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Climate change scenarios for Angola: an analysis of precipitation and temperature projections using four RCMs

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ABSTRACT: Climate change is expected to have a major impact on the world's environment, economy and society, especially in African countries such as Angola due to the dependence of many vital sectors on climate variability (e.g. agriculture) and their low adaptive capacity. With the advances in the availability of climate model data sets provided by programs such as the CORDEX, Angola can benefit from studies on future climate change using high-spatial-resolution data, which have previously been absent for this region. The purpose of this study is to analyse the projected changes in temperature and precipitation over Angola during the 21st century based on four regional climate models (RCMs). The spatial and temporal changes were analysed using a high- and medium-low radiative forcing scenario to consider the uncertainty in greenhouse gas emissions. Changes in the average annual precipitation, average annual temperature and a drought index are studied for short-, mid- and long-term projections. Compared to the reference period, relevant changes are projected in temperature and precipitation indices for the different models under both emission scenarios. These changes include an increase in both the maximum and minimum temperature of up to 4.9 °C by the end of the century and an intensification of droughts. The precipitation projections are highly variable – increasing and decreasing – across the region and dependent on the RCMs. Despite these differences, the precipitation generally decreases over time (approximately −2% by 2100), with the southern region experiencing a stronger decrease in precipitation. Further investigation is needed to minimize projections uncertain, as the annual mean precipitation was overestimated by three of the RCMs (especially in the northern coastal units). Overall, these projected changes in climate can have important implications for the future of Angola, because they are expected to magnify existing problems, thus creating new risks for human and natural systems.

KEY WORDS climate projections; regional climate models; temperature; precipitation; SPI; Angola

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1. Introduction

According to the recent Intergovernmental Panel on Climate Change assessment report (IPCC, 2013), climate change is expected to intensify regional differences in Africa's natural resources and worsen the vulnerability of the continent due to increasing temperatures and significant changes in precipitation regimes. Some studies show that changes in climate are already being observed in Africa (e.g. New *et al*., 2006; Christy *et al*., 2009; Sarr *et al*., 2013; Kusangaya *et al*., 2014). In particular, a trend towards an increase in temperature (e.g. Kruger and Shongwe, 2004) and a decrease in annual precipitation (Zengeni *et al*., 2014) has been recorded from meteorological stations in the southeastern coast of South Africa, during the last decades. Moreover, increasing trends in extreme precipitation events have been found in those regions that have shown an overall decrease in annual precipitation (IPCC, 2013). These changes are expected to have important impacts on key sectors such as agriculture (e.g. Gornall *et al*., 2010), which plays a dominant role in the economy and livelihood throughout most of Africa (Challinor *et al.*, 2007). Moreover, many studies (e.g. FAO, 2003; Osborne *et al*., 2013; Sengar and Sengar, 2014) have indicated that climate change will have a negative impact on crop productivity and livestock systems. Studying climate change and its impacts in many African countries is particularly difficult due to the lack of the necessary infrastructure and funds for collecting data and carrying out studies. One such country is Angola, where after 1974, the quantity and quality of meteorological records were considerably reduced. We do not believe that any studies have been carried out to analyse future changes in climate specifically in Angola under different scenarios. This type of study is critical to understand future impacts and vulnerabilities of climate change on the different sectors, especially considering Angola has a low adaptive capacity (Brooks *et al.*, 2005; Haddad, 2005). A recent example of Angola's low adaptive capacity is the severe drought experienced during much of 2013. It was one of the worst droughts in 30 years (WMO, 2015), and approximately 1.5 million people in southern Angola faced food insecurity, which led UNICEF to appeal for $14.3 million to fund the drought response (UNICEF, 2013).

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An investigation of trends from 1979 to 2007 by Morishima and Akasaka (2010) revealed an increasing annual mean temperature trend across Southern Africa, with particularly large rates in Angola, and a decrease in annual rainfall. In Angola, the local precipitation constitutes the main water supply; therefore, increasing temperatures and reduced precipitation can easily lead to serious water management issues (Shela, 2000; Mbaiwa, 2004; Gaughan and Waylen, 2012; Cain and Cain, 2015). Understanding the future climate in Angola is crucial for assessing impacts and vulnerabilities to climate change and supporting decision makers on the planning and implementation of adaptation measures, especially at a time when the Angola National Water Plan is being elaborated.

The research carried out by the Coordinated Regional Climate Downscaling Experiment (CORDEX) for Africa (Giorgi *et al.*, 2009; Hewitson *et al.*, 2012) provides an opportunity for studying the evolution of Angola's climate under different scenarios using regional climate models (RCMs). RCMs projections have been used for different parts of Africa, including northern Africa (e.g. Patricola and Cook, 2010), southern Africa (e.g. Tadross *et al.*, 2005) and West Africa (e.g. Druyan *et al.*, 2010; Paeth *et al.*, 2011). In these studies, the majority of the researchers tend to rely on just one model (e.g. Paeth *et al.*, 2005; Afiesimama *et al.*, 2006; Anyaha and Semazzib, 2007; Sylla *et al.*, 2009, 2010; Haensler *et al.*, 2011; Mariotti *et al.*, 2011) rather than looking at an ensemble of different models, which are important to build further confidence in model projections (Ziervogel and Zermoglio, 2009). Up to ten RCMs have been evaluated and compared for the African continent (Nikulin *et al.*, 2012; Kim *et al.*, 2014), Southern Africa (Kalognomou *et al.*, 2013; Abiodun *et al.*, 2016; Favre *et al.*, 2016), West Africa (Gbobaniyi *et al.*, 2014; Klutse *et al.*, 2016) and Eastern Africa (e.g. Endris *et al.*, 2016). All studies suggest that RCMs can be used to provide useful information on climate projections for the studied regions and note that the ensemble model mean outperforms most of the individual RCMs. However, these studies provide an evaluation of the different RCMs for rather large areas of Africa, most of which do not include Angola. As RCMs provide useful data for studying future local climate and associated impacts, it is still necessary to assess whether and which RCMs are able to simulate the current climate of a more limited area, such as at the country level.

This study performs the first analysis and comparison of a set of climate models and scenarios with a high spatial resolution for Angola for the 21st century. Studies on climate projections over Africa rarely have access to ground monitoring networks in Angola. In this study, an evaluation of the performance of four RCMs is performed for Angola using *in situ* observations. The analysis comprises the future temperature and precipitation anomaly trends and a first analysis of the evolution of the frequency and intensity of droughts throughout this century.

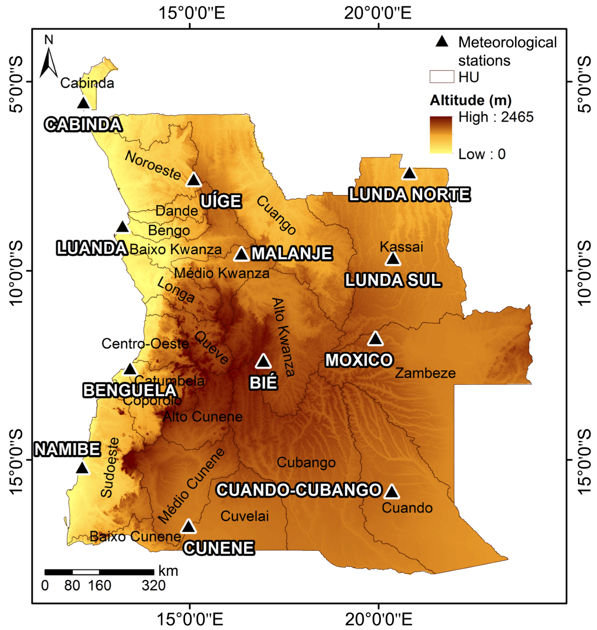

Figure 1. Map of the HUs of Angola. Location of the 12 meteorological stations used in the study. [Colour figure can be viewed at wileyonlinelibrary.com].

2. Data and methodology

2.1. Study area

The Republic of Angola is located on the west coast of Central Africa, between latitudes 4°22′ and 18°2′S and longitudes 11°41′ and 24°2′W, and is one of the largest countries on the continent, with an area of approximately 1 246 700 km^2 (Figure 1). The dominant climate in Angola varies from humid tropical to dry tropical. The climate is greatly influenced by (1) the geographic position, namely the proximity of the south Atlantic Ocean; (2) the topography, with the central plateau being the most prominent feature; (3) the Benguela cold-water current and (4) the movement of the Intertropical Convergence Zone (ITCZ), where the northern and southern air masses converge (Pombo and de Oliveira, 2015).

