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Assessment of Climate Change in Angola and Potential Impacts on Agriculture

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Abstract: Agroclimatic indicators help convey information about climate variability and change in terms that are meaningful to the agricultural sector. This study evaluated climate projections for Angola, particularly for provinces with more significant agricultural potential. To this end, 15 predefined agroclimatic indicators in 2041–2070 and 2071–2099, under the anthropogenic forcing scenarios RCP4.5 and RCP8.5, were compared with the historical period 1981–2010 as a baseline. We selected two climate scenarios and two temporal horizons to obtain a comprehensive view of the potential impacts of climate change in Angola. Data were extracted within the geographic window of longitudes 10–24° E and latitudes 4–18° S and from five general circulation models (GCM), namely MIROC-ESM-CHEM, HadGEM2-ES, IPSL-CM5A-LR, GFDL-ESM2M, and NorESM1-M. The set averages of agroclimatic indicators and their differences between historical and future periods are discussed in relation to the likely implications for agriculture in Angola. The results show significant increases in average daily maximum (2–3 °C) and minimum (2–3 °C) temperatures in Angola. For the future, a generally significant reduction in precipitation (and its associated indicators) is expected in all areas of Angola, with the southwest region (Namibe and Huíla) recording the most pronounced decrease, up to 300 mm. At the same time, the maximum number of consecutive dry days will increase across the country, especially in the Northeast. A widespread increase in temperatures is expected, leading to hot and dry conditions in Angola that could lead to more frequent, intense, and prolonged extreme events, such as tropical nights, the maximum number of consecutive summer days, hot and rainy days, and warm period duration index periods. These changes can seriously affect agriculture, water resources, and ecosystems in Angola, thereby requiring adaptation strategies to reduce risks and adverse effects while ensuring the sustainability of the country's natural resources and guaranteeing its food security.

Keywords: climate projections; agroclimatic indicators; temperature; precipitation; weather and climate extremes; Angola

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1. Introduction

Climate change is causing significant and potentially irreversible impacts across socioeconomic systems and ecosystems. The increasing frequency and intensity of extreme weather events are exposing millions of people globally to heightened food and water insecurity. Africa, Asia, Central and South America, the Least Developed Country Islands, and the Arctic are among the most affected regions. This includes adverse effects on indigenous peoples, small-scale food producers, and low-income households worldwide [1]. A study conducted by [2] points out that climate change has already significantly impacted global agriculture, mainly affecting the efficiency of agricultural production in the most vulnerable regions. The research, which focused on 43 countries around the world from 1992 to 2018, highlights the urgent need to develop adaptive technologies and strategies to ensure the resilience of the world's most important agricultural regions. The study uses climate models and agricultural productivity projections to assess the effects of climate change, considering different emissions scenarios and their impacts on key crops. Climate change has numerous implications for the farm sector, affecting crop growth, yield, and quality due to temperature, precipitation, phenology, pest dynamics, soil–plant interactions, and atmospheric CO_2 levels [3,4]. Rising global temperatures, heat and water stress, and shorter growing cycles reduce crop yields. As highlighted in [5], increasing average temperatures could shorten growing seasons, thus reducing final yields. These impacts would be more immediate and severe in regions where thermal conditions are already near the maximum tolerable limits for crops. Therefore, climate change may compromise agricultural production efficiency, especially in areas vulnerable to extreme weather conditions. Extreme events such as floods and heatwaves damage crops and degrade soil, while the proliferation of pests and diseases, driven by climate change, increases crop costs and reduces crop quality. Soil degradation and loss of agricultural biodiversity exacerbate the vulnerability of farming ecosystems, compromising their long-term sustainability and food safety and security [6,7].

In African countries, more specifically, climate change is expected to have far-reaching impacts on the environment, economy, and society due to the high dependence on climate-sensitive sectors like agriculture and a limited capacity for adaptation [8]. Southern Africa faces added pressure from rapid population growth and urbanisation, contributing to rising food demand. With a population currently estimated at 224 million and expected to grow to 241 million by 2050, the region must double food production to meet increasing demand, which is challenging for food security and safety [9]. Southern Africa is likely to be among the hardest-hit regions by climate change, with around 60% of its population living in marginalised and socioeconomically fragile rural areas [10,11]. Extreme heat and precipitation events have been observed in many Southern African regions, such as Angola, South Africa, Namibia, Mozambique, Zimbabwe, and Zambia, coupled with a general decline in annual precipitation [12]. This has also included increased drought frequency globally, a trend projected to persist even if global warming stabilises at 2 °C [12].

Angola, in particular, is among the most vulnerable countries to climate change, with its southern region experiencing prolonged droughts over the last decade, including what has been described as the worst drought in 40 years [12,13]. Thus, climate impacts are not merely a future threat but an ongoing issue for Angola. Assessments from the Climate and Development Report for Angola corroborate that warming has intensified in recent years, with average annual temperatures rising by 1.4 °C since 1951, while this trend is expected to continue and intensify over the next decades [12]. Additionally, increases in maximum and minimum temperatures alongside significant shifts in regional precipitation patterns are anticipated [12]. In Angola, as in much of Southern Africa, agriculture is predominantly rainfed, with nearly 95% of farming dependent on rainfall [14]. Irrigation is often unfeasible due to low water availability or high economic costs. This makes the agricultural sector highly vulnerable to climate change, given the region's low adaptive capacity to warmer and drier conditions [9,15–18].

Drought in Huambo, Huíla, and Bié, provinces responsible for more than 50% of the national cereal production, exposed 1.8 million people to food insecurity in 2012. Between

2011 and 2012, cereal production fell by 64%, from 1.4 million to 509 thousand tons. Other crops also recorded significant losses: the production of legumes decreased by 68.4%, while cassava, the country's main crop, decreased by 25.8%. Despite some improvements in 2013, cassava production fell again in 2014, with reindeer potatoes remaining [19]. In the early months of 2019, a new severe drought event caused a food security and nutrition crisis that affected 2.3 million people, including nearly half a million children under five. Water shortages for crops and animals led to a low 2018–2019 harvest. As a result, the cost of essential commodities like corn, flowers, beans, and sugar increased by 25%. Small farmers and pastoralists are also negatively impacted [19]. In Angola, around 7.6 million people live annually in areas affected by drought, of whom 1.9 million are directly impacted [19]. The impacts of climate change also come at a high price: climate-related catastrophes (floods, storms, and droughts) cost Angola around USD 1.2 billion between 2005 and 2017, and, on average, droughts alone affect around a million Angolans every year [20]. In 2019, it was estimated that 1.14 million people faced food insecurity in the southern provinces of Namibe, Cunene, Cuando Cubango, and Huíla [21]. Agriculture, vital for food security and employing 51% of the population, contributes only 9% to the GDP, reflecting an underdeveloped and low-productivity sector [20]. Agriculture has excellent growth potential, considering that only a third of arable land is under cultivation and less than 2% is mechanised [20].

Under future climate conditions, the number of affected people will increase to 3.4 million, reaching 7.9 million if climate and socioeconomic projections are considered [20]. Angola's agricultural sector is highly exposed to climate risks, with drops in annual precipitation, a reduction in rainy days, and intense rain events across the country [8]. This reduction in water availability will be especially critical for the south of the country, where temperatures could increase by between 2 and 3 °C [8]. With Southwest and Southeast Angola projected to become drier, hydroelectric power generation on the Cunene River, for example, is expected to be reduced. Furthermore, in urban areas, where two-thirds of Angolans live, climate change is likely to worsen water scarcity, intensify storms and coastal flooding, and increase risks associated with inadequate sanitation [20].

A recent example of Angola's low capacity to adapt to climate change was the severe drought suffered for much of 2013, one of the worst in 30 years, when approximately 1.5 million people in Southern Angola faced food insecurity, leading UNICEF to launch an appeal for USD 14.3 million to finance the drought response [22]. In 2020/2021, Angola again faced drought, with accumulated rainfall 30% below the long-term average, affecting 11.1 million people (37% of the population), many of whom depend on subsistence agriculture, dependent on rain [21].

Climate change is expected to significantly impact key sectors such as agriculture, health, and water, which play crucial roles in Angola's economy and livelihoods [22]. Economic losses in the agricultural sector caused by droughts could increase from USD 100 million annually to more than USD 700 million by 2100 [20].

Projections indicate that Angola's agricultural productivity may decrease by 7% by 2050 under continued climate impacts, threatening food security and exacerbating poverty [20]. Primary crops, including corn (*Zea mays*), sorghum (*Sorghum bicolour*), millet (*Pennisetum glaucum*), beans (*Phaseolus vulgaris*), cassava (*Manihot esculenta*), and potatoes (*Solanum tuberosum*), play crucial roles in the country's food security and rural development [23]. The corn (*Zea mays*) belongs to the family Poaceae, genus Zea, and species Z. mays, classified as Angiospermae, order Poales; sorghum (*Sorghum bicolour*) is in the family Poaceae, genus Sorghum, and species S. bicolour, also belonging to Angiospermae, order poales; and the millet (*Pennisetum glaucum*) belongs to the family Poaceae, genus Pennisetum and species *P. glaucum*, classified as Angiospermae, order Poales [24]. The beans (*phaseolus vulgaris*) belong to the family Fabaceae, genus Phaseolus, and species *P. vulgaris*, classified as Angiospermae, order Fabales; as for cassava (*Manihot esculenta*) belongs to the family Euphorbiaceae, genus Manihot, and species M. esculenta, classified as Angiospermae, order malpighiales [25]. Finally, the potatoes (*Solanum tuberosum*) belong to the Solanaceae family, Solanum genus, and S. tuberosum species, classified as Angiospermae, order Solanales [26]. In this study, a climate analysis will be carried out for each crop to assess how climate change affects their productivity and adaptability. The methodology will include analysing historical and projected climate data, considering indicators such as temperature, precipitation, and other agroclimatic factors to identify each crop's direct impacts and possible adaptation strategies.

Temperature and precipitation significantly influence crops and their yields, affecting key processes like photosynthesis, leaf area, and growing season length [18,27–30]. Rising temperatures can accelerate plant development and phenology, while declining seasonal precipitation increases evapotranspiration, causing crop water stress. In regions where temperatures approach the physiological limits for crop tolerance, such as tropical dry zones, rising temperatures intensify heat stress and exacerbate water loss through evapotranspiration [31]. Air temperature and soil moisture, primarily driven by precipitation, are key determinants of growing season duration, crop development, and water requirements. While higher temperatures can reduce frost periods, promoting cultivation in marginal farmlands, they also shorten crop cycles and reduce yields in arid and semi-arid areas due to intensified water stress [32].

Precipitation is the primary source of fresh water and a critical factor in soil moisture levels, essential for crop growth and development. Yield variability often correlates with precipitation irregularity, while crop evapotranspiration remains relatively stable, determining crop water needs [32]. Water deficits, even short-term, can significantly reduce cereal growth and production, often being a primary cause of crop loss [33]. Soil humidity also affects crop growth directly by altering plant water content and indirectly by influencing factors such as leaf growth, photosynthesis, pollination, and disease risk [30].

