Potential Impacts of Climate Change on the Sudan-Sahel Region in West Africa – Insights from Burkina Faso

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Abstract

The Sudan-Sahel region has long been vulnerable to environmental change. However, the intensification of global warming has led to unprecedented challenges that require a detailed understanding of climate change for this region. This study analyzes the impacts of climate change for Burkina Faso using eleven climate indices that are highly relevant to Sudan-Sahelian societies. The full ensemble of statistically downscaled NEX-GDDP-CMIP6 models (25 km) is used to determine the projected changes for the near (2031-2060) and far future (2071-2100) compared to the reference period (1985-2014) for different SSPs. Validation of the climate models against state-of-the-art reference data (CHIRPS and ERA5) shows reasonable performance for the main climate variables with some biases. Under the SSP5-8.5, Burkina Faso is projected to experience a substantial temperature increase of more than 4.3°C by the end of the century. Rainfall amount is projected to increase by 30% under the SSP5-8.5, with the rainy season starting earlier and lasting longer. This could increase water availability for rainfed agriculture but is offset by a 20% increase in evapotranspiration. The country could be at increased risk of flooding and heavy rainfall in all SSPs and future periods. Due to the pronounced temperature increase, heat stress, discomfort, and cooling degree days are expected to strongly increase under the SSP8.5 scenarios, especially in the western and northern parts. Under the SSP1-2.6 and SSP5-8.5, the projected changes are much lower for the country. Thus, timely implementation of climate change mitigation measures can significantly reduce climate change impacts for this vulnerable region.

Keywords: CMIP6; climate change; NEX-GDDP; West Africa; Burkina Faso

Plain Language Summary

The Sahel region, where Burkina Faso is located, is more vulnerable to the effects of climate change compared to other regions. To improve the resilience of the population living in Burkina Faso, we need to know what the future climate will be like. To fill this gap, we used the most current global climate models, called CMIP6 models, statistically downscaled to 25 km. This downscaling method refines the predictions for the country. The information on future climate change was produced under the new climate change scenarios called "Shared Socio-economic Pathways (SSP): SSP1-2.6 (sustainability), SSP2-4.5 (middle of the road), and SSP5-8.5 (fossil-fueled development). Burkina Faso could become much hotter by the end of this century, by more than 4.3°C in the SSP5-8.5 scenario, and it will also become uncomfortably hot in some areas, which could be risky for people's health. Precipitation amounts could increase by 30%, making more water available, but at the same time 20% more water could potentially evaporate into the air. There could also be more flooding and heavy rainfall, making the country more vulnerable to disasters. Policymakers and stakeholders need to know this information so they can make plans to protect the country and its people.

1. Introduction

Human-induced climate change is causing global warming (Trenberth, 2018). For instance, the burning of fossil fuels and intensive agricultural practices contribute significantly to the increase in greenhouse gas (GHG) concentrations in the atmosphere. These anthropogenic sources of GHGs amplify the physical process of the greenhouse effect and lead to an increase in global average temperature (Wang et al., 2021). Carbon dioxide (CO_2) has been considered as one the major sources of GHG emissions from human activities since the last decades. From 1950 to 2021, annual global CO_2 emissions have increased by 618.67% (Ritchie et al., 2020). This rapid increase, coupled with the impact of climate change on human well-being, has led scientists, governments, and policymakers to make considerable commitments to reduce the CO_2 emissions at the COP21. The Paris Agreement provides a benchmark for reducing the global carbon footprint and limiting global average temperature to 2°C, and more ambitiously to 1.5°C. Despite this historic agreement, signed by all parties, the impacts of climate change have become increasingly severe in recent years. The region of West Africa, considered one of the world's hotspots, is not spared from these effects.

West Africa region is expected to experience greater climate change impacts than other regions in Africa (Ezeife, 2014). However, the region is already experiencing the impacts of climate change through changing rainfall patterns, frequent extreme events and rising temperatures (Ngoungue Langue et al., 2023; Nkrumah et al., 2019; Salack et al., 2016; Kasei et al., 2010; Lebel and Ali, 2009). These changes have significant impacts on the socioeconomic activities of the population as well as on the environment. Since rainfed agriculture is practiced in the region, any significant change in rainfall patterns could lead to potential crop production uncertainties and subsequent famine. Therefore, the timing, frequency, and intensity of rainfall during the rainy season are important for good crop production. The study by Guan et al. (2015) showed that a delay in onset of rainfall negatively impacts crop yields in West Africa. Moreover, the onset and cessation of rainfall are expected to be sensitive to ongoing climate change (Lorenz et al., 2022; Dieng et al., 2018; Kumi and Abiodun, 2018). The changes in future rainfall characteristics could decrease the cereal crop yield in the region (Ahmed et al., 2015). On the other hand, the increase in temperature and extreme events may contribute to crop failure or decrease in crop yields (Sultan et al., 2019; Roudier et al., 2011; Verdin et al., 2005). In addition, climate change is likely to affect water resources in the region. A study by Sylla et al. (2018) found that most West African basins could suffer severe water shortages under 1.5°C warming level, with more pronounced changes under 2°C warming level. Peak flows in these basins could decrease under climate change (Rameshwaran et al., 2021).

These changes in rainfall patterns, temperature increases, frequent extreme events, and water scarcity pose serious concerns for agriculture, food security and water resources in West Africa, that may affect the socioeconomic growth of the region. The Sudan-Sahel region, which includes Burkina Faso, is more vulnerable to the impacts of climate change compared to many other areas around the world as many people live in extreme poverty and significant multi-decadal changes have been observed during the 20th century (Semde et al., 2021). The area is known to have experienced frequent severe droughts since the 1960s (Nicholson et al., 2018). For example, drought affected 96,000 people in Burkina Faso in the 1990s (Crawford et al., 2016).

In recent years, heavy rains and floods have also been frequent and have affected people's live (Tazen et al., 2019). This was the case with the major flood on September 1, 2009, when 261.3 mm of rain was measured in 24 h (e.g., Engel et al., 2017) and 150,000 people were affected in the city of Ouagadougou (Reliefweb, 2009). Previous studies in Burkina Faso have also highlighted an increase in surface temperature and changes in rainfall patterns (De Longueville et al., 2016; Ibrahim et al., 2014). The observed shifts in temperature and precipitation have been exacerbated in the production of annual crops such as millet and sorghum, where an average of 15% of yields were lost between 2000 and 2009 (Sultan et al., 2019). This poses a serious risk to the population as about 70% of them rely on agriculture (Sorgho et al., 2021). According to the National Adaptation Plan (NAP) of Burkina Faso, the agricultural sector is the most vulnerable sector to climate change (UNFCCC, 2015).

The future impacts of climate change in the Sahel have been studied in the literature. By the end of the century, the entire region is expected to experience a temperature increase higher than the global average under the Representative Concentration Pathway (RCP) 8.5 (Sylla, et al., 2016a). With a 2.5 °C warming, Burkina Faso could experience a 2 °C increase in 2040 compared to 1960 (Theokritoff and D'haen, 2022). A temperature increase is also expected in some major river basins in Burkina Faso such as the Dano and Volta rivers (Dembélé et al., 2022; Okafor et al., 2021 de Hipt, 2018). In addition, climate models project an increase in dry spells in the country, which will further weaken agricultural systems already vulnerable to climate change (Ibrahim et al., 2014). The country is likely to transition to more arid conditions, which could disrupt agricultural activities and trigger changes in biological communities and ecosystems overall (Sylla et al., 2016b). However, the above studies are generally based on climate scenarios from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012) models and corresponding downscaling initiatives such as CORDEX with their respective RCP scenarios. Nowadays, a new set of climate change scenarios is provided by CMIP6 (Coupled Model Intercomparison Project Phase 6) under the so-called "Shared Socioeconomic Pathways (SSPs)" climate scenarios. These new climate scenarios provide improved climate information that facilitates the integration of climate policy, mitigation, and adaptation (O'Neill et al., 2016). Updating climate change information for the West Africa region, particularly Burkina Faso, will provide useful information for the government, policymakers, and stakeholders to identify vulnerable sectors and develop targeted interventions to build resilience and minimize the negative impacts of climate change. Nonetheless, the global climate change scenarios of CMIP6 climate models are characterized by coarse spatial resolution, which are not suitable for reliable and future climate projections at local scales. Therefore, these climate models need to be refined to better represent local conditions and provide robust climate change information.

Taking advantage of the availability of CMIP6 data statistically downscaled to 25 km from NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP), this study aims to investigate the projected changes for several climate indices that are highly relevant for Sudan-Sahel region like Burkina Faso, such as the onset and cessation of rainfall, heat stress, discomfort index, and cooling degree days. The downscaled climate projections are based under three SSPs: SSP1-2.6, SSP2-4.5, and SSP5-8.5 for the near (2031-2060) and far (2071-2100) future relative to the 1985-2014 baseline period.

The paper is organized as follows. Section 2 presents the study area, the reference data used for model validation, the NEX-GDDP-CMIP6 data, and the methodology. The results and discussions of the model evaluation and the projection of the different climate factors are presented in Section 3. Finally, the conclusion of the study is presented in Section 4.

2. Materials and methodology

2.1. Study area

The study focuses on Burkina Faso (Fig.1). Burkina Faso is a landlocked country in the West Africa region with an area of 274,200 km^2 and subdivided into 13 administrative and territorial regions. Its population is estimated at about 22,752,315 (INSD, 2023). The terrain is almost flat, with some plateaus in the western part. According to the updated Köppen-Geiger climate classification, the country has a tropical savannah climate (western and southern parts) and a hot semi-arid climate (northern part). However, some areas at the extreme north depict a hot desert climate (Kottek et al., 2006). Annual rainfall is about 500-800 mm in the semi-arid climate, while it is about 900-1200 mm in the tropical savannah climate (Bliefernicht et al., 2021; De Longueville et al., 2016). The rainy season lasts from early May to late September in the southern part and peaks in August, while the rest of the year is a dry season (Bliefernicht et al., 2018; Stalled, 2012). The rainy season is determined by the West African monsoon (WAM), following the northward movement of the intertropical discontinuity (ITD) (Talib et al., 2022). The dry season, on the other hand, is characterized by the Harmattan period (December-January-February), a northeasterly wind from the Sahara Desert that brings dry and dusty air. In addition, the dry season is also characterized by a very hot period from March to May just before the onset of the monsoon, when the average daily maximum temperature can reach 42°C (Arisco et al., 2023).

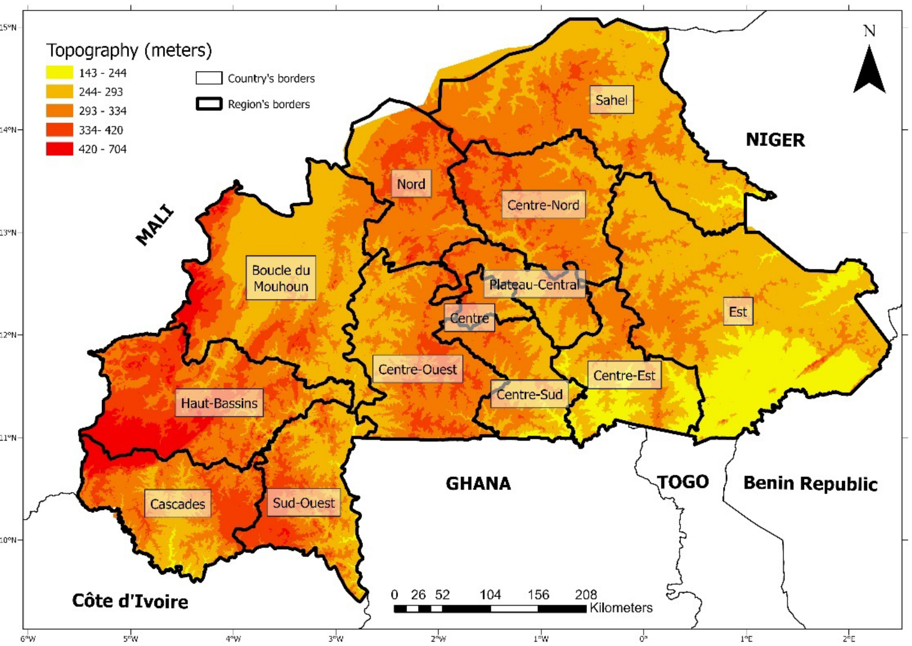

Figure.1: Study area showing the topography, the regions, and the neighbor countries of Burkina Faso. The grey labels indicate the name of the thirteen regions in Burkina Faso.

