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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 (Climate Hazards Group InfraRed Precipitation with Station data) and ERA5 (ECMWF Reanalysis v5)) 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, 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 SSP2–4.5, 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 and strengthen population resilience for a sustainable future.

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 are affecting human well-being. This has led scientists, governments, and policymakers to make considerable commitments to reduce 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 (Maslin et al., 2023). Despite this historic agreement, signed by all

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parties, the impacts of climate change have become increasingly severe in recent years (WMO, 2019). 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 (Langue et al., 2023; Nkrumah et al., 2019; Salack et al., 2016). 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). Additionally, global climate change is probably going to affect water resources within 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. This 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 1960 s (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 (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 (Ibrahim et al., 2014; De Longueville et al., 2016). 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., 2021a). According to the National Adaptation Plan (NAP) of Burkina Faso, the agricultural sector is the most vulnerable sector to climate change (Sorgho et al., 2021a; UNFCCC, 2015).

The future impacts of climate change in the Sahel have been studied in the literature. By the end of the century, the whole region is predicted to experience a temperature increase above the worldwide average under the Representative Concentration Pathway (RCP) 8.5 (Sylla et al., 2016). 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., 2016). 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 (Coordinated Regional Downscaling Experiment) with their respective RCP scenarios. However, RCP scenarios are more focused on radiative forcings pathways rather than socioeconomic indicators, which makes it difficult to evaluate the costs and benefits for mitigations actions (Stouffer et al., 2017). Therefore, a combination of radiative forcings pathways and socioeconomic indicators may provide a more holistic and realistic of potential future climate change scenarios. This is where climate change scenarios provided by CMIP6 (Coupled Model Intercomparison Project Phase 6) under the so-called "Shared Socioeconomic Pathways (SSPs)" come into play.

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 from NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6), 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, rainfall indices, heat stress, discomfort index, and cooling degree days. The NEX-GDDP-CMIP6 data is a global downscaled climate scenarios derived from the General Circulation Model and statistically downscaled to 25 km of spatial resolution. The downscaled climate projections used in this study are based under three SSPs: SSP1–2.6, SSP2–4.5, and SSP5–8.5. We also used two periods: near (2031–2060) and far (2071–2100) future and relative to the 1985–2014 baseline period to assess the impacts of climate change in Burkina Faso.

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, Section 4 presents the conclusion of the study.

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 and subdivided into thirteen administrative and territorial regions. 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.,

