al., 2017; Fotso-Nguemo et al., 2018; Sonkoué et al., 2019; Zebaze et al., 2019). Broadly, Creese and Washington (2016) demonstrated significant variations, including differences of up to a factor of 5 in certain months, in the representation of rainfall climatology among CMIP5 models. These models exhibit disparities in the location of rainfall maxima; some place it in the eastern region, while others place it in the west. The surplus or deficit of rainfall in coupled models is closely correlated with the overestimation or underestimation of modeled moisture flux convergence entering the region. These variations in moisture convergence indicate differences in the atmospheric circulation between the various models. Underlying all these discrepancies is the influence of warm biases in SSTs, which are a common feature in most CMIPs over the eastern equatorial Atlantic Ocean. Creese and Washington (2018) highlighted the impact of these SST biases. They compared CMIP5 models and their AMIP atmospheric-only counterparts, which are forced by observed SSTs, to underscore the effects of ocean-atmosphere coupling. They concluded that the excessive rainfall over the western Congo Basin is associated with warm SST biases. Warmer SSTs lead to increased evaporation and, consequently, greater moisture availability over the ocean. Conversely, SST biases strongly affect the representation of the shallow and single counterclockwise zonal circulation known as the Congo Basin Cell, as recently highlighted by Longandjo and Rouault (2020). Indeed, disparities in simulated SSTs result in errors in the modeling of land-sea thermal gradients and, subsequently, pressure contrasts. This, in turn, impacts the strength of the Congo Basin Cell and, consequently, the low-level westerlies, leading to inaccuracies in the amount of inland moisture transport (Taguela et al., 2022; Tamoffo et al., 2022, 2024a). The Met Office Unified Model GCM, on the other hand, has shown a dry bias over Central Africa during September–November (SON). This bias is associated with an overestimation of the sinking branch of the Atlantic-Congo zonal overturning circulation, which, in response to a strong, near-surface temperature and pressure gradient between Central Africa and the eastern Atlantic Ocean, results in excessively strong low-level westerlies. Consequently, this leads to depleted moisture along coastal regions (Taguela et al., 2022). Other studies (e.g., Taguela et al., 2024) examined the simulation of low-level westerlies and the Congo Basin Cell and found that the main characteristics of these two features were "reasonably well depicted," with observed improvements from CMIP5 to CMIP6.

Mid-tropospheric AEJs are identified as the primary driver of rainfall bias over the eastern Congo Basin, whereas SST biases in the tropical Atlantic and western Indian Ocean do not play a major role in the modeling of rainfall climatology (Creese and Washington, 2018). A southward shift of these jets promotes increased moisture convergence south of the equator while depleting moisture in the north. Composite analyses reveal that models exhibiting wet rainfall biases over the eastern Congo Basin feature anomalous equatorial westerlies, indicating weaker jet streams. Simultaneously, the TEJ has a robust influence, although further investigation is needed to clarify the relationship between the TEJ and rainfall (Nicholson and Klotter, 2021). A study by Kuete et al. (2023) revealed that several models fail to accurately represent the southeast-northwest orientation of the AEJ-N core, resulting in a gap of approximately 6° in the jet's location. They also reported that most CMIP5 models struggle to correctly position the AEJ-S over southern Central Africa. Additionally, the dispersion in simulated AEJ locations, when compared to reanalyses, is more significant for CMIP5 models in contrast to their CMIP6 counterparts, suggesting an improvement from CMIP5 to CMIP6 in the 16-model subset they diagnosed. The poor representation of AEJ-S by the CMIP6 models has also been noted by Adebiyi et al. (2023). However, besides the reasons mentioned above that are believed to be responsible for the CMIP rainfall biases, the coarse resolution of these models also plays a significant role. This argument is substantiated by the findings of Munday et al. (2021), who revealed that models with grid lengths of less than 60 km are necessary to accurately simulate the prominent characteristics of nocturnal easterly low-level jets (LLJs). Furthermore, they demonstrated that biases in simulated LLJs are reflected in rainfall climatology across the continent.