Agroclimatic indicators, in particular, serve as valuable tools in assessing the impacts of climate change on crops. These indicators allow a better assessment of climate change, variability, extremes, and their effects on crops, allowing us to anticipate and respond to changes in climate conditions, such as heat stress, drought, and excessive humidity [33–35]. Hence, this study aims to analyse a selection of agroclimatic indicators under climate change scenarios to provide key information for the adaptation of agricultural areas in Angola. It is essential to anticipate and minimise climate change risk by implementing timely and suitable adaptation measures, namely adjusting agricultural cultivation techniques to future climatic conditions [36].

2. Materials and Methods

2.1. Datasets

This study adopts a comprehensive approach to analysing agroclimatic indicators in Angola, focusing on their spatial patterns and recent and future values. The aim is to infer potential impacts on the country's agricultural sector. The analysis was conducted in two main steps: comparing agroclimatic indices under climate change scenarios and studying the suitability of some crops.

The input data were obtained from the Fast Track product of the Intersectoral Impact Model Intercomparison Project (ISIMIP), which provides bias-corrected daily climate data from General Circulation Models (CMIP5) covering the complete period from 1951 to 2099. The agroclimatic indices were generated using the WFDEI (Watch Forcing Data applied to ERA-Interim) methodology for the climatological period 1981–2010 [37]. Historical reference data were taken from the ERA-Interim Reanalysis (ECMWF), while climate projections were based on the RCP4.5 and RCP8.5 anthropogenic emissions scenarios.

For future projections, two time periods were analysed: 2041–2070 (medium-range future) and 2071–2099 (long-range future), which were then compared with the historical ERA-Interim period (1981–2010). To ensure the robustness of the predictions, five Global Climate Model (GCM) experiments were used: MIROC-ESM-CHEM (JAMSTEC, Yokosuka, Japan), IPSL-CM5A-LR (IPSL, Guyancourt, France), NorESM1-M (NCC, Oslo, Norway), HadGEM2-ES (UK Met Office, Exeter, UK), and GFDL-ESM2M (NOAA, Washington, DC, USA). Studies such as [38,39] validate the performance of these models, which are effective in simulating climate conditions in tropical and subtropical regions, such as Sub-Saharan Africa, particularly concerning temperature, precipitation, and extreme events (such as droughts and heatwaves). The selection of these models aims to reduce uncertainty in climate projections and ensure a more accurate analysis of climate impacts on agriculture in Angola. These GCMs were chosen due to their proven ability to accurately represent the relevant climatic conditions for the study, ensuring robustness and reliability in the results obtained. Ensemble means were then calculated to resolve variability between models, reducing uncertainty and increasing the reliability of climate predictions [40]. However, the standard deviation within the ensemble of five models was also calculated for each index separately to assess variability among models and the corresponding uncertainties in climate change projections. A more significant standard deviation implies greater uncertainty in the projected mean value for a given period and scenario. For greater clarity, the standard deviation isolines were superimposed on the maps of the differences between each index's future and historical periods.

Based on the agroclimatic indices projected for the RCP4.5 and RCP8.5 scenarios, the suitability of some crops in Angola was assessed, considering the impacts of climate change on future agroecological conditions. The crop suitability analysis focused on changes in temperature and precipitation conditions and how these variables affect the growth and productivity of crops such as corn (*Zea mays*), sorghum (*Sorghum bicolour*), millet (*Pennisetum glaucum*), beans (*Phaseolus vulgaris*), and cassava (*Manihot esculenta*), which are most relevant to Angolan agriculture.

Understanding the climatic needs of each crop is essential for sustainable production planning and enhancing resilience against climate variations [41]. Table 1 presents Angola's main crops and the suitable temperature and precipitation ranges that ensure their maximum growth, development, and productivity.

Table 1. Based on the outlined literature, indicative temperature and precipitation suitability ranges of Angola's main crops.

Culture	Author(s)	Suitable Temperature (°C)	Restricted Temperature (°C)	Anapta Temperature (°C)	Suitable Precipitation (mm/year)	Restricted Precipitation (mm/year)	Unsuitable Precipitation (mm/year)
Corn	[42–44]	20–30	10–20/30–35	<10/>35	500–800	400–500/ 800–1200	<400/>1200
Sorghum	[42,43]	20–35	15–20/35–40	<15/>40	400–600	300–400/ 600–800	<300/>800
Millet	[42,43]	25–35	20–25/35–40	<20/>40	200–600	100–200/ 600–800	<100/>800
Bean	[42–44]	18–24	15–18/24–30	<15/>30	500–800	400–500/ 800–1200	<400/>1200
Cassava	[42,43]	25–29	20–25/29–35	<20/>35	1000–1500	600–1000/ 1500–2000	<600/>2000
Potato	[42,43]	15–20	10–15/20–25	<10/>25	500–750	400–500/ 750–1000	<400/>1000

Given Angola's high vulnerability to climate change and its climates characterised by severe or extreme droughts and frequent heat waves, it is essential to consider climate scenarios that represent higher risk trajectories, such as RCP8.5. This scenario reflects a high emissions trajectory (energy production heavily based on fossil fuel consumption), allowing a conservative and robust analysis of potential adverse climate conditions to support the development of short- and medium-term adaptation strategies [40,45]. While both RCP4.5 and RCP8.5 scenarios are analysed in this study, the focus on RCP8.5 for the period 2041–2070 aims to prioritise adaptation actions in the medium term in response to more extreme climate conditions, aligning with the ongoing climate crisis in Angola. It is worth noting that these two scenarios are not substantially different in the medium-range period (2041–2070), as they begin to diverge more significantly towards the end of the century (2071–2099).

2.2. Study Area Characterisation

Angola is a large country with a total area of 1,246,700 km^2. Located in Southern Africa, the Republic of Angola is bordered 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 South Atlantic Ocean (Figure 1a). Furthermore, it covers the enclave of Cabinda, which borders the Republic of Congo to the north [12,46]. Angola is divided into administrative regions (so-called provinces), as shown in Figure 1b. In the southwestern provinces of Huila, Huambo, Benguela, Cuanza Sul, and Bié, agriculture is a prominent activity, illustrated by the cropland cover areas in Figure 1c. Vast areas of the country are covered by savanna, shrubland, grassland, tropical forest, or bare land. Most of the cropland regions are located on Angola's central plateau, with elevations above 1000 m (Figure 1d), thus having high-elevation cooler climates than in the rest of the country.

Overall, Angola's climates are characterised by hot, humid summers and mild, dry winters. The cold Benguela eastern boundary current (EBC), the high-elevation central plateau, and the location and strength of the Intertropical Convergence Zone (ITCZ) are key factors that determine regional climates. Together, these characteristics generate a strong north-south climate gradient. Angola is dominated by three climatic zones based on the Köppen classification: a hot and humid tropical zone in the North, a subtropical climate in the central plateau, and a desert climate in the Southwest [47]. The three types of climate mentioned above have a profound impact on the local ecosystems and socioeconomic activities.

The climate of the hot and humid tropical zone in the North is typical of regions close to the equator, where temperature and humidity are high throughout the year. Precipitation is frequent and abundant, generally concentrated in a well-defined hot, rainy season [48]. The more moderate subtropical/tropical climates in the central plateau are found in higher-elevation areas. They have milder temperatures than the low tropical zones, with a clear distinction between the dry and rainy seasons, but the temperature variation between the seasons is moderate [49]. The sub-arid/arid climates in the Southwest feature extremely high diurnal temperatures and relatively low nocturnal temperatures, with very low annual precipitation amounts (almost zero precipitation along the southernmost coast). In this area, air humidity is typically very low off the coast, being vegetation-sparse and adapted to arid/desertic conditions [50]. As such, the Northeast of Angola is the wettest region, while sub-arid/arid conditions prevail in the South and West [22,51]. Precipitation varies between less than 20 mm annually in the very Southwest to more than 1600 mm in the Northwest and Northeast [8,51]. The winter season (June, July, and August) is commonly the driest throughout the country, with generally scarce precipitation. Although the rainy season occurs between October and May, the summer months (December, January, and February) are responsible for the bulk of the annual precipitation [22].

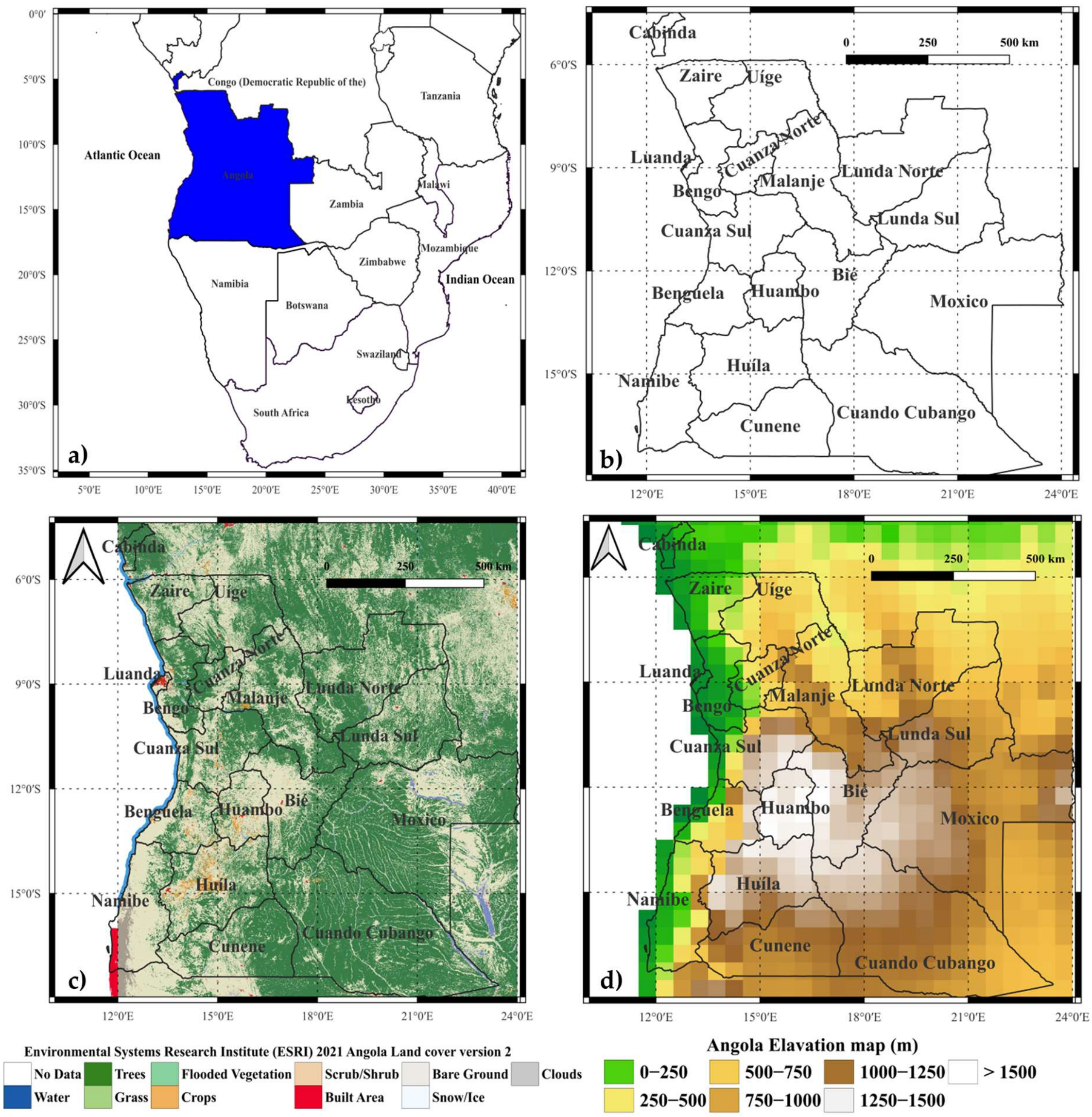

Figure 1. Map of Southern Africa: (**a**) the geographical location of Angola on the African continent is highlighted in blue; (**b**) the map of Angola with its provinces; (**c**) land use and land cover map of Angola for the year 2021 (data adapted from Karra, Kontgis, et al., 2021) [52]; (**d**) Angola elevation map [53].