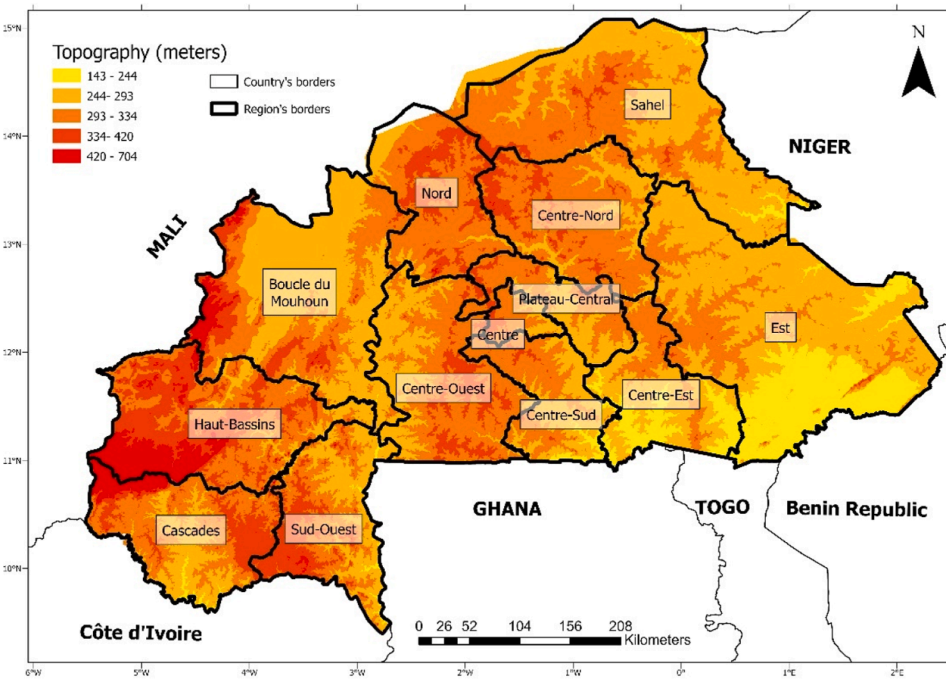

Fig. 1. Study area showing the topography, the regions, and the neighbor countries of Burkina Faso. The gray labels indicate the name of the thirteen regions in Burkina Faso.

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).

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). 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 center for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis data (Hersbach et al., 2019) for the variables tas, tasmin, tasmax and hurs. 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). 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 SI.1 (Supporting Information) summarizes the different NEX-GDDP-CMIP6 used in this study with the above variables.

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 projecting 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 (RX5days), maximum daily precipitation (RX1day), 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), 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 0.1 mm) 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.

To compute the RX5days, RX1day, RR20mm, we used the definition proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI).

RX5days 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). RX1day indicates the maximum daily precipitation, while RR20mm is defined as a number of days with daily precipitation of at least 20 mm. These indices are also used as an indicator for extreme rainfall. For the ET_0, we estimated it from (Jones, 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 $41\ ^\circ C \leq HI < 54\ ^\circ C$, which is classified as dangerous. The calculation of the index can be found in (Rothfusz and Headquarters, 1990). 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, RX5days, RX1day and ET_0 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). The robustness of the signal is shown as a pie chart for different climate scenarios and time frames. 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.

Moreover, we also analyzed the EnsMean trend analysis of different climate indices for the different climate change scenarios across Burkina Faso. To achieve that, we used the Mann-Kendall test (Mann, 1945; Kendall,1975), which is non-parametric statistical test to detect monotonic trends in time series. The projected changes in the various climate indices are shown as mean annual values.

3. Results and discussions

3.1. Model evaluation

Fig. 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. 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, particularly in the western and eastern regions 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.