2.2. Datasets

2.2.1. Reference data

We used two different datasets to assess the NEX-GDDP-CMIP6 datasets in Burkina Faso for daily precipitation amount (Pr), mean temperature (tas), minimum temperature (tasmin), maximum temperature (tasmax) and relative humidity (hurs). The Pr variable was taken from the Climate Hazards Group InfraRed Precipitation with Station data (Funk et al., 2015, CHIRPS), which is a global dataset that provides valuable information on rainfall pattern and trend. The CHIRPS data was developed by the Climate Hazards Group at the University of California, Santa Barbara, and to support the United States Agency for International Development Famine Early Warning Systems Network (FEWS NET) for drought monitoring. CHIRPS combines satellite imagery with ground station data to produce high-resolution precipitation estimates with smart interpolation technic (Funk et al., 2015). We retrieved the latest version of CHIRPS in a spatial resolution of 0.25°x0.25° from 1985 to 2014. The CHIRPS data has been widely used in previous studies for model evaluation of precipitation in the West Africa region (Romanovska et al., 2023; Quenum et al., 2021; Kumi and Abiodun, 2018).

On the other hand, we used the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis data (Hersbach et al., 2019) for the variables tas, tasmin, tasmax and hurs. The ERA5 reanalysis data is the fifth generation of ECMWF reanalysis data covering the globe with a period from 1940 to the present. It has a horizontal grid spacing of 31 km and 37 pressure levels from 1000 (surface) to 1 hPa. ERA5 data has demonstrated good performance in reproducing temperature in West Africa (Gbode et al., 2023). From the ECWMF platform, we retrieved hourly tas, dewpoint temperature and surface pressure for the 1985-2014 period. Using the hourly tas, we computed the daily tas, tasmin and tasmax. The hurs is calculated using the saturated water vapor approximation proposed by Alduchov and Eskridge (1996).

2.2.2. NEX-GDDP-CMIP6 datasets

Climate data used in this study are from NEX-GDDP-CMIP6 (Thrasher et al., 2022). The data is the latest version of NEX-GDDP, downscaled state-of- the-art CMIP6 climate models. The downscaled data include thirty-five CMIP6 models with different variants and experiments. The historical period ranges from 1960 to 2014, while the future period ranges from 2015 to 2100 and includes climate change scenarios for SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. The Global Meteorological Forcing Dataset (GMFD) for Land Surface Modeling with a spatial resolution of 0.25° was used to statistically downscale the CMIP6 data using the bias correction and spatial disaggregation approach proposed by Wood et al. (2004). In the end, the NEX-GDDP-CMIP6 has a spatial resolution of 0.25° (~25 km). After the downscaling process, quality control was performed to ensure that the downscaled results were within the realistic range of the different variables. More detailed information can be found in Thrasher et al. (2022). From the NASA Center for Climate Simulation platform, we retrieved daily Pr, tasmax, tasmin, tas, shortwave radiation (rsds), and hurs for four experiments (historical, SSP1-2.6, SSP2-4.5, and SSP-5.85). Table.1 summarizes the different NEX-GDDP-CMIP6 used in this study with the above variables.

Table.1: Different NEX-GDDP-CMIP6 and associated variables used in this study.

Acronym	Full name	Models used for different variables					
		pr	tasmax	tasmin	tas	hurs	rsds
ACCESS-CM2	Australian Community Climate and Earth System Simulator Climate Model Version 2	x	x	x	x	x	x
ACCESS-ESM1-5	Australian Community Climate and Earth System Simulator Earth System Model version 5	x	x	x	x	x	x
BCC-CSM2-MR	Beijing Climate Center- Climate System Model version 2- Medium Resolution	x	x	x	x	x	x
CanESM5	The Canadian Earth System Model version 5	x	x	x	x	x	x
CMCC-CM2-SR5	Euro-Mediterranean Centre on Climate Change climate model version 2	x			x		
CMCC-ESM2	Euro-Mediterranean Centre on Climate Change coupled climate model-Earth System Model Version 2	x	x	x	x	x	x
GISS-E2-1-G	Goddard Institute for Space Studies	x	x	x	x	x	x
HadGEM3-GC31-LL	Hadley Centre Global Environment Model in the Global Coupled configuration 3.1	x	x	x	x	x	x
MIROC6	Model for Interdisciplinary Research on Climate, Earth System version 6	x	x	x	x	x	x
MIROC-ES2L	Model for Interdisciplinary Research on Climate, Earth System version 2 for Long-term simulations	x	x	x	x	x	x
MPI-ESM1-2-HR	Max Planck Institute Earth System Model- high resolution	x	x	x	x	x	x
MPI-ESM1-2-LR	Max Planck Institute Earth System Model- low resolution	x	x	x	x	x	x
MRI-ESM2-0	The Meteorological Research Institute Earth System Model Version 2.0	x	x	x	x	x	x
NorESM2-LM	The Norwegian Earth System Model version 2- Low atmosphere-Low ocean resolution	x	x	x	x	x	x
NorESM2-MM	The Norwegian Earth System Model version 2- Medium atmosphere-Medium ocean resolution	x	x	x	x	x	x
TaiESM1	Taiwan Earth System Model version 1	x			x		
NESM3	Nanjing University of Information Science and Technology Earth System Model version 3	x			x		

2.3. Methodology

2.3.1. Climate change scenarios

Climate change scenarios are important for understanding long and/or short-term impacts and taking informed mitigation and adaptation actions to build resilience. In this study, we used the SSP scenarios. The SSPs were developed based on future socioeconomic trends and provide five different narrative pathways (SSP1, SSP2, SSP3, SSP4 and SSP5; O'Neill et al., 2017). These scenarios were used in the latest Intergovernmental Panel on Climate Change (IPCC) report, the Sixth Assessment Report (AR6), and many studies used the SSP scenarios to assess climate change impacts (IPCC, 2021). We used three SSPs: SSP1-2.6; SSP2-4.5 and SSP5-8.5 to ensure continuity with the RCPs. SSP1-2.6 corresponds to sustainability, is very close to 2°C target of the Paris Agreement and is one of the highest priority scenarios in AR6 (Meinshausen et al., 2020). SSP2-4.5 belongs to the "intermediate" socioeconomic family with a similar level of aggregate radiative forcing of 4.5 W m^{-2} by 2100, which corresponds to the RCP4.5 scenario. Finally, the SSP5-8.5 scenario indicates a world with high fossil fuel consumption in the 21st century with a radiative forcing of 8.5 W m^{-2}, like the RCP8.5 scenario.

2.3.2 Climate indices

For projected of climate change impacts in Burkina Faso, we examined eleven climate indices: onset of rainfall (ORS), cessation of rainfall (CRS) and length of rainy season (LRS), highest five-day precipitation amount (RX5day), number of days with daily precipitation of at least 20 mm (RR20mm), reference evapotranspiration (ET_0), precipitation (Pr), air temperature (tas), heat stress index (HI), discomfort index (DI) and cooling degree days (CDD).

For the ORS, we used the approach of Stern et al. (1981) to calculate the onset of rainfall. This approach considers the accumulation of a minimum of 25 mm of precipitation over a period of 5 days, with at least two days with rain (at least 0.1mm) within the 5 days. Subsequently, it considers the occurrence of a non-dry period lasting seven or more consecutive days within the following 30 days. We employed the approach of Omotosho et al. (2000) to determine the CRS that states any rain from 1st September onwards with 21 consecutive days less than 50% of the crop's water requirements. The LRS is defined as the difference between ORS and CRS.

We used the definition proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI). This index indicates the maximum of five-day precipitation amount. Let Pr_{kj} be the precipitation amount for the 5-day interval ending k, period j. $RX5day_j = max(Pr_{kj})$. The index is also used to determine periods with high risks of heavy rainfall and flood events (Xu et al., 2022). We also used the definition provided by the ETCCDI. RR20 mm is defined as a number of days with daily precipitation of at least 20 mm. $Pr \geq 20$. The index is also used as indicator for extreme rainfall. For the ET_0, we estimated it from Jones annd Ritchie (1990), which uses solar radiation, maximum and minimum temperature. It helps to understand the balance of the ecosystem, the irrigation scheduling, and the water resources management.

To assess projected changes in human comfort and health in Burkina Faso, we used HI, which combines temperature and relative humidity. Each HI category was assigned a range of values. In this study, we considered 41°C ≤ HI < 54°C, which is classified as dangerous. The calculation of the index can be found in (Rothfusz and Headquarters, 1990). We also used the DI provides insights into the potential impact of weather conditions on human comfort, well-being, and productivity. We followed the method of Thom (1959) to calculate DI. In this study, we consider DI ≥ 32°C which corresponds severe stress, leading to state of emergency indicating that the population is at risk. To estimate the energy required to cool a building, we employed the CDD. it represents the number of degrees that the average temperature exceeded the base temperature at a given day. The methodology employed here is based on the base temperature (Tb). 18°C is commonly used as the Tb to compute CDD (Ukey and Rai, 2021; Wang and Chen, 2014; Semmler et al., 2009). However, this Tb also depends on the local climate of the study area. For instance, Andrade et al. (2021) used 25°C as the Tb to examine the impacts of climate change on CDD in Portugal, while Odou et al. (2023) used 24°C as Tb in West Africa. In this study, we used 30°C as Tb in Burkina Faso to compute CDD and it is expressed as the number of days per year.

These climate indices allowed us to gain insight into the multi-layered impacts of climate change in Burkina Faso.

2.3.3. Analyses

In this study, we used the ensemble mean of the NEX-GDDP-CMIP6 (hereafter EnsMean) simulations for model evaluation and future projections. The EnsMean improves the reliability of future projections and enhanced signal-to-noise ratio of individual models (Hardiman et al., 2022; Tebaldi and Knutti, 2007). In addition, the EnsMean helps reduce biases and uncertainties inherent in individual models and provides policymakers and stakeholders with a unified view of climate change impacts for decision making (Hagedorn et al., 2005).

The analysis first involves of assessing the EnsMean with the reference data. This step is important to ensure that the EnsMean of the models can reproduce the pattern of the reference data. To achieve this, we plotted the spatial distribution of the different variables used in this study and computed the spatial correlation (r), root-mean-square error (RMSE) and mean absolute error (MAE) between the EnsMean and the reference data for Pr, tas, tasmin, tasmax and hurs. In a second step, the climate change is analyzed for Burkina Faso using eleven climate indices. This analysis is done for two time periods: near future (2031-2060) and far future (2071-2100) under SSP1-2.6, SSP2-4.5 and SSP5-8.5. The changes in Pr, RX5day and CDD are given as relative values, while the changes for the other variables are given in absolute values. For this study, we consider that the climate change signal is robust across the country when 80% of the models converge in the same direction (Fischer et al., 2014). We also used a t-test with a 95% confidence interval to assess the significant change. Significant changes are shown as a dot for each grid point. The projected changes in the various climate indices are shown as mean annual values.

3. Results and discussions

3.1. Model evaluation

Figure.2 displays the annual patterns of key variables Pr, tas, tasmax, tasmin, and hurs, for both the reference data and the EnsMean in the historical climate. The EnsMean accurately reproduces the observed spatial patterns of Pr, tas, tasmax, tasmin, and hurs indicated by high spatial correlation ranging from 0.71 to 0.99. Pr exhibits the highest correlation between the reference and EnsMean data, while tasmin shows the lowest correlation. Consistent with observations, the EnsMean exhibits high Pr values in the southwestern region and low values in the northern region of Burkina Faso. This pattern is associated with hurs high in the southwestern part and low values in the northern part. The EnsMean effectively captures this pattern with a correlation coefficient of 0.97, an RMSE of 6.91%, and an MAE of 6.64%. Both the reference data and the EnsMean indicate that tas varies between 26°C and 31°C. Moreover, there is strong agreement between the two datasets regarding the spatial distribution of tas, with high values found in the northern part and low values in the western part. Similar patterns are observed for tasmax and tasmin between the reference data and the EnsMean.