The climate variables exhibit notable gradients from north to south along the coast and west-central plateau. The north-east is the wettest region in Angola, and precipitation decreases towards the south and west. The rainy season often occurs between October and April and is controlled by the movement of the ITCZ. Conversely, June, July and August are the driest months with almost no rainfall.

Although the country has a tropical climate, the average temperatures tend to be cool with small seasonal variations (~20 °C in JJA and ~25 °C in DJF) (McSweeney *et al.*, 2010).

2.2. Data sets used and validation of RCMs

Analyses were performed using the data sets available from the CORDEX-Africa program. Table 1 identifies the four RCMs used in this study and the driving general circulation models (GCMs). Monthly data for minimum and maximum temperature and precipitation were used with a horizontal resolution of 0.44° by 0.44° (~50 km).

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Table 1. RCMs used in this study and driving GCMs.

RCM	Institution	Reference	Boundary forcing (GCM)	GCM resolution Resolution – Lat × Lon (at the equator)	Reference
CanRCM4	Canadian Centre for Climate Modelling and Analysis (CCCma)	Caya and Laprise (1999)	CanESM2	2.79° × 2.81°	Yang and Saenko (2012)
HIRHAM5	Danish Meteorological Institute (DMI)	Christensen *et al.* (2007)	EC-EARTH	1.12° × 1.12°	Hazeleger *et al.* (2010)
CCLM	Climate Limited-area Modelling Community (CLM-Community)	Rockel *et al.* (2008)	CNRM-CM5	1.40° × 1.40°	Voldoire *et al.* (2013)
RCA4	Swedish Meteorological and Hydrological Institute (SMHI)	Samuelsson *et al.* (2011) Kupiainen *et al.* (2011)	HadGEM2-ES	1.25° × 1.88°	Jones *et al.* (2011)

The data sets included historical runs and projections based on the Representative Concentration Pathways (RCPs) 4.5 and 8.5. RCP4.5 is a medium-low emissions scenario that corresponds to a radiative forcing peaking at 4.5 W m^{-2} (≈650 ppm CO_2 equiv.) by 2100 (Thomson *et al.*, 2011), whereas RCP8.5 is a high emissions scenario in which the increasing greenhouse gas emissions lead to a radiative forcing pathway of 8.5 W m^{-2} (≈1370 ppm CO_2 equiv.) (Riahi *et al.*, 2011). The historical data range from 1958 to 1987 (spanning 30 years of data), while the projections range from 2011 to 2100.

The validation of simulated data is limited by the availability of high-quality observed records for the study area with the appropriate spatial and time resolutions. Data collection in Angola has been considerably affected since 1974, and there is a severe lack of observations over long periods of time. This study investigates records with monthly resolutions from 1958 to 1974, which was the longest continuous period available. Data were obtained from 12 meteorological stations spread throughout the different regions of Angola (Figure 1).

The data from these 12 meteorological stations were obtained from the yearbooks of the Meteorological Office of Angola. Quality control of the observed data was performed, including tests for checking data homogeneity. In the literature, model performance evaluations have been achieved by computing statistical indicators, such as the mean bias, the Nash–Sutcliffe Efficiency (NSE), the root-mean-square error (RMSE) and the RMSE-observations standard deviation ratio (RSR) (e.g. Gbobaniyi *et al*., 2014; Zhou *et al*., 2014; Akinsanola *et al*., 2015; McMahon *et al*., 2015). The optimal values of the statistical indicators are: 0.0 for mean bias; 1.0 for NSE; the lower, the better for RMSE; and 0.0 for RSR. Following their approach, in this study, the performance of RCMs was assessed based on these indicators using data sets from the 12 meteorological stations (Figure 1), concerning the maximum and minimum temperature and precipitation. Student's *t*-test was also used to assess the difference between the models and observations (e.g. Mearns, 1997).

The projected changes in climate are shown for individual RCMs and their ensemble model (averaging the four RCMs' simulations). Although the use of ensemble models is expected to compensate for systematic errors resulting from, e.g. the sensitivity of RCMs to local processes, the average might mask the results and give a conservative estimate of the change.

2.3. Trends in annual precipitation and temperature

In this study, the Mann–Kendall nonparametric test (Gilbert, 1987) and Sen's nonparametric method (Sen, 1968) were used to explore the temperatures and precipitation trends over the 21st century.

The Mann–Kendall nonparametric test is based on both the null hypothesis that the data are randomly ordered in time and its alternative that sets the existence of a monotonic trend. The test compares each value with the values observed in the following periods, and no assumptions of data distribution are required. Another advantage of this test is the low sensitivity to abrupt breaks in a non-homogeneous time series (Jaagus, 2006).

Sen's estimator was used to calculate the change per unit time in a time series with a linear trend; this method computes the median slope amongst all lines through pairs of sample points. The advantages of Sen's estimator are well reported in the literature (e.g. Akritas *et al*., 1995; Peng *et al*., 2008). For example, Ohlson and Kim (2015) claimed a better efficiency when using the Sen's estimator than when using the simple least squares, considering the tested criteria, namely the inter-temporal stability of estimated coefficients, and the goodness-of-fit, as measured by the fitted values' ability to explain the actual values.

2.4. Analysis of droughts

Droughts were analysed using one of the most common global indexes from the last two decades, the Standardized Precipitation Index (SPI) (e.g. Hayes *et al*., 1999; Cancelliere *et al*., 2007; Livada and Assimakopoulos, 2007; Unal *et al*., 2012; Vicente-Serrano *et al*., 2012; Jenkins and Warren, 2014; Xu *et al*., 2015). The SPI was proposed by

McKee *et al.* (1993) and uses precipitation data to quantify conditions of deficit or excess precipitation at different time scales or regions with different climatic conditions. In this study, a 6-month time period (SPI-6) and a 12-month time period (SPI-12) were used. The SPI-6 explores the changes in precipitation over different seasons, so it is useful as an indicator of agricultural drought and reduced stream flow, whereas the SPI-12 indicates reduced reservoir and groundwater recharge.

The SPI was performed using the package 'SPEI' in the R software (Begueria and Vicente-Serrano, 2013). The calculation of SPI for the different scenarios was performed using the reference value for a continuous period of 30 years from 1958 to 1987 from the historical run of each RCM. A gamma function was adjusted on each of the data sets to define the relationship of probability to precipitation. The probability of any precipitation data point was then calculated and used along with an estimate of the inverse normal to calculate the precipitation deviation for a normally distributed probability density (with a mean of 0 and a standard deviation of 1). This output was the SPI for a specific precipitation data point (see McKee *et al.*, 1993 for a full description). The calculation of the number and magnitude of drought events was based on the definition provided by McKee *et al.* (1993).

3. Results

3.1. Performance of RCMs

This section evaluates and compares the performance of the RCMs in representing the past climate using the variables maximum and minimum temperature and precipitation.

3.1.1. Maximum and minimum temperatures

During the period 1958–1974, the observed annual mean of maximum temperature was 27.8 °C (Table 2). The estimates from the RCMs differ from the observations by −2.1 to 1 °C. In particular, the results for CanRCM4 and RCA4 showed the lowest mean bias (2.3 and 3.9%, respectively) compared to the CCLM and HIRHAM5 data sets (−7.8 and −6.1%). NSE, RMSE and RSR showed the best agreement between the simulations and observations for RCA4 and the worst for CCLM.

The observed annual mean of minimum temperature was 16.9 °C for the reference period (Table 2). On average, the RCMs overestimate the minimum temperature by 1.3 °C, with the exception of CanRCM4, which underestimates it by 0.9 °C. RCA4 has the best performance for maximum temperature according to the indicators NSE, RMSE and RMS. Table 2 shows the results for Student's *t*-test. At the significance level $\alpha = 0.05$, results for CanRCM4 and RCA4 are consistent with the null hypothesis that the means of observational and model data sets are equal. This is true for both maximum and minimum temperatures. On the other hand, HIRHAM5 is significantly different for both variables, while CCLM is only significantly different from the observations of minimum temperature.

3.1.2. Precipitation

Considering the 12 meteorological stations, the observed annual mean precipitation was 82.7 mm during the period 1958–1974 (Table 2). By comparing the results of the four RCMs, we found that the precipitation was overestimated (up to 68 mm). The estimated values from CanRCM4 were the most similar to the observations, whereas the values estimated from CCLM had the lowest concordance. These findings are maintained across all the tested statistical indicators. In relation to the results of Student's *t*-test, there is no evidence to reject the null hypothesis that the means of observational and RCMs data sets are equal, with the exception of CCLM (p-value < 0.05).