3.2. Climate projections

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

Fig. 3& 4 show the projected changes of the ORS, CRS, and LRS for

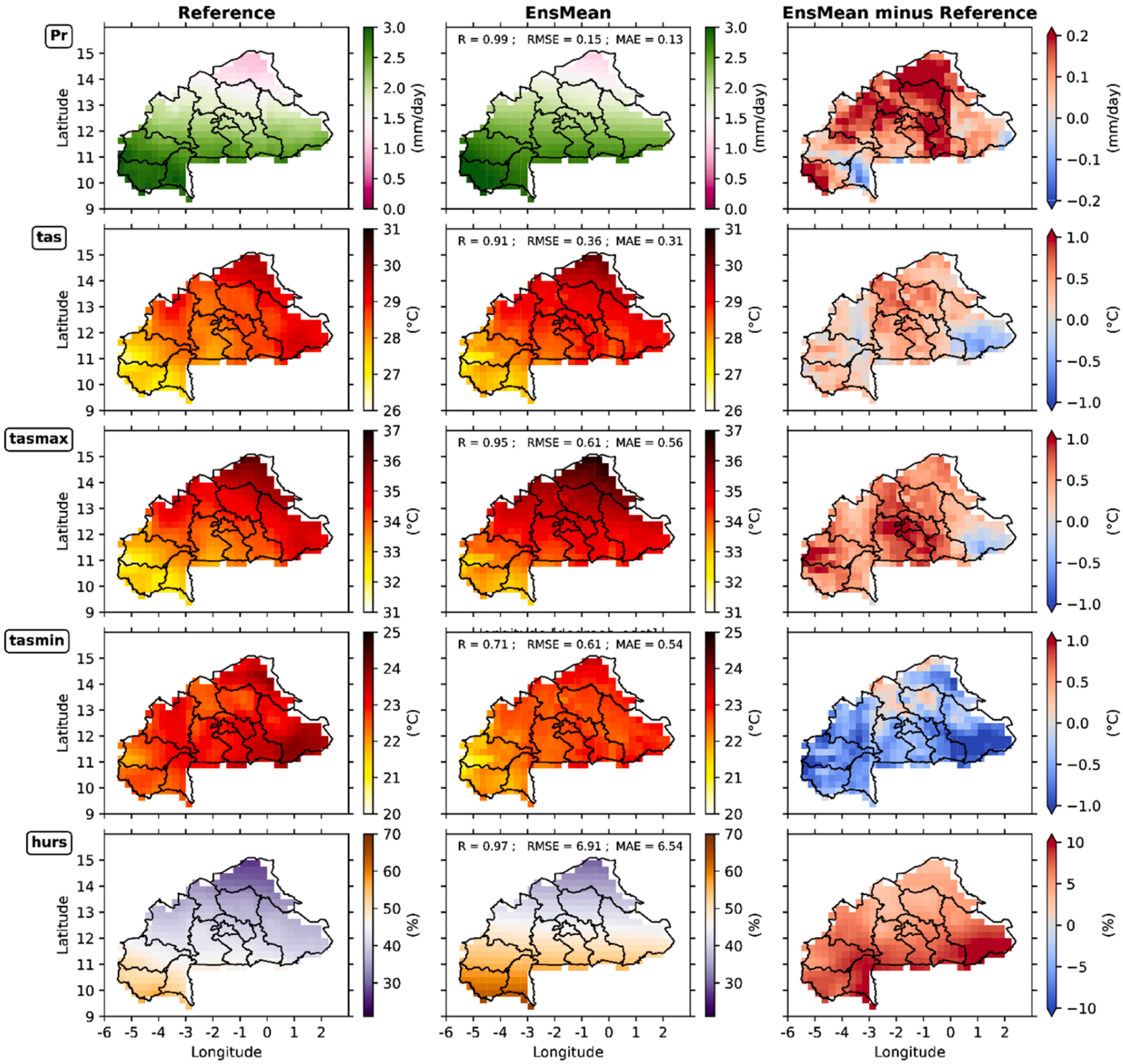

Fig. 2. Mean annual patterns of precipitation (Pr), air temperature (tas), maximum temperature (tasmax), minimum temperature (tasmin), and relative humidity (hurs) for the reference data (CHIRPS and ERA5) and the NEX-GDDP-CMIP6 ensemble mean (EnsMean) with their bias (EnsMean minus reference) in the 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.

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 could be linked 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 Atlantic 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. This is true 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. The amplified increase 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

