

PAPER • OPEN ACCESS

Climate change projections from a multi-model ensemble of CORDEX and CMIPs over Angola

To cite this article: Izidine Pinto *et al* 2023 *Environ. Res.: Climate* **2** 035007

View the [article online](#) for updates and enhancements.

You may also like

- [Spatial variability of cold waves over Southern Africa and their potential physical mechanisms](#)
Arlindo O Meque, Izidine S Pinto and Clifford Chuwah
- [Global review of human waste-picking and its contribution to poverty alleviation and a circular economy](#)
Jandira Morais, Glen Corder, Artem Golev et al.
- [Kinetic model of titanium laser induced plasma expansion in nitrogen environment](#)
A R Casavola, G Colonna and M Capitelli



UNITED THROUGH SCIENCE & TECHNOLOGY

 **The Electrochemical Society**
Advancing solid state & electrochemical science & technology

**248th
ECS Meeting**
Chicago, IL
October 12-16, 2025
Hilton Chicago

**Science +
Technology +
YOU!**

**SUBMIT
ABSTRACTS by
March 28, 2025**

SUBMIT NOW

ENVIRONMENTAL RESEARCH CLIMATE



PAPER

Climate change projections from a multi-model ensemble of CORDEX and CMIPs over Angola

OPEN ACCESS

RECEIVED
5 March 2023

REVISED
22 May 2023







ACCEPTED FOR PUBLICATION
27 June 2023

PUBLISHED
11 July 2023

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Izidine Pinto^{1,2,6,*} , Erin Coughlan de Perez^{1,3} , Catalina Jaime^{1,4} , Piotr Wolski² , Lisa van Aardenne² , Eddie Jjemba¹ , Jasmijn Suidman¹, Aleix Serrat-Capdevila⁵ and Arame Tall⁵

¹ Red Cross Red Crescent Climate Centre, The Hague, The Netherlands

² Climate System Analysis Group, University of Cape Town, Cape Town, South Africa

³ Feinstein International Center, Friedman School for Nutrition Science and Policy, Tufts University, Boston, MA, United States of America

⁴ Faculty of Geo-Information Science and Earth Observation, University of Twente, 7514 Enschede, AE, The Netherlands

⁵ World Bank, 1818 H St. NW, Washington, DC 20433, United States of America

⁶ Author current institution: Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands.

* Author to whom any correspondence should be addressed.

E-mail: izidine.pinto@knmi.nl

Keywords: Angola, climate projections, extremes, droughts, vulnerabilities

Supplementary material for this article is available [online](#)

Abstract

Angola has been characterized as one of the most vulnerable regions to climate change. Climate change compounded by existing poverty, a legacy of conflict and other risk factors, currently impede development and are expected to become worse as climate change impacts increase. In this study we analyze the signal of climate change on temperature and rainfall variables for two time periods, 2020–2040 and 2040–2060. The analysis is based on multi-model ensemble of the Coupled Model Intercomparison Projects (CMIP5 and CMIP6) and the Coordinated Regional Downscaling Experiments (CORDEX). Our findings from the observed dataset indicate that the mean annual temperature over Angola has risen by an average of 1.4 °C since 1951, with a warming rate of approximately 0.2 [0.14–0.25] °C per decade. However, the rainfall pattern appears to be primarily influenced by natural variability. Projections of extreme temperature show an increase with the coldest nights projected to become warmer and the hottest days hotter. Rainfall projections suggest a change in the nature of the rainy season with increases in heavy precipitation events in the future. We investigated how droughts might change in all river basins of Angola, and we found an increased uncertainty about drought in the future. The changes in climate and increased variability demonstrate the need for adaptation measures that focuses on reducing risks in key sectors with a particular focus on adaptation of cities in Angola given a potential increase in mobility towards urban areas.

1. Introduction

Angola has been characterized as one of the most vulnerable countries to climate change, and more specifically, the south has been suffering periods of drought from 2012 to 2022 (Cain 2017, Limones *et al* 2020, Serrat-Capdevila *et al* 2022). Studies show that some changes in climate are already being observed in Africa and that some of these changes would not be possible without human influence (Bezner Kerr *et al* 2022). Increasing trends in hot extremes and extreme precipitation events have been found in many regions in Africa accompanied with overall decrease in annual precipitation (Gutiérrez *et al* 2021). Moreover, there has been a noticeable rise in the frequency of droughts across various regions worldwide, and it is projected that this trend will persist in the future, even if global warming is stabilized at 2 °C (Seneviratne *et al* 2021). These changes are expected to have important impacts on key sectors such as agriculture, health and water which plays an enabling role in the economy and livelihoods of Angola. Situated on the south-west coast of

Africa, the Republic of Angola is bounded to the north and northeast by the Democratic Republic of Congo, to the east by Zambia, to the south by Namibia, and to the west by the Atlantic Ocean. In addition, it encompasses the exclave of Cabinda, which shares a border with the Republic of Congo to the north. According to the ND-GAIN index—an index that illustrates the relative resilience of countries comparative to one another—Angola is the 49th most vulnerable country and the 15th least ready country to deal with the impacts of climate change and other stressors (ND GAIN 2021). This score denotes high vulnerability and low readiness. The vulnerability to climate change that Angola faces varies regionally depending on the climatic variables, on the topography, and on socio-economic variables. Some regions are already experiencing frequent episodes of extreme weather events of concern such as heatwaves, droughts or floods, as well as coastal degradation (Meque *et al* 2022, Serrat-Capdevila *et al* 2022, Trisos *et al* 2022).

These climate shocks, compounded by existing poverty, a legacy of conflict and other risk factors, currently impede development and are expected to become worse as climate change impacts increase. Due to its high vulnerability to climate change, investment efforts in development and adaptation in Angola require information on the range of possible futures to expect. A report from the World Bank found that sector development plans in Angola require further climate information to adequately mainstream climate change adaptation, and described research on climate trends as ‘scarce’ (World Bank 2019). Previous research has demonstrated a wide variety of possible futures for rainfall in Angola, with most models agreeing that temperatures are likely to increase. Pinto *et al* (2016) used two regional climate models and found that total precipitation is projected to decrease, accompanied by increases in dry days over Angola. Carvalho *et al* (2017) described regional model trends in temperature and total annual rainfall, as well as in 6 month droughts, but did not provide detailed information on changes to the timing of the rainy season or other climate extremes indices. This study performs the first comprehensive analysis and comparison of a set of climate models and scenarios with a high spatial resolution for Angola for the 21st century. This work looks at future temperature and precipitation as projected by the CORDEX, CMIP5 and CMIP6 model datasets. The main focus of the analysis is on several climate variables and indicators, as well as the evolution of the frequency and intensity of droughts throughout this century.

2. Data and methods

2.1. Observational datasets (historical reference)

A set of five gridded observational global mean surface air temperature datasets were used for the analysis of mean surface temperature, namely, NOAA Global Temperature Analysis v5 (NOAA at 5 degree \times 5 degree resolution, Zhang *et al* 2019), Goddard Institute for Space Studies Surface Temperature Analysis V4 (GISTEMP at 2 degree \times 2 degree resolution, Lenssen *et al* 2019), Met Office Hadley Centre’s and the University of East Anglia Climatic Research Unit (HadCRUT5 at 5 degree \times 5 degree, Morice *et al* 2021), Kadow (Kadow at 5 degree \times 5 degree, Kadow *et al* 2020) and Berkeley Earth Surface Temperature (BEST at 1 degree \times 1 degree, Rohde and Hausfather 2020). These datasets represent a combination of surface air-temperature fields over land and sea-surface temperature fields over the ocean. The period of analysis of this data set is from 1951 to 2020. Rainfall and temperature data from the European Centre for Medium range Weather Forecasts (ECMWF) ECMWF Reanalysis version 5 or simply ERA5 (Hersbach *et al* 2020) was also used. ERA5 has a spatial resolution of 31 km and is available from 1979 to present. Observational and reanalysis climate datasets are critical tools for studying climate trends and variations. However, observational and reanalysis datasets are not without their limitations and uncertainties. For example, some areas of the world have fewer weather stations or satellite coverage, which can lead to data gaps. Other sources of uncertainty include spatial and temporal resolution, sampling error, bias correction and data assimilation. For more details on uncertainty of observational climate datasets refer to (Zumwald *et al* 2020).

2.2. Climate models (future projections)

Available model simulations from the Coupled Model Intercomparison Project (CMIP5 (29 models) and CMIP6 (27 models), (Taylor *et al* 2012, Eyring *et al* 2016)) and the Coordinated Regional Downscaling Experiments (CORDEX-Africa, Giorgi *et al* 2009, Gutowski *et al* 2016) were also used. CORDEX Africa project downscaled a set of CMIP5 global models across the full African continent at a grid resolution of around 0.44° horizontally (50 km). The higher spatial resolution of the participating dynamical downscaling models enables the CORDEX ensemble to more realistically represent regions of complex topography and localized rainfall (Pinto *et al* 2016, Dosio *et al* 2019). We use a set of available models over Angola in the understanding that these models should provide an improved representation of the impact of the regional topography on the climate and change in the climate. The CMIP5 experiment utilized representative

Table 1. List and descriptions of rainfall and temperature indices.

Abbreviation	Indicator name	Description of Indicator	Units
PRCPTOT	Total wet day precipitation	Mean annual total precipitation	mm
SDII	Simple Daily Intensity Index	Mean precipitation amount that is registered on wet days	mm
Rx1day	Max 1 d precipitation amount	Maximum 1 d precipitation total	mm
Rx5day	Max 5 d precipitation amount	Maximum 5 d precipitation total	mm
CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	Days
TXx	Hot days	Maximum value of daily maximum temperature	°C
TNn	Cold nights	Minimum value of daily minimum temperature	°C
SU30	Summer days	Frequency of days with daily maximum temperature above 30 °C	Days

concentration pathways (RCPs, Van Vuuren *et al* 2011) to describe different future socio-economic scenarios and their associated emissions related scenarios (greenhouse gases (GHGs), aerosols and land use change). Here we include RCP 4.5 which represents a middle of the road scenario with strong mitigation action culminating in an increase in 4.5 W m^{-2} in equivalent radiative forcing by 2100, as well as RCP 8.5 which represents a very negative scenario with very little mitigation of emissions into the future. The 6th iteration of the CMIP experiment was developed in preparation for the IPCC 6th assessment report. While deploying a different approach to future emissions scenarios called shared socio-economic pathways (O'Neill *et al* 2014), the experiment designers did choose to align the Shared Socioeconomic Pathways (SSPs)s with the CMIP5 RCPs in terms of radiative forcing. This means that we can analyze largely equivalent scenarios across CMIP5 and CMIP6. In this case we analyze SSP5 8.5 and SSP2 4.5 as roughly equivalent to RCP 8.5 and RCP 4.5. Table S1 shows the full list of the combination of global climate models (GCMs) downscaled and the regional climate models (RCMs) used.