Despite the good spatial agreement in terms of correlation and other measures, the analysis shows biases for the different variables. For instance, the EnsMean overestimates Pr by about 0.2 mm/day, especially in the northern and central parts of the country. Similar results were reported by Ajibola et al. (2020), who showed an overestimation of CMIP6 data compared to GPCC (Global Precipitation Climatology Center) data in West Africa. The study of Faye and Akinsanola (2022) also showed that CMIP6 data tend to overestimate precipitation amounts in West Africa. Additionally, the EnsMean tends to overestimate for tas, tasmax and hurs. Conversely, the EnsMean underestimates the tasmin by about 1°C mostly in the western and eastern parts of the country. This suggests that biases still exist in the NEX-GDDP -CMIP6 for Burkina Faso compared to ERA5 and CHIRPS. The bias in the NEX-GDDP -CMIP6 data could be related to the reference datasets (GMFD) used for the bias correction or the inherent uncertainties from different CMIP6 or biases in CHIRPS or ERA5 datasets. Substantial biases were observed in many CMIP5 studies compared to reanalysis or satellite data for West Africa, but with similar or even slightly higher biases compared to our results (Sawadogo et al., 2019; Heinzeller et al., 2018; Diallo et al., 2016). This gives us confidence that NEX-GDDP-CMIP6 can be used for climate change analysis in this challenging region.

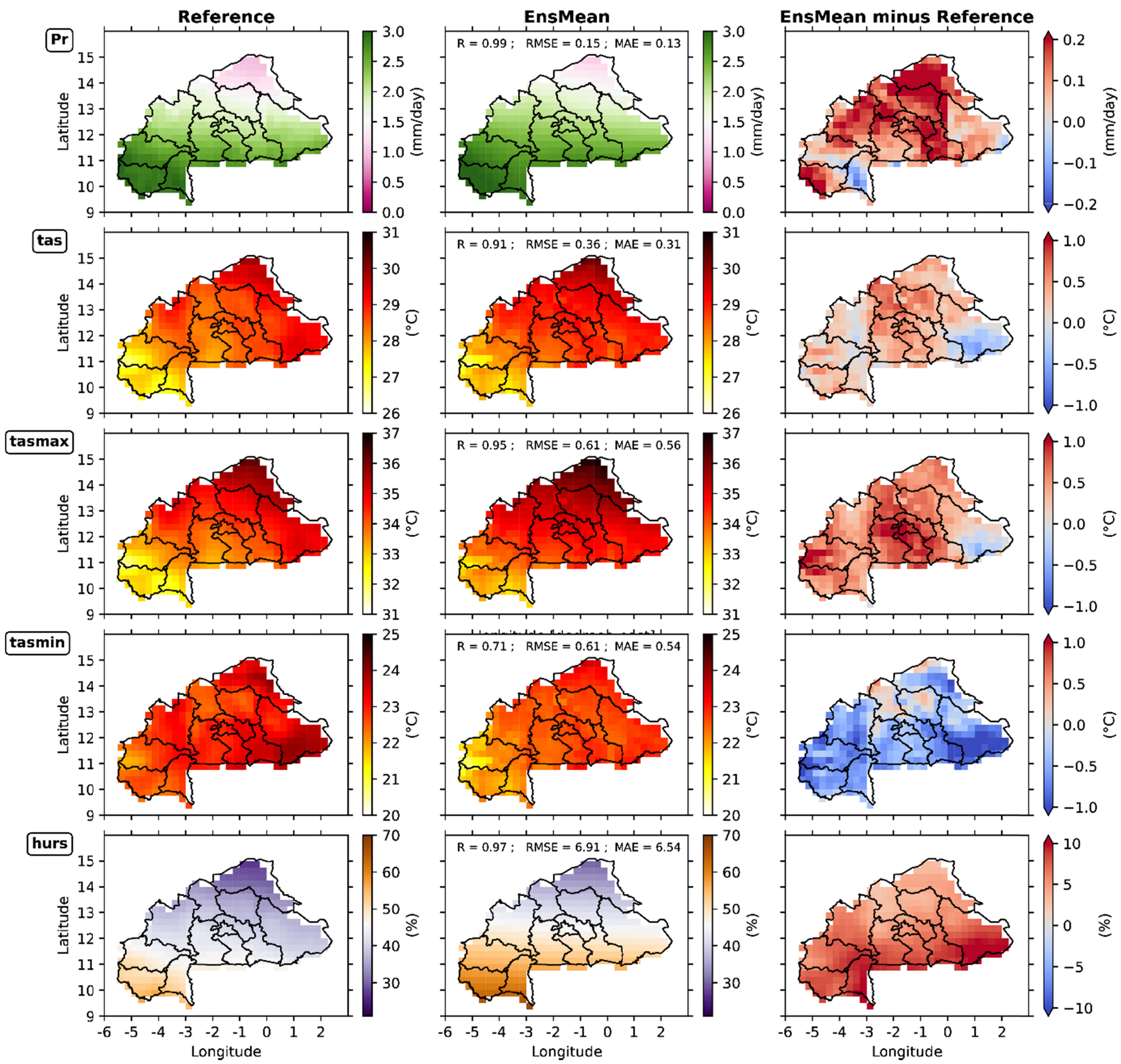

Figure.2: Mean annual patterns of precipitation (Pr), air temperature (tas), maximum temperature (tasmax), minimum temperature (tasmin), and relative humidity (hurs) for the reference data (CHIRPS and ERA5) and the NEX-GDDP-CMIP6 ensemble mean (EnsMean) with their bias (EnsMean minus reference) in the present climate (1985-2014). The R indicates the spatial correlation. The RMSE and the MAE shows the spatial root mean square error and the mean absolute error for the spatial patterns, respectively.

3.2. Climate projections

3.2.1. Onset, cessation of rainfall and length of the rainy season

Figs. 3 & 4 show the projected changes of the ORS, CRS, and LRS for the near and far future, respectively. In general, the EnsMean projections indicate an early ORS date across the country. Some areas in the north show significantly earlier ORS up to 5 days under the SSP2-4.5 scenario, while some areas in the southwestern part of Burkina Faso exhibit a slight increase in the ORS date in the near future under SSP5-8.5. In the far future, these areas could experience a significant late ORS up to 10 days. In addition, some areas in the southern and northern parts could also experience a slight delay in the ORS date. However, there is a strong discrepancy in the projections of the ORS date over the country in all scenarios and periods. For instance, 41% of the models indicate a late onset, while 59% show an early ORS under SSP1-2.6. This discrepancy may be attributed to the inability of some climate models to accurately represent the WAM jump, as the onset of rainfall and the WAM jump are interconnected (Mounkaila et al., 2015; Sylla et al., 2013). Moreover, this disagreement could be also related to the discrepancy among climate models to the strength of the future weakening of the Meridional Overturning Circulation (AMOC) (Bellomo et al., 2021; Weijer et al., 2020; Cheng et al., 2013) as this climate process modulates the response of WAM to climate change (Schmidt et al., 2017).

In contrast, projected changes of the CRS are more robust with 80% of the models showing a significant increase across the country under all scenarios and time periods, except for SSP1-2.6 in far future. The increases are more pronounced under SSP5-8.5 and toward the end of the century. This is consistent with the results of Wainwright et al. (2021) using CMIP6 datasets. This suggests that the LRS may increase in some areas of Burkina Faso. This is supported by the projected change in the LRS. The northern and eastern parts show a significant increase in the LRS season up to 10 days, while the western part shows a decrease under SSP5-8.5 and for the far future (5 days). This is in line with the findings of Kumi and Abiodun (2018) using 8 RCMs of CORDEX-CMIP5 under the RCPs 4.5 and 8.5 scenario. Though, there are some discrepancies in the sign of the change, especially for the period 2070-2100.

In general, climate change may impact the ORS, CRS and LRS in Burkina Faso. Therefore, farmers need to adapt their cropping practices to the expected changes in the onset and duration of the rainy season to reduce crop loss or failure.

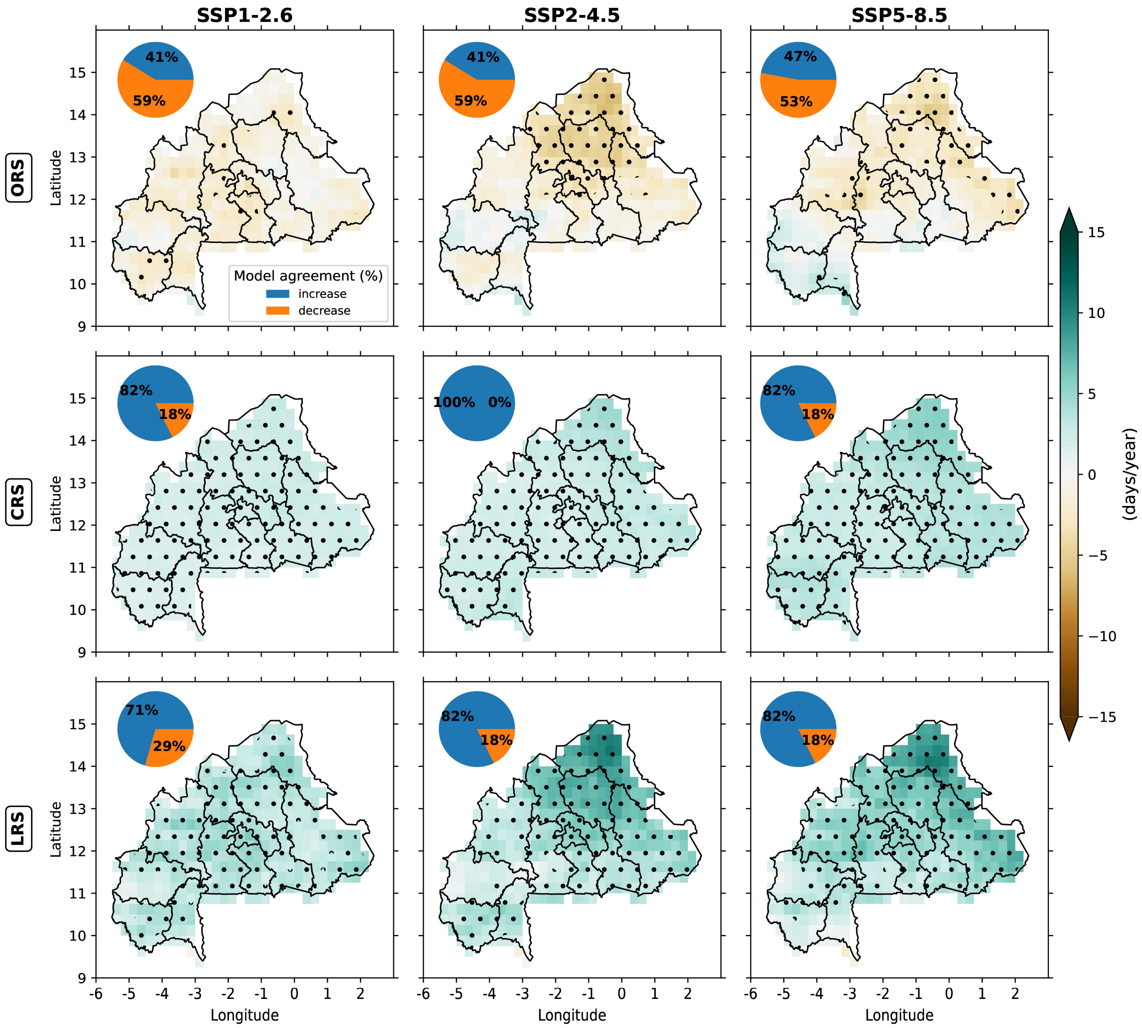

Figure.3: Projected changes of the onset, cessation, and length of the rainy season over Burkina Faso under different SSPs for the near future (2031-2060) based on the ensemble mean of statistically downscaled CMIP6 scenarios. Dots indicate areas where changes are significant at the 95% confidence level. The pie chart in each panel shows the model's agreement on the sign of the change in the country mean.