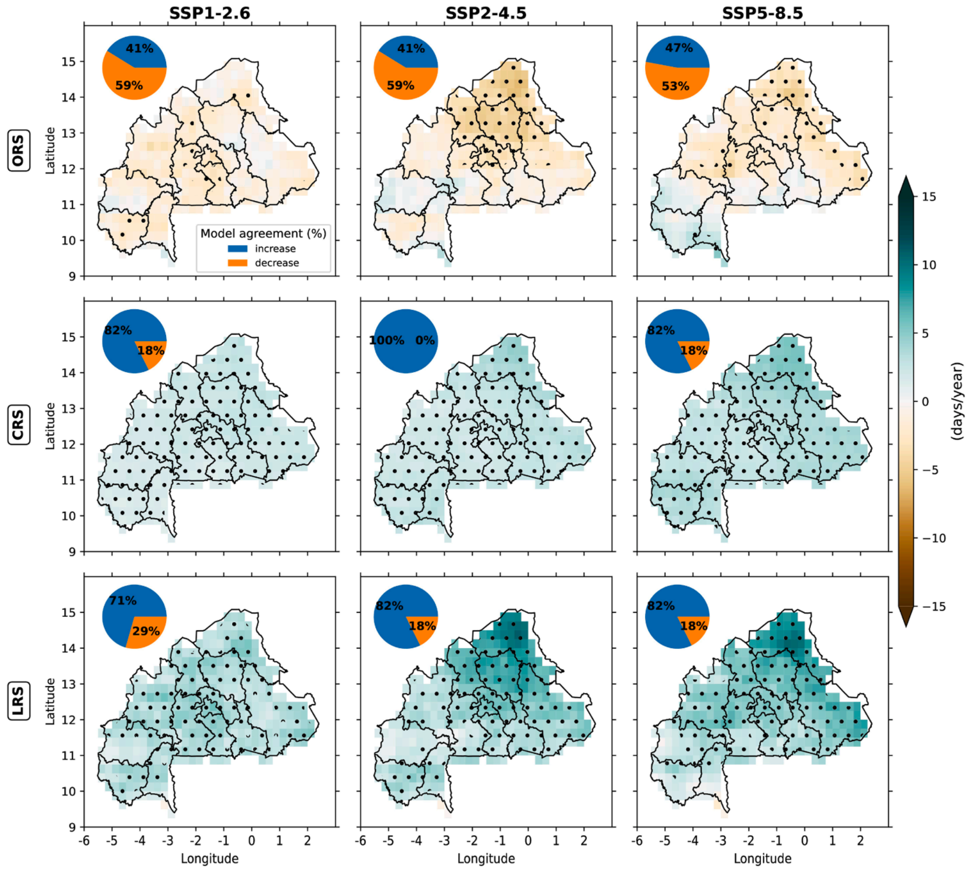

Fig. 3. Projected changes of the onset, cessation, and length of the rainy season over Burkina Faso under different SSPs for the near future (2031–2060) based on the ensemble mean of statistically downscaled CMIP6 scenarios. Dots indicate areas where changes are significant at the 95 % confidence level.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

the western part shows a decrease under SSP5–8.5 and for the far future (5 days). These patterns align are 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.

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. 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 socioeconomic sectors in Burkina Faso such as agriculture and solar energy (Sawadogo et al., 2019; Diarra et al., 2017).