2.3. Climate indices

Future projections were analyzed for two time periods, 2020–2040 and 2040–2060, and compared to the current WMO climate normal period of 1981–2010. The two future horizons are the same used in the IPCC AR6 and are considered long enough to show future changes in rainfall and temperature when averaging over ensemble members of multiple models, and short enough to enable the time dependence of changes to be shown throughout the 21st century. These periods provide climate change information for the near (2030s) and mid future (2050s), thus supporting decision making processes at different planning horizons.

Table 1 lists a collection of eight climate indices associated with temperature and precipitation, selected from the Expert Team on Sector-Specific Climate Indices (ET-SCI). These indices are specifically designed to characterize moderate extreme events with a recurrence interval of one year or less, as described in Klein Tank *et al* (2009) and Zhang *et al* (2011). One of the indices, the maximum 5 d precipitation index (RX5day), represents the highest accumulation of 5 d precipitation and is often utilized to evaluate potential flood hazards. Heavy rain conditions over multiple consecutive days can contribute to flood conditions (Sillmann *et al* 2013). Simple daily intensity index (SDII) describes the daily precipitation amount averaged over all wet days in a year, and is an indication of how heavily rain falls. The number of wet days (RR1) represents days with precipitation above 1 mm. The consecutive dry-day index (CDD) is a measure of the longest continuous stretch of dry days within a year, where a dry day is defined as having less than 1 mm of rainfall. CDD is commonly referred to as a drought indicator since it is utilized to depict the tail or low end of the precipitation distribution (e.g. Sillmann *et al* 2013). Since drought is a multifaceted phenomenon that relies on numerous factors aside from insufficient precipitation, CDD can only offer insight into meteorological drought. Therefore, it should be evaluated in conjunction with other precipitation indices such as Standardized Precipitation Index (SPI) and Standardized Precipitation Evaporation Index (SPEI) for a more comprehensive understanding.

2.4. Analysis of droughts

For the analysis of droughts, we deploy two very widely used drought indices. The first is the SPI (McKee *et al* 1993) which is a drought index based just on rainfall deficit. The usefulness of SPI is that rainfall deficits (or excesses) are standardized relative to the baseline distribution, thus allowing us to compare across regions with varying baseline rainfall distributions. However, the SPI only uses precipitation data to characterize droughts. The index assumes that precipitation is the most significant factor for the user and that the variability of precipitation surpasses the variability of other variables such as temperature,

evapotranspiration, wind speed, and relative humidity that contribute to droughts. It also assumes that there are no trends in these other variables. However, as a result, SPI may not consider the impact of rising temperatures (i.e. global warming) on drought characteristics (Abiodun *et al* 2021). To overcome this limitation we used the SPEI (Vicente-Serrano *et al* 2010). This index is based on climate water balance (CWB), which is the difference between precipitation (P) and potential evapotranspiration (PET) (i.e. $CWB = P - PET$), and so comes closer to identifying hydrological drought. The PET data (for calculating CWB) were obtained from the maximum and minimum temperature data using the Hargreaves method (Hargreaves and Samani 1982). Here we apply a 12 month accumulation period ending at the end of October in order to capture the annual time scale rainfall deficits. This study concentrates on droughts that are classified as being at least moderate droughts (i.e. ≤ -1.0), and thus, a threshold of -1.0 was applied to identify droughts in the 12 month scale SPEI and SPI datasets. Both the SPEI and SPI indices have been employed for identifying, monitoring, and project droughts in Africa (e.g. Meque and Abiodun 2014), as well as in other regions of the world (e.g. Spinoni *et al* 2020).

2.5. Water availability (WA)

In order to evaluate water resources implications of changing climate, we use a simple WA index, which is defined as follows:

$$WA = P - PET \text{ when } P - PET > 0, \text{ and } 0 \text{ when } P - PET < 0.$$

This was done with WA values calculated on a monthly basis, and then summed up to annual values. WA is therefore a simple index of relevance to water resources that can be obtained without use of sophisticated hydrological models, only from climate data. The index considers the 'surplus' of rainfall (P) over PET and expresses the water that is effectively available in the environment to generate groundwater recharge and surface runoff.

When analyzing the results of regional climate models ensembles, it is important to consider the consensus amongst models and the statistical significance of future changes, i.e. how the change compares with natural variability. There are many different methods to define the robustness of the climate change signal. Here we use the same method used in the IPCC AR5 which is based on the models' agreement in terms of both significance and sign of the projected change. The projected change is considered robust if the ensemble mean change is significant and at least 70% of the models agree on the direction of change. The change is considered uncertain, if the change is not statistically significant and less than 70% of models agree on the sign of change. Although in many studies higher thresholds are used (e.g. 80% for the agreement in sign in the IPCC methodology), here a lower threshold is used to make it applicable to small ensembles (such as CORDEX) for which, otherwise, robustness may be too strongly dependent on the results of a single model.

2.6. River basin scale analysis

A more detailed regional analysis is done over eight regions in Angola. Here, we initially focused on homogeneous climate regions, attempting to define regions that are characterized by similar climate variability, reflecting similar drivers of climate, and consequently, likely similar patterns of changing climate. Due to limitations, observational data could not be used for that purpose, nor could then be used for identification of the best 'surrogate' gridded dataset. We thus worked with several different rainfall gridded datasets attempting identification of climate regions that would be robust, i.e. similar across most of them. That turned out to be impossible—regions differed significantly between datasets and could not be defensibly aggregated. This is likely because differences between rainfall gridded datasets can often be very large, especially in regions where station networks are sparse (Dosio *et al* 2021) such as Angola. We therefore divided the country into regions corresponding to the main river basins of Angola, with some modification in the north-west of the country. Such defined regions are relevant from the water resources point of view, but also from an administrative point of view, and by nature capture main differences in climate across the country. The following are the eight basins, along with their respective areas: Congo (271 752 km²), Cunene (94 113 km²), Zambezi (256 014 km²), Cuvelai (54 181 km²), Okavango (150 199 km²), South Coast (173 355 km²), Cuanza (127 042 km²), and North Coast (134 043 km²). In the time-oriented analyses presented in this study, spatial climate data of various nature were averaged over these eight regions shown in figure 1(b).

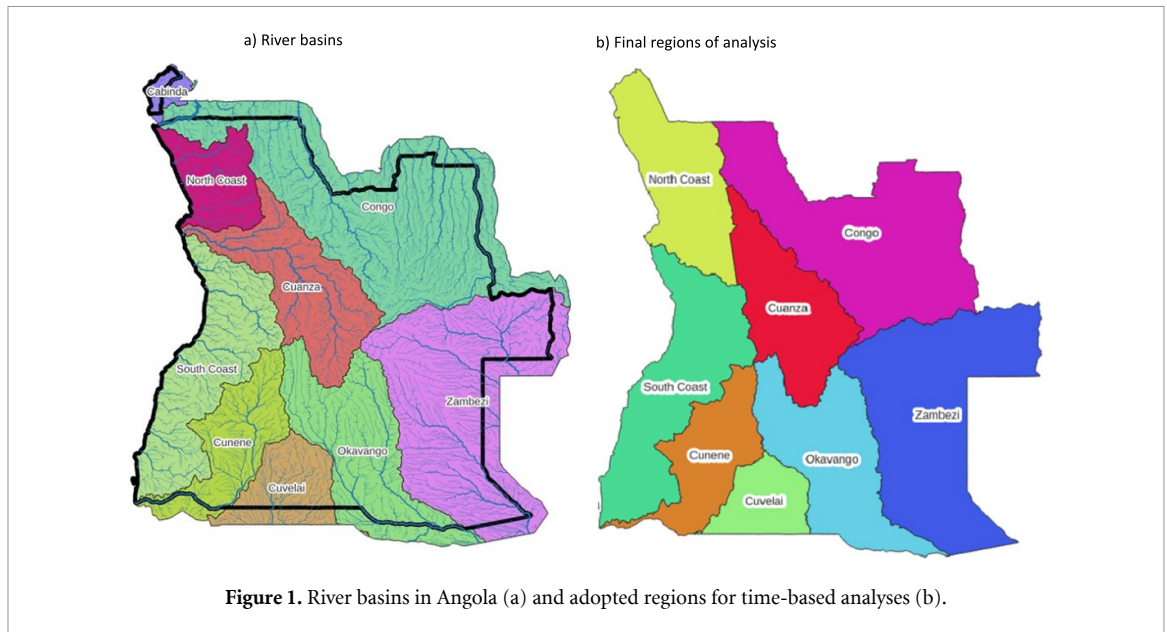


Figure 1. River basins in Angola (a) and adopted regions for time-based analyses (b).