2.3. Agroclimatic Indicators

The 15 selected agroclimatic indicators (Table 2) were retrieved from the Copernicus Climate Change Service (C3S) platform, with global coverage at a horizontal resolution of 0.5° latitude × 0.5° longitude (~55 km grid spacing), covering the period from 1951 to 2099. Depending on the indicator, data are available at various time scales (daily, 10-day, seasonal, and annual) [37]. Among the 15 indicators, the maximum number of consecutive dry days (CDD), the maximum number of consecutive summer days (CSU), the maximum number of consecutive wet days (CWD), warm and wet days (WW), and the warm spell duration index (WSDI) are available at the seasonal resolution, whereas the remaining indicators are available at the 10-day temporal resolution. Absolute/relative differences between future and historical periods were calculated for each agroclimatic indicator, allowing for the identification of robust changes. Results were analysed by regions (provinces) of Angola, highlighting the heterogeneity of regional climate change signals and their likely impacts on agriculture.

Table 2. Agroclimatic indicators [37].

N°	Name	Symbol	Units	Description
1	Biologically effective degree days	BEDD	°C	Sum of daily mean temperatures (TG) above 10 °C and less than 30 °C, over 10 days.
2	Heavy precipitation days	R10 mm	day	Number of days per 10 days when RR > 10 mm, where RR is the daily precipitation sum. This indicator provides information on crop damage and runoff losses.
3	Maximum number of consecutive dry days	CDD	day	Longest consecutive days when RR < 1 mm, where RR is the daily precipitation sum. This indicator is used for drought monitoring.
4	Maximum number of consecutive summer days	CSU	day	Longest consecutive days when TX > 25 °C, where TX is the daily maximum temperature. This indicator provides information on drought stress or on optimal growth for C4 crops (crops that use the C4 carbon fixation pathway, e.g., maize).
5	Maximum number of consecutive wet days	CWD	day	Longest consecutive days when RR > 1 mm, where RR is the daily precipitation sum. This indicator provides information on drought, oxygen stress, and crop growth (i.e., less radiation interception during rainy days).
6	Mean of daily maximum temperature	TX	°C	Mean value of TX over 10 days, where TX is the daily maximum temperature. This indicator provides information on long-term climate variability and change.
7	Mean of daily mean temperature	TG	°C	Mean value of TG over 10 days, where TG is the daily mean temperature. This indicator provides information on long-term climate variability and change.
8	Mean of daily minimum temperature	TN	°C	Mean value of TN over 10 days, where TN is the daily minimum temperature. This indicator provides information on long-term climate variability and change.
9	Precipitation sum	RR	mm	The sum of RR over 10 days, where RR is the daily precipitation sum. This indicator provides information on possible water shortage or excess.
10	Simple daily intensity index	SDII	mm	Mean of RR over 10 days in which RR > 1 mm (wet days), where RR is the daily precipitation sum. This indicator provides information on possible runoff losses.
11	Tropical nights	TR	day	Number of days per 10 days when TN > 20 °C, where TN is the daily minimum temperature. This indicator indicates the occurrence of various pests.
12	Very heavy precipitation days	R20 mm	day	Number of days per 10 days when RR > 20 mm, where RR is the daily precipitation sum. This indicator provides information on crop damage and runoff losses.
13	Warm and wet days	WW	day	Number of days per 10 days when TG > TG75th and RR > RR75th; where TG is the daily mean temperature, TG75th is the calendar day 75th percentile, RR is the daily precipitation sum, and RR75th is the 75th percentile of precipitation on wet days.
14	Warm spell duration index	WSDI	day	Number of days per season with at least six consecutive days when TX > TX90th, where TX is the daily maximum temperature and TX90th is the calendar day 90th percentile.
15	Wet days	RR1	day	Number of days per 10 days when RR > 1 mm, where RR is the daily precipitation sum. This indicator provides information on intercepted reduction.

3. Results

3.1. Agroclimatic Projections for Angola

3.1.1. Precipitation-Related Indices

A set of 15 agroclimatic indicators were used to assess the effects of climate change in Angola. These indicators were mainly selected due to their close connection with factors that affect agricultural productivity. These factors can directly affect climate suitability for growing a given crop, as well as cultural practices (e.g., irrigation).

The following precipitation-related agroclimatic indicators are analysed herein: precipitation sum (RR), number of wet days (RR1), and simple daily intensity index (SDII). Figure 2 presents maps for historical and future climate data based on the RCP8.5 scenario (Figure S1 in Supplementary Material is similar to Figure 2 but for RCP4.5). The data is split into the following periods: 1981–2010 (historical), 2041–2070 (mid-range future), and the difference between the two periods (Figure S2 shows the corresponding results for the long-range period, 2071–2100). In general, these indicators have a sharp southwest-northeast gradient and are characterised by strong seasonality, thus reflecting the aforementioned spatial pattern and temporal regime of precipitation in Angola [3].

Historically, Angola shows regional contrasts in precipitation: the North, Northeast, and Central regions receive between 1000 mm and 1400 mm, while the South records significantly lower volumes, such as in Namibe (below 200 mm) and Cunene, Cuando Cubango, and Huíla (400 mm to 600 mm). In the future, precipitation is expected to remain stable in most parts of the country. Reductions of 200 mm to 400 mm are projected for Cuanza Norte, Cuanza Sul, southern Benguela, northern Namibe, and Huíla. Slight increases (up to 100 mm) are anticipated in the North, particularly in Malanje and Lunda Norte.

For RR (Figure 2a–c) and during the historical period, Angola's North, Northeast, and Centre experienced high amounts of precipitation. In the North, the province of Uíge stands out; in the Northeast, the province of Lunda Norte and a part of Lunda Sul, with precipitation around 1400 mm. In central Angola, Huambo, Bié, and a part of southern Cuanza, we have rainfall between 1000–1400 mm. In contrast, the South of Angola had lower precipitation amounts, mainly the province of Namibe, with precipitation below 200 mm; for Cunene, Cuando Cubango, and Huíla, precipitation varies from 400 mm to 600 mm. The projections indicate that, in most parts of the country, there are no significant changes in RR. The exception is in some regions of the coastal provinces (Benguela and Cuanza Sul) and the province of Cuanza Norte, and this reduction will be most significant in Cuanza Norte, Cuanza Sul, southern parts of Benguela, northern parts of Namibe, and Huíla, ranging from 200 to 400 mm. On the other hand, projections show a slight increase of 100 mm in precipitation sum in some parts of the North of the country, particularly in Malanje and Lunda Norte provinces.

For the historical period, northern and northeastern Angola showed a high (RR1), with more than 210 per year (Figure 2d–f). In contrast, southern Angola recorded fewer RR1, with less than 120 per year. In this region, the province of Namibe stands out with fewer than 30 wet days, as it is an arid/desertic climate province. Projections also indicate a reduction in the RR1 in several regions of the country, specifically in the northern, coastal, and northeastern regions, reaching values of up to 40 days. In Southern Angola, the provinces of Namibe and Huíla are expected to record a slight increase in the RR1, ranging from 10 to 20 days.

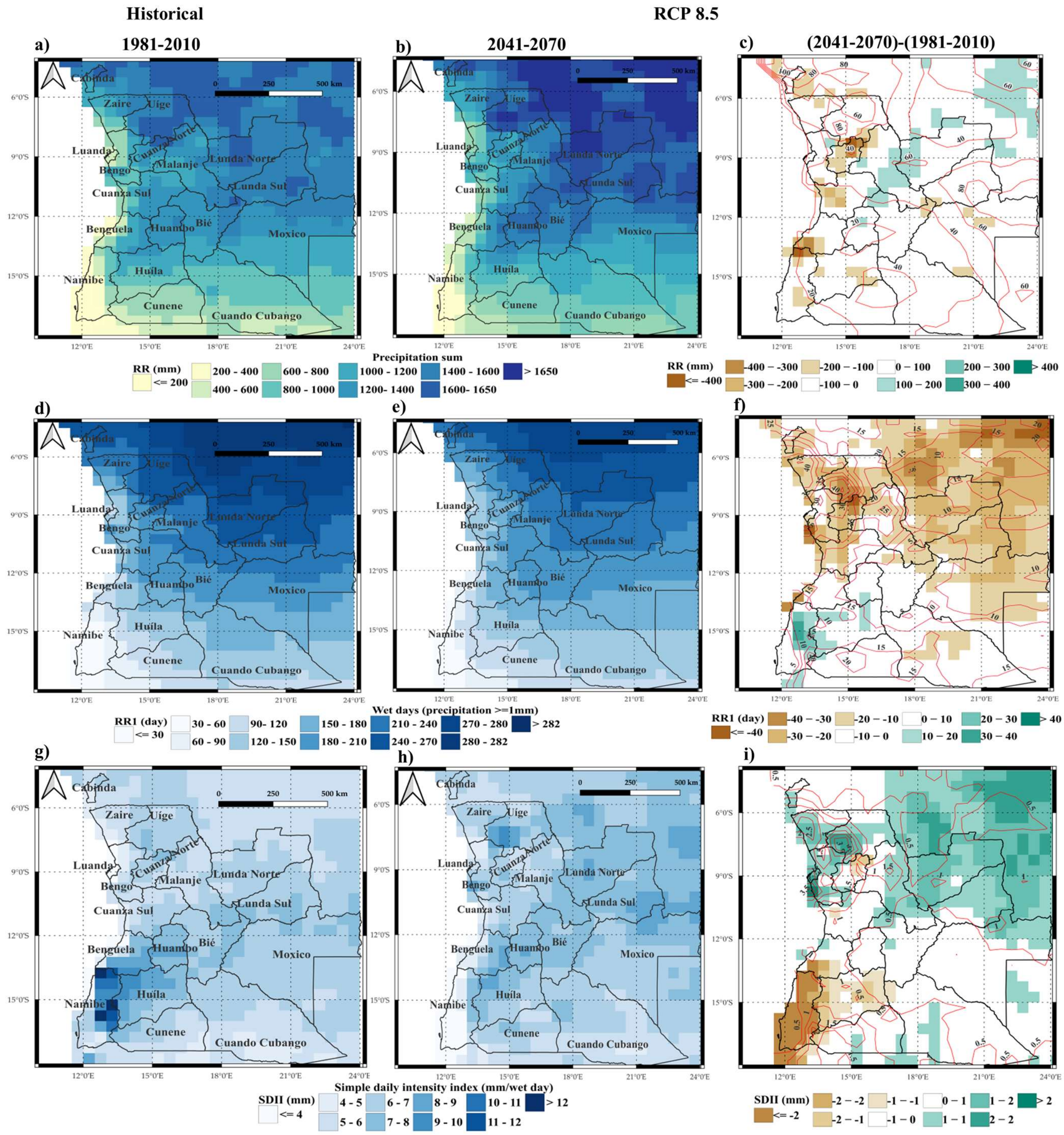

Figure 2. Climate means of the outlined agroclimatic indicators (RR: precipitation sum; RR1: wet days; SDII: simple daily intensity index for wet days) for the historical period 1981–2010 (**a**,**d**,**g**), the five-member ensemble mean projections for the future period 2041–2070 under RCP8.5 (**b**,**e**,**h**), and the corresponding differences (**c**,**f**,**i**) future minus historical period). The corresponding ensemble standard deviation isolines are overlaid on the different maps. See respective legends for scales and units.