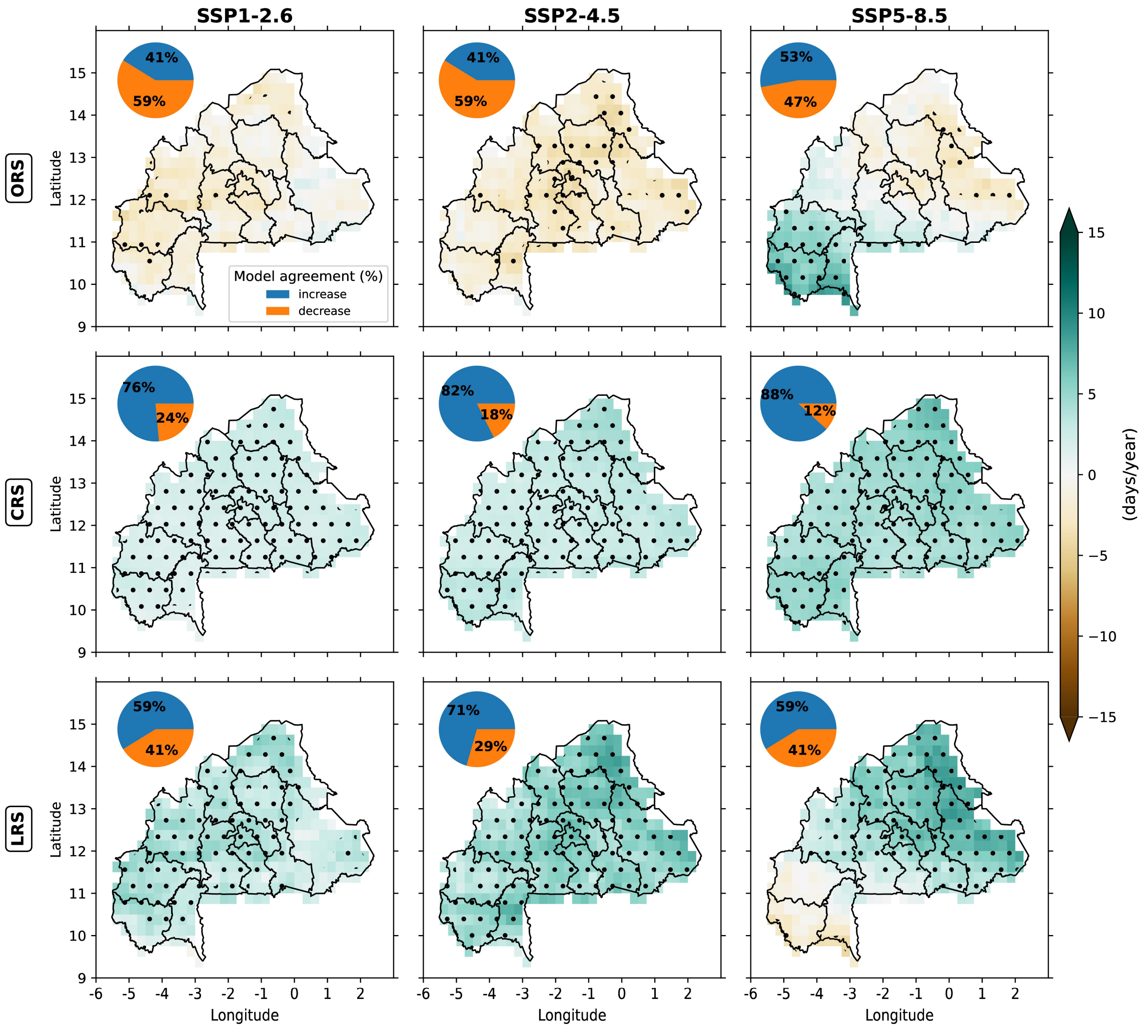

Figure.4: Same as Fig.3, but for the far future (2071-2100).

3.2.2. Air temperature

The projected temperature change under the different SSPs and time periods are presented in Fig.5. The EnsMean projects significant warming across the country. In addition, more than 90% of the models agree on the sign of the changes. The warming is much more pronounced under the SSP5-8.5 scenario in the period 2071-2100 compared to the other scenarios. The northern part could experience more warming compared to the other regions. In response to the SSP5-8.5 scenario, 1.5°C of warming is expected in the northern part in the near future, while projected of more than 4.3°C in the far future. Irrespective of the scenarios and time periods, certain areas could have a minimum warming of 0.8°C.

On country average, 1.0°C of warming is expected under SSP1-2.6, while a warming of 1.7°C is projected under SSP2-4.5 in the near future and the SSP5-8.5 scenario exhibits the highest level of warming reaching 2.8°C (Fig.6). However, the warming is more pronounced towards the end of the century in all SSP scenarios. For example, in the period of 2031-2060, an increase of 0.9°C is expected, whereas a warming of 1.1°C is projected in the period of 2071-2100 under SSP1-2.6. Under SSP5-8.5, the country could experience an annual increase of 4.2°C by the end of the century. From November to May, the EnsMean projects an increase of about 4.5°C under SSP5-8.5, while under SSP1-2.6, 1.3°C is expected. Note that even during the Harmattan period (December-January-February), the EnsMean projects an increase in tas in all scenarios and time periods.

However, warming in Burkina Faso could stabilize at SSP1-2.6 (1.0˚C) and SSP2-4.5 (2.0˚C) by the end of the century (Fig.7). The future temperature changes show very similar patterns and only slight differences in magnitude among the three SSP scenarios until 2040. Beyond 2040, these scenarios begin to deviate from each other. This suggests that the pathways and magnitudes of future temperature changes in the country after 2040 are increasingly different between the scenarios. Moreover, the SSP5-8.5 scenario projects further warming beyond 2100, with the country warming by about 5°C by the end of the century. The 90th quantile of the model simulations even project the country to warm by as much as 7°C. Similar results have been also reported by Fan et al. (2020) for the Africa region using CMIP6 models. The overall results are also align with previous studies using SSP and RCP scenarios over the West Africa region (Almazroui et al., 2020; Sylla et al., 2016; Daron, 2014). The expected strong temperature increase could negatively impact important socio-economic sectors in Burkina Faso such as agriculture and solar energy (Sawadogo et al., 2019; Diarra et al., 2017).

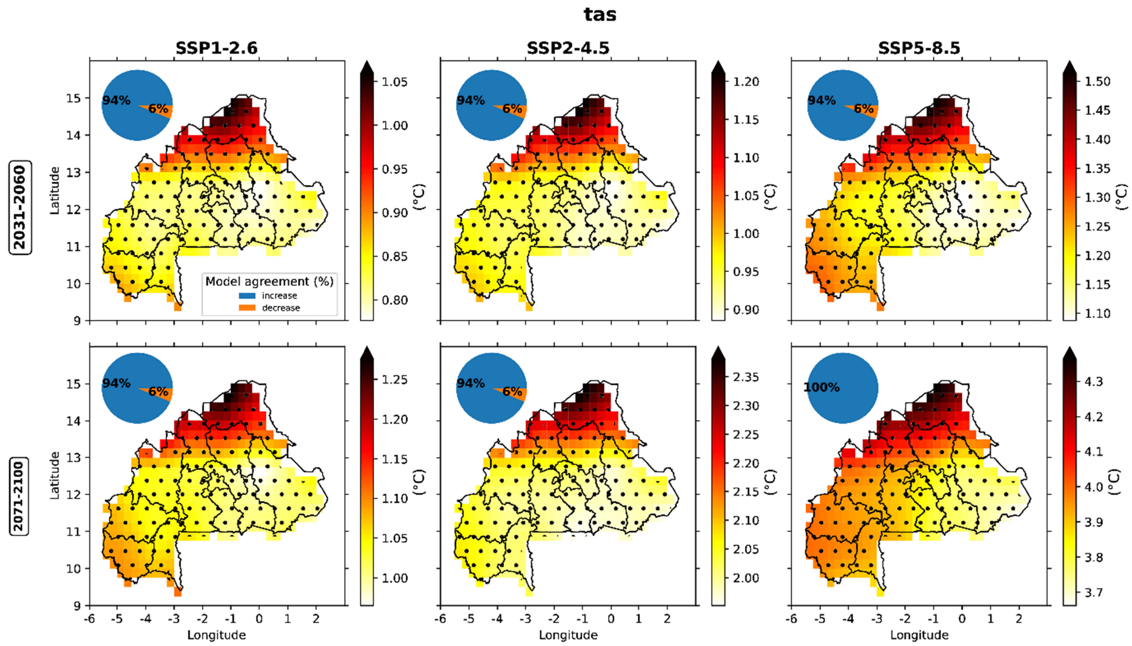

Figure.5: Projected changes in mean annual air temperature under different SSP scenarios and time periods in Burkina Faso based on the ensemble mean of statistically downscaled CMIP6 scenarios. Dots indicate areas where changes are significant at the 95% of confidence level. The pie chart in each panel shows the model's agreement on the sign of the change in the country mean.

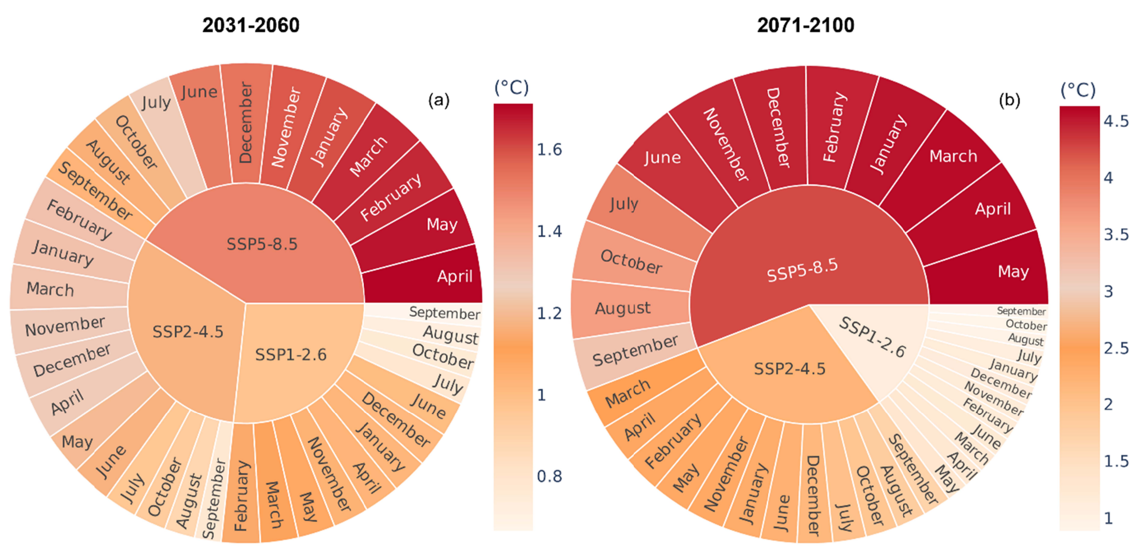

Figure.6: Projected annual and monthly air temperature changes for Burkina Faso illustrated as pie chart for the based on the ensemble mean of statistically downscaled CMIP6 scenarios. Panel (a) indicates the change in near future (2031-2060), while panel (b) shows the change in far future (2071-2100). The individual months and the SSP scenarios are ranked according to their temperature change.

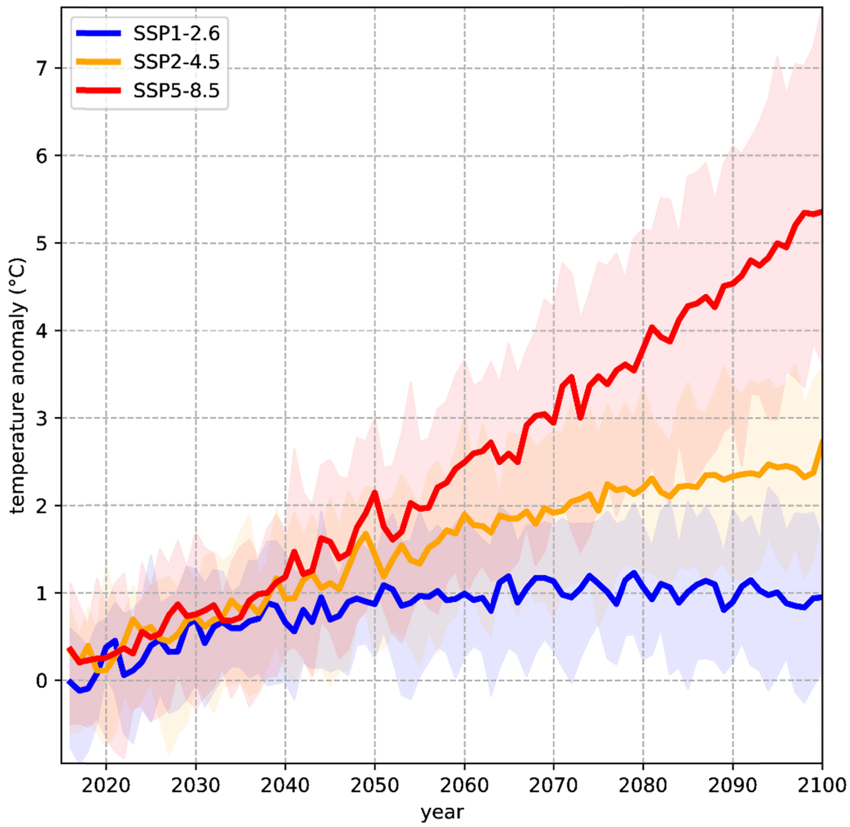

Figure.7: Temporal change in mean annual air temperature for Burkina Faso from 2015 to 2100 compared to the reference period (1985 to 2014) based on statically downscaled CMIP6 scenarios. The blue, orange, and red lines indicate the ensemble mean for the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, respectively. The shaded regions describe the uncertainty of the climate model simulations represented by the 10th and 90th percentiles.