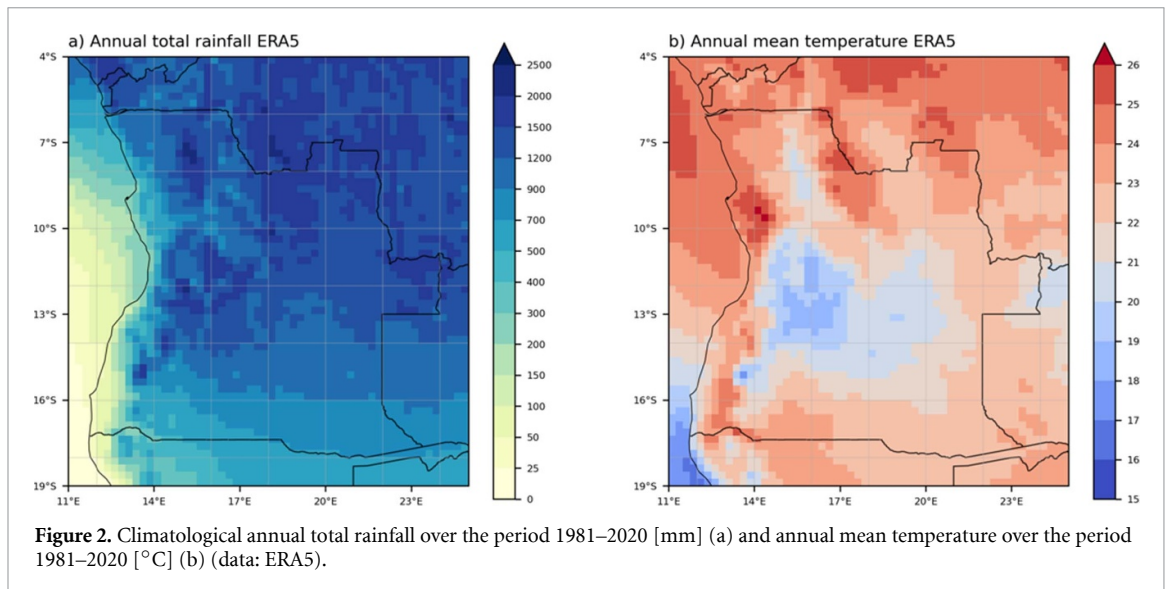


Figure 2. Climatological annual total rainfall over the period 1981–2020 [mm] (a) and annual mean temperature over the period 1981–2020 [°C] (b) (data: ERA5).

3. Results and discussion

Angola is dominated by three climate zones based on the Köppen classification: hot and humid tropical zone in the north; temperate tropical climate over the central plateau; and a desert climate in the south-west. Precipitation levels exhibit a marked southwest-northeast gradient and are characterized by strong seasonality. The north-east is the wettest region in Angola, and precipitation decreases towards the south and west (figure 2(a)). Precipitation variability is influenced by the seasonal interplay between subtropical high-pressure systems and the migration of easterly flows associated with the Intertropical Convergence Zone (ITCZ) (Munday and Washington 2017). A secondary convergence zone, the Congo Air Boundary (CAB) also influences precipitation patterns over Angola (Howard and Washington 2019). The ITCZ and CAB are regions of pronounced convective activity over southern Africa in summer. Variations in sea-surface temperatures in the oceans affect precipitation variability over Angola. This relationship is influenced by the interaction of broad-scale climate variability modes such as the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Subtropical IOD, Southern Annular Mode (SAM), as well as the sea-surface temperatures affected by the Benguela current and the tropical warm Angola current (known as Benguela Niños) (Richard et al 2001, Florenchie et al 2003, Manhique et al 2015, Gaughan et al 2016, Hoell et al 2017, Fogt and Marshall 2020). Average temperature varies between 15 °C and 28 °C with a minimum of 15 °C in the central plateau (figure 2(b)).

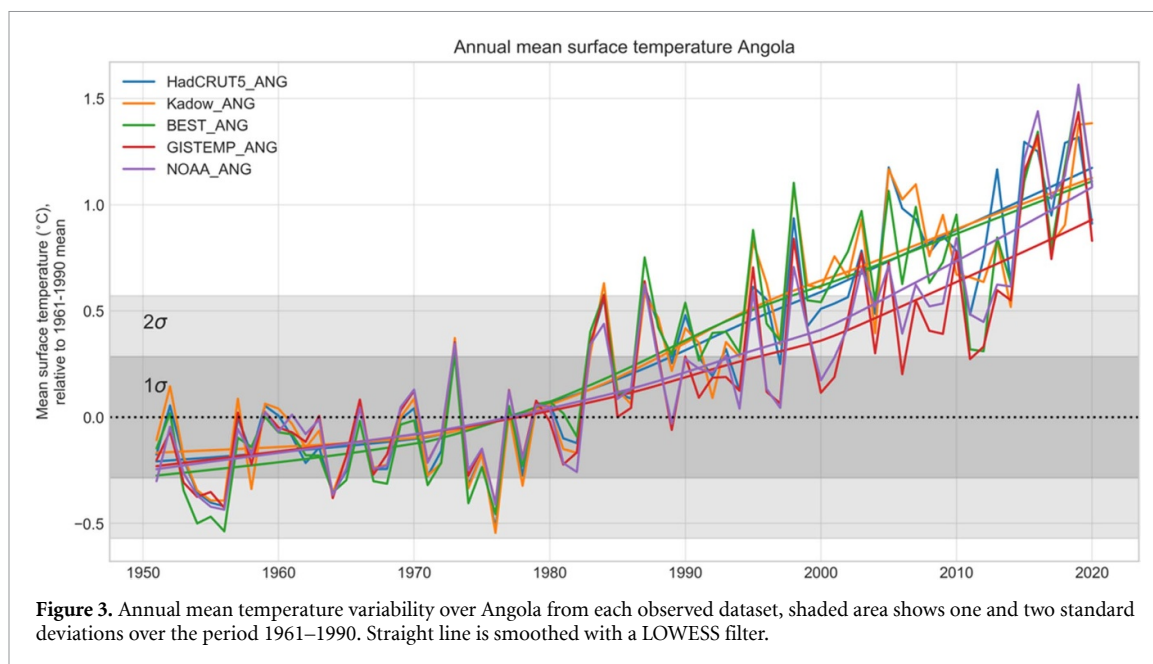


Figure 3. Annual mean temperature variability over Angola from each observed dataset, shaded area shows one and two standard deviations over the period 1961–1990. Straight line is smoothed with a LOWESS filter.

Global mean surface air temperature between 2011 and 2020 was $1.09\text{ }^{\circ}\text{C}$ higher than it was during the pre-industrial era. Furthermore, over the past half-century, the rate at which the global mean surface air temperature has risen is unprecedented in at least the last 2000 years (Gulev *et al* 2021). Over Angola, warming is evident from multiple datasets over the period 1951–2020 (figure 3). There is a strong consensus that the recent observed warming is robust throughout the country. On average, the mean annual temperature has increased by $1.4\text{ }[1.01\text{--}1.78]\text{ }^{\circ}\text{C}$ at a rate of $0.2\text{ }[0.14\text{--}0.25]\text{ }^{\circ}\text{C}$ per decade since 1951. According to the climate report from the IPCC (2021), the frequency and intensity of hot extremes have increased and those of cold extremes have decreased globally since 1950, including over Angola.

There is high model agreement that temperatures are projected to increase in Angola in the future (figure 4). Beyond increases in average temperatures, the IPCC (2021) AR6 summary for policy makers states that ‘It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase. It is very likely that heat waves will occur with a higher frequency and duration’. Figure 4 shows the projected mean changes in temperature indices over Angola for the near future (2020–2040) and the mid future (2040–2060). These changes are compared to the recent past (1981–2010) under two representative concentration scenarios, RCP45 and RCP85 respectively. Climate projections for the near future and mid future under RCP2.6 are very similar to RCP45 (not shown). For this reason, the focus of this study is on projections based on RCP45 and RCP85 scenario.

Mean temperature is projected to increase everywhere in the country independent of scenario (figure 4(a)). Under RCP4.5 mean temperatures are projected to increase between $1\text{ }^{\circ}\text{C}$ and $2\text{ }^{\circ}\text{C}$ from near to mid-term future. Under RCP8.5 mean temperatures are projected to increase between 1 and $3\text{ }^{\circ}\text{C}$ from the near- to mid-term future. As mean surface temperatures increase, extremes are also projected to increase in many parts of Angola. The number of days in which temperature exceeds $30\text{ }^{\circ}\text{C}$ are projected to increase, on average, by between 60 and 90 d in the south of the country over the near future and mid future (figure 4(b)). The implication is that regions that are already hot, will become even hotter and have more days exceeding critical thresholds. The coldest (TNn) and hottest (TXx) day of a year, simulated in the CORDEX ensemble, are shown in (figures 4(c) and (d)). The spatial patterns of change in TNn and TXx are similar in magnitude. The minimum amount of projected change is around $1\text{ }^{\circ}\text{C}$ for the near future under RCP45 scenario. The minimum amount of projected change is around $1.5\text{ }^{\circ}\text{C}$ for the near future under RCP45. Under RCP85, the TXx and TNn are projected to increase up to $3\text{ }^{\circ}\text{C}$ for the mid future. This difference suggests that smaller temperature increases are more likely under a low emissions scenario and larger temperature increases are more likely under a high emissions scenario.