During the historical period, the south of the country (Huíla and Namibe) revealed a high SDII, varying from 8 to 12 mm/day. On the other hand, some provinces, both inland (Cunene and Cuando Cubango) and coastal (Bengo and Luanda), experience low values of this index (4–5 mm). Projections suggest small changes in this agroclimatic indicator in several parts of the country, but a slight increase of 2 mm/day will be expected in the northern and northeastern regions. In comparison, there will be a significant reduction in the SDII of 2 mm/day in the South, specifically in Namibe, Huíla, and part of Benguela in the South and Cuanza Norte in the North.

The standard deviation analysis of the 15 agroclimatic indicators provides a measure of variability and agreement among climate models across Angola. It highlights regions of higher and lower consistency in projections, with significant variability often indicating greater uncertainty in future scenarios. This information is critical for understanding regional disparities in climate impacts and guiding adaptive strategies.

Regarding the standard deviation of RR, which reflects model agreement or uncertainty in future projections, it is highest in the Northwest (>80 mm) and in Lunda Sul (Northeast). In comparison, it is lowest in the Southeast (<20 mm). Model agreement is more substantial in the central and southeastern regions, while disagreement is more pronounced in the northern areas. The standard deviation for RR1 reaches its peak in the Northwest (>35 days) and its lowest values in the central and southeastern regions (<10 days). The central and southeastern areas show greater model consistency, contrasting with the higher variability observed in the northern regions. For SDII, the highest standard deviations are found along the central coast (Bengo and Luanda) and in the Northwest (Zaire and Uíge) (>2.5 mm). Conversely, the lowest values are observed in the Central East (<0.5 mm). Agreement among models is more significant in the Central East, while variability increases in the southern and western regions.

The analysis of the maps indicates that the degree of uncertainty varies according to the index and region. RR shows a high standard deviation in the Northwest and Northeast but represents a small fraction of the projected values (5–10%), suggesting moderate uncertainty. Regarding RR1, variability is proportionally higher in regions such as the Northwest, reaching up to 20% of the projected values, indicating more significant uncertainty. SDII, although showing a high standard deviation in some coastal regions, generally represents less than 10% of the projected values, indicating reduced uncertainty across most territories. These proportions show that uncertainty is more relevant in areas of lower agreement among the models, especially for variables related to precipitation frequency.

Figure 3 presents maps with historical and future climate data, based on the RCP8.5 scenario, of the following precipitation-related agroclimatic indicators: heavy precipitation days (R10 mm), very heavy precipitation days (R20 mm), maximum number of consecutive wet days (CWD), and maximum number of consecutive dry days (CDD).

During the historical period, the lowest R10 mm was observed in the southern and coastal provinces of Angola, reaching values below 5 days in some regions. On the other hand, in the future, the R10 mm should be reduced by up to 20 days in a large part of the country, especially in the South, Centre, and Northwest of Angola. On the other hand, there is a significant increase in this indicator of about 15 days in the Northeast of the country, specifically in the province of Lunda Norte, and a slight increase of 10 days in some parts of the provinces of Uíge and Malanje.

Most of the country recorded very low values of R20 mm, which may not exceed one day in some coastal areas of the provinces of Namibe, Benguela, and Luanda. In contrast, the mountainous region of Huila and Huambo, as well as the southern part of Benguela, showed significantly higher values, around 12 days (Figure 3d–f). Projections point to an increase of 2 to 4 days in days of R20 mm in the northern and northeastern regions, that is, in some parts of the provinces of Bengo, Uíge, Lunda Norte, and Lunda Sul. On the other hand, the province of Huíla and parts of Benguela and Namibe will have a reduction of 6 to 8 days of R20 mm.

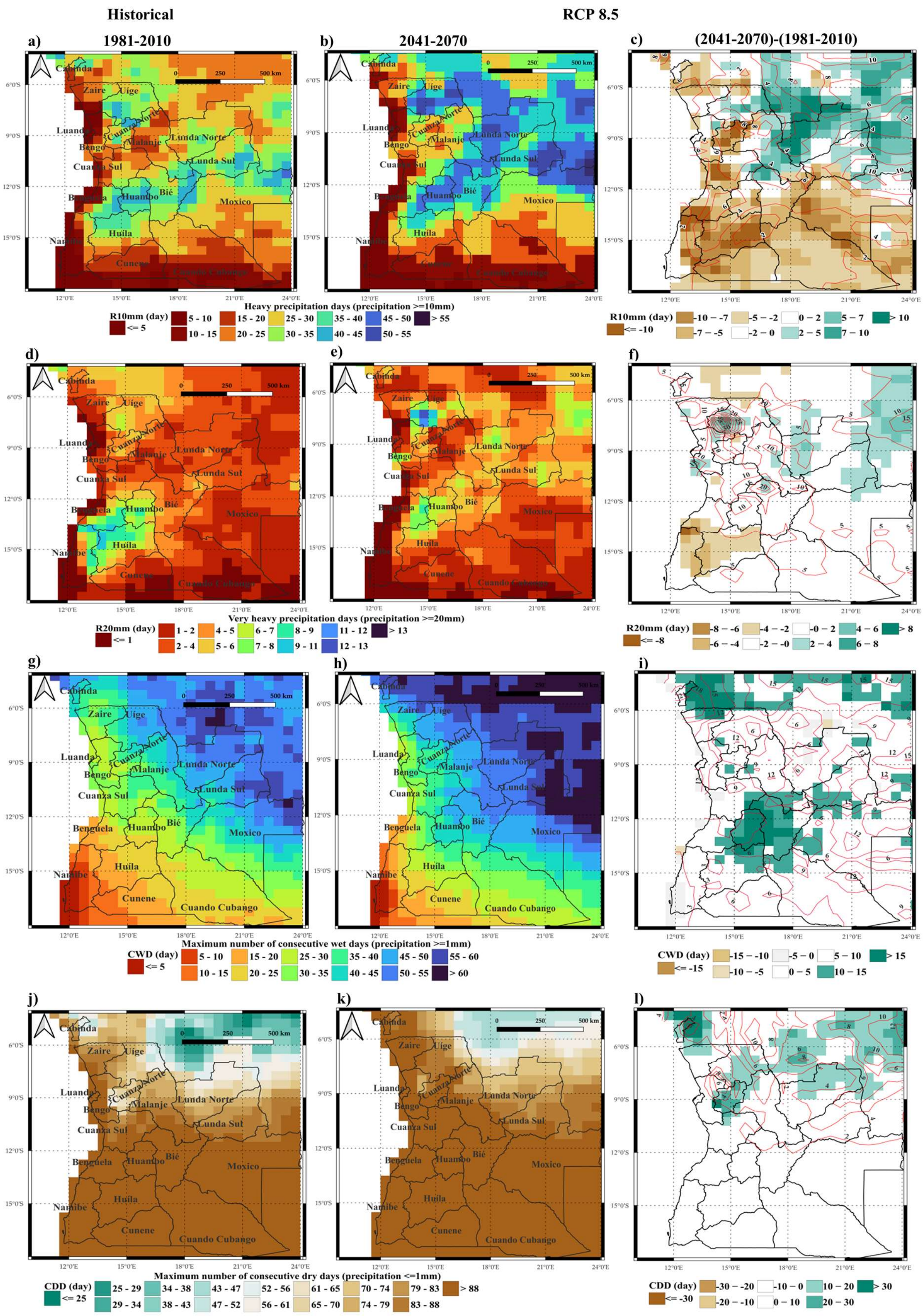

Figure 3. Climate means of the outlined agroclimatic indicators (R10 mm: heavy precipitation days; R20 mm: very heavy precipitation; CWD: maximum number of consecutive wet days; CDD: maximum number of consecutive dry days) for the historical period 1981–2010 (**a**,**d**,**g**,**j**), the five-member ensemble mean projections for the future period 2041–2070 under RCP8.5 (**b**,**e**,**h**,**k**), and the corresponding differences (**c**,**f**,**i**,**l**). The corresponding ensemble standard deviation isolines are overlaid on the different maps. See respective legends for scales and units.

Regarding the CWD and for both the historical period and the future, there is a strong southwest-northeast gradient (Figure 3g,h) that divides the country into almost two distinct parts. While the southwestern part has the lowest CWD values, the northeastern part has the highest CWD values. However, there is a slight difference between these two periods (Figure 3i), especially in the Centre and extreme Northwest of the country, where there is an increase in the future period of CWD values greater than 15 days in the provinces of Cabinda and Zaire in the North, and Huambo and Bié in the Centre.

In both historical and future periods, southern and central provinces consistently show high CDD values (>92 days), while northern and northeastern regions record lower values (56–79 days). Projections indicate increases of up to 30 days in Cabinda and Cuanza Norte, with additional rises in Cabinda, Uíge, Zaire, Lunda Norte, and Malanje, while other provinces are expected to maintain historical patterns.

Both for the historical period and for the future, there is a notable similarity between the CDD in the southern and central provinces of the country, where this agroclimatic indicator reaches a value greater than 92 days. The CDD ranges from 56 to 79 in some northern and northeastern provinces. Projections indicate an increase in CDD in the northern and northeastern regions and a significant increase in the Cabinda and Cuanza Norte provinces of up to 30 days. There is also an increase in the provinces of Cabinda, Uíge, and some parts of the provinces of Zaire, Lunda Norte, and Malanje, while the other provinces maintain the pattern (Figure 3j–l).

For R10 mm, the standard deviation peaks in Cuanza Norte (>8 days) and Moxico (>10 days). In contrast, it is lowest in the central-southern regions (<2 days). Greater consistency is observed in the central and southern areas, while variability is more pronounced in the northern and eastern regions. The highest standard deviations for R20 mm are found in the Northwest (>30 mm), while the lowest values are seen in the South and East (<5 mm). Agreement is stronger in the southern and eastern regions, whereas the Northwest displays higher variability. In the case of CWD, the standard deviation reaches its maximum in the Northwest (>15 days) and its minimum in the Southeast (<5 days). The central and southeastern areas show greater consistency, with increased variability in the northern and western regions. When analyzing CDD (Consecutive Dry Days), the northern regions exhibit the highest standard deviations (>30 days), while the central areas record the lowest (<10 days). The central regions demonstrate higher consistency, with greater variability noted in the North.

Regarding R10 mm, the standard deviation is high in the North and Centre but represents about 10–15% of the projected values, indicating moderate uncertainty. For R20 mm, uncertainty is higher in the Northwest, where the standard deviation can represent up to 20% of the projected values, suggesting greater variability among the models. As for CWD, variability is proportionally higher in the Northwest, but in other regions, the standard deviation represents less than 10% of the projected values, pointing to reduced uncertainty in most of the territory. For CDD, uncertainty is low across most of the territory, with the standard deviation representing less than 5% of the projected values, reinforcing greater consistency among the models. These results highlight that uncertainty is more significant for variables related to extreme precipitation events in the North and Northwest, while in the southern and southeastern regions, variability is proportionally lower, providing greater confidence in the projections.