Figure 2 shows the annual mean precipitation for the different hydrographic units (HUs) based on observations and RCMs simulations. Records from 303 meteorological and udometric stations were obtained by the Angola Met Office, which carried out their quality control through double mass plots, randomness tests and replacement of missing values. Data were then interpolated by inverse distance squared weighted into 360 grid points, covering the entire territory. In Figure 2 the annual mean precipitations were averaged and represented according to the HUs.

Different spatial patterns of annual mean precipitation distribution were found between the RCMs. Overall, CanRCM4 had the highest agreement with the observed spatial precipitation distribution (also exhibited by Pombo *et al.*, 2014), namely, a decreasing precipitation trend in the northeast–southwest direction over Angola. The lower values of precipitation (<400 mm) were found to occur in the south (southwest), which is also true for the majority of the RCMs. CCLM, HIRHAM5 and RCA4 seem to overestimate the mean annual precipitation for most HUs, which is most evident in the northern coastal units. The CCLM in particular shows a pattern of annual mean precipitation that seems contrary to the observed; i.e. the entire littoral zone is conspicuously wet.

3.2. Projections for temperature and precipitation over the 21st century

3.2.1. Maximum and minimum temperature

Figure 3 shows an increase of maximum and minimum temperatures during the 21st century. In comparison to the reference period, the average maximum temperature is projected to increase from 2.9 to 4.9 °C (Figure 4) by the end of the century, whereas the average minimum temperature is projected to increase between 2.6 and 4.5 °C (Figure 5). The results are very similar for all models and RCPs, although higher increases of both temperatures are projected by both CanRCM4 and RCA4 (Figure 3) under RCP8.5. Similar uncertainty is observed when comparing the same time period of each model. Moreover, as expected, the last period (2071–2100) under RCP8.5 is the one with the highest uncertainty.

Figure 4 displays the mean anomaly of the maximum temperatures (based on the ensemble) for the 22 HUs in Angola, the two emission scenarios and the three time

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Table 2. Comparison of observed and simulated data sets by four RCMs for the period 1958–1974.

	Annual mean		Coefficient variation	Bias (%)	NSE	RMSE	RSR	*p*-value
Maximum temperature (°C)	Observed	27.8	0.1	–	–	–	–	–
	CanRCM4	28.4	0.1	2.3	−3.5	4.0	2.12	0.538
	CCLM	25.7	0.1	−7.8	−5.2	4.7	2.49	0.059
	HIRHAM5	26.2	0.1	−6.1	−2.4	3.5	1.80	0.034
	RCA4	28.8	0.1	3.9	−1.7	3.1	1.70	0.083
	Ensemble	27.3	0.1	−1.9	−1.9	3.2	1.70	0.487
Minimum temperature (°C)	Observed	16.9	0.2	–	–	–	–	–
	CanRCM4	16.0	0.3	−7.9	−0.2	2.9	1.10	0.110
	CCLM	18.6	0.3	8.0	−0.2	2.9	1.11	0.038
	HIRHAM5	18.9	0.2	10.2	−0.3	3.0	1.10	0.005
	RCA4	17.5	0.2	4.6	0.2	2.3	0.90	0.482
	Ensemble	17.7	0.2	3.7	0.5	1.9	0.71	0.107
Precipitation (mm)	Observed	82.7	1.2	–	–	–	–	–
	CanRCM4	83.5	1.1	2.6	0.2	81.7	0.90	0.642
	CCLM	150.5	1.2	74.5	−3.1	183.6	2.01	0.031
	HIRHAM5	102.1	1.0	27.9	−0.1	94.7	1.04	0.050
	RCA4	95.9	1.1	20.1	0.0	90.7	1.00	0.080
	Ensemble	108.0	0.9	31.3	0.0	92.6	1.02	0.043

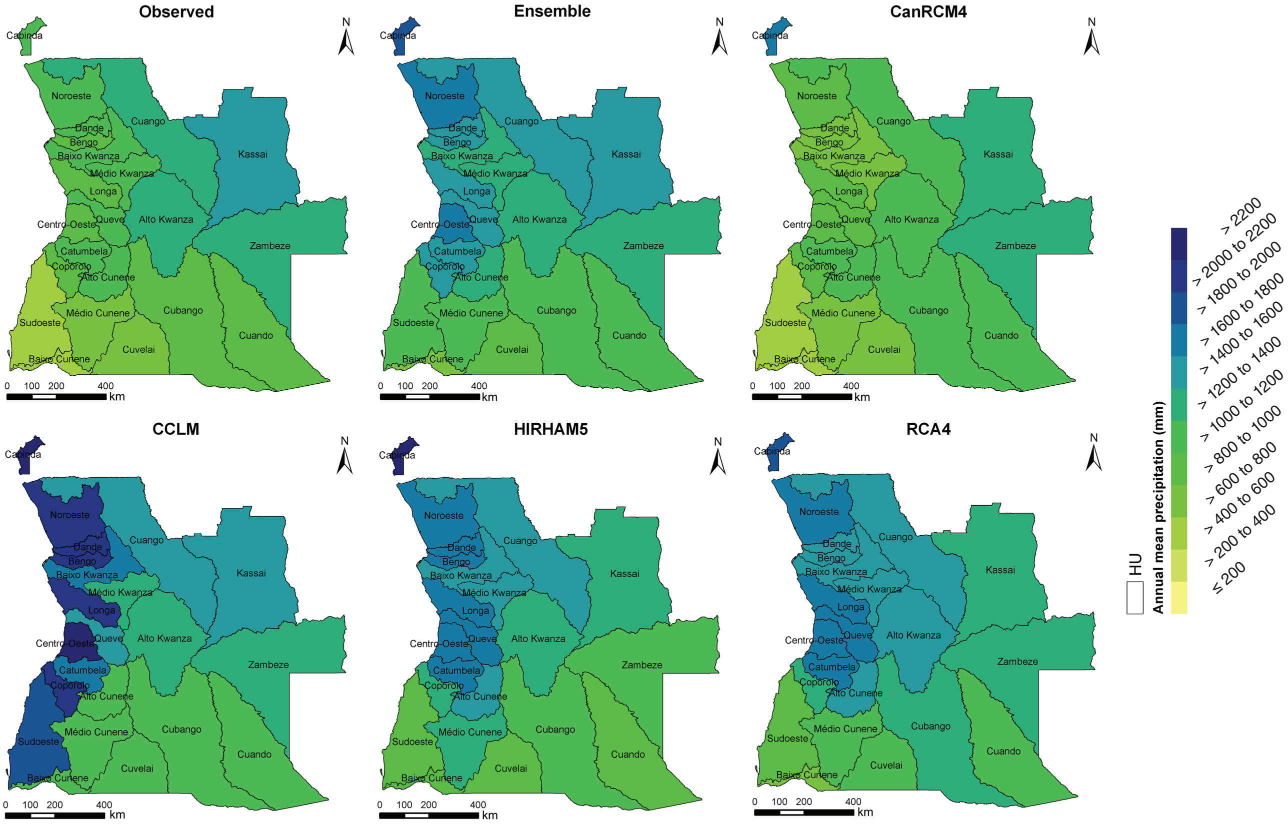

Figure 2. Distribution of annual mean precipitation based on the observations, the four RCMs and the RCMs ensemble for the period 1958–1974. Data were averaged within each hydrological boundary unit. [Colour figure can be viewed at wileyonlinelibrary.com].

periods. The results show an increase in the maximum temperature throughout the century for both scenarios (mean anomalies vary between 2.9 and 4.9 °C for the end of the century for RCP4.5 and RCP8.5, respectively).

By comparing the results of each HU, we found that the increase in the maximum temperature will affect the whole territory (Figure 4); however, that increase is not similar across all units. For the northern coastal HUs, the projections indicate a lower increase in the maximum temperature, whereas the southeast has the highest projected increase, approximately 5 °C, by the end of the century (under RCP8.5).