Dynamical downscaling methods using RCMs have been employed to overcome the issue of coarse GCM resolution. This downscaling is designed to better capture smaller-scale physiographic processes associated with the finer resolution (Laprise, 2008; Rowell, 2013; Giorgi and Gutowski, 2015; Moufouma-Okia and Jones, 2015). CORDEX simulations have shown substantial progress in assessing model biases of precipitation characteristics over Central Africa and indicate the added value of RCMs relative to driving CMIP5 GCMs and reanalyses (Nikulin et al., 2012; Laprise et al., 2013; Dosio and Panitz, 2016; Fotso-Nguemo et al., 2017a, 2017b). However, despite the progress afforded by CORDEX, substantial biases in simulated precipitation still exist, and the reason remains less understood (Haensler et al., 2013; Fotso-Nguemo et al., 2017a; Vondou and Haensler, 2017; Tamoffo et al., 2019a; Taguela et al., 2020), although some studies have noted that these biases may arise because of improperly simulated mechanisms (James et al., 2018; Tamoffo et al., 2020). Among others, most CORDEX RCMs generally simulate strong wet rainfall biases over the Guinea Gulf and coastal regions (Nikulin et al., 2012; Dosio and Panitz, 2016; Fotso-Nguemo et al., 2017a, 2017b; Fotso-Kamga et al., 2020; Taguela et al., 2020; Tamoffo et al., 2019a, 2019b, 2022). Vondou and Haensler (2017) and Tamoffo et al. (2019a) attributed this to the failure of RCMs to adequately reproduce land-sea contrasts. They found that while REgional MOdel (REMO; developed Max Planck Institute for Meteorology) exhibit high rainfall biases over the eastern Atlantic Ocean, they feature less rainfall over the Congo Basin, in accordance with earlier findings by Fotso-Kamga et al. (2020) using COSMO. Tamoffo et al. (2019b) reached similar conclusions using the Rossby Centre regional climate model RCA4. In general, the process-based evaluation of RCMs over Central Africa (Tamoffo et al., 2019a, 2020, 2022, 2023b, 2024a) has revealed that the reasons behind RCM rainfall biases are similar to those for CMIP GCMs. These reasons include the models' misrepresentation of regional teleconnections, land-sea thermal and pressure contrasts, which induce biases in atmospheric circulation, and land–atmosphere feedback leading to errors in the regional hydrological cycle.

The CORDEX-CORE simulations, where RCMs are run at a higher horizontal resolution (~25 km) compared to the former CORDEX RCMs (~50 km), have also been analyzed across Central Africa. Unlike the earlier phase of CORDEX, where the choice of GCMs was left to individual RCM modeling groups, the CORDEX-CORE protocol requires all participating RCMs to downscale the same set of driving GCMs. Despite this coordination and the advance in horizontal and vertical resolution, the CORDEX-CORE initiative does not provide substantial progress in modeling climate systems. Other parameterization aspects, such as convection and some surface schemes, remain the same as in the previous RCMs participating in CORDEX. Moreover, neither the CORDEX nor CORDEX-CORE RCMs are coupled with an ocean model, which may limit the realistic modeling of land–atmosphere–ocean feedback. A recent study by Weber et al. (2023) showed that regionally coupled RCMs considerably improve SST biases, leading to more realistic simulated precipitation characteristics over most coastal regions of sub-Saharan Africa and over southern Africa.

Finally, the parameterization of convection in CMIP and CORDEX RCMs constitutes an important source of bias in the results of climate models over equatorial Africa. Indeed, some studies (e.g., Hamada et al., 2015; Raghavendra et al., 2018; Alber et al., 2021) have demonstrated that although an increase in vertical motion is a strong indication of tropical convection, enhanced convection does not necessarily mean strengthened rainfall over the Congo Basin. They based their arguments on the observed drying trend in the Congo Basin despite increased thunderstorms. The new generation of convection-permitting models (CPMs; i.e., RCMs run at very high resolutions of around 5 km or less) are giving promising results and should be used for verifying these assumptions. These simulations have shown significant improvements in small-scale precipitation characteristics (such as intensity and diurnal cycle). However, such simulations require significant computational resources, and their results are currently available over Africa for only a very limited period (10 years or less) (Kendon et al., 2019; Kouadio et al., 2020; Senior et al., 2021).