Analysis of the temporal evolution of mean temperature averaged over hydrological basins for Angola (see figure 2(b)) are shown in figure 5. These graphs represent data for three different model experiments and generations, the CORDEX and Coupled Model Intercomparison Projects (CMIP5 and CMIP6). All of the three ensembles show a consistent upward trend in mean temperature for all the river basins. The increases in temperature are higher under the higher emission scenario RCP85/SSP585. The current

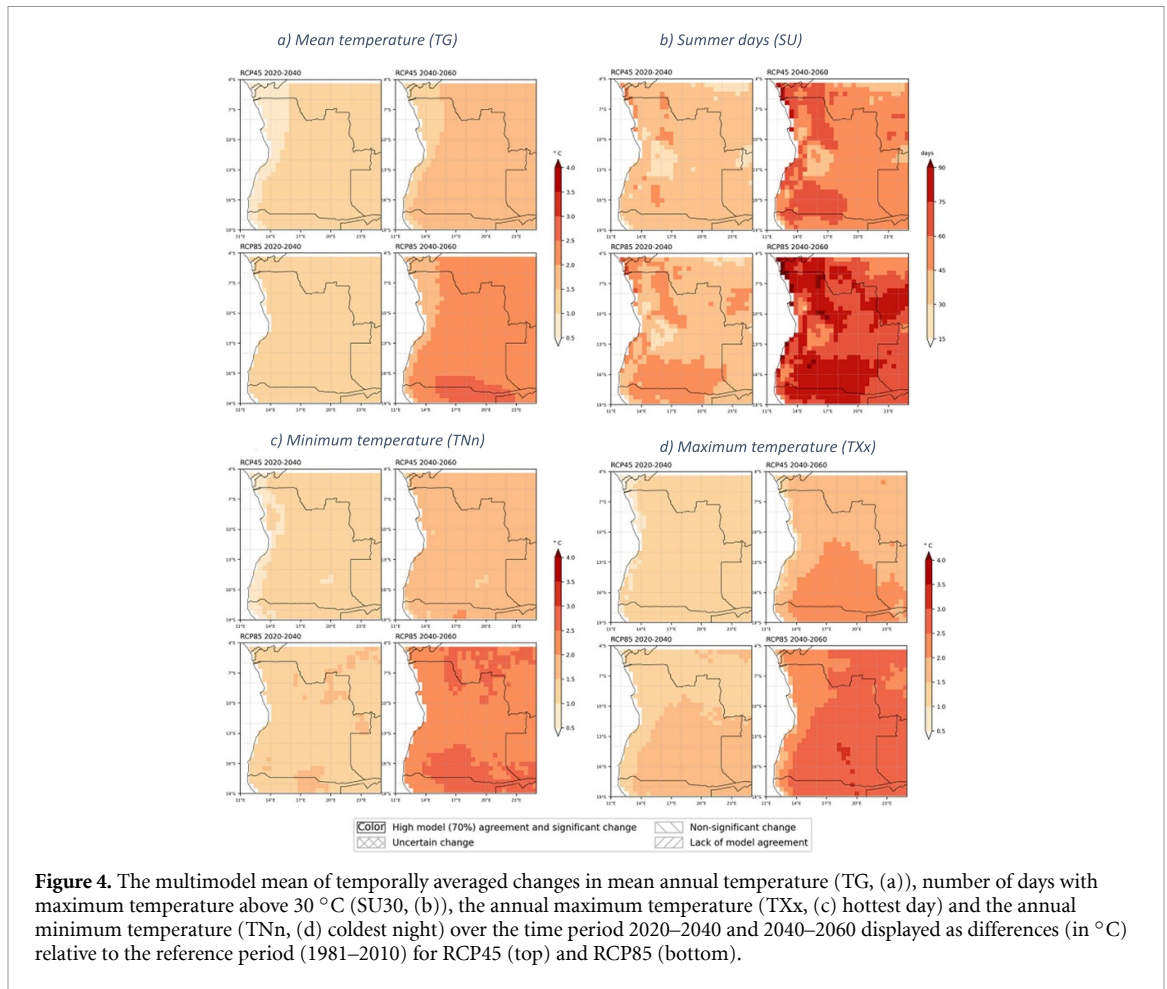


Figure 4. The multimodel mean of temporally averaged changes in mean annual temperature (TG, (a)), number of days with maximum temperature above 30 °C (SU30, (b)), the annual maximum temperature (TXx, (c) hottest day) and the annual minimum temperature (TNn, (d) coldest night) over the time period 2020–2040 and 2040–2060 displayed as differences (in °C) relative to the reference period (1981–2010) for RCP45 (top) and RCP85 (bottom).

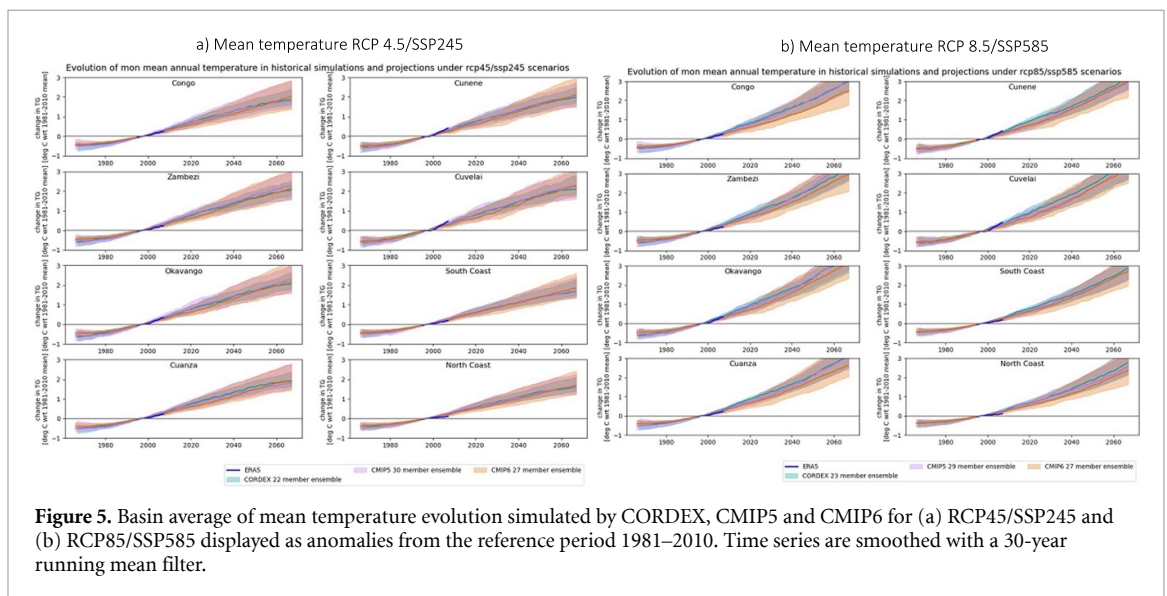
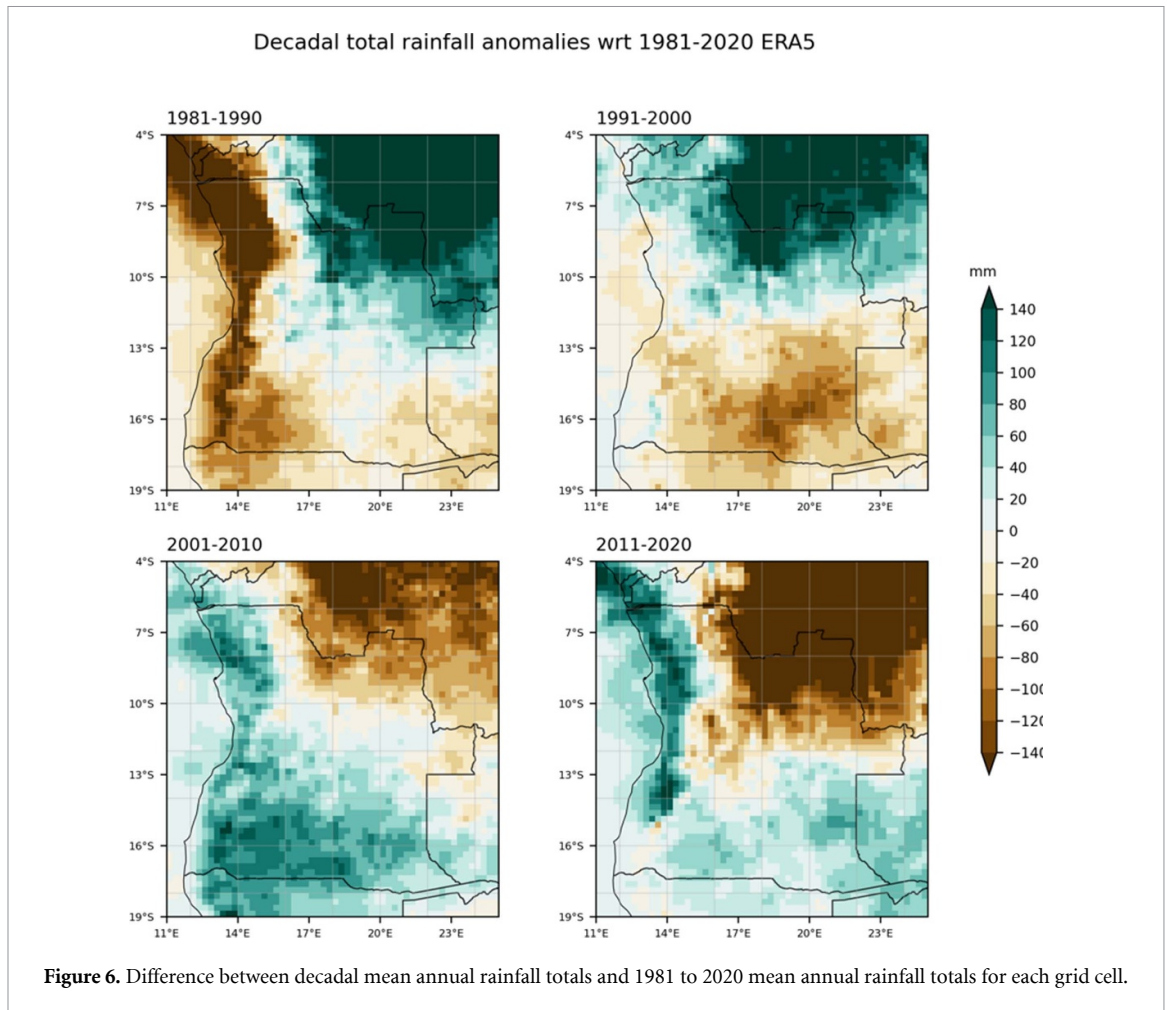


Figure 5. Basin average of mean temperature evolution simulated by CORDEX, CMIP5 and CMIP6 for (a) RCP45/SSP245 and (b) RCP85/SSP585 displayed as anomalies from the reference period 1981–2010. Time series are smoothed with a 30-year running mean filter.

projected changes in climate in combination with existing vulnerabilities have the potential to significantly impact key sectors in different ways across Angola. Increases in temperature are likely to affect agriculture systems that are not adapted throughout the country. Extreme high temperatures can have a negative impact on livestock and will require changes to livestock management (Bezner Kerr *et al* 2022). Ongoing high temperatures can require an increased need for irrigation in areas where evaporation reduces WA (Caretta *et al* 2022). In the absence of risks reduction measures, extreme heat events can cause health impacts, especially among those who already have underlying health conditions such as cardiovascular and respiratory diseases. The elderly, pregnant women and young children are also particularly vulnerable to these extreme