The increase in the minimum temperatures is more homogenous throughout the HUs compared to the pattern observed for maximum temperature (Figure 5); i.e. the range of temperature classes is narrower. However,

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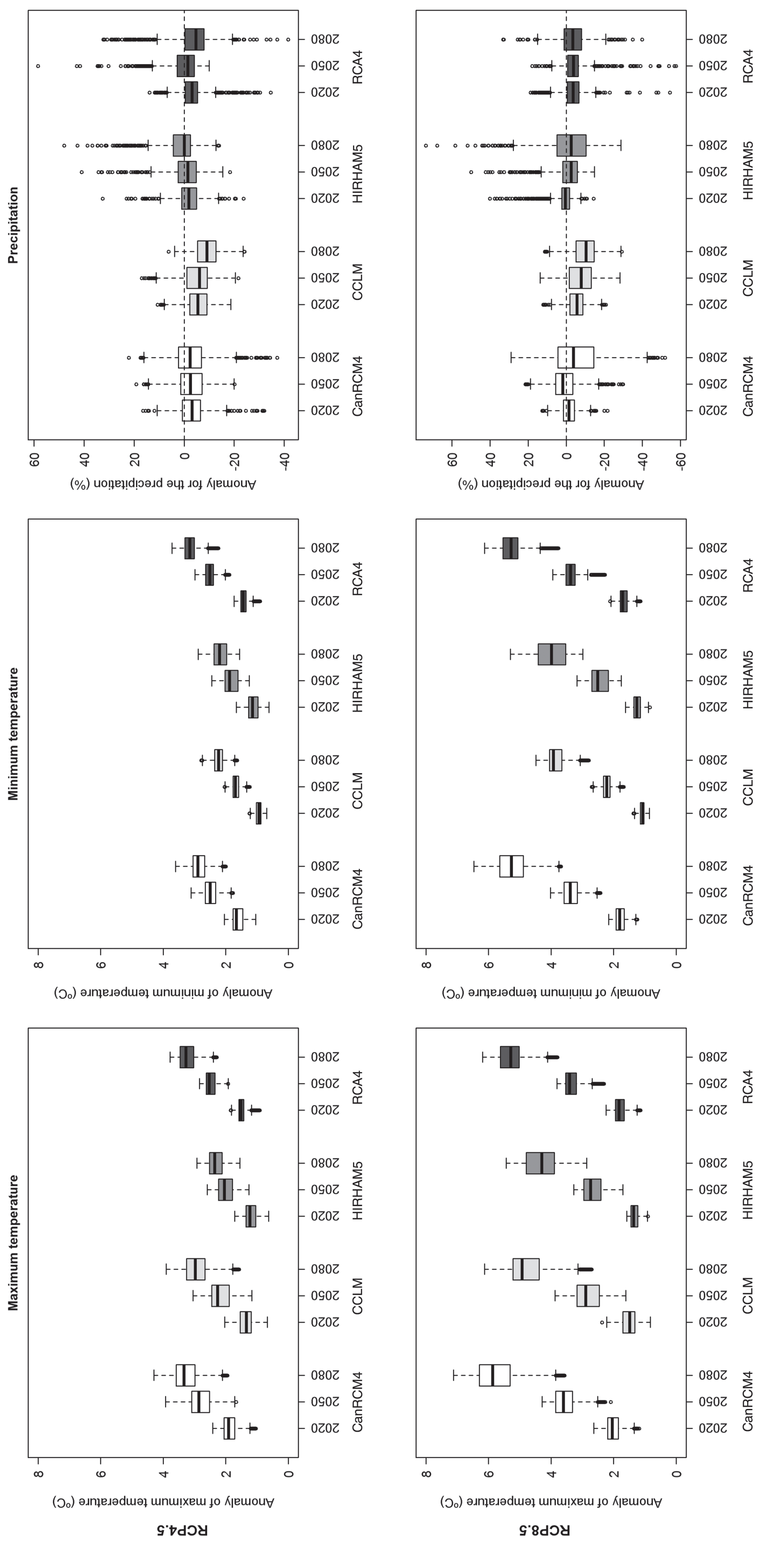

Figure 3. Anomaly of maximum and minimum temperature and precipitation for three time periods for the four RCMs (CanRCM4, CCLM, HIRHAM5 and RCA4) according to two RCPs.

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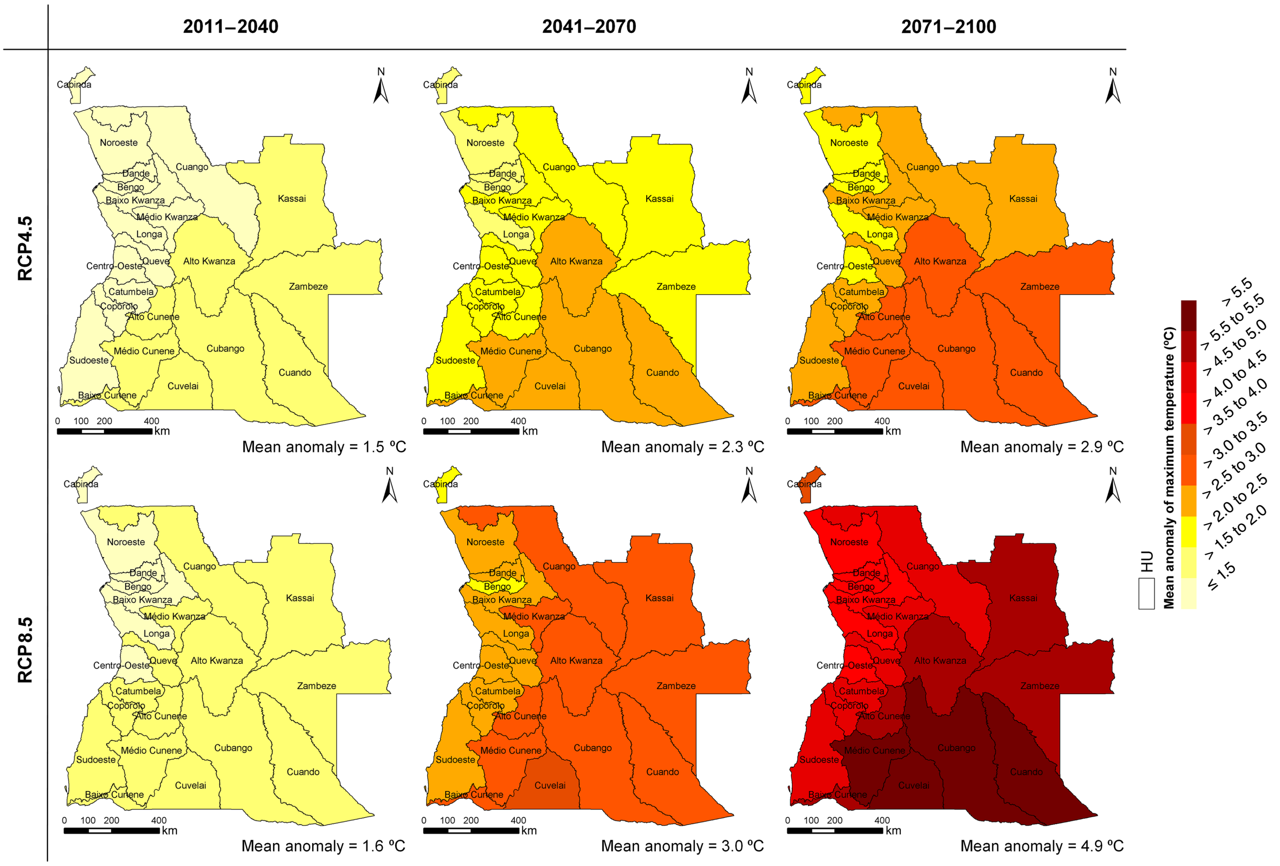

Figure 4. Mean anomaly of maximum temperature for the three time periods and two RCPs based on the RCMs ensemble. [Colour figure can be viewed at wileyonlinelibrary.com].

the anomalies in the minimum temperatures projected for inland units (particularly southern units for RCP8.5) are still higher (approximately 0.5 °C) than those projected for the coastal units.

The trend tests were performed for maximum and minimum temperature anomalies throughout the period (2011–2100), considering data from the four RCMs and under both scenarios. According to Sen's estimator, on average, the increase in both the maximum and minimum temperature anomalies will be approximately 0.4 °C (standard deviation = 0.2 °C) per decade. The results from the Mann–Kendall nonparametric test show that trends are statistically significant for the entire country.

To better understand the impact of climate change on intra-annual temperatures, Figure 6 shows the monthly mean anomalies of maximum and minimum temperatures for the time period where the changes are expected to be higher, i.e. during 2071–2100 under RCP8.5. The increase in both the maximum and minimum temperatures is expected to be higher during the dry season (May–September) and earlier wet season (October and November).