2.3. *Southern Africa*

Southern Africa (south of 10°S) is home to about 277 million people, and 60% of its population lives in rural areas dependent on rainfed agriculture (Tanyanyiwa and Hakuna, 2014). The present climate of southern Africa is diverse, ranging from arid and semiarid to wet and subhumid (Huang et al., 2016). Southern Africa receives most of its precipitation during austral summer, mainly between December and March (DJFM; see Fig. 3), due to the southward migration of the ITCZ (Daron et al., 2019). The highest precipitation is seen in the deep tropics, while the rest of the subcontinent is characterized by a strong east-west precipitation gradient; some areas of the west receive less than 40 mm of rain per annum, while more than 1200 mm is observed in the east annually. The extreme southwest part of the region receives rainfall during austral winter, from June to August, while the south coast receives precipitation all year round with small peaks in spring and autumn (Jury, 2013; Daron et al., 2019). Mean precipitation and variability in this subregion are known to be driven by a complex mix of processes from global to local scales (Jury, 2013). Due to its geographic position, southern Africa is also dominated by both mid-latitude and tropical weather systems, with regional oceanic phenomena exerting a strong influence on precipitation (Jury, 2013; Desbiolles et al., 2018; Nkwinkwa Njouodo et al., 2018; Mahlobo et al., 2024). Rainfall seasonality in the tropics is dominated mostly by the seasonal migration of the African rain belt (e.g., Nicholson, 2000). The latter extends to the subtropics through the convergence of low-level moisture-bearing winds from the tropical and southwestern Indian Ocean as well as the tropical Atlantic, supporting the Subtropical Indian Ocean Convergence Zone (SIOCZ). The strength of the SIOCZ, however, is modulated by multiple regional circulation features, namely the Angola Low (Munday and Washington, 2018; Pascale et al., 2020), Kalahari heat low, Mozambique Channel Trough (Barimalala et al., 2018, 2020), and Botswana High (Reason, 2016; Driver and Reason, 2017), and by different low-level jets such as the Limpopo and Zambezi River Valley jets (Barimalala et al., 2021; Munday et al., 2021).

The Angola Low, a semi-permanent low-pressure system that develops in the lower troposphere over southern Angola and northern Namibia, has been documented to have a large influence on precipitation over the region. A strong (weak) Angola Low is associated with above (below) average summer rainfall over southern Africa (Munday and Washington, 2018). The strength of the low-pressure system has been found to be sensitive to regional SSTs (Desbiolles et al., 2020). The Kalahari heat low develops over the Kalahari Desert when the maximum insolation moves southward. It maintains the moisture gradient observed over the Kalahari Desert by limiting the penetration of moisture from the southwestern Indian Ocean into the subcontinent (Taljaard, 1986). Namibia-Botswana, on the other hand, is characterized by the Botswana high (BH) pressure system, with a strong BH linked to drought and extreme temperatures in different regions of subtropical southern Africa. Farther east, moisture transported from the southern Indian Ocean is dynamically adjusted by the topography of Madagascar during austral summer. Such adjustment leads to the formation of the Mozambique Channel Trough (MCT), which modulates the amount of rainfall over southern Africa (Barimalala et al., 2018). A weaker (stronger) MCT leads to excess (deficient) rainfall over the mainland and a deficit (excess) in Madagascar. On synoptic timescales, one key rainfall-generating mechanism over southern Africa is tropical-temperate troughs (TTTs) (Cook et al., 2004). TTTs consist of tropical–extratropical interactions and are characterized by deep convective activity. In southern Africa, TTTs contribute to a large proportion of the precipitation (Harrison, 1984; Todd and Washington, 1999; Cook et al., 2004; Hart et al., 2013; Macron et al., 2014; Manhique et al., 2015). The combination of large-scale processes such as ENSO and the Indian Ocean Dipole (IOD) with these regional circulations and synoptic systems challenges the climate scientific community not only to understand the physical mechanisms behind regional climate but also to represent these mechanisms with current state-of-the-science climate models, which persistently show large precipitation biases in the area.

Most updated global models within the CMIP6 initiative continue to suffer from large systematic biases (Kim et al., 2020); most models generate too much rainfall over the region, with a large range in magnitude (Christensen et al., 2007; Lazenby et al., 2016; Munday and Washington, 2018; Karypidou et al., 2022; Samuel et al., 2023) (Figs. 2a, b).

Biases are also present in atmosphere-only models (Goddard and Graham, 1999; Cook, 2000; Lazenby et al., 2016). Although the pattern of bias varies between models, the ensemble mean and some models show excessive rainfall over mainland southern Africa and a deficit over Madagascar (Figs. 2a, b). Munday and Washington (2018) found that some CMIP5 models (7 out of 10) overestimate rainfall by up to 300% compared to observations. On the other hand, regional climate simulations from CORDEX driven by CMIP5 models show a decrease in rainfall biases over the mainland compared to the driving models (Pinto et al., 2016, 2018; Karypidou et al., 2022) (Fig. 5). The observed northward shift of the rainband from March onward is also evident in the CORDEX-Africa models, while regions of high precipitation are still depicted in the CMIP5 and CMIP6 models. Moreover, Weber et al. (2023) show an improvement in rainfall biases over southern Africa using a regionally coupled atmosphere–ocean model.