3.2.3. Precipitation and potential evapotranspiration

The EnsMean projects a significant increase of the annual rainfall amount in Burkina Faso (Fig.8). The signal is robust under all scenarios and time periods, except in the far future under SSP1-2.6, where 25% of the model simulations exhibit a decrease in rainfall. The small increase may occur under SSP1-2.6 in both time periods; the maximum increase of the rainfall amount is up to 0-10%. Under the SSP2-4.5 scenario, the increase may raise to 10-15%, while under SSP5-8.5, it may reach 20-30%. This suggests that climate change is likely to increase the rainfall amount in Burkina Faso. Moreover, the increase in rainfall is most pronounced in northern part of the country. Our results are also similar to projections of rainfall in the central Sahel (including Burkina Faso) in previous studies that analyzed CMIP5 simulations under different RCP scenarios (Akinsanola and Zhou, 2019; Monerie et al., 2017; Biasutti, 2013). The increase of the rainfall amount is also relatively consistent to the results presented by Almazroui et al. (2020), in which the CMIP6 simulations where analyzed for the entire African continent. Nevertheless, it is important to note that this increase may exhibit considerable variability, as shown in Fig.9. Moreover, this variability becomes more pronounced as we move from low to high GHG emission scenarios, suggesting that the future rainfall variability in Burkina Faso depends on the SSP scenarios. GHG emissions are one of the main factors that contribute to the variability of the monsoon in the West Africa region (Monerie et al., 2022). Under the SSP5-8.5 scenario, the mean temporal change in the precipitation amount shows an increase of about 15% by 2100. 90% of the models even project an increase in rainfall amount of more than 60%, while 10% exhibit a decrease of about -20%. Similar results were also obtained by Biasutti (2013) where 80% of the CMIP5 models showed an increase in rainfall in the central Sahel.

The increase in precipitation could be attributed to the projected strong warming across the country. The warming of the atmosphere in the Sahel region leads to an intensification of the low-level moisture flux and the northward movement of the WAM; which in turn leads to an increase in precipitation (Gaetani et al., 2017). The EnsMean also projects a significant and robust increase in ET_0 among all SSPs and time periods (Fig.10). The increase is more robust towards the end of the century. In the near future, the projected change in ET_0 has a similar magnitude (5-10%) in all scenarios. In the far future, however, there are some differences between the SSPs, with the SSP5-8.5 scenario having the highest increase of 20%. This suggests that warming would lead to an increase in ET_0, which is in line with previous studies (Abiodun et al., 2021; Abiye et al., 2019). The increase in ET_0 in the Sahel may pose a serious problem for the agricultural sector because more water could evaporate from vegetated soils (Sissoko et al., 2011). In addition, off-season agriculture (typically in dry season), which contributes to food security in Burkina Faso (Ouedraogo, 2020), could become more challenging due to higher ET_0 therefore less soil water availability during this time period. Overall, despite the increase in rainfall, the increase in ET_0 could outweigh the positive rainfall effects for the country.

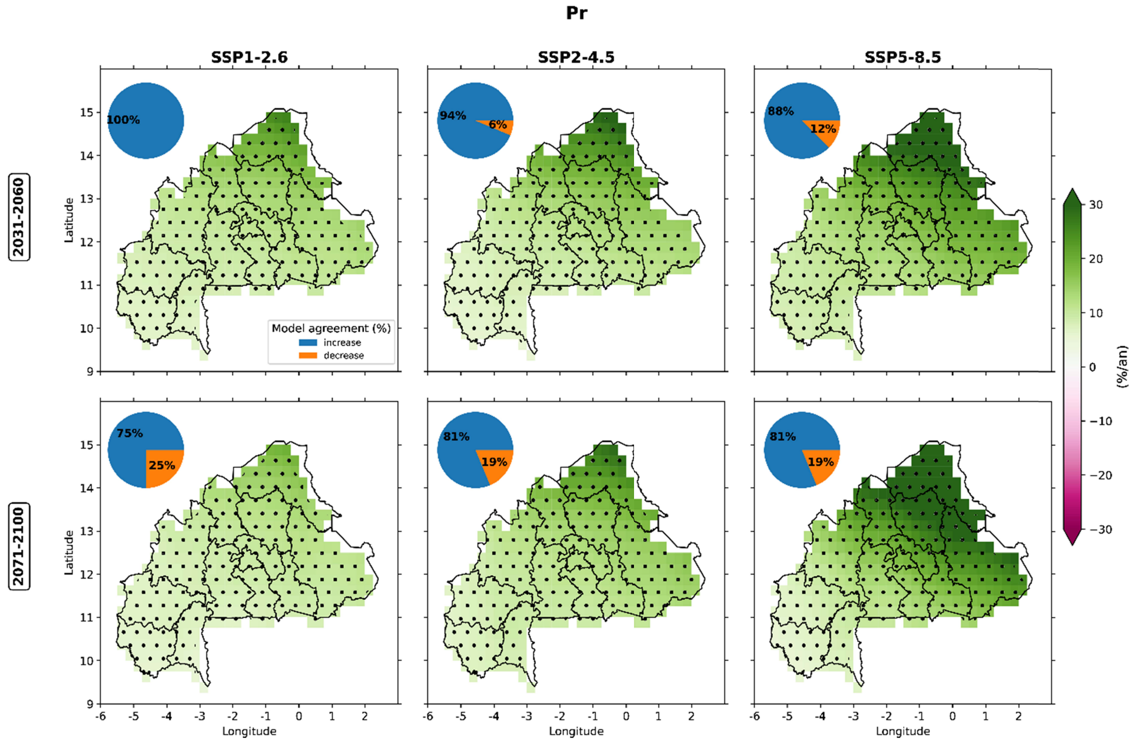

Figure.8: Similar as in Fig.5, but for mean annual precipitation amount. The projected precipitation changes are indicated as relative values. Green area corresponds to an increase of the annual precipitation amount over Burkina Faso and therefore wetter conditions.

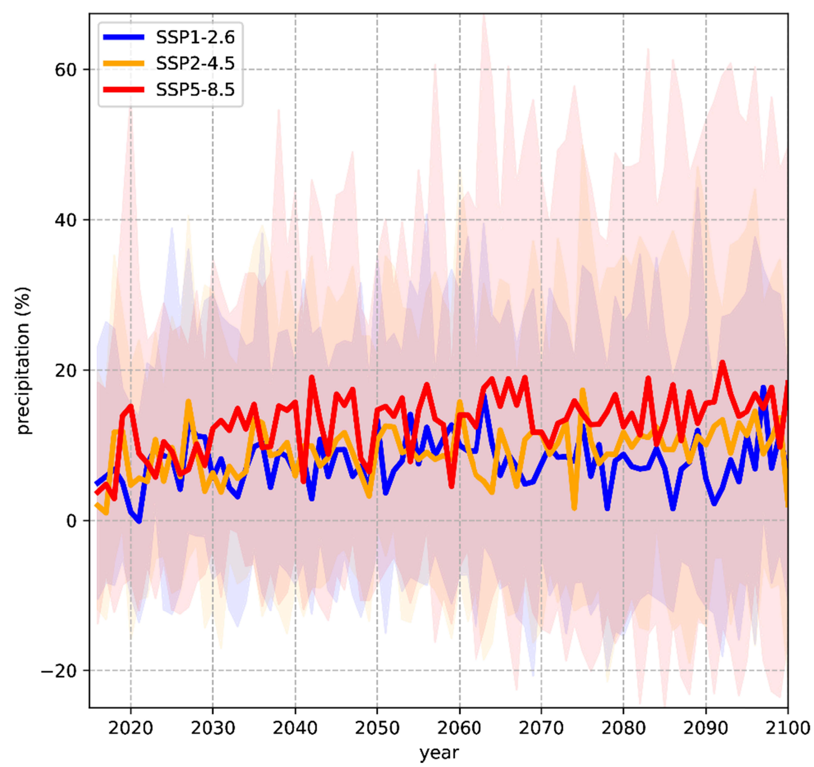

Figure.9: Similar as in Fig.7, but for the annual precipitation amount. The projected precipitation changes are indicated as relative values. A positive value indicates an increase of the precipitation amount.

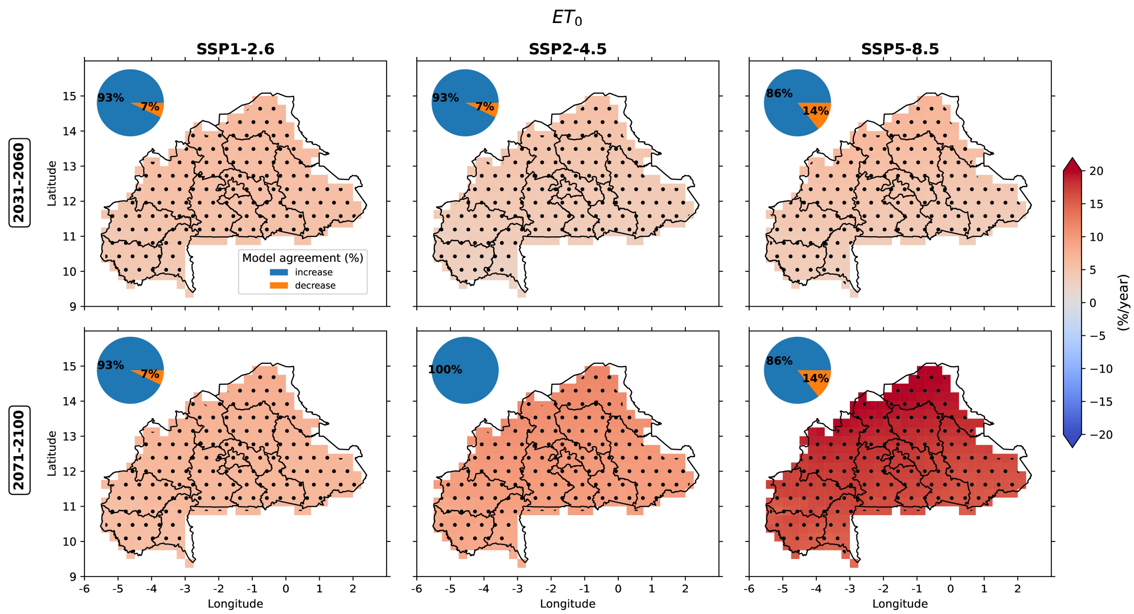

Figure.10: Similar as in Fig.6, but for the mean annual reference evapotranspiration. The projected evapotranspiration changes are indicated as relative values. Red areas correspond to an increase of the potential evapotranspiration over Burkina Faso.

3.2.3. RX5days and RR20mm

The RX5days is typically used as an indicator of flood risk, while the RR20mm is typically used for the risk of heavy rain events leading to flooding. Fig.11 & 12 show the annual projected changes in RX5days and RR20mm in Burkina Faso. Similar to rainfall and ET_0, the EnsMean projects an increase in RX5days in all scenarios (Fig.11). The projected changes are consistent and significant in all areas. This shows that climate change may increase the risk of flooding in the country. In the period 2031-2060, the northern part of the country could be affected by floods up to 15% more frequently, while in the period 2071-2100 most areas could be at risk. The estimated increase in RX5days could exceed 20% in the SSP5-8.5 scenario in the far future. In the near future, the magnitude could reach 10-15% in all scenarios.

Additionally, the number of heavy rainfall events in the country is likely to increase (Fig.12). More than 80% of the models show a significant increase in RR20mm. The SSP5-8.5 scenario shows the highest increase with a value of 2-4 days and 4-6 days per year in the near and far future, respectively. The EnsMean shows a greater magnitude in the far future period.