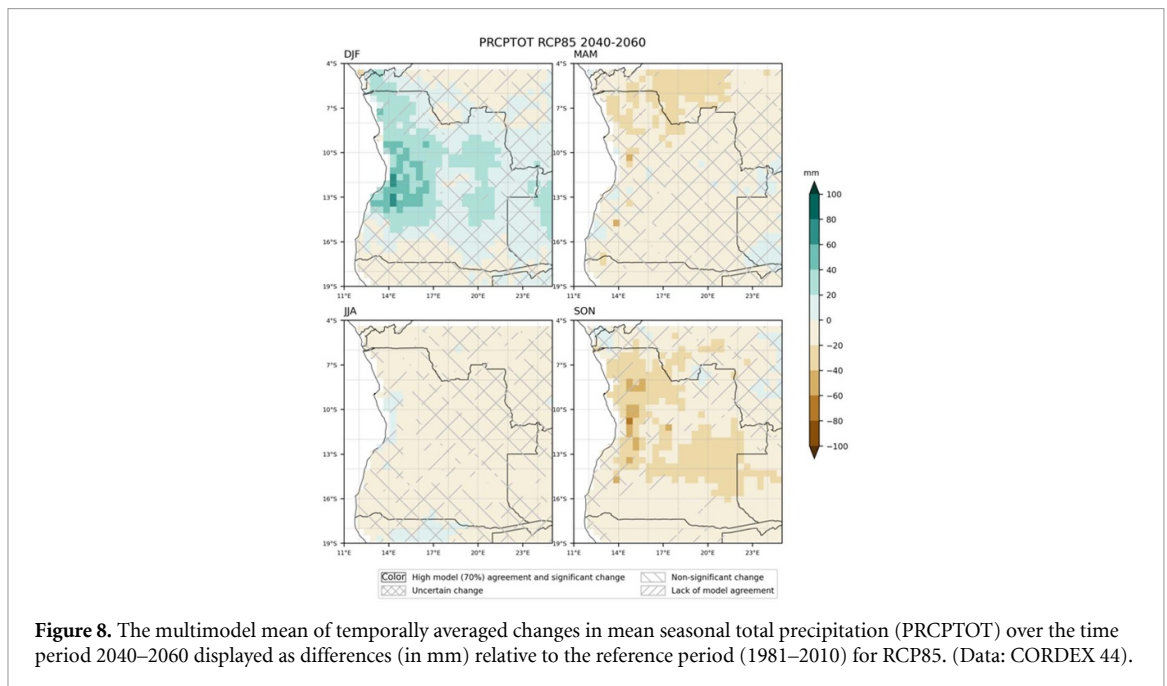
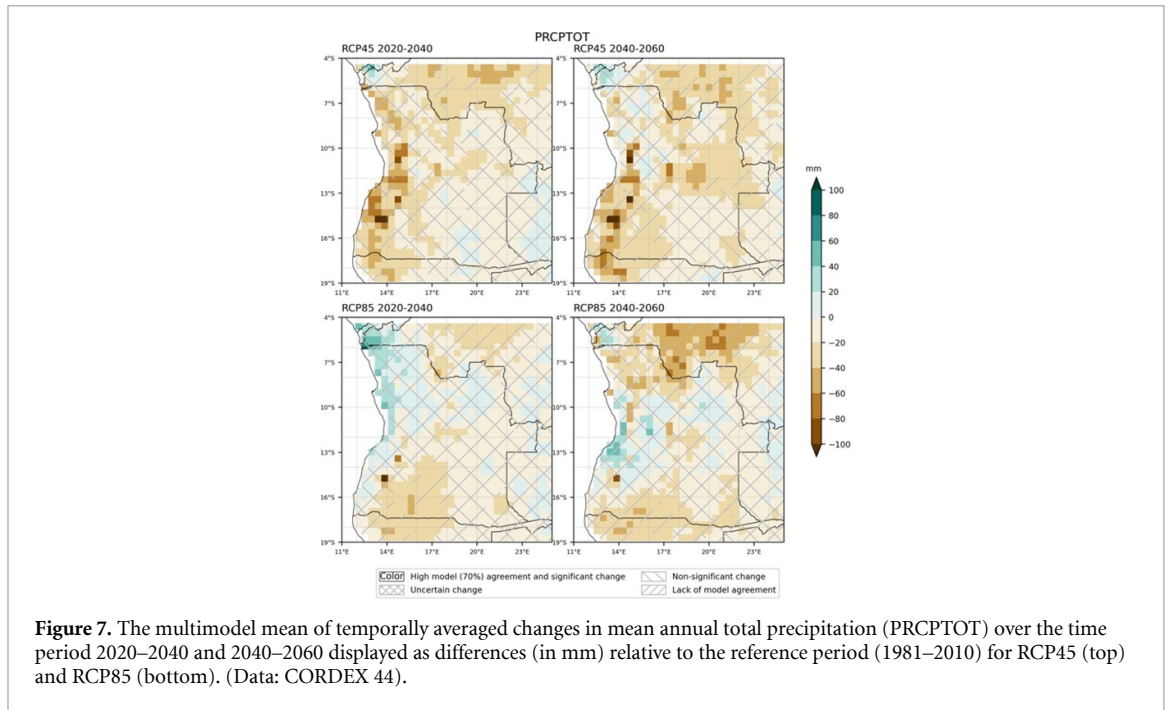


events. Climate effects on crops, income, or disease prevalence can also affect nutritional outcomes, especially in children (O'Neill *et al* 2022). Vulnerable people living in urban areas have greater exposure to extreme heat, because urban areas are hotter than rural areas (the urban heat island effect). Without adaptation, there can be increased costs for service provision to urban areas, including meeting demand for cooling, sanitation, and supply of safe potable water. Transport can be affected by extreme heat (softened asphalt and expanded rails) as well as extreme flooding events.

Rainfall exhibits greater spatial and temporal variability than temperature. The climate system's decadal and longer-term variability arises from both internal and external natural processes. Major modes of variability such as ENSO, IOD, and SAM can significantly influence global and regional atmospheric circulation patterns on decadal, multi-decadal, and centennial timescales. These large-scale natural variability modes imply that a decade may be hotter or colder, and drier or wetter, than the previous decade without any alterations to external influences on the climate system. However, external forcings on the climate system, such as solar cycles, volcanic eruptions, biosphere processes, and more recently, human emissions of GHGs and aerosols (i.e. particulates in the atmosphere), can also induce variability and change on long timescales.

Figure 6 shows the areas that were wetter (green) and drier (brown) during each of the last four decades. The colors represent the difference between the total mean annual rainfall for each decade and the total mean annual rainfall over the 1981–2020 (see figure 2(a)) period at each grid cell. This demonstrates significant rainfall variability on decadal time scales. For many locations, there is a distinct contrast in observed rainfall between certain decades and their preceding decades. For instance, the 1980s were much drier than the average in most locations across Angola, whereas the 2000s were much wetter.

In Angola, natural variability on interannual, decadal and multi-decadal time scales, as experienced in the past, is expected to continue to be the dominant influence on future rainfall. Figure 7 shows the projected changes in annual total precipitation on days with at least 1 mm of precipitation (PRCPTOT). The colors depict the ensemble mean anomalies from the CORDEX models for the mid and far future periods under RCP45 and RCP85. The hatching on the maps, shown over the land surface area, indicate regions where the changes are uncertain, i.e. the model agreement in the direction of change is low (see methods section for



more details). The ensemble-mean changes in PRCPTOT at annual timescales show a similar pattern of little change over most of Angola. More definite projected changes are evident at seasonal timescales under RCP85: projected increases in PRCPTOT during December–January (DJF), reductions in PRCPTOT are projected during the wet-season onset and cessation periods of September–November (SON) and March–May (MAM), respectively (figure 8). Some reduction in rainfall by the end of the century may be associated with delayed wet-season onset in spring resulting in a shorter wet season (Dunning *et al* 2018). The reductions in rainfall are due to a northward shift and delayed breakdown of the moisture convergence zone, the CAB (Howard and Washington 2020).

While there is widespread agreement regarding the direction of change in temperature indices regardless of the region under consideration, projected changes in mean annual total precipitation are less uniform. A further analysis was performed for each basin to obtain a more detailed regional picture of the extent of model agreement on projected changes in the rainfall. Figure 9 shows the average of annual total mean precipitation change for each basin. Rainfall projections for the near future do not indicate any significant or

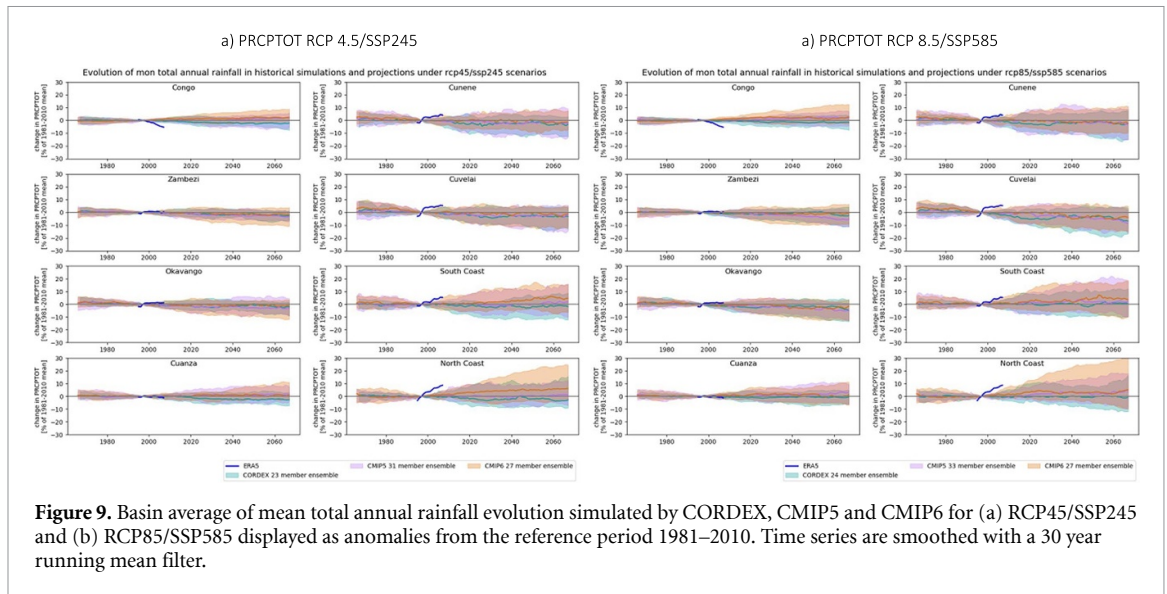


Figure 9. Basin average of mean total annual rainfall evolution simulated by CORDEX, CMIP5 and CMIP6 for (a) RCP45/SSP245 and (b) RCP85/SSP585 displayed as anomalies from the reference period 1981–2010. Time series are smoothed with a 30 year running mean filter.

systematic changes in total annual rainfall, although there is some propensity towards drier future in the southern regions of Cuvelai, Okavambo and Zambezi.