Analyses of a set of models within CMIP5 show that TTTs are depicted by all models, with circulation features similar to observations. However, there is a large spread in the number, intensity, and position of TTTs, which is linked to differences in the spatial distribution of tropical convective activity and regional circulation features in the models (James et al., 2020). Therefore, the relation between TTTs and southern African rainfall in CMIP5 is model dependent. Some models with too few TTTs tend to be drier than those with many TTTs, whereas other groups of models with significantly large numbers of TTTs compared to observations do not present large rainfall biases (James et al., 2020). On the other hand, a pan-Africa convective-permitting simulation shows improvement in the representation of the annual cycle of TTTs with respect to the driving model, as well as a reduction of up to 50% in the large rainfall biases over the mainland (Hart et al., 2018; Senior et al., 2021). The improvement is explained by a strong vertical mass flux in the tropics associated with a strong local Hadley overturning into the summer hemisphere (Hart et al., 2018). Nevertheless, James et al. (2020) suggest the importance of both realistic orography and tropical convection in the representation of the southern African rainfall. In addition, Desbiolles et al. (2018) stress that mesoscale SST variability favors tropical–extratropical interactions and, thus, TTT development over the subcontinent.

By examining the representation of the Angola Low (AL) pressure system in CMIP5 models, Munday and Washington (2018) show that 40%–60% of the inter-model variability in precipitation between CMIP5 models is associated with the simulated strength of the AL. This agrees with Lazenby et al. (2016), where AMIP and CMIP models were found to exaggerate the moisture circulation in the AL compared to reanalysis, which could lead to excessive precipitation over the mainland, independent of SST biases in the models. However, Desbiolles et al. (2020) suggest that mesoscale SST variability over the Angola-Benguela Frontal Zone plays a key role in AL activity during late summer. No significant improvement in the simulation of the AL is found in CMIP6 models (Karypidou et al., 2022). On the other hand, the CORDEX-Africa ensemble depicts a weaker AL relative to CMIP5, which could partially explain the reduced rainfall biases in the regional models (Karypidou et al., 2022).

Finally, excess precipitation over the southern African subcontinent in the CMIP5 models is associated with anomalously strong northeasterly moisture transport penetrating across the high topography of Tanzania and Malawi (Munday and Washington, 2018). Models with lower topography over Tanzania have a reduced tendency to block the northeast-

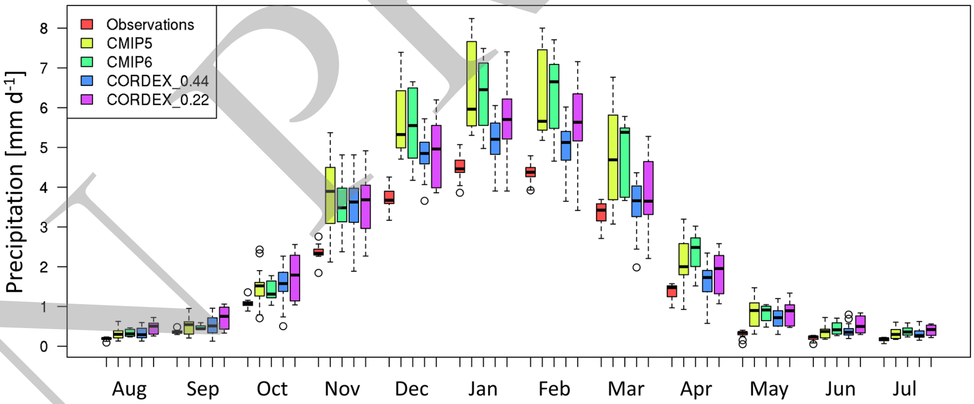

Fig. 5. Annual cycle of monthly precipitation during 1986–2005 for the ensemble of observational data (gauge-based, satellite, and reanalysis), CMIP5 (Coupled Model Intercomparison Project Phase 5), CMIP6 (Coupled Model Intercomparison Project Phase 6), CORDEX 0.44° (Coordinated Regional Climate Downscaling Experiment - Africa domain with a spatial resolution equal to 0.44° × 0.44°) and CORDEX 0.22° (CORDEX-Africa simulations with a spatial resolution equal to 0.22° × 0.22°). The thick horizontal black lines indicate the ensemble median for each month, the box encloses the interquartile range, and the tails denote the full ensemble range. Circles represent the outliers for each ensemble. [Figure from Karypidou et al. (2022)].