Other studies also reported an increase in RX5days and RR20mm in some parts of West Africa, including Burkina Faso (Worou et al., 2023; Akinsanola and Zhou, 2019; Diallo et al., 2016). The increase in RX5days and RR20mm could be related to the availability of moist air in a warmer atmosphere, as the convergence of atmospheric moisture fluxes in the central Sahel is expected to increase with global warming (Okoro et al., 2020). Population growth, land use, and land cover change have been also identified as factors that may contribute to the increase in heavy rainfall and flooding in Burkina Faso (Sougué et al., 2023; Tazen et al., 2019).

The response to temperature rise could increase the number of heavy rain events and flood disasters in Burkina Faso. The study by Tazen et al. (2019) found that the number of floods and heavy rain events in Burkina Faso has increased by five per year in recent decades. These events have caused significant loss and damage in the country. For example, the recovery costs from the consequences of the 2009 flood alone was estimated at about 1.5% of the country's GDP (UNDRR, 2009). To mitigate the impact of flood disasters, policymakers and stakeholders should prioritize the implementation of appropriate measures, including early warning systems, nature-based solutions, and social protection initiatives to minimize loss and damage.

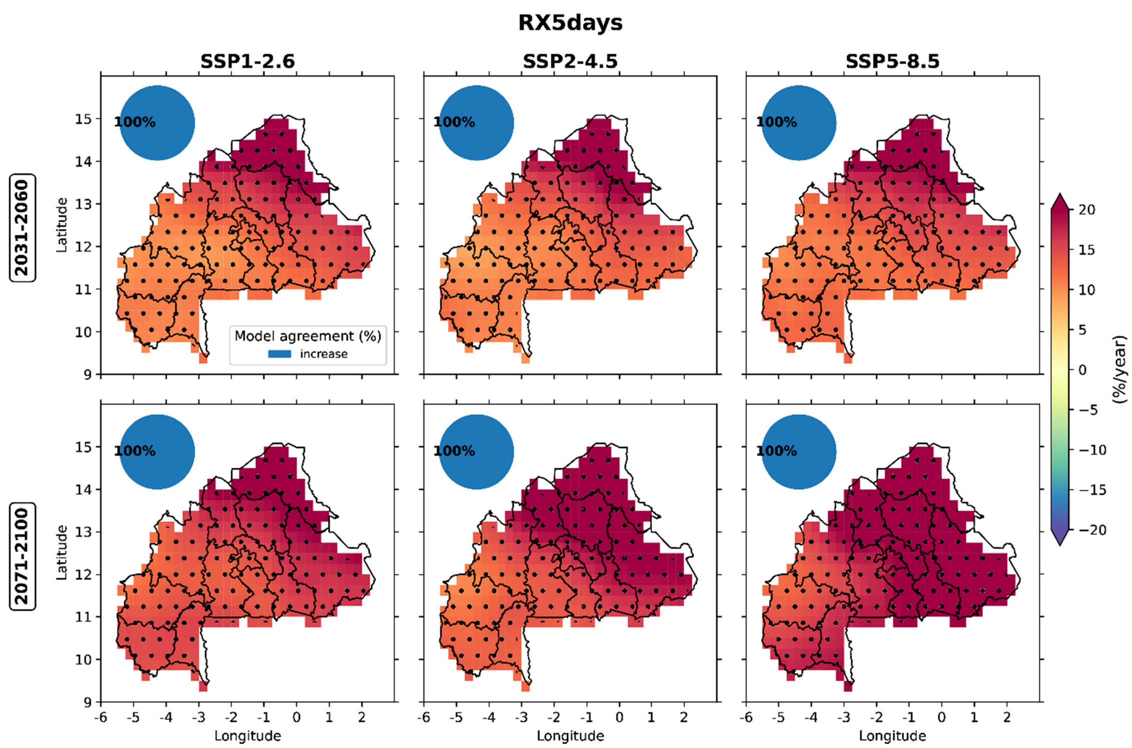

Figure.11: Similar as in Fig.6, but for the maximum of five-day precipitation amount (RX5days). The projected RX5days changes are indicated as relative values. Red areas correspond to an increase of

the five-day precipitation amount over Burkina Faso and therefore to wetter and more extreme conditions during the monsoon period.

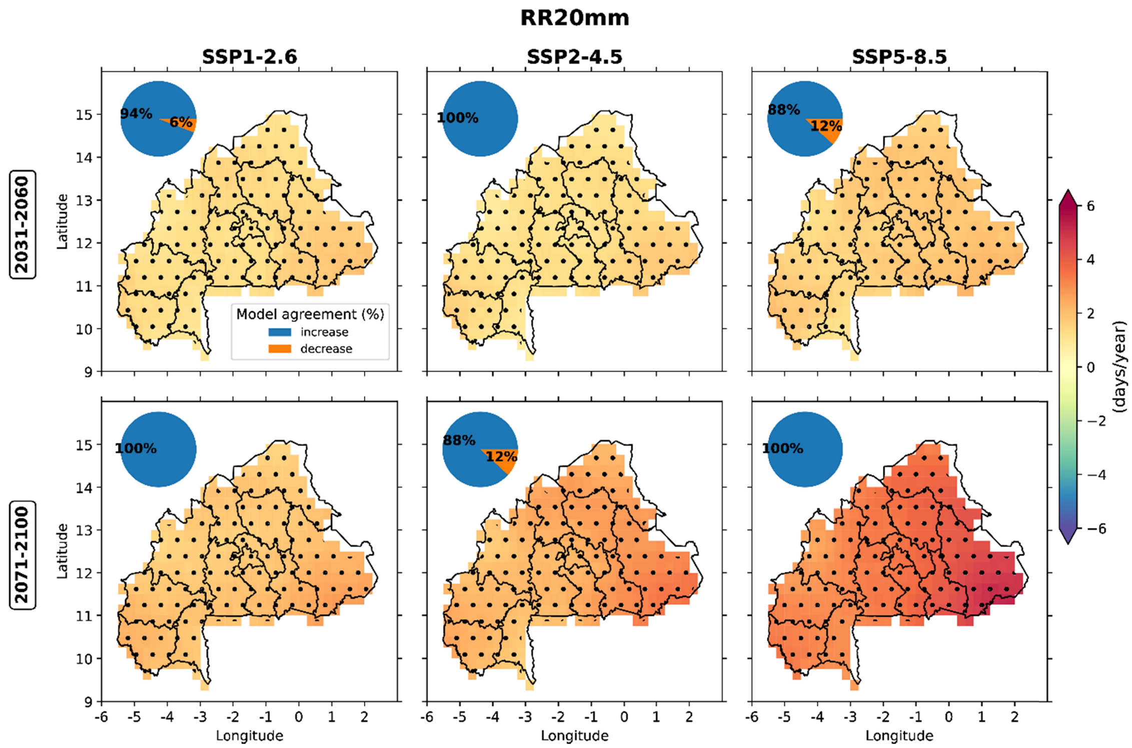

Figure.12: Similar as in Fig.6, but for the annual number of days with daily precipitation of at least 20 mm (RR20mm) as indicator for heavy rainfall events. The projected changes are given as absolute values. Red areas correspond to an increase of heavy rainfall events over Burkina Faso.

3.2.4. Heat stress (HI) and discomfort index (DI)

Figure 13 shows the projected changes in the number of days for the HI category "dangerous" under different SSP scenarios and time periods in Burkina Faso. The frequency of dangerous HI days is expected to increase towards the end of the century. All models agreed on the significant changes in HI and the changes are even greater in the far future. SSP5-8.5 indicates the strongest changes. SSP1-2.6 and SSP2-4.5 show similar changes in the near future but differ in the far future. Notably, in the far future, some areas in the western part seem to be the hotspot of the HI under the SSP2-4.5 (~ 140 days); and these areas become more pronounced under the SSP5-8.5 scenario by more than 180 days. This means that the population living in these areas could be stressed and at risk of heat-related illnesses such as heat cramps, heat stroke and heat exhaustion for about 50% days of the year. In the near future, about 40-60 days per year are expected in Burkina Faso. These findings align with previous studies, including Sylla et al. (2018), who used the CORDEX-CMIP5 simulations and found an increase of more than 30 days of dangerous days under the RCP8.5

scenario at 2°C global warming level. These results are comparable to our projections for the near future. Moreover, the level of 2°C global warming used in the study of Sylla et al. (2018) corresponds to the period we defined for the near future. Another study showed an increase of HI of danger category of 100 to 130 days under RCP8.5 for the period 2080-2099 relative to the baseline period of 1981-2000 (Sun et al., 2019). With the SSP scenarios, our results are consistent with the study of Zeppetello et al. (2022) in terms of the increase of dangerous HI days per year.

Unlike HI, DI provides a more comprehensive assessment of how weather conditions are likely to affect human comfort. Although HI and DI show a similar pattern, they differ in magnitude. Moreover, 100% of the model converges in the sign of the changes. Again, the changes are larger in the far future and under the SSP5-8.5 scenario. The EnsMean projects for the near future an increase of less than 50 days under SSP1-2.6, while 50-70 days are expected under the SSP5-8.5 scenario. A threefold increase in the number of days is projected for the far future under the SSP5-8.5 scenario compared to the other SSPs. Moreover, the western part proves to be a hotspot for the increase of DI in Burkina Faso. Our results are comparable to the projected change in DI in the near future for the SSP5-8.5 scenario (Sylla et al., 2018).

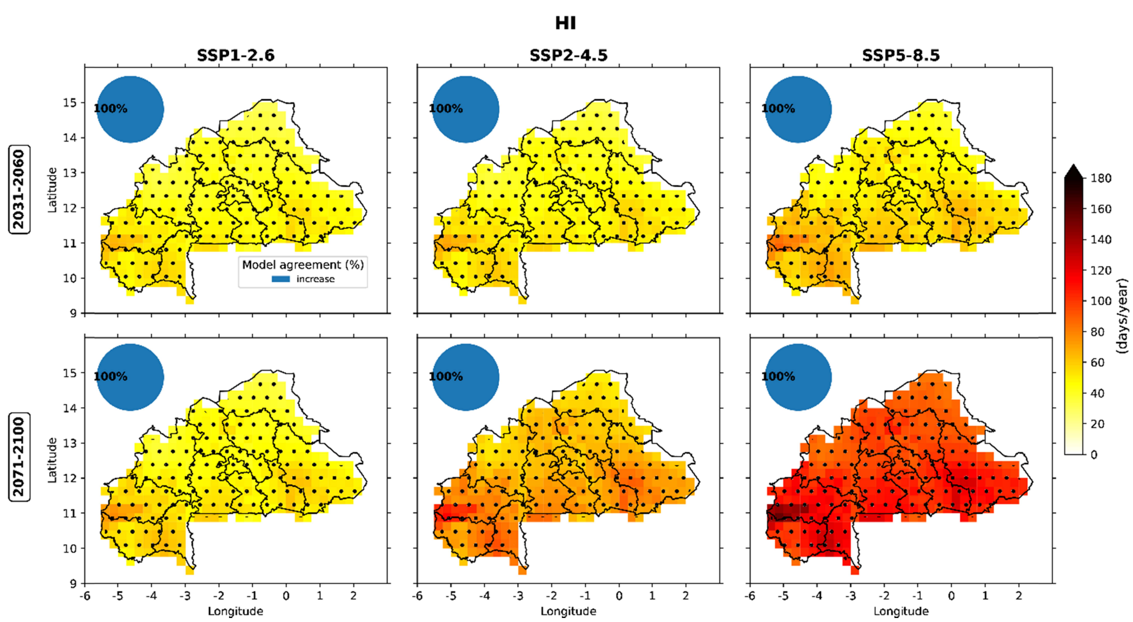

Figure.13: Similar as in Fig.6, but for heat stress index (HI).