3.1.2. Temperature-Related Indices

Temperature-related agroclimatic indicators, namely, the mean daily mean temperature (TG), mean daily maximum temperature (TX), mean daily minimum temperature (TN), and biologically effective degree days (BEDD), are now analysed. Figure 4 presents maps with historical and future climate data in different regions based on the RCP 8.5 scenario. The data is divided into three periods: 1981–2010 (historical), 2041–2070 (future), and the difference between the two periods.

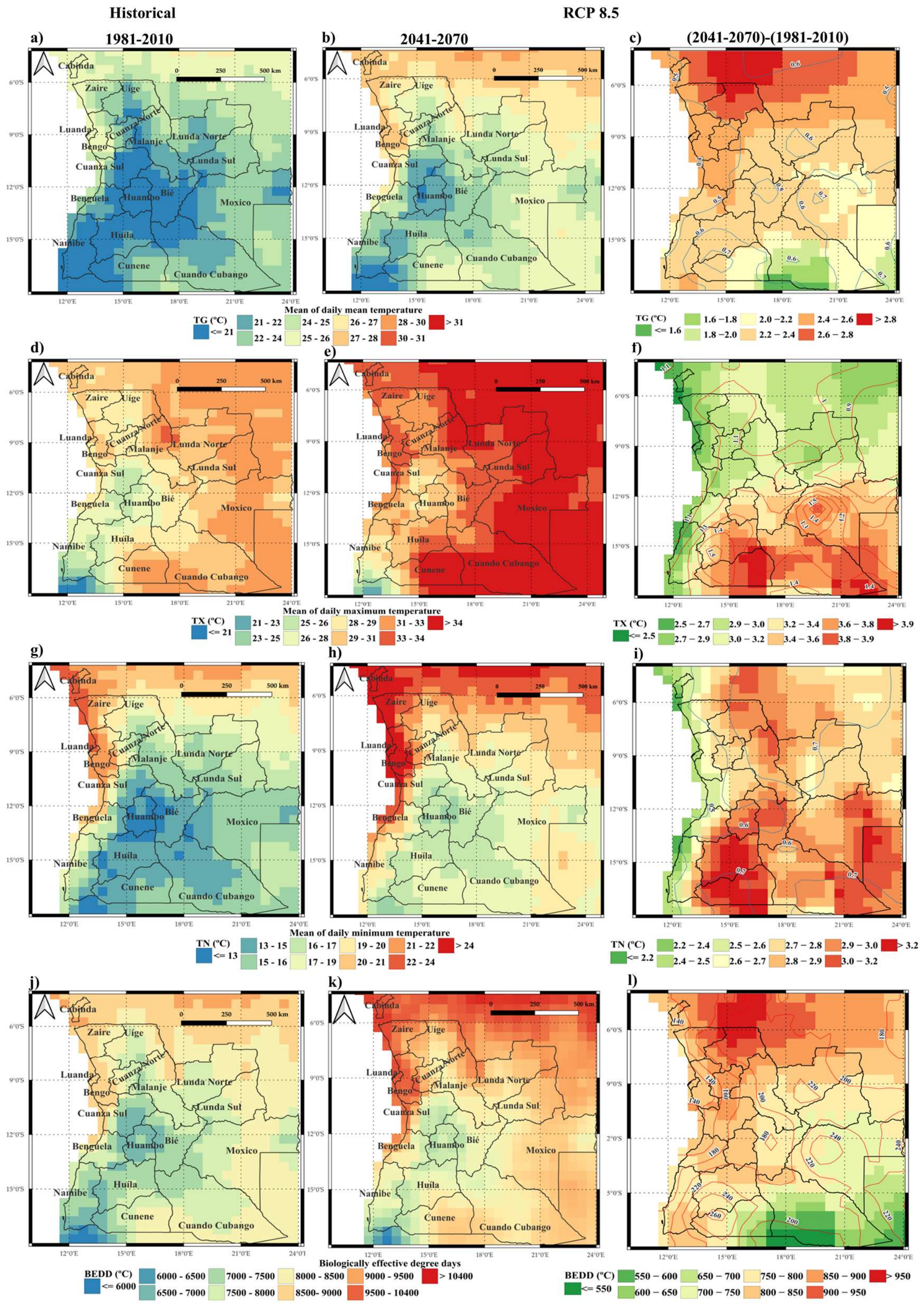

Figure 4. Climate means of the outlined agroclimatic indicators (TG: mean of daily mean temperature; TX: mean of daily maximum temperature; TN: mean of daily minimum temperature; BEDD: biologically effective degree days) for the historical period 1981–2010 (**a**,**d**,**g**,**j**), the five-member ensemble mean projections for the future period 2041–2070 under RCP8.5 (**b**,**e**,**h**,**k**), and the corresponding differences (**c**,**f**,**i**,**l**). The corresponding ensemble standard deviation isolines are overlaid on the different maps. See respective legends for scales and units.

TG values in Angola ranged from 21 to 22 °C in southern and central regions to 24–25 °C in northern and coastal areas. Projections show a general TG increase, with rises of 2.1–2.4 °C in coastal, central, and northern provinces, over 2.8 °C in Uíge and Zaire, and the smallest increase (~1.6 °C) in Cuando Cubango.

In the historical period, the TG values were observed in the southern and central regions, ranging from 21 to 22 °C. In contrast, the northern and coastal regions recorded higher TG values, ranging from 24 °C to 25 °C (Figure 4a–c). Projections show a slight increase in this agroclimatic indicator in all regions of the country, a more pronounced increase of 2.1 to 2.4 °C in the coastal, central, and northern provinces of Angola and may reach a value of greater than 2.8 °C in the extreme north of Uíge and Zaire. It is worth noting that, compared to the other provinces, the province of Cuando Cubango will register the smallest increase in this indicator of about 1.6 °C.

TX values varied from 22 to 26 °C in Huambo, Bié, Namibe, Cuanza Sul, and Huíla, and 27–32 °C in Cunene, Cuando Cubango, and Lunda Norte. Projections show TX increases nationwide, with significant rises (3.2–3.8 °C) in central, southern, and eastern provinces and smaller increases (2.2–2.6 °C) in coastal northern regions.

During the historical period, the provinces of Huambo, Bié, Namibe, parts of Cuanza Sul, and Huíla presented the lowest TX, ranging between 22–26 °C. The other provinces registered slightly higher values, ranging between 27–32 °C, especially in Cunene, Cuando Cubango, and Lunda Norte (Figure 4d–f). An increase in values of TX is predicted in all regions. In fact, a significant increase of 3.2 to 3.8 °C will be observed in the central (Bié and Huambo) and southern (Huíla, Cunene, and Cuando Cubango) regions and in the province of Moxico in eastern Angola. The northern region has already had higher maximum temperatures in the historical period, and a slight increase is expected in the future in coastal areas, ranging from 2.2 to 2.6 °C.

Concerning the TN and during the historical period (Figure 4g–i), the lowest values, ranging between 13 and 15 °C, were observed in the southern and central regions, while the highest values of TN, varying between 19 and 22 °C, were located in the northern coastal regions. Projections indicate an increase in the values of this agroclimatic indicator in all inland regions of the country, more significant (2.9 to 3.2 °C) in the central (Bié and Huambo) and southern (Huíla, Cunene, and Cuando Cubango) regions and the Moxico province in eastern Angola. On the other hand, the coastal provinces will experience a slight increase in TN of about 2.2 °C.

Similarly to TN, the BEDD registered, during the historical period, the lowest values in the southwestern and central regions, with values ranging between 6500 and 7000 °C. For the same period, the coastal provinces in the north of the country observed the highest values of this agroclimatic indicator, ranging from 8500 to 9000 °C (Figure 4j–l). The projections indicate (i) greater increases in this indicator in the northern provinces (Uíge, Zaire, and Cuanza Norte) and central provinces (Cuanza Sul, Malange, and Huambo), (ii) moderate increases in the central inland provinces (Lunda Sul and Moxico), and (iii) less significant increases in the southern provinces (Cunene and Cuando Cubango.

The standard deviation of TG is highest in the North (>0.7 °C) and lowest in the Central South (<0.5 °C). More excellent agreement is observed in the central-southern regions, while the North exhibits more significant variability. The highest standard deviations for TX occur in the South (>1.5 °C), with the lowest values in the Central East (<0.5 °C). Model agreement is more substantial in the Central East, whereas the South shows more significant disagreement. The standard deviation of TN reaches its peak in the South and West (>0.7 °C) and its minimum in the Central East (<0.5 °C). Greater consistency is evident in the Central East, contrasting with higher variability in the South and West. In the case of BEDD, the standard deviation is highest in the North (>240 °C) and lowest in the South

(<140 °C). Model agreement is more substantial in the South, while the North experiences more significant disagreement.

The uncertainty of TG is low in most of the territory, with the standard deviation representing less than 10% of the projected increase (values between 2–3 °C), indicating high confidence in the projections. Regarding TX, uncertainty remains low, with variability among models representing less than 10% of the projected values (2.5–3.9 °C increase), suggesting consistency in future scenarios. TN shows higher uncertainty in some southern areas, where variability can reach 15% of the projected values, while in the rest of the territory, it is below 10%, reinforcing greater confidence in projections for the North and Centre. Despite the projected increase being high (>950 °C in some regions), BEDD's uncertainty is proportionally low, with variability representing less than 10% of the projected values in most of the country. These analyses show that, for temperature indicators, the projections are generally consistent, allowing greater confidence in using this information for agricultural planning.

Figure 5 shows the agroclimatic indicators: tropical nights (TR), maximum number of consecutive summer days (CSU), warm and wet days (WW), and warm spell duration index (WSDI).

TR values were $\leq$10 days in most of Angola, except in the northwest and central coastal zones (Cabinda, Zaire, Luanda, Bengo, Kwanza Sul, Benguela) with 200–300 days. Projections show TR increases across Angola, with modest rises (~30 days) in Huíla, Huambo, Cuanza Sul, and Bié and significant increases (~180 days) in northern provinces.

During the historical period, the agroclimatic parameter related to TR indicates values less than or equal to 10 days in practically the entire country. The exception is observed in the extreme northwest and central coastal zones (Cabinda, Zaire, Luanda, Bengo, Kwanza Sul, and Benguela), where the values vary between 200 and 300 days. (Figure 5a–c). Projections indicate an increase in this agroclimatic indicator in almost all regions of the country, less pronounced in the Huila, Huambo Cuanza Sul, and Bié provinces reaching an increase of about 30 days. On the other hand, the northern provinces will experience higher values of TR with an increase of about 180 days.

In the historical period, CSU values in Angola were generally high (80–90+ days), except in the central and southwestern regions (Huambo, Cuanza Sul, Huíla, Namibe: 10–40 days) and parts of the North (Uíge, Cuanza Norte: ~45 days). Projections indicate a widespread CSU increase, with more pronounced growth in regions that historically had lower values.