erly flow, leading to higher precipitation biases. Similarly, an appropriate representation of the topography of Madagascar is found to lead to a more realistic Mozambique Channel Trough (MCT), which then modulates moisture transport from the southwestern Indian Ocean into the subcontinent in idealized simulations (Barimalala et al., 2018, 2020). However, in CMIP6 models, the link between the MCT and rainfall over southern Africa appears to be missing, possibly masked by other processes, including the strength of the AL, moisture fluxes from adjacent oceans, and overestimated convective activity in the Mozambique Channel (Barimalala et al., 2024).

2.4. *Eastern Africa*

The region of eastern Africa, while in the deep tropics, does not exhibit either a wet climate in terms of annual mean precipitation or a monsoonal climate in terms of precipitation annual cycle. Instead, eastern Africa is dominated by a semiarid/arid climate with a bimodal annual cycle of precipitation characterized by long rains during boreal spring (March–May) and short rains in autumn (October–December, OND; Fig. 3). The rainfall seasons are driven principally by the movement of the ITCZ (Gamoyo et al., 2015). One major factor responsible for the climate in eastern Africa is the complex topography (Anyah et al., 2006; Lyon, 2014; Fig. 1). The topography of eastern Africa can be generally characterized by the coastal plain to the east and the predominantly north-south orientation of the interior highlands. The highlands to the north (Ethiopian highlands) and to the south (East African highlands) are separated by a narrow gap (Turkana channel), which connects the area of relatively low topography to the northwest and the eastern coastal plain. These topographical features play an important role in low-level atmospheric circulations and moisture transport (Findlater, 1969; Kinuthia and Asnani, 1982; Kinuthia, 1992; Nicholson, 2017; Munday et al., 2023; Palmer et al., 2023).

Previously, the aridity was considered to be associated with the dominant low-level divergence (Trewartha, 1961), which, in turn, was assumed to be caused by a wind stress contrast between land and ocean. However, Yang et al. (2015) disputed the wind stress mechanism. They found the atmosphere over eastern Africa to be convectively stable in general year-round but with an annual cycle dominated by surface moist static energy (MSE), which is in phase with the annual precipitation cycle. They propose that the semiarid/arid climate in eastern Africa and its bimodal annual precipitation cycle can be explained by a ventilation mechanism, in which atmospheric convective stability over eastern Africa is controlled by the importation of low-MSE air from the relatively cool Indian Ocean off the coast. They demonstrate that during the rainy seasons, the off-coast SST increases (and is warmest during the long rainy season), and consequently, the air imported into eastern Africa becomes less stable. During the dry seasons, there are strong low-level cross-equatorial monsoonal winds, especially in summer, which are thought to bring air with much lower MSE from the winter hemisphere into eastern Africa and stabilize the atmosphere. The north-south-oriented highlands act to block the importation of high-MSE air from the west and also lead to the formation of the east African low-level jet (Findlater, 1969).

The SST-forced models of the CMIP5 AMIP experiments capture the climatology of precipitation in eastern Africa, the recent drying trend in the eastern African long rains (Gebrechorkos et al., 2019), and much of the decadal variability since the 1950s. However, most CMIP5 coupled models fail to properly simulate the annual cycle (Ongoma et al., 2019), typically reversing the amplitudes of the short and long rains relative to observations (Fig. 3). The models also have a dry (wet) bias during the long (short) rains and a 1-month lag in the peak of the long rains relative to observations (Fig. 3), mainly due to their climatological SST biases. Additionally, Hirons and Turner (2018) showed that the wet biases during the short rains are due to the inability of some models to capture the westerlies over the Indian Ocean. These biases persist in most models in CMIP6 (Lyon, 2022; Makula and Zhou, 2022; Mbigi et al., 2022). A comparison of CMIP6 and CMIP5 models in simulating mean and extreme precipitation over the region by Ayugi et al. (2021) shows that the CMIP6 multi-model ensemble mean performs better in the local annual mean cycle simulation with a better representation of the rainfall within the two peaks, especially the MAM rainfall relative to CMIP5. They also found the simulation of extreme indices to be well captured in CMIP6 models relative to CMIP5. Akinsanola et al. (2021) showed that the multi-model ensemble mean generally provides a better representation of observed precipitation and extreme precipitation compared to individual CMIP6 models.