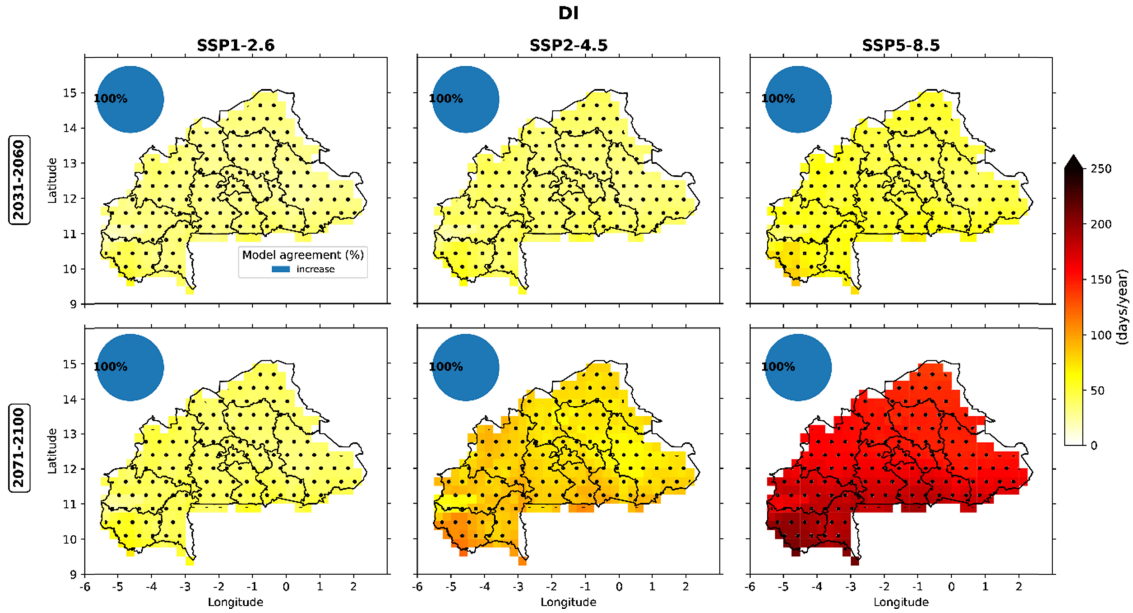

Figure.14: Similar as in Fig.6, but for discomfort index (DI).

3.2.5. Cooling-degree days (CDD)

Under the different SSPs, the number of days per year in CDD will increase in the near and far future (Fig.15). These changes exhibit robust and significant patterns across the entire country, with more pronounced effects towards the end of the century. The SSP1-2.6 scenario exhibits the lowest increase, while the SSP5-8.5 indicates the highest increase. The number of days under the SSP5-8.5 scenario is expected to exceed 200 days in the period 2071-2100. In the period 2031-2060, the value is about 50 days. Odou et al. (2023) found an increase in CDD in the West Africa region with greater increase in the RCP8.5 scenario and at the end of the century. Indeed, CDD serves as a proxy for energy planning (Semmler et al., 2009). This means that energy demand for cooling buildings will rise under climate change. CDD is projected to rise, indicating a greater need for cooling, it is crucial to consider energy planning strategies to ensure sustainable and efficient cooling solutions. In summary, Burkina Faso needs to adapt or/and upgrade its building designs to increase thermal comfort and reduce energy required for cooling purposes.

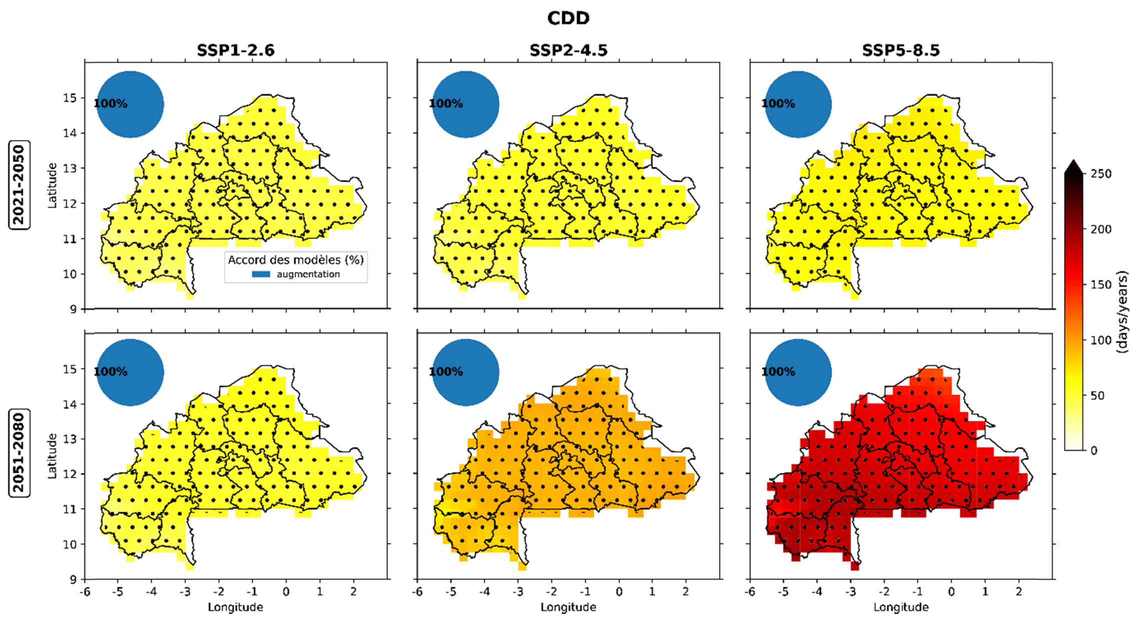

Figure.15: Similar as in Fig.6, but for cooling degree days (CDD).

3.2.5. Regional changes in tas, Pr, HI, and CDD

Fig.16 depicts the projected changes in tas, Pr, HI and CDD for the 13 administrative regions of Burkina Faso under different SSPs and time periods. The Sahel and the Nord regions exhibit the highest increase in warming under all SSPs (Fig.16 a & e). The SSP5-8.5 scenario indicates the highest increase of 4°C. These trends generally intensify towards the latter part of the century. For both regions, there is an increase of 3°C between the SSP1-2.6 and SSP5-8.5 scenarios. For all time periods and scenarios, the Sahel region has the highest warming. Moreover, the Sahel region exhibits the highest increase in Pr of about 30% and 40% under SSP5-8.5 in the near and far future, respectively (Fig.16 c & g). This could directly increase the frequency flooding in the region (Fig.16 d & h). At the same time, the Sahel region has the highest projected change in ET_0 (see Appendix Fig.17 b & f). The combination of an increase in tas, Pr, RX5day and ET_0 could potentially increase the risk of flooding and water stress (during the dry season) and thus reduce livestock sustainability, as several studies have pointed out (Godde et al., 2021; Chikwanha et al., 2021; Ngarava et al., 2021). The Sahel region is the top livestock-producing in Burkina Faso, accommodating approximately 64% of the sheep and goat population (Ilboudo and Somda, 2018). So, the impacts of climate changes could reduce the meat supply chain from the Sahel region.

Heat stress has also been identified as one the source of reduced productivity of livestock (Thornton et al., 2022). The Sahel region has the lowest increase in HI compared to other regions. However, this relatively small increase could also impact the livestock well-being in this region. On the other hand, the Haut Bassins region could be more affected by the increase in HI by the end of the century as the humidity is high there (see Fig.2). From the near to far future, the number of days in HI is expected to double under SSP5-8.5 scenario. In the far future period, about 120, 90, and 55 days are expected under SSP5-8.5, SSP2-4.5 and SSP1-2.6 scenarios, respectively. This region is known to be the vital economic force of the country. Several studies emphasized that the rise in HI could reduce the capacity of workers to engage in physical labor (Parsons et al., 2022; Romanello et al., 2021; Kjellstrom et al., 2018). This labor capacity losses may have an impact on the socio-economic activities of the region. The study by Saeed et al. (2022) revealed that the loss of labor due to heat stress in agriculture (~18%), mining (~6%), construction (~6%), manufacturing (~4%) and all sector (~4%) could substantially reduce the GDP by 4% in Burkina Faso. This suggests that climate change could have significant impact on the socio-economic activities of the country. Therefore, appropriate measures need to be undertaken to mitigate the potential adverse effects of rising HI in this region. One of the key areas that require attention is the protection of vulnerable people, particularly those engaged in outdoor activities and occupations exposed to extreme heat conditions. Implementing heat safety regulations and guidelines can help minimize the risk of heat-related illness among vulnerable people.

Figs.17 & 18 in the Appendix also present other climate factors used in this study for the 13 administrative regions.

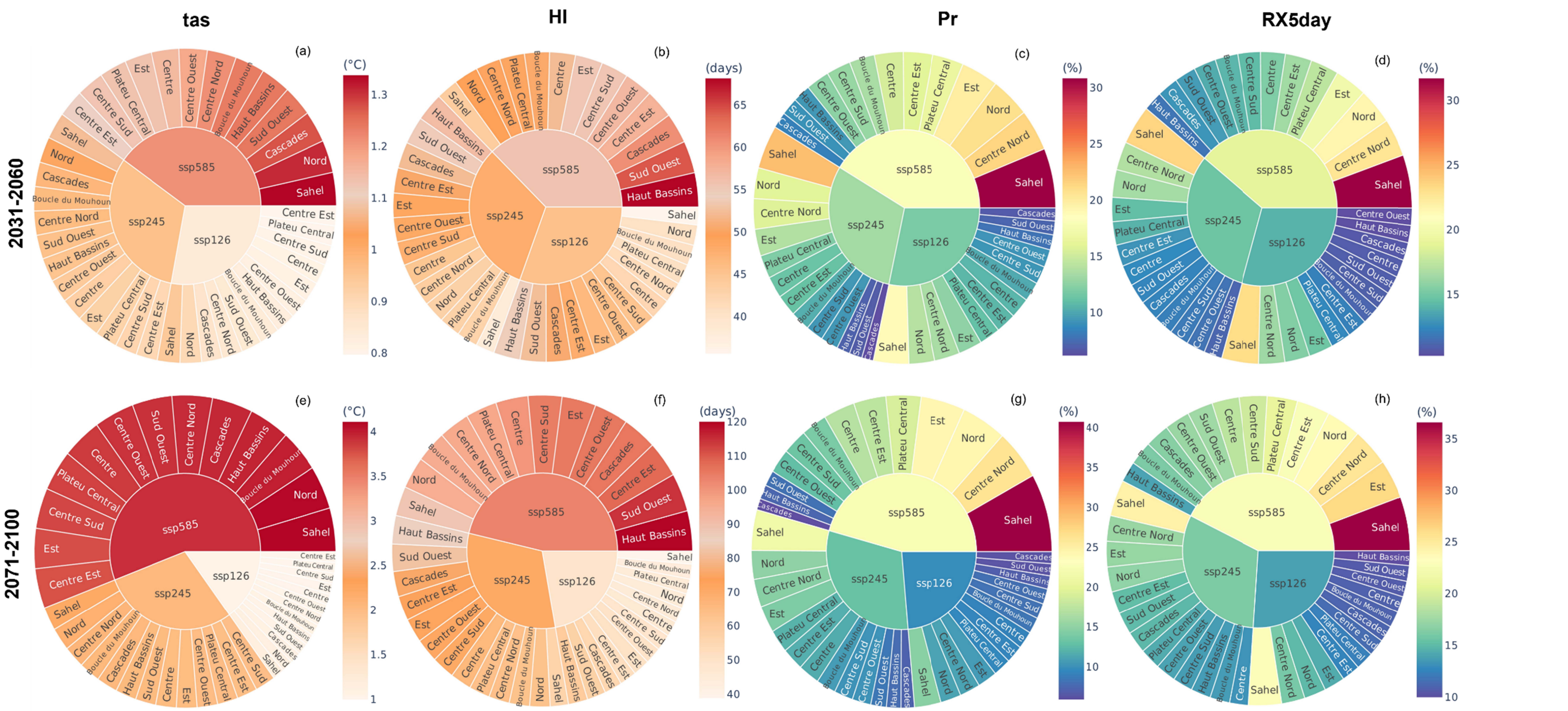

Figure.16: Average projected changes in tas, HI, Pr, and RX5day over the 13 administrative regions in Burkina Faso under SSP scenarios and future periods. The individual administrative regions and the SSP scenarios are ranked according to their climate index change.