3.2.2. *Precipitation*

Figure 3 shows the anomalies (%) of annual precipitation according to each RCM for the three time periods. In general, a slight decrease in precipitation is projected by the four RCMs throughout the 21st century. However, HIRHAM5 projects opposite trends for both of the scenarios. For scenario RCP4.5, it shows an increase in precipitation throughout the century, whereas for RCP 8.5, it shows a decrease. These differences, however, are small. The CCLM model projects the largest decrease in precipitation during the century.

Figure 7 represents the anomalies in annual precipitation for the HUs according to the three time periods and both RCPs. The precipitation amounts are projected to decrease on average by 2.6 to 4% in relation to the reference period. The precipitation anomalies of the HUs range from −15 to 5% (both the highest and the lowest values were observed for the end of the century under RCP8.5). Despite the variability between the HUs being evident, the anomalies are negative for the majority of the areas (the mean of the anomalies varies between −4.0 and −2.6%). The decrease in precipitation will be higher for the south of the country, in particular in Baixo Cunene and Cuvelai. In contrast, the projections for the central coastal region (for example, the Centro-Oeste unit) show a slow increase in precipitation.

Figure 6 shows that precipitation for the period 2071–2100 and under RCP8.5 is expected to have a greater decrease between April and October, i.e. during the dry season. Nevertheless, to understand the effects of this decline, it should be considered that rainfall is almost negligible during the driest months (June, July and August). To better understand the variability of the annual

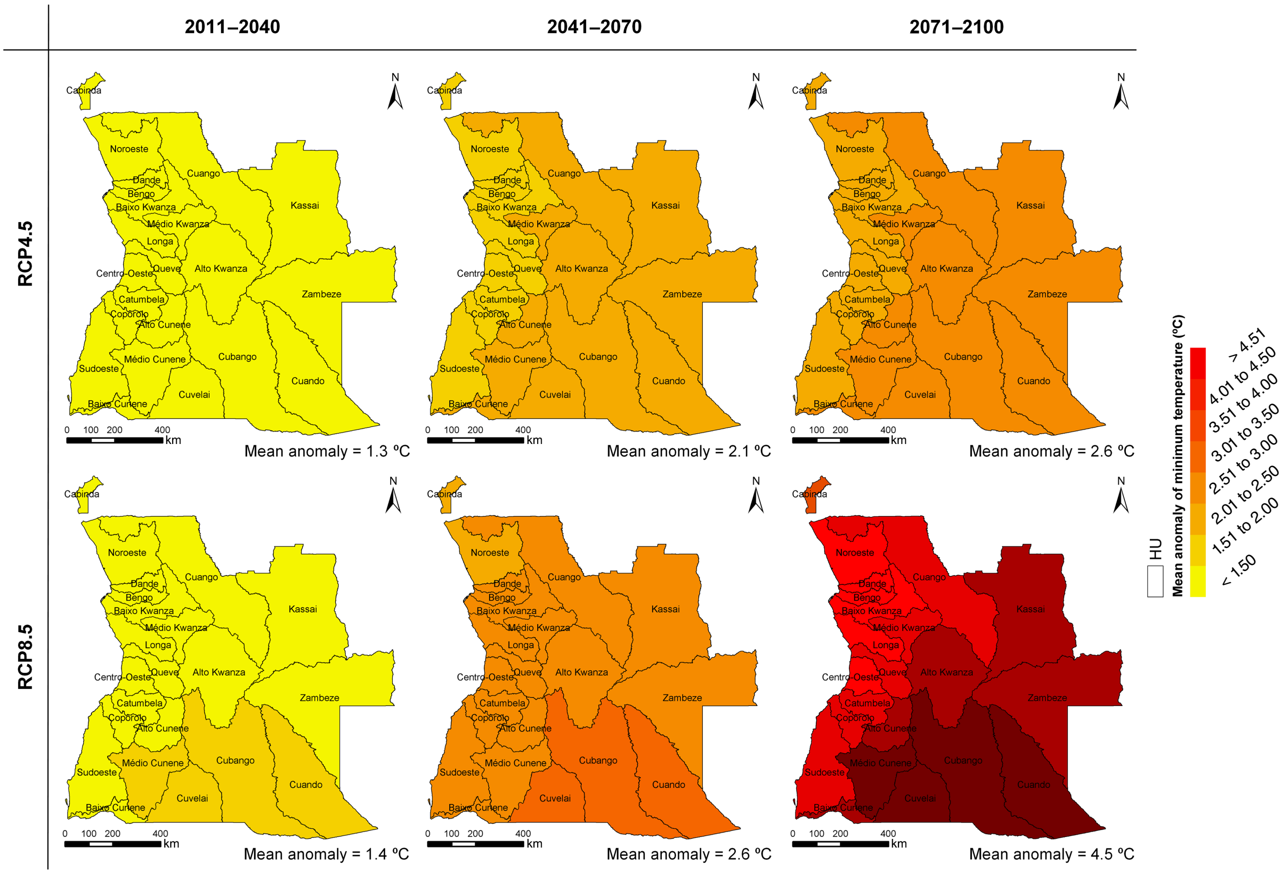

Figure 5. Mean anomaly of minimum temperature for the three time periods and two RCPs based on the RCMs ensemble. [Colour figure can be viewed at wileyonlinelibrary.com].

precipitation anomalies, trend tests were used. Figure 8 represents the spatial distribution of precipitation anomaly trends for different RCMs and climatic scenarios. Despite the high variability noticed between the RCMs and scenarios (trends range from −6.6 to +6.7 mm decade^{-1}), the majority of the trends are not statistically significant (pixels highlighted with oblique lines). This fact can be related to the high level of precipitation fluctuations through the century, representing cycles of several years alternating between high and low precipitation.

All RCMs show reductions and increases in precipitation anomalies under both scenarios, depending on the region. In spite of their high variability, in general, the results from the models and scenarios indicate a reduction in precipitation anomaly (around −2 mm decade^{-1}) in the south of Angola and an increase (about +2 mm decade^{-1}) in precipitation in coastal units, mainly in the centre. Moreover, more areas present trends that are statistically significant under RCP8.5. In the north of the country, in general, a decline in precipitation anomalies is observed, particularly for the coastal units. The more relevant exceptions are the results obtained for the model HIRHAM5, which projects an increase in precipitation anomalies for all coastal units.

3.3. Projections of droughts over the 21st century

With the projected increase in temperatures and decrease in precipitation, it can be useful to explore drought indexes. Figure 9 shows the number of events and the mean magnitude of droughts under two RCPs, computed from SPI-6, and based on the RCMs ensemble. Both the number and the magnitude of the droughts gradually increase over the 21st century. Moreover, this increase is more severe both under scenario RCP8.5 and for long-term projections (e.g. increases of five events and 6 months of magnitude in relation to the reference period).

Concerning SPI-12 (Figure 10), the evolution of the number of events over time is not very clear (the median varies between 7 and 8). Moreover, a slight increase in the projections' uncertainty is observed for the end of the century.

Although the frequency of droughts generally remains constant over the century, climate change is likely to have a larger effect on their magnitude. Indeed, an increase in the severity of droughts is expected over the different periods under RCP8.5, which can double in magnitude by the end of the century. When comparing the reference period and the short-term projections, an increase in magnitude is also expected under RCP4.5, although that increase remains constant throughout the century.