In the historical period and throughout Angola, the CSU presented high values ranging between 80 and more than 90 days. The exception was observed in the central and southwest regions, in Huambo and part of the provinces of Cuanza Sul, Huíla, and Namibe, which recorded the lowest values between 10–40 days. The small values of CSU were also observed in Uíge and Cuanza in the North of the country reaching 45 days. (Figure 5d–f). Projections indicate that there will be a widespread increase in this agroclimatic parameter, and this increase will be more pronounced in areas where the historical CSU values were low.

In the historical period and concerning the WW indicator, the southern, central, and some northwestern (Luanda, Bengo, and Cuanza Norte) provinces experienced fewer hot and humid days (<4 days). The remaining regions registered a slightly higher number of about 9 days (Figure 5g–i). Projections indicate a very high increase in this indicator in all provinces, not significant in the South, about 5 to 15 days, and highly pronounced in the central and northern regions, reaching impressive values ranging from 40 to 45 days.

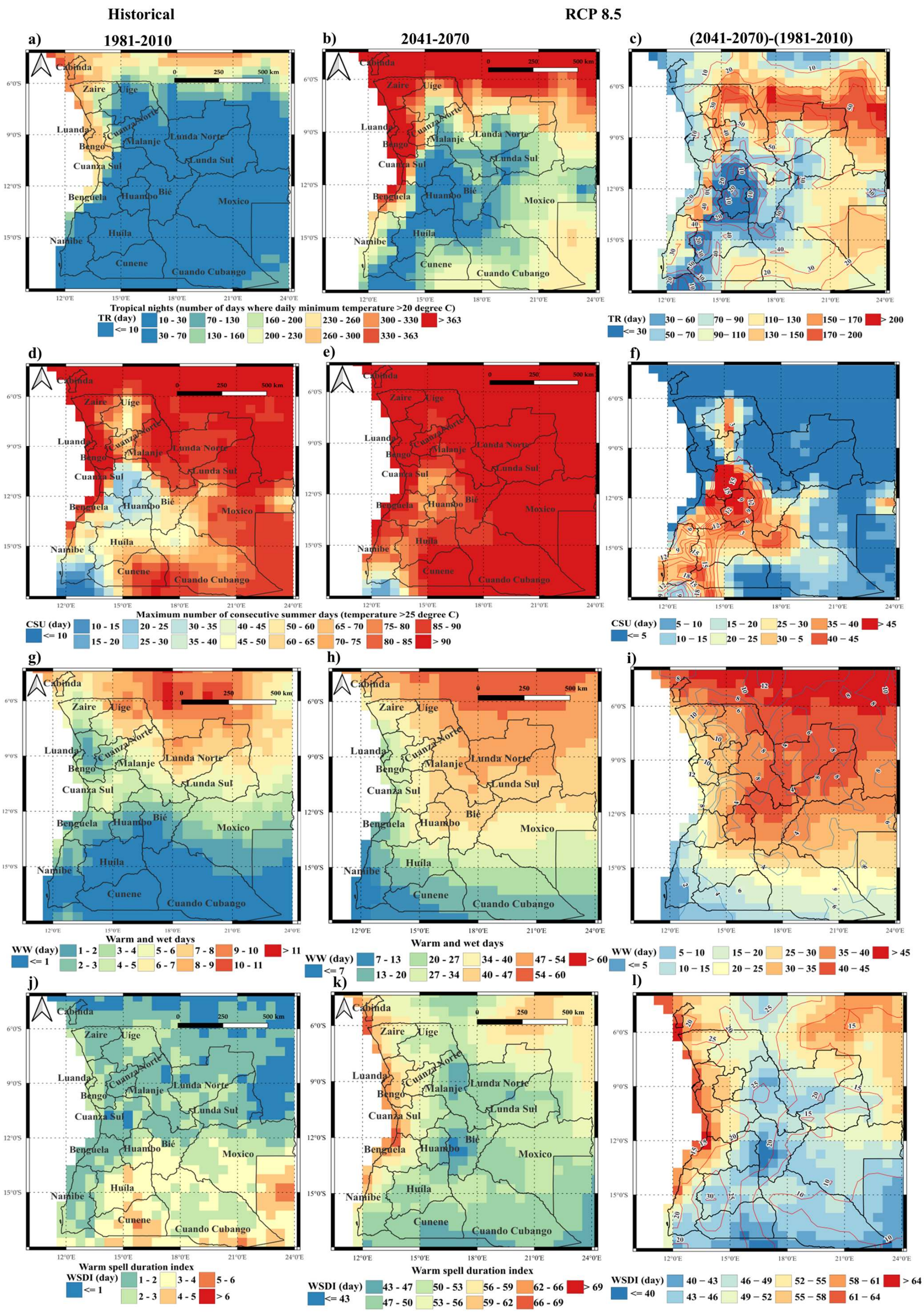

Figure 5. Climate means of the outlined agroclimatic indicators (TR: tropical nights; CSU: maximum number of consecutive summer days; WW: warm and wet days; WSDI: warm spell duration index for the historical period 1981–2010 (**a**,**d**,**g**,**j**), the five-member ensemble mean projections for the future period 2071–2099 under RCP8.5 (**b**,**e**,**h**,**k**), and the corresponding differences (**c**,**f**,**i**,**l**). The corresponding ensemble standard deviation isolines are overlaid on the different maps. See respective legends for scales and units.

The WSDI indicator is more significant in the southern and central inland provinces, with maximum values greater than 5 days in some regions. As for the WW indicator, projections of WSDI show a substantial increase in the country, more pronounced in the North and Coast, with some regions recording impressive values up to 64 days.

The standard deviation of TR is highest in the North (>50 days) and lowest in the South (<20 days). Agreement is stronger in the South, while variability is greater in the North. The highest standard deviations for CSU are observed in the Northwest (>15 days), with the lowest values in the East (<5 days). Greater consistency is noted in the East, while the Northwest shows more pronounced disagreement. For WW, the standard deviation peaks in the North (>12 weeks) and drops to its lowest in the South (<5 weeks). The southern regions display greater agreement, whereas the northern areas exhibit higher variability. The standard deviation of WSDI is greatest in the North (>25 days) and smallest in the South (<10 days). Agreement is higher in the South, while more significant variability is seen in the North and Northwest.

The uncertainty of TR is relatively low, with the standard deviation representing less than 10% of the projected values (>150–200 days in the Northwest), suggesting high confidence in projections for most of the territory. For CSU, uncertainty is high in the Northwest, where variability among models represents up to 20% of the projected values (>40 days), indicating greater difficulty in predicting the frequency of these extreme events in the region. As for WW, uncertainty is moderate, with the standard deviation representing less than 15% of the projected values in most regions (>12 weeks in the Northwest and Centre). Finally, WSDI shows more significant uncertainty in the Northwest and Northeast, where variability represents up to 20% of the projected values (>60 days), while in the South and Centre, it is below 10%, indicating greater consistency in these areas. These analyses suggest that while projections for temperature indicators (TR and WSDI) are reliable in some regions, extreme temperature events like CSU and WW exhibit greater variability, especially in the Northwest, requiring more attention for adaptive planning in these areas.

3.2. Summary of the Main Climate Change Impacts

To summarise the aforementioned results, the tables below describe the main climate impacts for each region separately, highlighting the most affected provinces and the relevant agroclimatic indicators. It is worth noting that projections indicate a generalised increase in the temperature and its associated agroclimatic indicators throughout the country, with emphasis on WW and WSDI. The significant increase in the latter indicator could be harmful to crops because it may potentially affect yields during reproductive growth by reducing the amount of time for the male (tassel) and female (silk flower) flowering periods, mainly corn [54]. On the other hand, it is important to note that projections indicate a large increase in the CSU in the central and southwestern provinces, which extends to Cuanza Norte and Uíge, combined with a slight increase in TR.

Regarding the indicators associated with precipitation and analysing the future period, there is a certain geographical continuity in these parameters. On the one hand, there will be a generalised reduction in these indicators in the southwest, southeast, central, coastal, and Cuanza Norte regions, and on the other hand, there will be a noticeable increase in these indicators in the remaining north and northeastern regions. However, there are certain particularities to some of these indicators, especially (i) a generalised decrease/increase in the RR1/SDII indicator in all the central regions and the north of the country and an increase/decrease in this indicator in the southwest region, and (ii) a large increase in the CWD indicator in the central region (Huambo and Bié) and the far north of the country in the northwest region (Cabinda and Zaire).

According to future projections, the provinces in the Southwest of the country are expected to suffer significantly from the impacts of climate change, particularly a huge reduction in precipitation and an increase in temperature. These adverse weather conditions are particularly worrying for agriculture, which plays an important role in the local economy. A particular highlight is the province of Huíla, known for its agricultural capacity, making it especially vulnerable to reduced water availability.

The central region, the largest agricultural producer in Angola, plays a crucial role in the country's food security. However, on the one hand, projections indicate a significant increase in CWD, which will highly and positively impact agriculture, but on the other hand, an increase in the temperature and all associated indicators could negatively alter agricultural regimes and crop cycles.

The northeast and northwestern regions stand out as important agricultural areas of the country. Although the projections in these regions indicate a considerable increase in precipitation and SDII, they also indicate a significant reduction in RR1 and an increase in CDD.

The coastal provinces were included in the table due to their importance in the climatic context. As shown in Figure 1c Benguela, Cuanza Sul, and Bengo are provinces with some level of agricultural production. The climate in coastal regions directly influences the country's overall climate, impacting precipitation, temperature, and wind patterns [55]. Projections indicate a widespread reduction in precipitation and RR1, with the rare exception of a part of Bengo, which will experience a slight increase in R20 mm. These areas are also vulnerable to sea level rise, coastal erosion, and other climate-related impacts [56].

Finally, the region formed by the province of Cuanza Norte is a particular case compared to its neighbouring provinces, with distinct agroclimatic indicators. In fact, Cuanza Norte will experience a drastic fall in all parameters associated with precipitation, especially RR, RR1, and R10 mm, and, in contrast, a huge increase in the CDD indicator.

The rate of plant growth and physiological development largely depends on the environmental temperature around the plant. At the same time, each species has a specific thermal suitability range (thermal niche) that can be roughly represented by lower- (restricted) and upper-limit (unsuitable) temperatures [57]. Similar considerations can be made for suitable precipitation ranges, which are particularly relevant for rainfed crops, as precipitation deficits can be largely offset for irrigated crops.

Therefore, combining the data in Table 1, which presents the temperature and precipitation ranges for the different main crops in Angola, with the results listed in Tables 3–9 on the agroclimatic indicators in the RCP8.5 scenario for the periods 2041–2070, some areas of Angola will be considered suitable, restricted, and unsuitable for the cultivation of these crops, referring to the suitability of climatic conditions for ideal growth and development.

Table 3. Main impacts in the provinces of the Southwest.

Region	Provinces	Agroclimatic Indicators (Future)	Main Impacts (Projection)
Southwest	Namibe, Huíla	- RR: reduction (Namibe: 200–400 mm, Huíla: 400–1000 mm) - RR1: increase (Namibe: 30–60 days, Huíla: 60–120 days) - SDII: reduction (−2–0 mm/wet day) - R10 mm, R20 mm: reduction - CWD: reduction in Namibe, increase in Huíla - CDD: no significant changes - TG, TX, TN, BEDD: generalised increase - TR, CSU, WW, WSDI: increase	- Slight reduction in precipitation - Reduction in R10 mm and R20 mm - Increase in RR1 - Increase in CDD - Generalised increase in temperatures (TG, TX, TN, BEDD) - Slight increase in the TR - Large increase in CSU, WW, and WSDI

Table 4. Main impacts in the provinces of the Southeast.