Figure 10 shows the spatial pattern of future anomalies from the multimodel mean over near- and mid-future for selected precipitation indices. There is an overall increase in five day maximum rainfall (RX5day) throughout the future time horizons and for both scenarios. Increases in annual one day maximum rainfall (RX1day) have similar patterns and directions of change as in RX5day. RX5day is projected to increase between 5%–10% in the near term and 10%–15% in some regions in Angola for the period 2040–2060 under RCP8.5. Rainfall intensity or SDII is projected to increase everywhere in Angola for both periods and scenarios. Increases in magnitude of wet extremes are associated with increased convective rainfall intensity (e.g. thunderstorms) which is expected to increase with global temperature increases. On the other hand, dry extremes are projected to increase. The increases of CDD are higher and statistically significant in the southern regions of Angola for the period 2040–2060 under RCP85. The number of wet days or rain days is also projected to decrease everywhere in the country. Increases in CDD are combined with increases in and RX5day, RX1day, SDII and decreases of RR1 indicating an intensification of both wet and dry seasons in these regions. Relatively high/low increases are more likely under a higher/lower GHG emissions scenario. This overall trend towards more extreme precipitation, decreases in total precipitation and increases in dry conditions is consistent with the scientific understanding of the impacts of global warming on the Earth's climate system (e.g. IPCC 2021).

Our analysis shows that the rainy season is likely to become more concentrated in the middle months, with less rain at the beginning and the end. This has implications for agriculture management practices, which will need to adjust to avoid reductions in crop yields. This should also include management options focused on an increased frequency of extreme rainfall events. Post-harvest processing and storage will also need to consider the possibility of more frequent extreme events. Rule curves for hydroelectric power generation will need to adjust to changes in the timing of rainfall throughout the season. These should also adjust to account for an increasing variability in rainfall, with greater amounts coming in extreme events, to avoid the risk of downstream flooding. Management should also account for greater amounts of evaporation with increasing temperatures. Extreme rainfall events can foster breeding of mosquitoes, which can increase the risk of vector-borne diseases such as malaria. Storage of water during dry spells and droughts can also increase breeding habitat, with similar results if preventative measures are not taken. Flood events can increase the prevalence of water-borne diseases, such as cholera. Flood events can also disrupt food supply chains. Without adaptation, any of these outcomes can reduce food access or increase diseases, which can ultimately increase malnutrition. Mental health can also be impacted by crisis events. Climate-related shocks can be a push factor for people to move, temporarily or permanently, to urban areas. Urban areas are vulnerable to extreme rainfall events, storm surges, and extreme temperature events, which can affect urban infrastructure and water quality.

Figure 11 shows the annual mean of WA (see methods section) over each basin. Increased temperature and thus increased PET, combined with projections of weak change in rainfall, is likely to lead to lower WA in the future. Under RCP45 the projected changes in WA are uncertain in many basins. Under RCP85 this

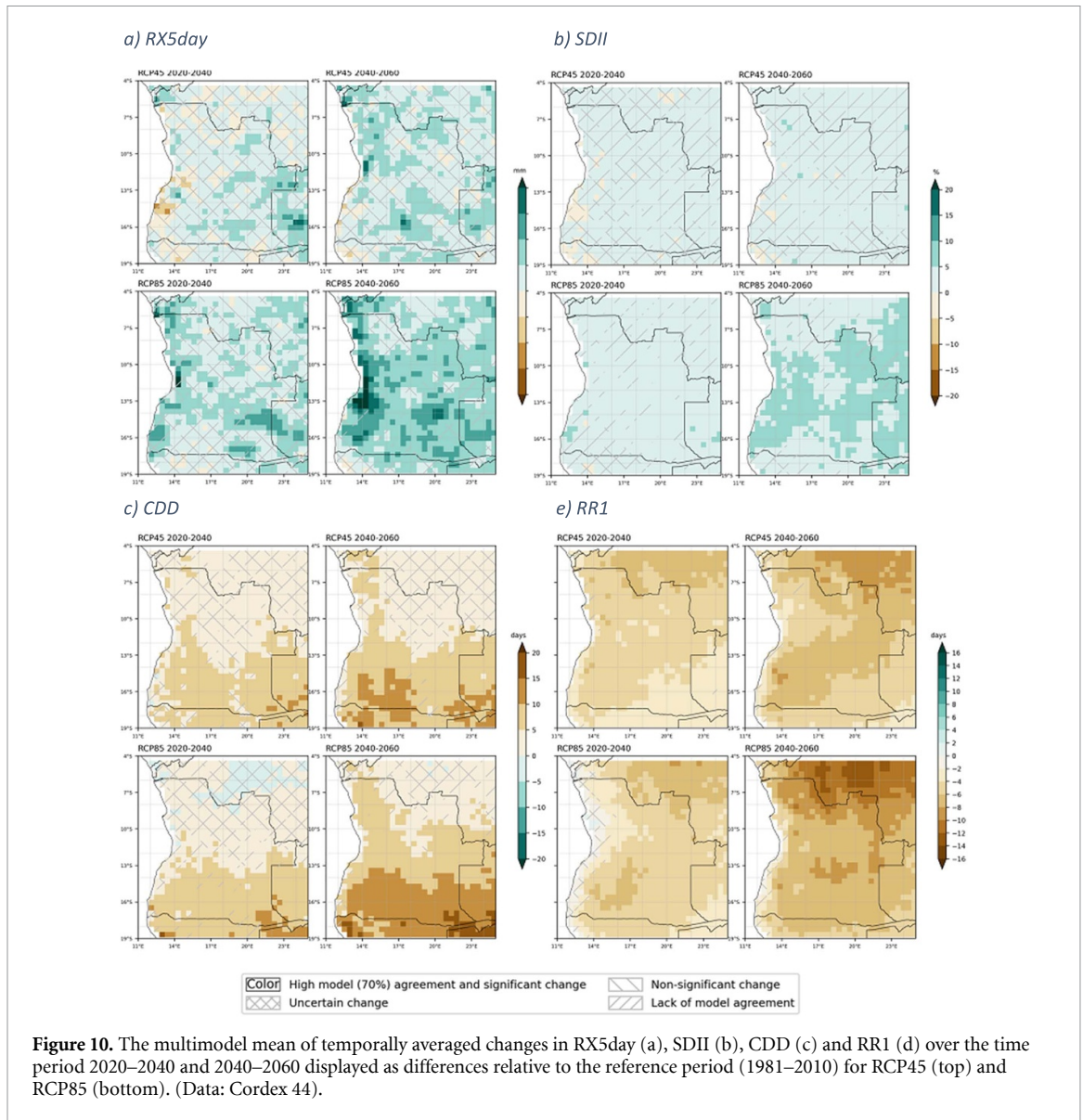


Figure 10. The multimodel mean of temporally averaged changes in RX5day (a), SDII (b), CDD (c) and RR1 (d) over the time period 2020–2040 and 2040–2060 displayed as differences relative to the reference period (1981–2010) for RCP45 (top) and RCP85 (bottom). (Data: Cordex 44).

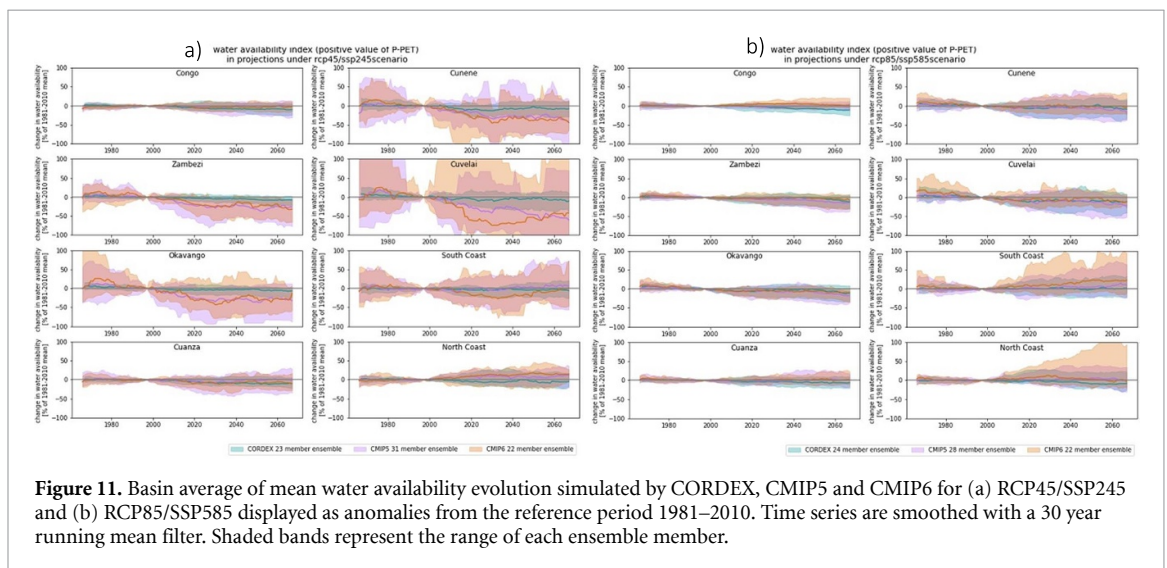


Figure 11. Basin average of mean water availability evolution simulated by CORDEX, CMIP5 and CMIP6 for (a) RCP45/SSP245 and (b) RCP85/SSP585 displayed as anomalies from the reference period 1981–2010. Time series are smoothed with a 30 year running mean filter. Shaded bands represent the range of each ensemble member.

uncertainty is reduced and the projected reductions are seen over Zambezi, Okavango and Cuvelai. Only in the North Coast region is there a likelihood of increased WA, but a drier future is also possible there.