To understand if a drier future is projected consistently over the country, Table 3 shows the number and magnitude of drought events according to the 22 HUs. Comparing the results from SPI-6, it can be seen that with the exception of Cabinda (for 2041–2070), all of the HUs will experience an increase in the number of droughts. Moreover, in comparison to the north, the south of Angola (e.g. Baixo

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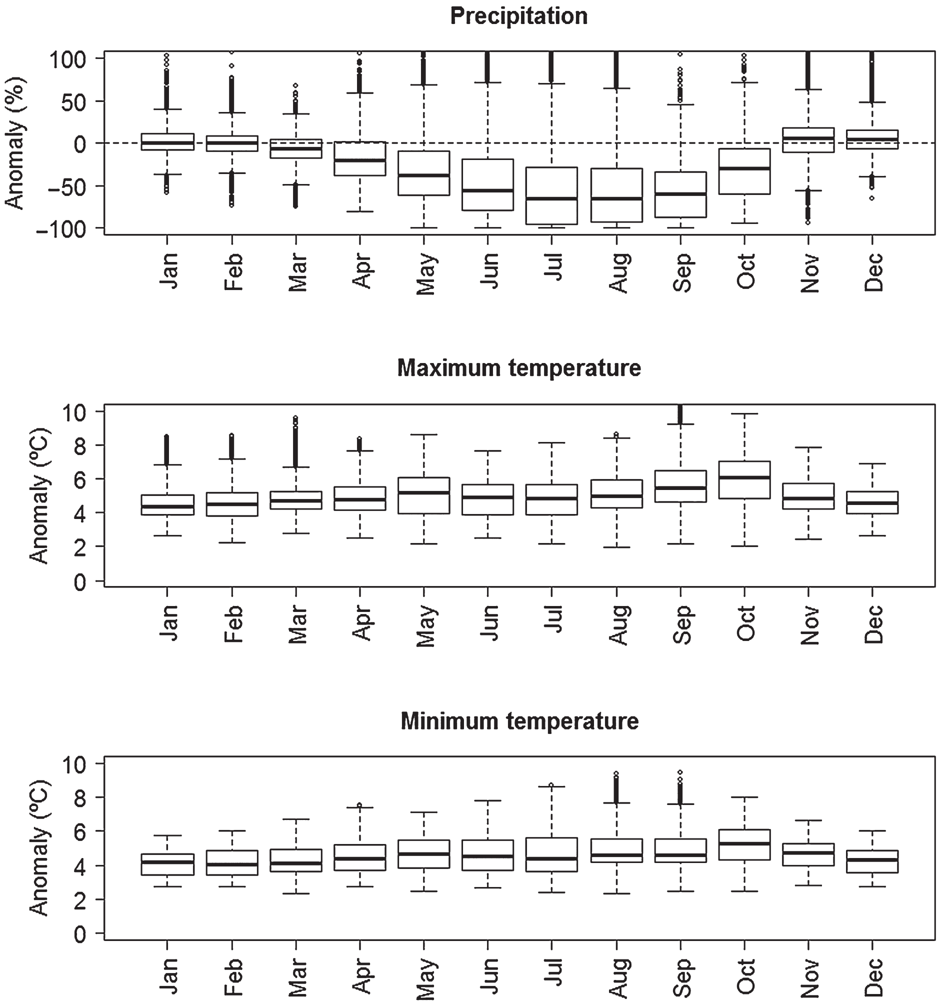

Figure 6. Monthly mean anomalies of precipitation and maximum and minimum temperature for the period 2071–2100 and the RCP8.5 based on the RCMs ensemble.

Cunene, Médio Cunene and Cuvelai) will have a greater number of drought events.

In relation to SPI-12, as mentioned before, the anomalies in the number of events are not high (approximately one unit), although the majority of the HUs will have an increased number of droughts. The units that show a decrease in the number of drought events are mostly situated near the coast.

In addition, Table 3 shows that the magnitude of events will increase through the 21st century. The spatial distribution suggests higher severity of events in the northwestern (e.g. Cuango) rather than the southern (e.g. Cuvelai) part of the country. The HUs where the magnitude might decrease in relation to the reference period are situated in the coastal part of the country, where some regions were also expected to have fewer events.

4. Discussion and conclusions

Angola is a country that is highly vulnerable to climate change (Brooks *et al.*, 2005), and yet little research in climate projections have been done for this region. In this study, the projections of temperature and precipitation were analysed for Angola over the 21st century. The analyses were performed using four RCMs under two scenarios (RCP4.5 and 8.5).

The RCMs CanRCM4 and RCA4 present the best overall performance considering the three climatic variables: maximum and minimum temperature and precipitation. However, CanRCM4 can better simulate the spatial precipitation distribution across Angola, whereas RCA4 overestimates the precipitation in the northern coastal HUs. The difficulties in modelling precipitation in comparison with temperature have already been noted in current RCMs for Africa (Gbobaniyi *et al.*, 2014).

Results of the models' validation are conditioned by the availability and quality of *in situ* observations. It was difficult to obtain accurate meteorological records in Angola, a developing country that has been severely affected by civil war and poor infrastructure networks. The 12 meteorological stations used in this study present the best-observed data available for Angola. This data, however, has the highest quality for the decades before 1974 and for a limited number of additional years, which makes it difficult to validate the performance of RCMs and other types of products available (Pombo *et al.*, 2014;

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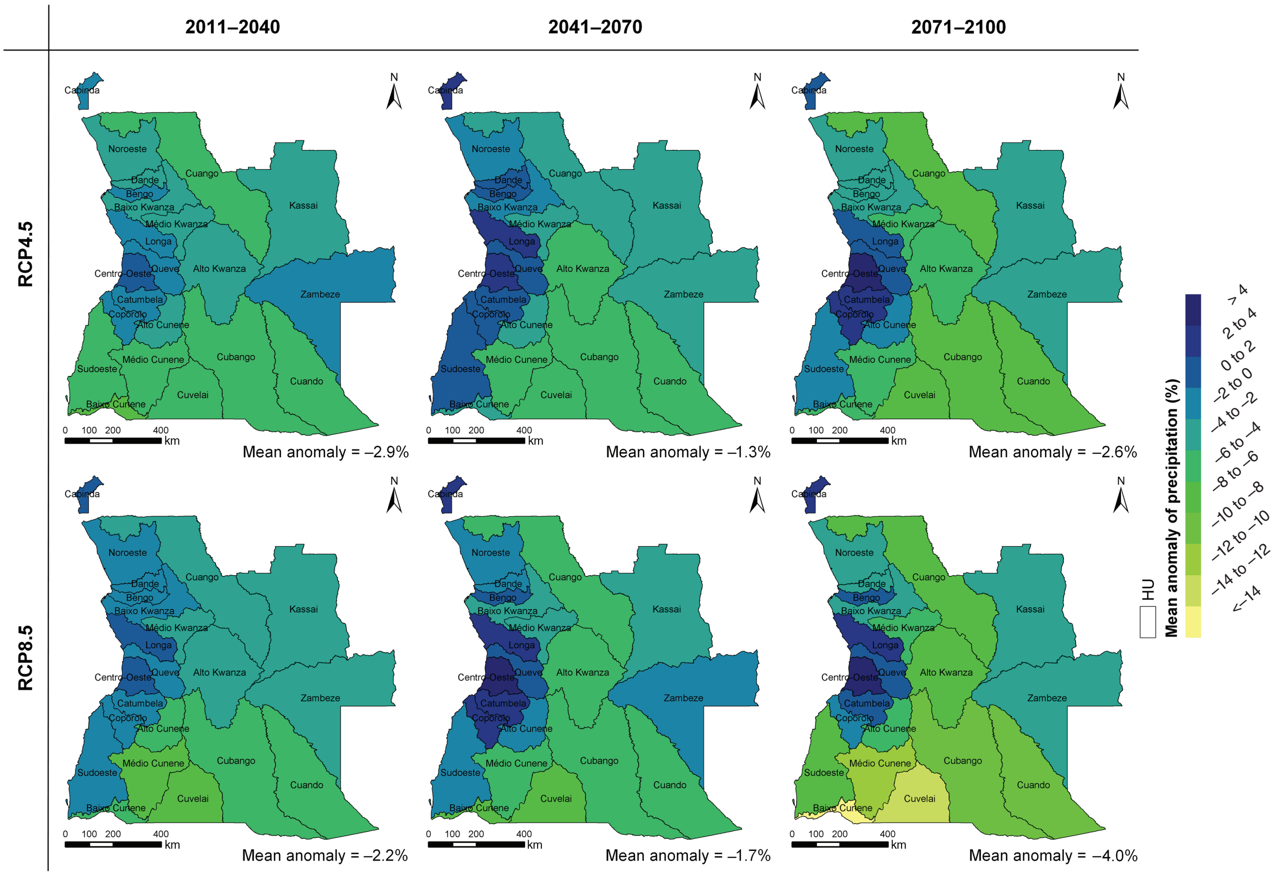

Figure 7. Mean anomaly of precipitation for the three time periods and two RCPs based on the RCMs ensemble. [Colour figure can be viewed at wileyonlinelibrary.com].

Pombo and de Oliveira, 2015). Further research could possibly use remote-sensing data for validation of RCMs, but these products also suffer from associated errors and inaccuracies. It is particularly difficult to obtain accurate data from products that do not use *in situ* ground measurements to correct estimations, which is a common issue for Angola due to its undeveloped and unmaintained meteorological station network (Pombo *et al.*, 2014).