Region	Provinces	Agroclimatic Indicators (Future)	Main Impacts (Projection)
Southeast	Cunene, Cuando Cubango, Moxico	- RR: no significant changes (400–800 mm) - RR1: reduction (Cuando Cubango: 90–120 days, Moxico: 120–150 days) - SDII: slight increase (1–2 mm) - R10 mm: slight reduction (5–20 days) - R20 mm: no significant changes (1–4 days) - CWD: slight increase (10 days) - CDD: no significant changes - TG, TX, TN, BEDD: generalised increase - TR: significant increase (10–200 days) - CSU, WW, WSDI: strong increase	- Slight reduction in precipitation - Slight reduction in wet days - No significant changes in CDD - Generalised increase in temperatures - Significant increase in TR, WW, and WSDI

Table 5. Main impacts in the provinces of the Centre.

Region	Provinces	Agroclimatic Indicators (Future)	Main Impacts (Projection)
Centre	Huambo, Bié	- RR: slight increase (1200–1400 mm) - RR1: no significant changes - SDII: slight increase in north Bié - R10 mm: reduction (30–50 mm) - R20 mm: no significant changes - CWD: significant increase (35–55 days) - CDD: no significant changes - TG, TX, TN, BEDD: increase - CSU, WW, WSDI: strong increase - TR: increase (30–70 days)	- Slight increase in precipitation - Reduction in R10 mm - No changes in RR1 and CDD - Significant increase in CWD - Widespread increase in temperatures (except for a reduction in TR)

Table 6. Main impacts in the provinces of the Northeast.

Region	Provinces	Agroclimatic Indicators (Future)	Main Impacts (Projection)
Northeast	Malanje, Lunda Norte, Lunda Sul	- RR: slight increase (Malanje: 1200–1600 mm, Lunda Norte: 1400–1650 mm) - RR1: reduction (180–270 days) - SDII: slight increase (6–7 mm) - R10 mm, R20 mm: increase - CWD: slight increase - CDD: slight increase (70–92 days) - TG, TX, TN, BEDD: slight increase - WW, TR, WSDI: increase - CSU: slight increase	- Slight increase in precipitation - Reduction in RR1 - Slight increase in CWD and CDD - Slight widespread increase in temperatures

Table 7. Main impacts in the provinces of the Northwest.

Region	Provinces	Agroclimatic Indicators (Future)	Main Impacts (Projection)
Northwest	Cabinda, Zaire, Uíge	- RR: slight reduction (Zaire: 600–1200 mm, Uíge: 1200–1600 mm) - RR1: reduction (150–270 days) - SDII: slight increase (6–9 mm) - R10 mm: no significant changes - R20 mm: increase in Uíge (5–12 days) - CWD: increase (30–50 days) - CDD: increase (65–92 days) - TG, TX, TN, BEDD: significant increase - TR: increase (130–363 days) - WW, WSDI: significant increase - CSU: no significant changes	- Slight increase in precipitation - Reduction in wet days - Generalised increase in CDD - Widespread increase in temperatures (and associated indicators) - Significant increase in WW, WSDI, and CSU

Table 8. Main impacts in the provinces of the Central Coast.

Region	Provinces	Agroclimatic Indicators (Future)	Main Impacts (Projection)
Central Coast	Luanda, Bengo, Cuanza, Benguela	- RR: reduction (Luanda and Bengo: 600–800 mm, Benguela and Cuanza Sul: 400–1000 mm) - RR1: reduction (90–120 days) - SDII: increase (1–2 mm) - R10 mm: reduction (5–30 days) - R20 mm: reduction - CWD, CDD: no significant changes - TG, TX, TN, BEDD: significant increase - TR, WW, WSDI: increase - CSU: slight increase	- Widespread reduction in precipitation - Reduction in RR1 - No significant changes in CWD and CDD - Widespread increase in temperatures (and associated indicators)

Table 9. Main impacts in the provinces of the Cuanza Norte.

Region	Provinces	Agroclimatic Indicators (Future)	Main Impacts (Projection)
Cuanza Norte	Cuanza Norte	- RR: reduction (800–1000 mm) - RR1: reduction (120 days) - SDII: slight reduction (−4–6 mm) - R10 mm: significant reduction (20–30 days) - R20 mm: slight reduction (1–5 days) - CWD: slight increase (35–45 days) - CDD: increase (92 days) - TG, TX, TN, BEDD: increase - CSU, WW, WSDI: increase - TR: significant increase (260–300 days)	- Significant reduction in precipitation - Reduction in RR1 - Slight increase in CWD - Increase in CDD and TR - Significant increase in CSU, WW, and WSDI

The temperature range was considered as follows:

Suitable: one where the crop develops optimally, promoting healthy growth, flowering, fruiting, and maximum yield [58]. These conditions ensure the plant can complete its life cycle without significant thermal stress.

Restricted: This temperature range still allows crop growth but with some limitations. Plants may experience some heat stress, resulting in suboptimal growth, lower yield, or lower final product quality. This range includes temperatures that are slightly lower or higher than ideal [58].

Unsuitable: those temperature ranges that seriously harm or make crop growth impossible. These extreme temperatures can cause significant damage to plants, preventing proper development, drastically reducing yield, or even killing the plant [58].

Similarly, precipitation is considered [58] as follows:

Suitable: this range of precipitation provides the optimal amount of water for the crop to develop healthily and robustly. It supports the plant through its entire growth cycle, ensuring sufficient water for germination, growth, flowering, fruiting, and ultimately achieving maximum yield. This range avoids both drought stress and waterlogging, which can adversely affect plant health and productivity.

Restricted: precipitation in this range allows crops to grow but with some limitations. While the plants may survive, they may experience periods of water stress, either from too little or too much water. This can lead to suboptimal growth, lower yield, or reduced final product quality. This range includes precipitation levels slightly below or above the ideal range, causing moderate plant stress.

Unsuitable: this range of precipitation is a hindrance to crop growth. It includes levels that can severely impede or even halt crop development. Extremely low precipitation can lead to drought conditions, causing water stress that can stunt growth, reduce yields significantly, or even kill the plants. Conversely, excessively high precipitation can result in waterlogging, root damage, increased susceptibility to diseases, and, ultimately, crop failure. These extreme precipitation levels prevent proper plant development and drastically reduce yield, if not lead to complete crop loss.

Figure 6 presents maps of agricultural suitability in Angola under climate projections for the period 2041–2070, emphasising the impact of changes in temperature and precipitation on key crops such as maize, sorghum, millet, cassava, beans, and potatoes. This study identifies regions classified as “suitable”, “restricted”, and “unsuitable” for cultivation, using climate projection models that account for variability and expected trends in crucial climatic factors affecting agriculture. The graphical representations (Figure 6a–f) on the map provide a comprehensive overview of how each crop may respond to the projected climate conditions. The analysis reveals that factors such as rising temperatures and changes in precipitation patterns may lead to a redistribution of areas suitable for cultivation. For instance, crops like sorghum and cassava exhibit greater resilience in semi-arid regions, whereas crops such as maize and millet are more sensitive to climate change, resulting in a larger number of areas classified as “unsuitable”. This visual approach is critical for supporting strategic decisions in agricultural planning, focusing on adaptive practices that ensure food security and climate resilience in the country. Understanding these shifts is essential for developing agricultural policies that foster sustainability and mitigate the adverse effects of climate change on Angola’s agricultural production.

The subfigures (a–f) illustrate the agroclimatic suitability of various crops in Angola, based on projected climate conditions for the period 2041–2070. The suitability was determined using the sum of annual precipitation and the mean of daily mean temperature, which are critical climatic factors for the cultivation of each crop. This analysis provides a general trend or a broad overview of Angola’s agroclimatic suitability, as the absence of detailed local data (e.g., microclimates) prevented a more granular analysis. Suitability is categorized into three classes: “Suitable”, “Restricted”, and “Unsuitable.”

Subfigure (a)—Corn (Maize):

Displays the agroclimatic suitability for maize cultivation. Green areas indicate regions where the combination of precipitation and temperature is favorable for maize, yellow areas represent restricted suitability, and red areas denote unsuitable conditions.

Subfigure (b)—Sorghum:

Shows the climatic suitability for sorghum, a drought-resistant crop. Green areas correspond to provinces where the projected climatic conditions are suitable, yellow zones indicate restricted suitability, and red zones represent unsuitable regions.

Subfigure (c)—Millet:

Highlights the suitability for millet cultivation, a crop adapted to arid and semi-arid conditions. Green areas represent suitable regions, yellow areas indicate restricted conditions, and red areas mark unsuitable zones, often associated with water deficits or extreme temperatures.

Subfigure (d)—Cassava:

Represents the climatic suitability for cassava, a highly resilient crop. Most provinces show suitable (green) or restricted (yellow) conditions, while a few regions, marked in red, are classified as unsuitable.

Subfigure (e)—Bean:

Depicts the suitability for bean cultivation. Green zones dominate regions where the combination of precipitation and mean temperature is favorable, yellow areas indicate marginal conditions, and red areas are unsuitable.

Subfigure (f)—Potato:

Illustrates the agroclimatic suitability for potato cultivation, a crop requiring specific temperature and precipitation ranges. Green zones represent suitable provinces, yellow areas indicate restricted conditions, and red areas are unsuitable for potato farming.