Recent studies have shown that coupled climate models often simulate a weaker-than-observed west-east SST gradient in the western Indian Ocean. This results in a higher simulated SST near the coast of eastern Africa compared to observations, while SSTs in the eastern Indian Ocean are either close to or lower than observed. This is especially so during the boreal late autumn-early winter months (Conway et al., 2007; Han et al., 2012; Cai and Cowan, 2013; Liu et al., 2014). This might be one reason why coupled models generally tend to overestimate short rains. Simulating the climate in eastern Africa is, however, a great challenge for GCMs due to the region's complex topography (Fig. 1) and diverse climate conditions, ranging from semiarid to tropical monsoon (Flato et al., 2013). With a customized RCM, Gudoshava and Semazzi (2019) showed that during long rains, the inter-annual rainfall variability over the Lake Victoria region was associated with an SST anomaly over the Indian Ocean, and for eastern Africa, the associations were weak. Endris et al. (2013) evaluated the performance of 10 CORDEX RCMs for their ability to capture and characterize rainfall patterns over eastern Africa as well as their ability to reproduce the response to large-scale global signals during the period 1990–2008. The RCMs were forced by the ERA-Interim reanalysis. They found that most RCMs reasonably simulated the main features of the rainfall climatology over the region and also reproduced the majority of the documented regional responses to ENSO and IOD forcing. All RCMs realistically simulated the rainfall belt associated with the ITCZ over the region during JJAS and OND, but most indicated a wet bias. The RCMs were found to represent the correct shape of the mean annual cycle of rainfall over both the northern and southern parts of the region but with a small shift in capturing the correct peak of the dominant bimodal rainfall regimes over the eastern horn. Most of the models captured the regional rainfall anomaly associated with ENSO and IOD and were in agreement with the observations. The multi-model ensemble mean outperformed the results of individual models, and even ERA-Interim, in most areas, suggesting that downscaling GCM output improves rainfall representation at the regional scale.

3. Challenges and prospects in modeling precipitation over Africa

Despite significant advances in understanding past precipitation characteristics over the African continent with the aid of climate models, many challenges remain. These include but are not limited to the unavailability of reliable observational data necessary to efficiently constrain model results. High-quality interpolated gauge-based data play an important role in the development and validation of climate models. Africa has low-quality historical gauge data, and its rainfall weather stations are few and unevenly distributed. Enhancing the quality and availability of observational data—both in situ and satellite—holds promise for advancing climate monitoring and modeling. This is particularly relevant for supporting modeling efforts, which, while showing progress in Africa, still face challenges due to limited high-resolution data. Historically, studies have often depended on gridded observational products that combine rain gauges, satellite data, reanalyses, and models. These products, though useful, come with inherent limitations that underscore the need for more robust observational networks. Dosio et al. (2021a) analyzed the spatial distribution and annual cycle of precipitation over Africa using a large ensemble of gridded observational products including reanalysis as well as gauge-based and satellite-based products. They found large uncertainties across datasets over most areas and argued that it is not possible to select a single "best" gridded observation dataset for a realistic representation of all precipitation features and that comparing model results to a very limited set of observations is not only pointless but can even be misleading. Hence, improvement in observational networks is still critical for continued progress in the application of high-resolution modeling for robust assessment of climate change. Collaborative efforts around the continent, such as the Enhancing National Climate Services (ENACTS) initiative, led by Columbia University's International Research Institute for Climate and Society (IRI), are important in addressing data quality and human skill challenges. The project combines quality-controlled station observations with global proxies to generate spatially and temporally complete climate datasets (Dinku et al., 2022). This demonstrates how African research institutions such as universities can lead and collaborate with different stakeholders on meteorological research. Another initiative that seeks to improve observational networks and climate databases involves jointly performed activities under the framework of WASCAL and SASSCAL, where collaboration between Germany and countries in West and Southern Africa has been established. Additionally, growing interest in the application of artificial intelligence and machine learning (AI/ML) techniques in climate science is likely to improve the quality of climate products.

Furthermore, many critical physical processes that modulate precipitation over Africa, such as the dynamics of the West African Monsoon, convective systems, and land–atmosphere interactions, are poorly represented in climate models. This is partly because these models are often optimized for simulating the climate of regions where they are developed, typically the mid- and high-latitudes of the Northern Hemisphere. It is worth noting that while GCMs are designed for global application, their performance can vary significantly across different regions, often struggling to accurately capture tropical and subtropical processes. The challenge lies not only in the location of model development but also in the depth of understanding of local climatological processes, which is crucial for accurate model tuning, configuration, and parameterization.