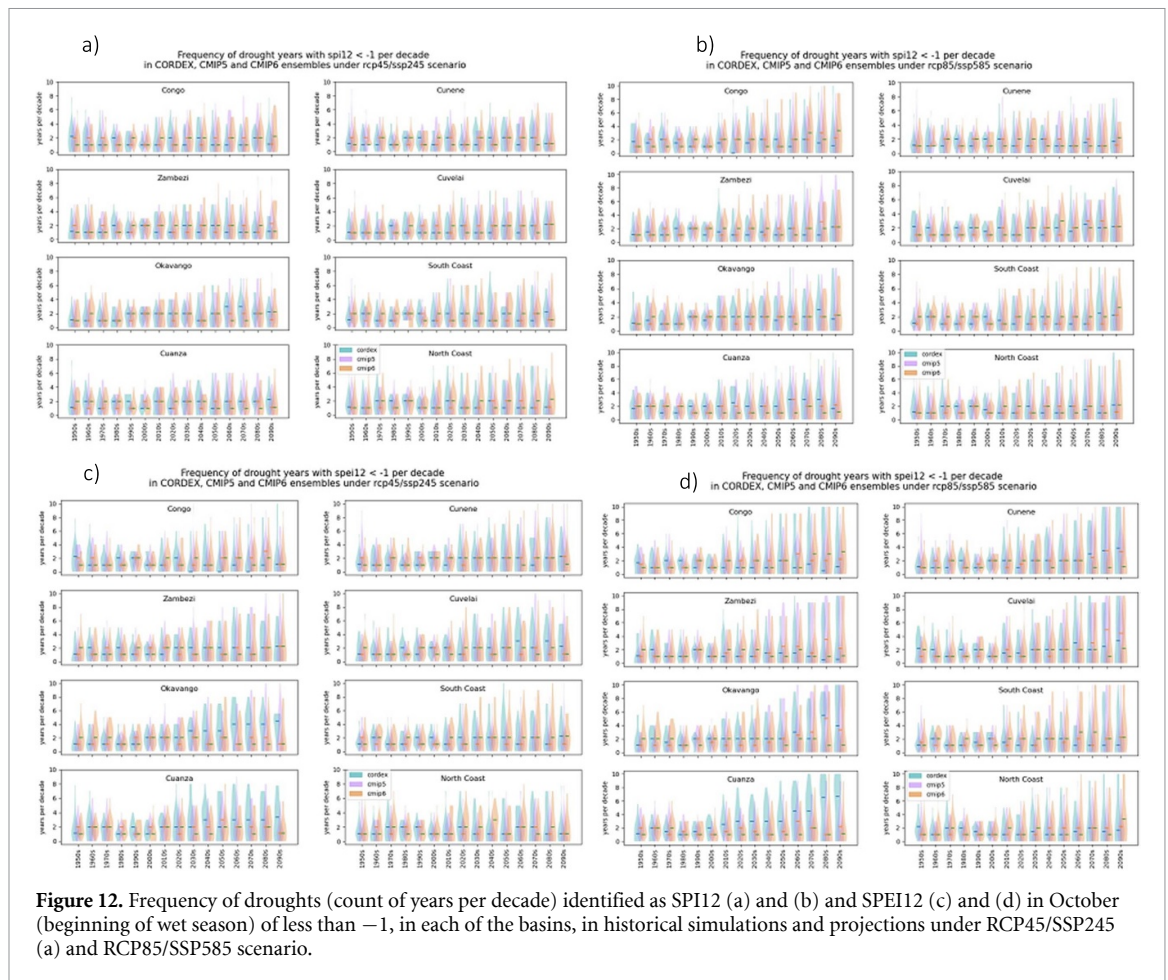


Figure 12. Frequency of droughts (count of years per decade) identified as SPI12 (a) and (b) and SPEI12 (c) and (d) in October (beginning of wet season) of less than -1 , in each of the basins, in historical simulations and projections under RCP45/SSP245 (a) and RCP85/SSP585 scenario.

Figure 12 shows the projected changes in the frequency of droughts in sets of ten years (decades) where SPI or SPEI is lower than -1.0 (see methods). An SPI or SPEI of less than -1.0 is only a moderate drought condition, and would normally be expected around 2–3 times per decade. These plots are divided into 10 year segments extending from the past into the future. Each segment has three sub-plots that are violin plots representing the ensemble distribution of values from each ensemble. Overall, rainfall-driven droughts (SPI) do not show a strong change in the future—as indicated by the tendency of the individual ensembles. Projections by individual models, however, encompass possible increases in frequency of drought years and these should be considered as one of the possible futures. SPEI also does not show a strong change in the future—as indicated by the tendency of the individual ensembles. CORDEX projections, on the other hand, indicate a strong increase in drought, particularly in the south of Angola and in the Cuanza region. In every region, projections by individual models encompass increases in drought events. These droughts, again, should be considered as one of the possible futures.

Our results demonstrate that there is a possibility of an increase in short-term and multi-year droughts which would require improvements in water management for agriculture. Occasional droughts coupled with high temperatures can increase the risk of fires, which may affect those who rely on the forests for fuel. Extreme hazards such as heat, floods, and fires, can also impact electricity power distribution infrastructure.

4. Conclusions

The climate across Angola includes arid, temperate and tropical conditions. Most of the region receives the majority of its rainfall in the warm summer months (Nov-Mar). Temperature and rainfall vary on annual, decadal and multi-decadal timescales. The year-to-year differences are influenced by large-scale seasonal atmospheric patterns as well as the changing conditions over the cool South Atlantic Ocean. Rainfall has displayed significant decadal fluctuations over the last four decades. Specifically, portions of southern Angola experienced exceptional dryness during the 1980s and 1990s, whereas they were abnormally wet during the 2000s and 2010s. Conversely, other regions of Angola witnessed the inverse pattern. Climate change has already affected the entire country, and the most conspicuous impact of climate change has been an increase

in temperatures. Mean annual temperatures have increased by approximately 1.4 [1.01–1.78] °C since 1951. The current rate of warming is about 0.2 [0.14–0.25] °C per decade.

Compared to temperature trends, rainfall trends over the previous four decades are less apparent, and there are significant fluctuations in both the magnitude and direction of rainfall changes across all regions. The changes also depend on the time period over which they are considered, which reflects the role of the decadal variability mentioned earlier.

Future projections of temperature change show significant increases across the region. Under moderate GHG emission scenarios, projected increases in average annual temperatures range from 1 to 2 °C by mid-term future (i.e. by 2050s). That range reflects uncertainty of climate projections. Under a high emission scenario, changes are projected to reach as much as 3.5 °C. Extreme temperature events will also continue to increase; the coldest nights will be warmer and the hottest days will be hotter. The annual number of very hot days (days with daily maximum temperature above 30 °C) is projected to rise dramatically in the future and with high certainty. The actual values depend on the pace of changes in GHGs emissions, there will be greater impacts on all temperature-related indices if GHG emissions are not curbed quickly enough.

Rainfall projections suggest a change in the nature of the rainy season, with less rain falling at the beginning (during September–October–November) and the end (March–April–May) of the rainy season. In contrast, models project an increase in rainfall in the middle of the season, during December–January–February. These changes represent a shortening but intensification of the wet season, but with little overall effect on total annual rainfall. These seasonal differences in rainfall are likely to be stronger in the western part of the country.

The severity of heavy precipitation events is projected to increase in the future during the wet season. The rainfall events are, however, likely to be fewer, with longer dry periods with no rain in between. The projected changes are consistent with the physics of atmospheric processes: a warmer atmosphere can hold more water, and therefore can ‘dump’ more precipitation in single, intense events.

Even if changes in rainfall are small, increased temperatures will likely increase evaporative demand of the atmosphere (PET). In the future, rainfall surplus (i.e. an excess of rainfall over the evaporative demand) is likely to reduce. This reduction would mean that groundwater recharge and surface runoff, and thus usable water resources, will also likely be reduced in the future. Only in the North Coast region, where increases in rainfall during the wet season are expected to be strongest, is there a likelihood of increased WA, but a drier future is also possible in that region. Overall, rainfall-driven droughts do not show a strong and consistent change in the future, but scenarios encompass both an increase and a decrease of droughts. Increase in short term and multi-year droughts should thus be considered as a plausible future.

The change in hazards exposure studied demonstrate the need for adaptation measures that focuses on reducing risks in key sectors, such as agriculture and health and with a particular focus on adaptation of cities in Angola given a potential increase in mobility towards urban areas.

4.1. Future research and implications for planning and management

This paper presents a comprehensive study on future climate projections over Angola and sets the foundation for further research on the uncertainty of climate impacts on specific sectors and systems, as well as on the Government’s future development plans and investments. Future research to evaluate the vulnerability of specific sectoral systems to future climates may include the following.

Basin simulations with hydrological models beyond the current use of P-PET in this paper—continuing to use a stochastic approach to capture uncertainty from climate projections—to better quantify hydrological changes with a focus on hydrological extreme events: floods and hydrological droughts. Then, using these hydrological datasets for future climates, do stress-test simulations on existing and potential sectoral systems to determine their specific vulnerability to climate change. For example, simulating hydropower production in the Kwanza or Cunene River Basins may provide insights on future constraints and potential needs to adjust reservoir operations and energy production. The same could be assessed for irrigated agriculture and other water uses such as water resources systems that supply urban centers. Integrating uncertain climate change projections into water resources planning and design is not a trivial task but clear methodologies have been designed and tested to effectively do so in a practical way, such as the Decision Tree Framework (Ray and Brown 2015).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgments

We thank all the climate modelling groups that produced and made available their model output. We acknowledge the World Climate Research Programme's Working Groups on Regional Climate and Coupled Modelling, respectively the coordinating bodies of CORDEX and CMIP. We also acknowledge the Earth System Grid Federation infrastructure, an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP). We would like to thank Simon Mason for providing useful comments in this study.