The results of the performance of RCMs are similar to those found in Gbobaniyi *et al.* (2014), Nikulin *et al.* (2012) and Kalognomou *et al.* (2013), over different parts of Africa. In particular, these studies noted that the individual models have their inherent deficiencies; thus, an ensemble of different models could provide a better result. In this study, the ensemble performed better in reproducing the maximum and minimum temperatures, but overestimated precipitation. This is related to the fact that three of the RCMs (CCLM, HIRHAM5 and RCA4) overestimated the annual mean precipitation for most HUs, especially in the northern coastal units. The common tendency to overestimate precipitation by CCLM and RCA was noticed before by Gbobaniyi *et al.* (2014) in West Africa and by Kim *et al.* (2014) in relation to HIRHAM5. The overestimation in these two RCMs results from the boundary conditions imposed by the driving GCMs, as both have been shown to actually underestimate the precipitation for coastal and northern areas of Angola (Dosio *et al.*, 2015; Kim *et al.*, 2014, respectively). This is certainly true for CCLM. In a recent study, Dosio *et al.* (2015) compared the results of CCLM to those of four different driving GCMs. The authors verified the inability of CCLM to systematically and homogeneously improve GCMs simulations. The study showed CCLM had a general dry bias over central Africa, but when forced by the GCM used in this study (i.e. CNRM-CM5) there is a clear overestimation of precipitation along the coast of Angola.

Despite the difference in RCMs' performance (in particular for precipitation), consistent results were found in climate projections (anomalies and trends relative to the reference period) estimated by the four RCMs. The projections of both maximum and minimum temperatures indicate an increase (up to 4.9 °C) by the end of the 21st century, which is in close agreement with other studies (e.g. Sillmann *et al.*, 2013). The projections for northern coastal areas indicate a lower increase of maximum temperature, whereas the southeast inland areas have the highest increase. This pattern has already been discussed by Ragab and Prudhomme (2002) for mean annual and seasonal temperatures considering projections from the global climate model HadCM2 for the time horizon of the 2050s, and was previously observed (between 1960 and 2003) by Kruger and Shongwe (2004) for annual mean maximum temperatures in South Africa, presenting particularly higher trends for inland stations relative to those closer to the coast.

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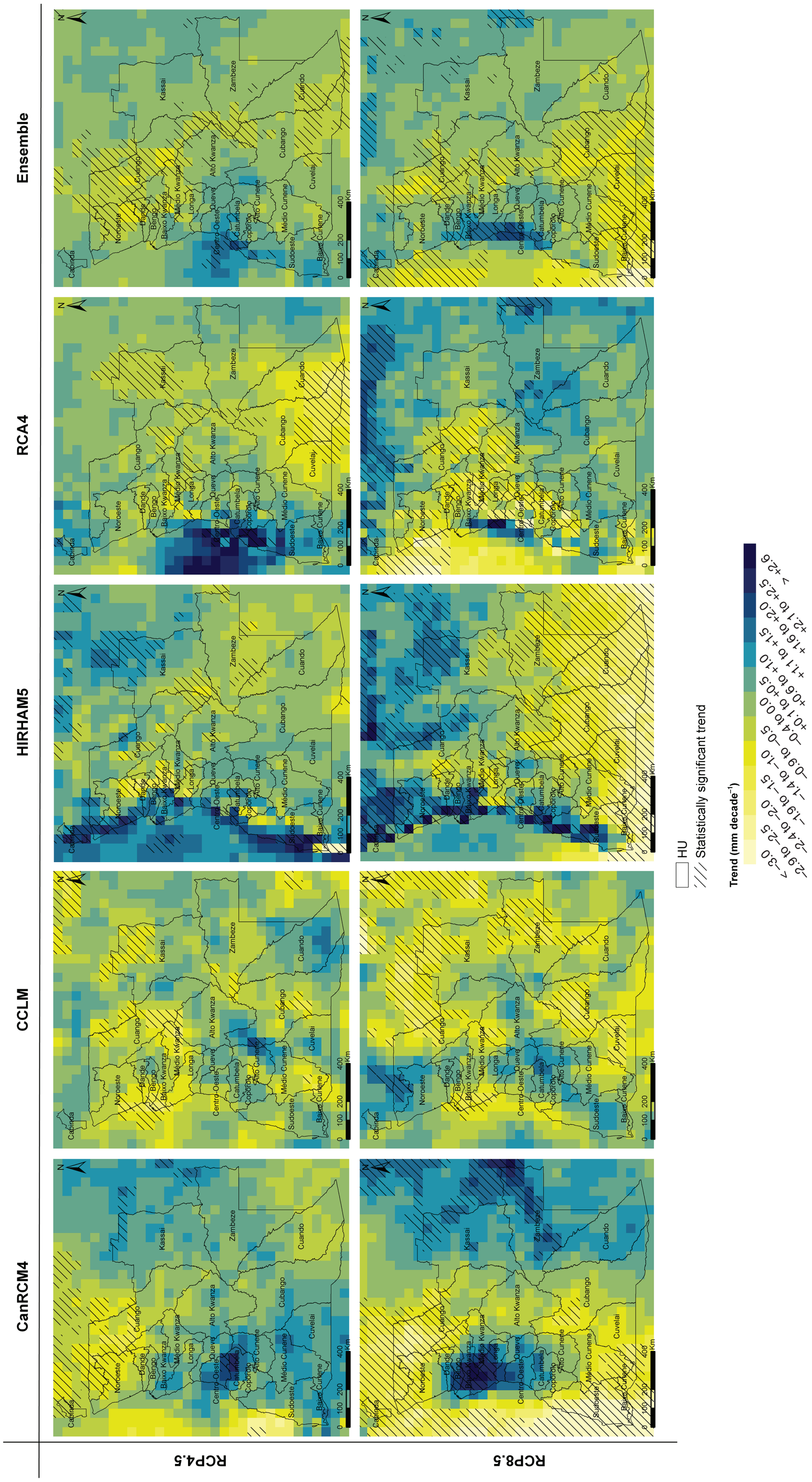

Figure 8. Annual mean precipitation anomaly trends for the period 2011–2100 for four RCMs and the RCMs ensemble, under two RCPs. [Colour figure can be viewed at wileyonlinelibrary.com].

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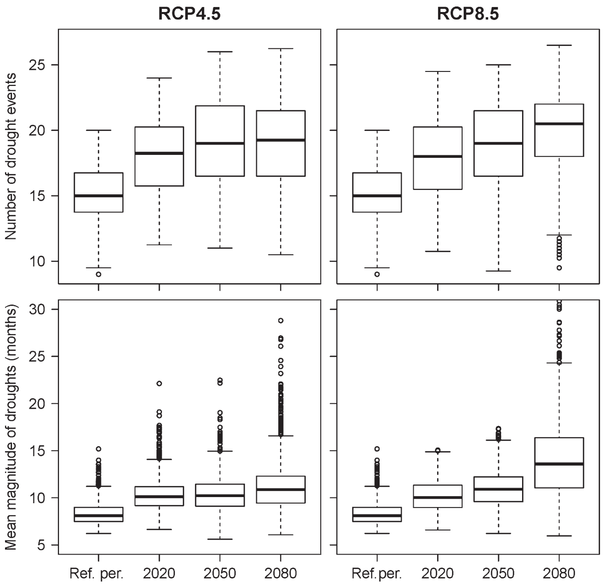

Figure 9. Number of events and mean magnitude of droughts for different time periods, according to two RCPs, computed from SPI-6, and based on the RCMs ensemble.

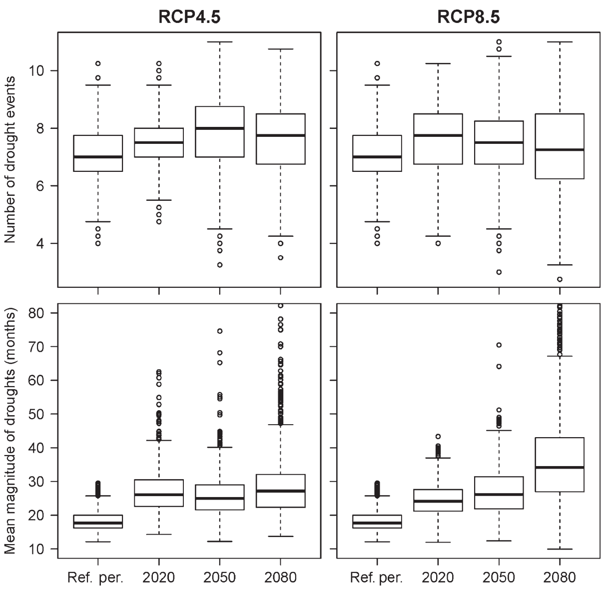

Figure 10. Number of events and mean magnitude of droughts for different time periods, according to two RCPs, computed from SPI-12, and based on the RCMs ensemble.