A related concern is that the varying topography and large water bodies that influence precipitation distribution over Africa are not well captured in either GCMs or RCMs, and that orographic-related precipitation is poorly represented, adding to overall model biases. Ogwang et al. (2014) used the ICTP version 4.0 Regional Climate Model (RegCM4.0) to show that a reduction in topography of 25% reduces mean OND rainfall over eastern Africa by about 19%. Using WRF, Ntwali et al. (2016) observed an improvement in precipitation simulations over Rwanda but noted that the model underestimated or overestimated rain gauge measurements depending on the region and season. Abba Omar and Abiodun (2021) used multi-ensemble simulations from the WRF model version 3.8.1 to show that topography influences the quantity and spatial distribution of rainfall from cut-off lows in southern Africa. Removing topography in the simulation resulted in less extreme rainfall from cut-off lows; hence, topography contributes to the occurrence of extreme precipitation in southern Africa (Abba Omar and Abiodun, 2021). The topography of Madagascar has also been shown to partly determine the strength of the MCT and, thus, the rainfall distribution over southern Africa (Barimalala et al., 2018, 2021). Over West Africa, Sylla et al. (2012) showed that high- and low-elevation terrain along the coast of the Gulf of Guinea regulated the regional response of the climate change signal in RegCM3 as opposed to the smoothed climate change response captured by the driving GCM. A more recent study by Hamilton et al. (2020) varied the topography across eastern Africa using WRF and found that this altered the structure of the AEJ and AEWs, not just across eastern Africa but across West Africa as well. These studies inform the call to modeling centers to further improve and or redesign parameterization schemes to better capture Africa's topography.

Coupled GCMs are increasingly transitioning to Earth system models (ESMs), which include physical, chemical, and biological processes to better represent the complexity of the Earth system, and many RCMs may also follow this path (Giorgi, 2019) and become regional Earth system models (RESMs). As the demand for high-resolution future climate projections to inform adaptation increases, their usage in more diverse climate and environmental change and prediction issues will also increase. In this endeavor, a role remains for both global and regional high-resolution models. The representation of topography, convection, land-sea contrasts, and human influence can be better represented at the appropriate spatial scales within both RESMs and ESMs. With this progress, these models will be able to better address the variability and change in precipitation along with other climate factors that exert large human impacts.

4. Summary and conclusion

Precipitation is one of the most important meteorological variables as it affects water resources, agricultural production, and hydroelectric power generation, among other things; most people's livelihoods and the economies of most African countries depend on it. Thus, understanding its characteristics (e.g., amount, frequency, intensity, and timing), variability, change, and predictability has great socioeconomic implications. One approach to understanding past and present climate processes, as well as predicting future meteorological variables like precipitation, is through the use of climate models. In this paper, a review of the recent progress and ongoing efforts in the modeling of African precipitation is presented, and some of the challenges that remain to be addressed are synthesized. We note early efforts by isolated initiatives and a small number of modeling groups with widely varying and often incomparable experimental designs. These efforts in Africa, as in other world regions, have focused mostly on evaluating the capability of a particular GCM/AOGCM in addition to an RCM in reproducing the general features of the African climate, especially over southern and West Africa. Such efforts have nonetheless produced invaluable knowledge about most aspects of climate over the continent, which continues to be improved with the various phases of CMIP to keep pace with the rapid advances in model design as well as expanding computational resources (e.g., CMIP6; Eyring et al., 2016 and CORDEX; Giorgi et al., 2009; Jones et al., 2011). Over the past decade, significant progress has been made in understanding how models represent the characteristics and drivers of precipitation in Africa. For instance, there are still considerable differences among models regarding the total and annual cycle of precipitation, particularly between coarse-resolution GCMs and higher-resolution RCMs. Both GCMs and RCMs still suffer from structural/systematic model errors, which likely prevent reasonable representation of the complex climatic processes and associated precipitation over the continent. We also note that the strong wet/dry biases in the CMIP5 models that are still evident in CMIP6 are considerably reduced in the RCM ensemble, highlighting the potential added value of higher-resolution RCM simulations.