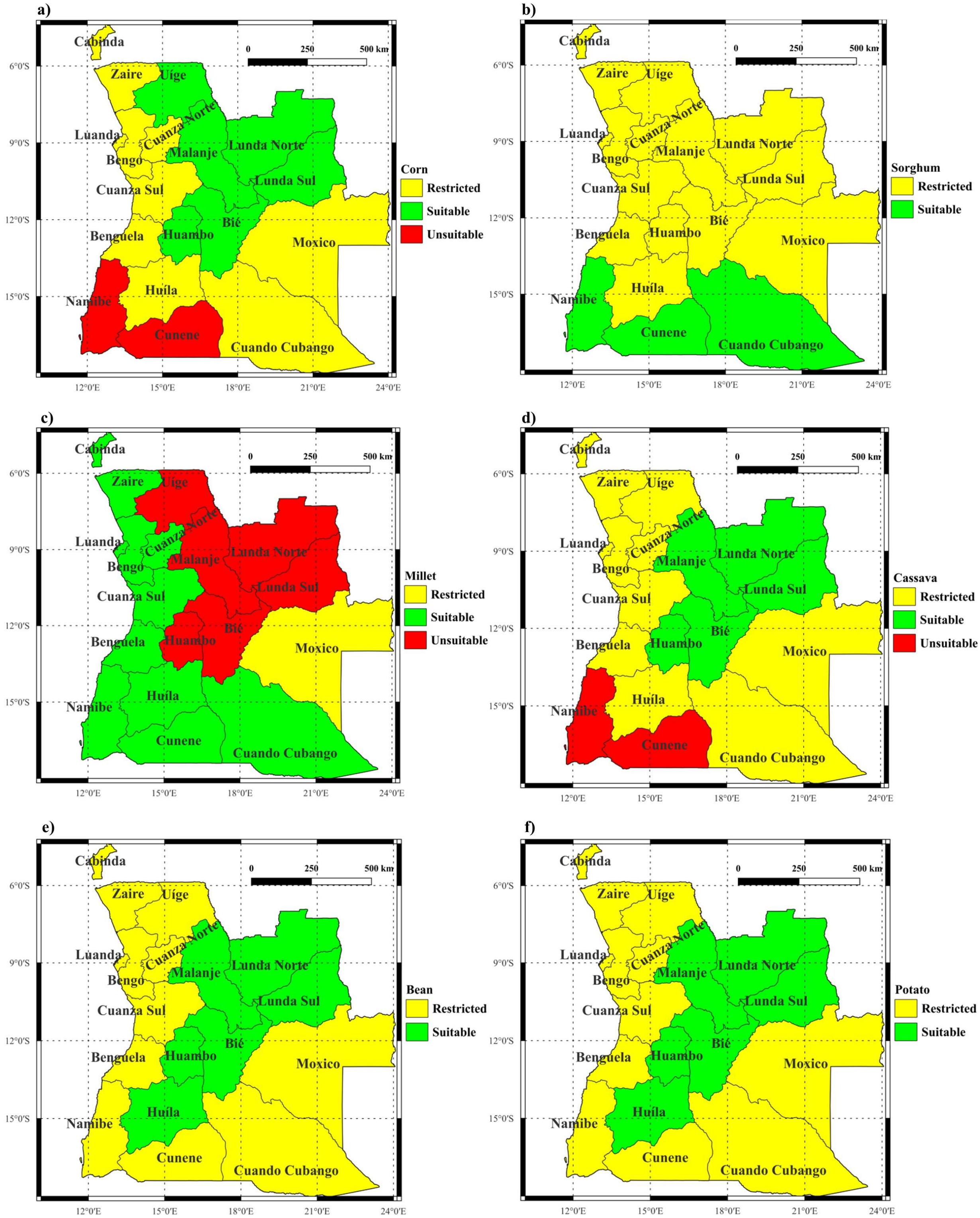

Figure 6. Agricultural crop suitability in Angola: impact of temperature and precipitation under climate projections (2041–2070, RCP8.5).

3.3. Study Limitations

The CMIP5 has several significant limitations. First, the spatial resolution of the models is limited, typically around $1^\circ \times 1^\circ$ or $2^\circ \times 2^\circ$, which can lead to inaccuracies in capturing local and regional climatic phenomena, such as precipitation patterns and extreme events. This makes it difficult to accurately model specific areas, such as those related to agriculture. Additionally, there are uncertainties in simulating climate feedback, as the models struggle to represent the complex interactions between the atmosphere, oceans, ice, and biosphere, leading to uncertainties about climate impacts, especially regarding CO_2 increase and cloud dynamics. Long-term projections, such as those extending to 2100, are also associated with significant uncertainties due to ever-changing variables, such as greenhouse gas emission scenarios and unpredictable natural and socioeconomic processes. Another critical point is that, as CMIP5 is a global model, it lacks specificity in capturing local and regional climatic characteristics, especially in areas with high climate variability, such as Angola. Finally, the model may not account for all factors affecting the climate, such as land use changes or mitigation policies, which could compromise the accuracy of projections, particularly in regional contexts. These limitations should be considered when interpreting the CMIP5 results, especially in regional climate impacts and agriculture studies. As the maps were created using data at national and regional scales, this approach may fail to capture local microclimatic variations, which may also be essential for local agriculture. The study focuses primarily on temperature and precipitation as the determining factors for agricultural suitability, overlooking other relevant factors such as soil fertility, the availability of water resources for irrigation, and agricultural management practices. Lastly, the study assumes that land use will remain relatively stable without accounting for future changes such as deforestation, urbanisation, or agricultural expansion, which could influence agrarian suitability. An essential limitation of this study is the absence of data from local meteorological stations in Angola, as these data were not available, which prevented the validation of climate projections with local-scale data.

4. Discussion and Conclusions

This study analysed the impacts of climate change on Angola, focusing on agroclimatic indices related to precipitation and temperature. The precipitation indices included the total precipitation sum, RR; the number of wet days, RR1; the simple daily intensity index for wet days, SDII; the number of heavy and very heavy precipitation days, R10 mm and R20 mm, respectively; the maximum number of consecutive wet days, CWD; and the maximum number of consecutive dry days, CDD. The temperature indices included daily mean temperatures, TG; maximum, TX; minimum, TN; biologically effective degree days, BEDD; the number of tropical nights, TR; the maximum number of consecutive summer days, CSU; the number of warm and wet days, WW; and the warm spell duration index, WSDI. Changes in agroclimatic indices, such as the increase in CDD and CSU, suggest a higher risk of drought and water stress conditions, particularly in the southern and southwestern regions. This will likely affect drought-sensitive crops like maize (Zea mays) and beans (Phaseolus vulgaris), which thrive in moderate temperature and precipitation conditions. These crops will face stress from reduced rainfall and rising temperatures (water and heat stress), leading to decreased productivity and potential crop failure in certain areas [12]. Since abnormally low precipitation can cause sudden droughts in agriculture [34,59], this decrease in precipitation combined with rising temperatures can exacerbate soil moisture losses, limiting crop growth [60]. The reduction in CWD, which may also manifest as a decrease in precipitation associated with an increase in CDD, has implications for the onset of the rainy season in Angola and is likely to occur, especially in areas of traditional rainfed agriculture [22,61]. Patterns of climate variability analysed through the standard deviation among climate models highlight that Angola's northern and eastern regions exhibit more significant disagreement in climate indicators, particularly in precipitation-related variables (R10 mm, R20 mm) and minimum and mean temperatures (TN, TG). In contrast, the southern part of the country shows lower variability and more excellent agreement among models, indicating higher climatic predictability in this region. This scenario reflects the spatial heterogeneity of projected climate impacts, with areas of more significant disagreement facing more unpredictable challenges for agriculture. High climatic variability and disagreement among models in the northern and eastern regions suggest that these areas are more susceptible to uncertainties regarding the magnitude of climate change, representing a significant risk for rainfed agriculture, which is predominant in these regions. On the other hand, more excellent agreement in the South indicates that adaptation strategies can be planned with more confidence, as future scenarios are more consistent. This disparity in projections reinforces the need for region-specific adaptation policies. In areas of higher disagreement, such as the North and East, it is crucial to strengthen climate monitoring capacity and implement early warning systems for extreme events. Meanwhile, in the South, where greater predictability facilitates planning, proactive agricultural strategies, such as adjusting planting calendars and diversifying crops, can be adopted. Finally, considering areas with higher and lower climate variability among models emphasises the importance of integrated agricultural planning. This approach should address the mitigation of climate change impacts in the most vulnerable regions while leveraging adaptation opportunities in areas with more significant and more remarkable climatic agreements. In the southeastern and southwestern regions, where reduced precipitation and increased temperatures are more pronounced, adopting more efficient water management practices, such as drip irrigation, will be essential. This technique can optimise water usage and ensure crop productivity, especially for drought-sensitive and commercial crops like maize and beans. Additionally, crop diversification will be an essential strategy, focusing on more drought-resilient crops such as sorghum and millet, better suited to these harsh climatic conditions. The implementation of rainwater harvesting systems should also be considered to maximise the utilisation of available water. In the Northeast and North, which experience higher precipitation and lower climate variability, crops such as cassava (Manihot esculenta) and potatoes (Solanum tuberosum) may remain viable. However, rising temperatures could affect potato productivity, so it will be necessary to monitor climate conditions and adjust agricultural practices as needed continuously. Soil management strategies such as organic fertilisation and mulching can help improve moisture retention and soil health to promote food security and stable harvests. Climate change projections indicate significant impacts on Angola's agricultural economy. Rising temperatures and changes in precipitation patterns may reduce the productivity of key crops such as maize (*Zea mays*), sorghum, millet, potatoes, cassava, and beans due to thermal and water stress. The increased frequency of extreme weather events, such as droughts and floods, may damage crops and heighten food insecurity, raising food prices and affecting the most vulnerable communities. Additionally, climate variability may affect the country's agricultural exports, impacting the trade balance. The adaptive capacities of smallholder farmers in Angola are limited due to the lack of access to appropriate technologies, financial resources, and information on resilient agricultural practices, which hinders the implementation of effective strategies against the impacts of climate change. In addition, the social implications of these changes, such as increased food insecurity and forced migration of rural communities, can intensify social inequalities, negatively affecting local economies and social stability. For regions with greater climate variability, such as the Southeast and Southwest, it is crucial to strengthen climate monitoring capacity and implement early warning systems for extreme weather events, such as prolonged droughts and heavy rains. A complementary strategy will be using drought- and heat-resistant seed varieties. As demonstrated in semi-arid regions, research and development of cultivars adapted to water and heat stress conditions could increase crop resilience and ensure long-term agricultural sustainability. Water scarcity and land fragmentation have reduced farmers' incomes, forcing them to modify their practices and crops. Furthermore, plant diseases may be triggered by extreme weather conditions [62]. Drought, an increasingly prevalent consequence of climate change, causes physiological and biochemical changes in maize crops, including reduced photosynthesis, decreased water absorption, and nutrient absorption deficiencies. These changes can result in stunted growth, reduced plant height, fewer tillers, and crop failure, ultimately affecting production, food security, local economies, and livelihoods [60]. Ongoing climate research indicates that areas already prone to drought will likely experience more intense and prolonged drought periods in the future [63], further exacerbating social, environmental, and economic stress, as well as agricultural production in Angola, particularly in the southwest and southeast regions. Therefore, given the projected warming and water and heat stress on crops, implementing adaptive and climate-smart agricultural practices will be crucial to ensuring food security and the sustainability of rural economies in Angola. This study demonstrates that the projected climate changes will significantly impact agriculture in Angola, especially maize, beans, and potatoes, which are sensitive to heat and water stress. The south and southwest regions will be the most affected, with increasing temperatures and reduced precipitation. At the same time, sorghum, millet, and cassava, which are more resistant to heat and drought, will thrive under the expected climatic conditions. Adaptation strategies, such as crop diversification, adjusting planting calendars, improving water management, and using heat-resistant varieties, will be essential to mitigate the impacts. Integrated agricultural planning, considering climate variability and the need for region-specific policies, can strengthen the resilience of farming communities and ensure food security in the future. Implementing sustainable water management practices and enhancing climate monitoring and early warning systems will be critical to facing future climate challenges.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/cli13010012/s1, Figure S1: Climate means of precipitation sum (RR), wet days (RR1), and simple daily intensity index (SDII) for the historical period (1981–2010) and future projections (2071–2099) under RCP8.5, along with differences between the two periods. Figure S2: Climate means of heavy precipitation days (R10mm), very heavy precipitation (R20mm), maximum consecutive wet days (CWD), and maximum consecutive dry days (CDD) for the same periods and scenario as Figure S1. Figure S3: Climate means of daily mean temperature (TG), daily maximum temperature (TX), daily minimum temperature (TN), and biologically effective degree days (BEDD) for the same periods and scenario as Figure S1. Figure S4: Climate means of tropical nights (TR), maximum consecutive summer days (CSU), warm and wet days (WW), and warm spell duration index (WSDI) for the same periods and scenario as Figure S1. Figures S5–S8: Indicators described in Figures S1–S4, but for projections under RCP4.5 (2041–2070). Figures S9–S12: Indicators described in Figures S1–S4, but for projections under RCP4.5 (2071–2099.

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