Funding

This work was funded and produced under the World Bank Group Angola Country Climate and Development Report (CCDR) Advisory Service and Analytics (ASA).

ORCID iDs

Izidine Pinto  <https://orcid.org/0000-0002-9919-4559>
Erin Coughlan de Perez  <https://orcid.org/0000-0001-7645-5720>
Catalina Jaime  <https://orcid.org/0000-0002-1053-8344>
Piotr Wolski  <https://orcid.org/0000-0002-6120-6593>
Lisa van Aardenne  <https://orcid.org/0000-0002-9848-0940>
Eddie Jjemba  <https://orcid.org/0000-0003-0378-4640>

References

- Abiodun B J, Odoulami R C, Sawadogo W, Oloniyo O A, Abatan A A, New M, Lennard C, Pinto I, Egbeyi T S and MacMartin D G 2021 Potential impacts of stratospheric aerosol injection on drought risk managements over major river basins in Africa *Clim. Change* **169** 31
- Bezner Kerr R et al 2022 Food, fibre, and other ecosystem products *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H-O Pörtner et al (Cambridge University Press) (<https://doi.org/10.1017/9781009325844.007>)
- Cain A 2017 *Water Resource Management under a Changing Climate in Angola's Coastal Settlements* (JSTOR)
- Caretta M A et al 2022 Water cycle changes *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H-O Pörtner et al (Cambridge University Press) (<https://doi.org/10.1017/9781009325844.006>)
- Carvalho S C P, Santos F D and Pulquério M 2017 Climate change scenarios for Angola: an analysis of precipitation and temperature projections using four RCMs *Int. J. Climatol.* **37** 3398–412
- Dosio A, Jones R G, Jack C, Lennard C, Nikulin G and Hewitson B 2019 What can we know about future precipitation in Africa? Robustness, significance and added value of projections from a large ensemble of regional climate models *Clim. Dyn.* **53** 5833–58
- Dosio A, Pinto I, Lennard C, Sylla M B, Jack C and Nikulin G 2021 What can we know about recent past precipitation over Africa? Daily characteristics of African precipitation from a large ensemble of observational products for model evaluation *Earth Space Sci.* **8** e2020EA001466
- Dunning C M, Black E and Allan R P 2018 Later wet seasons with more intense rainfall over Africa under future climate change *J. Clim.* **31** 9719–38
- Eyring V, Bony S, Meehl G A, Senior C A, Stevens B, Stouffer R J and Taylor K E 2016 Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization *Geosci. Model Dev.* **9** 1937–58
- Florenchie P, Lutjeharms J R, Reason C J C, Masson S and Rouault M 2003 The source of Benguela Niños in the south Atlantic Ocean *Geophys. Res. Lett.* **30** 10
- Fogt R L and Marshall G J 2020 The southern annular mode: variability, trends, and climate impacts across the Southern Hemisphere *Wiley Interdiscip. Rev. Clim. Change* **11** e652
- Gaughan A E, Staub C G, Hoell A, Weaver A and Waylen P R 2016 Inter- and intra-annual precipitation variability and associated relationships to ENSO and the IOD in southern Africa *Int. J. Climatol.* **36** 1643–56
- Giorgi F, Jones C and Asrar G 2009 Addressing climate information needs at the regional level: the CORDEX framework *WMO Bull.* **58** 175
- Gulev S K et al 2021 Changing state of the climate system *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte (Cambridge University Press)
- Gutiérrez J M et al 2021 Atlas *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte (Cambridge University Press)
- Gutowski W J Jr. et al 2016 WCRP coordinated regional downscaling experiment (CORDEX): a diagnostic MIP for CMIP6 *Geosci. Model Dev.* **9** 4087–95
- Hargreaves G H and Samani Z A 1982 Estimating potential evapotranspiration *J. Irrig. Drain. Div.* **108** 225–30
- Hersbach H et al 2020 The ERA5 global reanalysis *Q. J. R. Meteorol. Soc.* **146** 1999–2049
- Hoell A, Funk C, Zinke J and Harrison L 2017 Modulation of the southern Africa precipitation response to the El Niño Southern Oscillation by the subtropical Indian Ocean dipole *Clim. Dyn.* **48** 2529–40
- Howard E and Washington R 2019 Drylines in southern Africa: rediscovering the Congo air boundary *J. Clim.* **32** 8223–42

- Howard E and Washington R 2020 Tracing future spring and summer drying in Southern Africa to tropical lows and the Congo air boundary *J. Clim.* **33** 6205–28
- IPCC 2021 Summary for policymakers *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte (Cambridge: Cambridge University Press) pp 3–32
- Kadow C, Hall D M and Ulbrich U 2020 Artificial intelligence reconstructs missing climate information *Nat. Geosci.* **13** 408–13
- Klein Tank A M, Zwiers F W and Zhang X 2009 Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation (WMO) (available at: http://library.wmo.int/pmb_ged/wmo-td_1500_en.pdf) (Accessed 12 July 2019)
- Lenssen N J L, Schmidt G A, Hansen J E, Menne M J, Persin A, Ruedy R and Zyss D 2019 Improvements in the GISTEMP uncertainty model *J. Geophys. Res. Atmos.* **124** 6307–26
- Limones N, Marzo-Artigas J, Wijnen M and Serrat-Capdevila A 2020 Evaluating drought risk in data-scarce contexts. The case of southern Angola *J. Water Clim. Change* **11** 44–67
- Manhique A J, Reason C J C, Silinto B, Zucula J, Raiva I, Congolo F and Mavume A F 2015 Extreme rainfall and floods in southern Africa in January 2013 and associated circulation patterns *Nat. Hazards* **77** 679–91
- McKee T B, Doesken J J and Kleist J 1993 Analysis of standardized precipitation index (SPI) data for drought assessment *Water* **26** 1–72
- Meque A and Abiodun B J 2014 Simulating the link between ENSO and summer drought in Southern Africa using regional climate models *Clim. Dyn.* **44** 1881–1900
- Meque A, Pinto I, Maïre G and Beleza A 2022 Understanding the variability of heatwave characteristics in southern Africa *Weather Clim. Extremes* **38** 100498
- Morice C P, Kennedy J J, Rayner N A, Winn J P, Hogan E, Killick R E, Dunn R J H, Osborn T J, Jones P D and Simpson I R 2021 An updated assessment of near-surface temperature change from 1850: the HadCRUT5 data set *J. Geophys. Res. Atmos.* **126** e2019JD032361
- Munday C and Washington R 2017 Circulation controls on southern African precipitation in coupled models: the role of the Angola low *J. Geophys. Res.* **122** 861–77
- ND GAIN 2021 Angola (available at: <https://gain-new.crc.nd.edu/country/angola>) (Accessed 21 October 2021)
- O'Neill B C, Krieglner E, Riahi K, Ebi K L, Hallegatte S, Carter T R, Mathur R and van Vuuren D P 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400
- O'Neill B M et al 2022 Key risks across sectors and regions H-O Pörtner ed *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) pp 2411–538
- Pinto I, Lennard C, Tadross M, Hewitson B, Dosio A, Nikulin G, Panitz H J and Shongwe M E 2016 Evaluation and projections of extreme precipitation over southern Africa from two CORDEX models *Clim. Change* **135** 655–68
- Ray P A and Brown C M 2015 Confronting climate uncertainty in water resources planning and project design: the decision tree framework (World Bank Publications) (available at: <https://openknowledge.worldbank.org/handle/10986/22544>)
- Richard Y, Fauchereau N, Pocard I, Rouault M and Trzaska S 2001 20th century droughts in southern Africa: spatial and temporal variability, teleconnections with oceanic and atmospheric conditions *Int. J. Climatol.* **21** 873–85
- Rohde R and Hausfather Z 2020 The Berkeley earth land/ocean temperature record *Earth Syst. Sci. Data Discuss.* **4** 1–16
- Seneviratne S I et al 2021 Weather and climate extreme events in a changing climate *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte (Cambridge: Cambridge University Press) pp 1513–766 (available at: www.ipcc.ch/)
- Serrat-Capdevila A, Limones N, Marzo-Artigas J, Marcus W and Petrucci B 2022 Water security and drought resilience in the South of Angola
- Sillmann J, Kharin V V, Zwiers F W, Zhang X and Bronaugh D 2013 Climate extremes indices in the CMIP5 multimodel ensemble: part 2. Future climate projections *J. Geophys. Res. Atmos.* **118** 2473–93
- Spinoni J, Barbosa P, Bucchignani E, Cassano J, Cavazos T, Christensen J H, Christensen O B, Coppola E, Evans J and Geyer B 2020 Future global meteorological drought hot spots: a study based on CORDEX data *J. Clim.* **33** 3635–61
- Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98
- Trisos C H et al 2022 Africa H O Pörtner ed *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press) pp 1285–455
- Van Vuuren D P et al 2011 The representative concentration pathways: an overview *Clim. Change* **109** 5–31
- Vicente-Serrano S M, Beguería S and López-Moreno J I 2010 A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index *J. Clim.* **23** 1696–718
- World Bank 2019 *Environment and Renewable Natural Resources in Angola* (World Bank) **10.1596/31529**
- Zhang H-M et al 2019 Updated temperature data give a sharper view of climate trends *Eos* **100** 1961–2018
- Zhang X, Alexander L, Hegerl G C, Jones P, Tank A K, Peterson T C, Trewin B and Zwiers F W 2011 Indices for monitoring changes in extremes based on daily temperature and precipitation data *Wiley Interdiscip. Rev. Clim. Change* **2** 851–70
- Zumwald M, Knüsel B, Baumberger C, Hirsch Hadorn G, Bresch D N and Knutti R 2020 Understanding and assessing uncertainty of observational climate datasets for model evaluation using ensembles *WIREs Clim. Change* **11** e654