While our understanding of precipitation processes and the reasons for biases in simulating the climate in Africa has increased, there is still more work to do to leverage our understanding to inform model development. For instance, a reduction in simulated warm SST biases over the eastern tropical Atlantic would result in a more realistic representation of atmospheric circulation patterns, including the Congo Basin Cell as well as inland moisture transport, and this could result in a better representation of the mean precipitation over West and Central Africa. Furthermore, an improved model representation of both the location and intensity of the Tropical Easterly Jet, African Easterly Jet, African Easterly Waves, and Saharan Heat Low, among other features, would lead to significant improvements in the representation of precipitation over West and Central Africa, as all subregions are connected to either the AEJ-N or AEJ-S as well as the TEJ.

Over Central Africa, understanding the source of moisture in different models, as well as the reasons behind discrepancies in the position of simulated maximum moisture convergence would assist in reducing the large uncertainties in simulated mean rainfall in the area. Such insight could also be linked to the further understanding of land–atmosphere interactions, which play an important role in the hydrological cycle of the area. Moreover, coupled climate models struggle to realistically simulate air–sea interaction over the tropical Indian Ocean basin, leading to persistent biases in the mean eastern African short rains. An advanced understanding of the drivers of SST biases in the Indian Ocean, therefore, represents a research avenue for model improvement in the area. In southern Africa, model biases are mainly attributed to the misrepresentation of the strength of the Angola Low, which could be a focal point for model development. It is also shown that both southern and eastern Africa would benefit from realistic orography and improved model representation of tropical convection.

In each subregion, most existing studies focus on individual driving mechanisms separately. However, it is important to understand how these mechanisms are linked to each other and how the models represent these links. For instance, the interaction of local and remote processes, such as the impacts of soil moisture, vegetation cover, topography, and land–atmosphere interactions, is not fully explored in models. Moreover, works on African precipitation have been mainly divided into subregions, as presented in this review. The possibility of pan-African mechanisms that could link the subregions is understudied and could be a relatively new avenue to explore both in observations and to inform model development.

One critical advancement in climate modeling is the use of convection-permitting models (CPMs), which offer higher-resolution simulations that can explicitly resolve the convective processes that are crucial for accurate precipitation forecasts. To improve the representation of precipitation and clouds over Africa, a rigorous quantitative analysis is essential. This would involve the use of satellite data and in-situ observations to evaluate and validate the performance of CPMs in capturing the spatial and temporal characteristics of precipitation and cloud cover. By comparing model outputs with observational data, researchers can identify biases, refine parameterizations, and enhance model accuracy. This approach not only aids in better understanding current climate processes but also builds confidence in the models' ability to project future precipitation patterns, particularly in regions like Africa, where convection plays a significant role in weather and climate dynamics.

Another pivotal advancement lies in the generalization of downscaling techniques applied to CMIP6 simulations. Downscaling allows global climate model outputs to be translated into finer-scale information, which is crucial for understanding regional climate impacts. By systematically downscaling CMIP6 simulations, researchers can generate the high-resolution datasets essential for in-depth analyses and impact studies, particularly in regions where small-scale processes significantly influence climate variability and change. This process involves not just simple statistical or dynamical downscaling but also the emulation of complex regional climate processes to provide more accurate projections at a local scale. For Africa, where climate variability and extremes can have significant socioeconomic impacts, the ability to produce reliable, high-resolution climate information is critical. These datasets enable more precise assessments of future climate risks, informing adaptation strategies and policy decisions grounded in robust scientific evidence.

When models are undergoing improvement, developers must have access to information about inherent biases and associated processes. Since almost all GCMs and RCMs have been developed outside of Africa, concerted efforts to document and alleviate the specific biases that impact African climate have not received as much attention and resources. To overcome this issue, more in-depth coordinated sensitivity studies are needed to assess the potential for using a particular model for long-term rainfall projection, seasonal rainfall forecasts, or impact assessment applications to meet the needs of various regions of Africa.

Another pending issue is related to the availability of reliable, high-quality observational datasets covering either the entire African continent or most of its regions. Such data are of major relevance, particularly for evaluating models over regions of complex topography, such as the East African Highlands and Cameroon Highlands. In fact, the collation and creation of high-resolution spatial and temporal observational datasets over Africa for model evaluation, detection of climate change signals, and improved understanding of climate processes across the continent should be a high priority for the governments of African nations and the international community. We also recognize the need to develop modeling infrastructure and human resources sourced from within the continent itself. This would result in lessening the dependence of regional scientists on international research frameworks to perform and generate the RCM/GCM experiments and simulations pertinent to the subregions of the continent and to disseminate their results throughout Africa.

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