4. Summary and conclusion

The study examined the impact of climate change in Burkina Faso. Compared to previous study done for the West African region, we used statistically downscaled CMIP6 simulations (~ 25 km) provided by NEX-GDDP to determine the projected changes for eleven climate indices. The analysis was carried out under SSP1-2.6, SSP2-4.5 and SSP5-8.5 climate change scenarios for the near future (2031-2060) and far future (2071-2100) relative to a recent baseline period of 1985-2014. In addition, CHIRPS and ERA5 reanalysis data were used to evaluate the performance of the ensemble mean of the climate model simulations for some key variables (e.g., precipitation, minimum and maximum temperature, and relative humidity) in the historical climate. The main results of the study based on the ensemble mean can be summarized as follows:

- The statistically downscaled CMIP6 simulations were able to reproduce the spatial patterns of selected climate variables with some biases.
- Significant warming is expected across all areas, with the northern part showing the highest warming level of more than 4.3°C under the SSP5-8.5 scenario.
- An increase of the annual precipitation amounts up to 30% is projected in some areas, which could potentially increase water availability. However, this increase in water availability may be offset by a projected 20% increase of evapotranspiration, which could lead to water stress and therefore additional challenges for rainfed agriculture and water resource management.
- Moreover, the length of the rainy season in Burkina Faso could potentially increase by up to 10 days under the SSP5-8.5 scenario, with a slightly early onset, especially in the Sahel region.
- The risk of flooding is likely to increase due to an increase of heavy rainfall events. These increases are greater under the SSP5-8.5 scenario and in the far future period.
- Due to strong temperature increase, the number of days of heat stress days, discomfort days and cooling degree days is expected to increase in a substantial manner in all scenarios and time period in Burkina Faso.

The strong response to global warming in Burkina Faso could strongly weaken socioeconomic development, as climate change will affect most development sectors. However, our analysis also revealed that the projected changes for the different climate indices are much lower under the socio-economic pathways SSP1-2.6 and SSP2-4.5. Thus, the timely implementation of mitigation measures could significantly reduce climate change impacts for this vulnerable region. The results of this study are consistent with previous studies on the West Africa region, mainly in the Sudan-Sahel, where most climate hazards are amplified by global warming (Diba et al., 2022; Vogel et al., 2020; Diasso and Abiodun, 2018). However, our results suggest that the statistically downscaled CMIP6 simulations show higher warming in Burkina Faso compared to the CMIP5 simulations where 2.5°C is expected under the RCP8.5 scenario for the 2071-2100 period (Deme et al., 2017; Brown and Crawford, 2008) although a relatively recent baseline period was selected in our study. This disparity between CMIP5 and CMIP6 temperature projections has been also shown in previous studies (Cos et al., 2022; Zhu et al., 2021; Fan et al., 2020) and it has been attributed to the higher climate sensitivity in CMIP6 data (Zelinka et al., 2020). While various climate indices were considered in this study, it should be noted that these variables are not intended to be comprehensive. Further studies could examine the impacts of heatwaves, droughts, and strong winds in Burkina Faso with corresponding indices. Indeed, heatwaves, droughts, and strong winds occur frequently and have significant impacts on human health and crops (Sawadogo, 2022; Sorgho et al., 2021b; Visser et al., 2003).

In addition, further assessment of climate change impacts in Burkina Faso is needed in various sectors such as agriculture, water resources and health to gain deeper insights of the impacts of climate change and to formulate appropriate measures for climate protection. Many West African countries elaborate their National Adaptation Plans (NAP) every five years to mitigate the impacts of climate change in their respective countries. The results of this study provided useful information on climate change impacts in Burkina Faso based on the latest climate change scenarios. The findings could be incorporated into Burkina Faso's NAP to enhance preparedness and resilience in this country and could serve as an important reference study for NAPs of other Sudan-Sahelian countries. However, the development and implementation of climate protection measures is still pending in West Africa or failing due to lack of financial resources. Therefore, a joint global effort is needed for vulnerable countries like Burkina Faso to secure funding for the development of adaptation strategies and their timely implementation in order to mitigate the negative impacts of climate change in this region as efficiently as possible.

Acknowledgment

The authors thank the NASA center for climate simulation making the NEX-GDDP-CMIP6 dataset public available. We are also grateful to the European Centre for Medium-range Weather Forecast (ECMWF) for providing the ERA5. We also thank the Climate Hazards Group at the University of California, Santa Barbara for the CHIRPS data. The work was partially supported by the German Federal Ministry of Education and Research under the ENERSHELF project and the CONCERT and FURIFLOOD project of the WASCAL phase II programme. Thankful to Capacity-building Initiative for Transparency (CBIT) project through the Ministry in charge of Environment Burkina Faso for funding support.

Data Availability

The NEX-GDDP-CMIP6 can be download via the NASA center for climate simulation platform (https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6). The CHIRPS data is available from this website http://data.chc.ucsb.edu/products/. The ERA5 reanalysis data can be retrieved via the Copernicus platform (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview)

Appendix

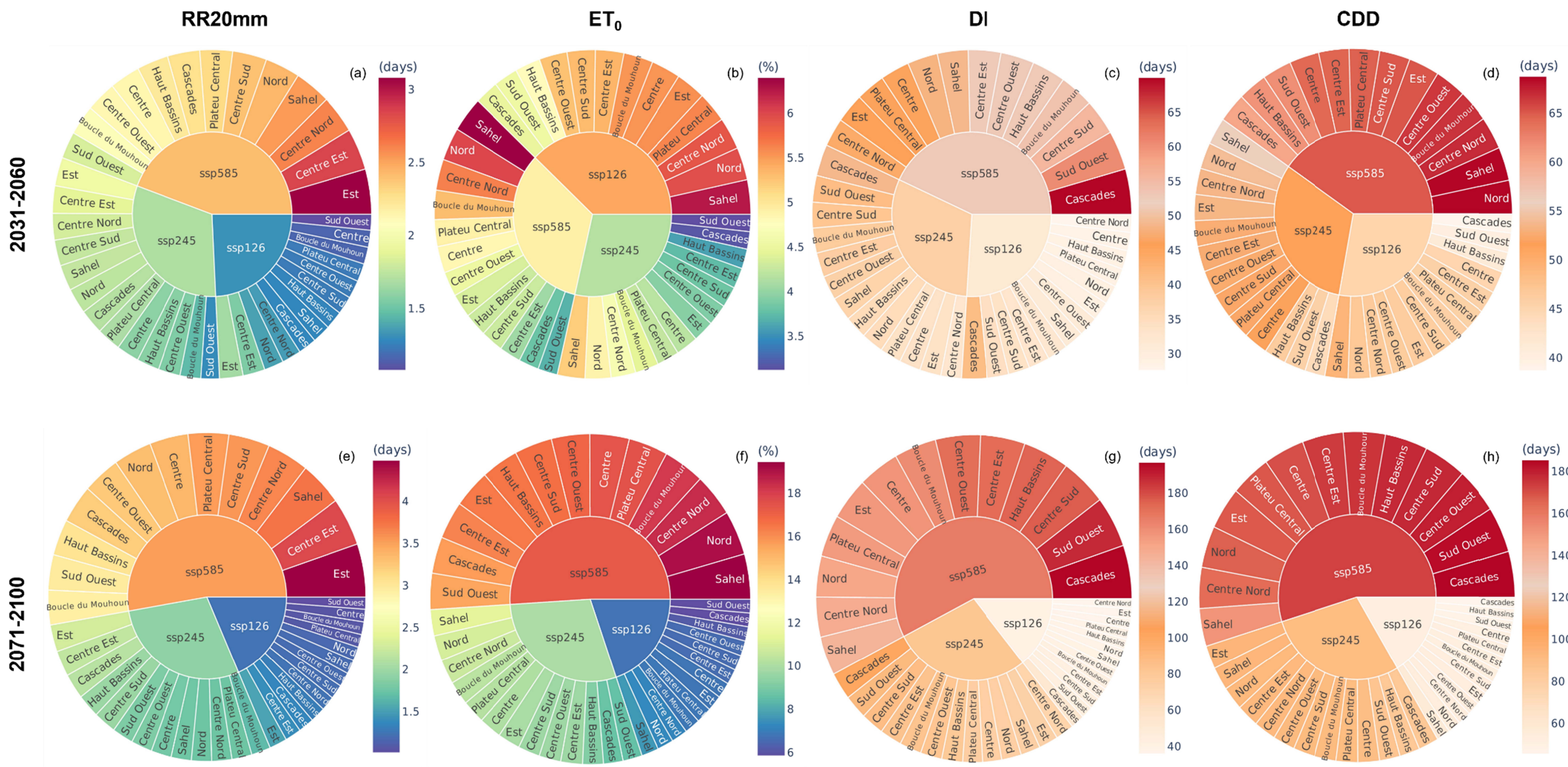

Figure.17: Average projected changes in RR20mm, ET_0, DI and CDD over the 13 administrative regions in Burkina Faso under SSP scenarios and future periods.

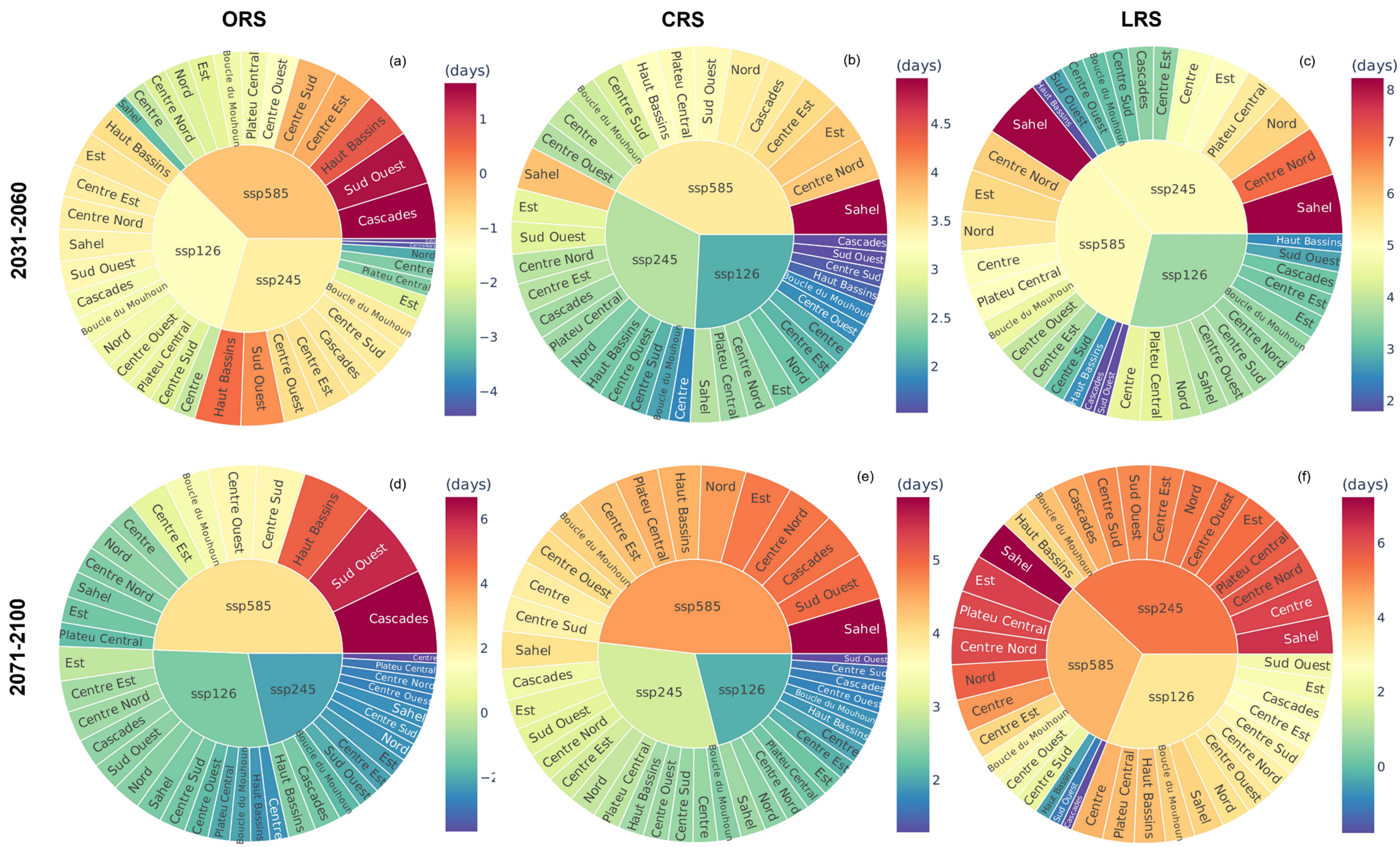

Figure.18: Similar to Fig.18, but for Onset, Cessation and LRday.

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