Contrary to the temperature, the precipitation generally decreases (country average is approximately −2%) throughout the century. In particular, a stronger decrease is expected in the southern part of the country and during the dry months, as compared to the wet season (see also Ragab and Prudhomme, 2002). As this region is already affected by water scarcity, it raises concern for the use and management of water resources, pointing to the need for adaptation.

Despite the difficulties found using nonparametric tests to detect a trend besides the natural variability of precipitation, trends of annual mean precipitation anomaly were obtained ranging from −6.6 to +6.7 mm decade^{-1}. The magnitude of this variable does, however, vary considerably amongst different RCMs and in space. These findings agree with linear changes of annual precipitation obtained by Paeth *et al.* (2011), for West Africa in the period 2001–2050 from ten individual RCMs. The authors noted that although all of the trend patterns are characterized by substantial regional variations, different RCMs do not agree in terms of projections. In particular, three tested models projected a wetter tropical Africa, three models projected negative trends and another three models showed a more mixed signal. Differences between model results may be caused by different representations of the physical processes by each model, the boundary conditions inherited from the driving GCM (Dosio *et al.*, 2015), and the local climate forcing. The latter was highlighted by Buontempo *et al.* (2015), which analysed a five-member ensemble of climate projections for Africa using a 50-km resolution.

The central coastal region is one of the regions where the projections indicate a slow increase in precipitation, contrasting with the general decreasing pattern seen for the rest of the country. This effect is most likely related to the atmospheric forcing mechanisms examined by Nicholson and Entekhabi (1987), which act on both the rainfall variability and the sea surface temperatures (SST) over the coast of Angola. According to Hoegh-Guldberg *et al.* (2014), annual average SST over the Atlantic ocean is projected to increase by approximately 3 °C over the period of 2010–2099 (data are anomalies from the 1986 to 2006 average of the HadISST1.1 under RCP8.5). The relationship between high SST and abundant rainfall was already stated by Hirst and Hastenrath (1983); in particular, the authors claimed that SST modulates the rainfall by controlling the moisture and stability of the lower troposphere.

Whereas the choice of RCMs and driving GCMs could strongly affect spatial patterns of precipitation distribution, as well as the extents of variable changes, the scenarios have been found to affect mainly the magnitude of changes. For example, fluctuations are smaller for RCP4.5 than for RCP8.5. These results confirm the necessity of using various models and scenarios to cover the range of uncertainties over Angola.

Climate change is very likely to bring stronger droughts throughout the 21st century, which will affect both human and environmental systems (e.g. water availability and wildfires potentials). To our knowledge, there is no previous research addressing future changes in drought indexes for Angola. In this study, when considering the SPI-6, the RCMs ensemble projects both a higher frequency and magnitude of droughts for most of the country, likely resulting in negative impacts on things such as crop production. As regards SPI-12, despite the stability of drought frequencies over time, larger drought magnitudes are projected by the end of the century, especially under RCP8.5.

Overall, the results obtained from the range of RCMs, climate scenarios and climate variables used in this study

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Table 3. Number and magnitude of drought events and anomalies between projections and the reference period concerning the 22 HUs, based on SPI-6 and SPI-12, and using two RCPs and the RCMs ensemble.

HU	SPI-6				SPI-12			
	Number of drought events	Anomaly			Number of drought events	Anomaly		
	Ref. period	2011–2040	2041–2070	2071–2100	Ref. period	2011–2040	2041–2070	2071–2100
Cabinda	11.9	0.5	−0.4	0.3	6.3	−0.6	−0.9	−1.2
Cuango	14.9	2.0	3.7	3.3	7.2	0.6	1.0	0.3
Kassai	14.6	3.0	4.0	4.4	7.4	0.6	0.6	0.7
Noroeste	12.7	0.6	2.3	2.4	6.5	0.2	−0.1	−0.5
Dande	13.6	1.7	3.3	3.7	6.8	0.9	0.5	0.8
Bengo	12.7	0.5	3.5	5.1	6.8	−0.3	−0.8	−0.6
Alto Kwanza	15.8	3.5	4.6	5.4	7.6	0.4	0.9	1.3
Medio Kwanza	15.1	2.8	4.8	5.0	7.0	0.8	0.9	1.0
Baixo Kwanza	13.4	2.5	4.2	4.4	6.5	0.6	0.2	0.1
Longa	14.4	1.9	3.6	4.2	6.5	0.4	−0.1	−0.2
Queve	15.1	2.5	4.3	5.7	7.1	−0.1	0.7	0.3
Centro-Oeste	15.1	1.5	2.8	3.8	6.9	−0.6	−0.5	−0.8
Catumbela	15.8	2.5	3.9	4.8	7.2	0.0	0.1	0.4
Zambeze	16.1	2.8	3.8	3.7	7.9	−0.1	−0.1	0.4
Alto Cunene	16.8	3.4	4.4	5.2	7.3	0.3	0.6	1.0
Medio Cunene	16.3	4.5	6.8	6.5	6.9	0.8	1.5	1.3
Baixo Cunene	15.2	4.4	6.8	7.4	6.7	0.6	1.4	0.5
Coporolo	15.9	3.0	4.0	5.3	6.6	0.5	0.3	0.6
Sudoeste	15.7	3.8	5.5	6.4	6.0	0.8	0.7	0.8
Cuvelai	17.3	3.9	5.8	5.2	7.7	0.4	0.9	0.6
Cubango	16.1	4.3	6.1	5.4	7.2	0.9	1.1	1.6
Cuando	17.3	3.1	4.5	4.8	7.7	0.5	0.7	1.4
HU	Magnitude of drought (months)	Anomaly (months)			Magnitude of drought (months)	Anomaly (months)		
	Ref. period	2011–2040	2041–2070	2071–2100	Ref. period	2011–2040	2041–2070	2071–2100
Cabinda	10.8	−0.4	−0.3	2.2	21.0	−1.6	−1.1	10.1
Cuango	8.6	3.3	4.0	7.7	17.7	11.0	12.9	31.0
Kassai	8.3	2.8	3.5	4.7	16.4	10.3	10.7	14.3
Noroeste	10.6	1.5	0.3	4.6	21.4	3.5	2.6	19.6
Dande	9.6	2.8	2.7	4.9	19.4	7.7	11.9	15.9
Bengo	10.6	1.2	−1.1	−0.6	19.9	3.3	2.7	4.3
Alto Kwanza	7.8	2.5	4.2	4.9	16.2	10.7	15.4	13.9
Medio Kwanza	8.3	1.9	1.6	4.0	17.5	6.0	6.1	11.7
Baixo Kwanza	9.7	1.0	0.3	2.5	20.3	3.8	3.5	10.0
Longa	9.4	0.1	−0.7	0.9	21.3	0.8	−1.1	3.5
Queve	8.5	0.4	−0.4	0.4	18.5	4.0	−2.0	1.4
Centro-Oeste	8.4	0.1	−0.7	0.0	19.0	2.7	−2.6	0.8
Catumbela	7.7	1.5	0.9	1.5	17.5	6.5	2.5	3.4
Zambeze	7.6	2.3	2.6	4.5	16.1	9.4	9.6	12.2
Alto Cunene	7.5	1.4	1.5	2.6	17.2	5.9	4.2	4.5
Medio Cunene	8.0	2.1	2.1	4.9	19.4	9.6	6.0	13.7
Baixo Cunene	8.1	1.8	1.4	3.8	20.4	7.8	3.4	15.4
Coporolo	7.6	1.2	0.9	1.7	19.8	3.3	0.3	2.9
Sudoeste	7.8	1.2	0.6	2.3	22.8	4.5	−0.2	6.7
Cuvelai	7.6	2.5	3.1	6.9	16.7	13.3	12.9	25.5
Cubango	7.8	2.4	2.8	6.3	17.6	9.7	10.9	16.7
Cuando	7.2	3.1	4.0	6.3	16.1	12.2	13.6	15.7

indicate that Angola is likely to face a pronounced warming and drying trend through the 21st century, which will require the implementation of adaptation measures, especially for water resources and agriculture.

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