3.2.3. *Precipitation*

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

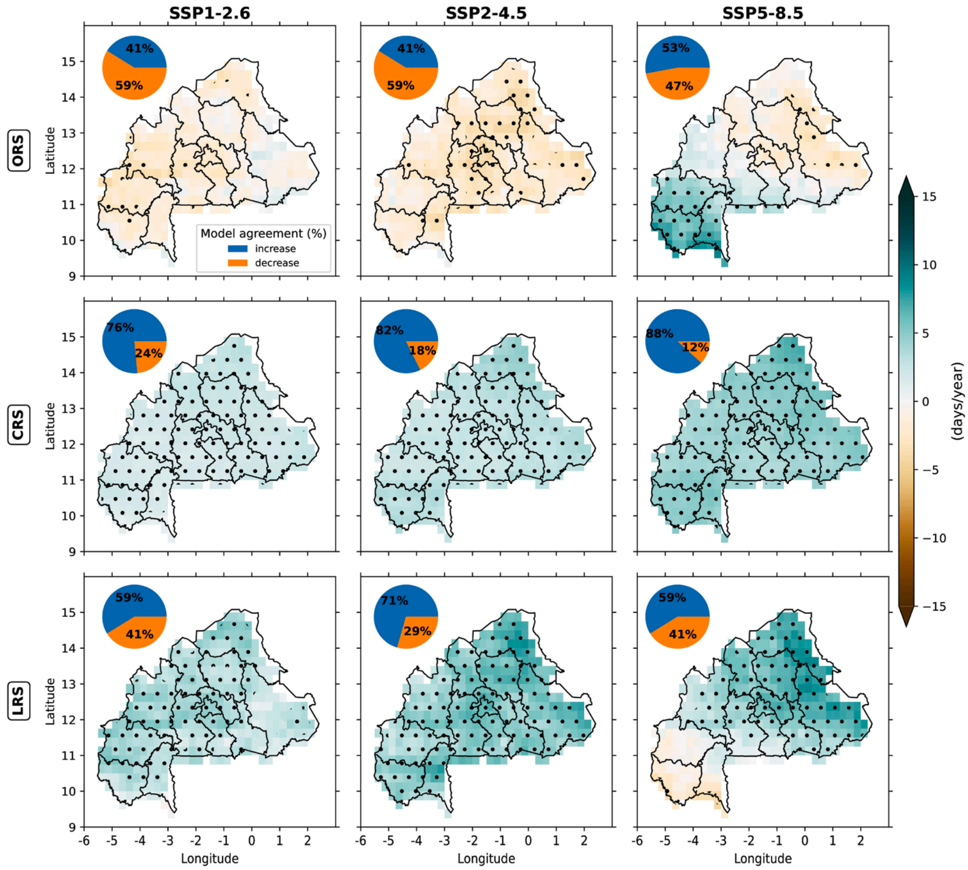

Fig. 4. Same as Fig. 3, but for the far future (2071–2100).

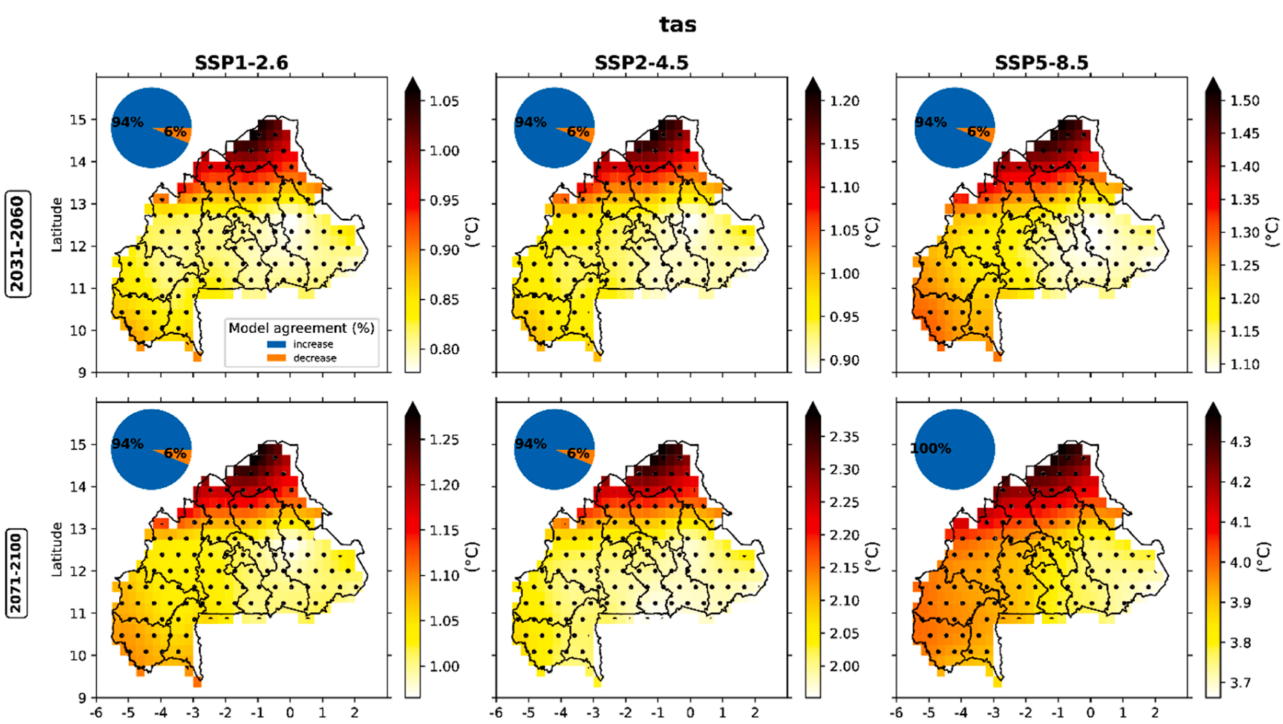

Fig. 5. Projected changes in mean annual air temperature under different SSP scenarios and time periods in Burkina Faso based on the ensemble mean of statistically downscaled CMIP6 scenarios. Dots indicate areas where changes are significant at the 95 % of confidence level. The pie chart in each panel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

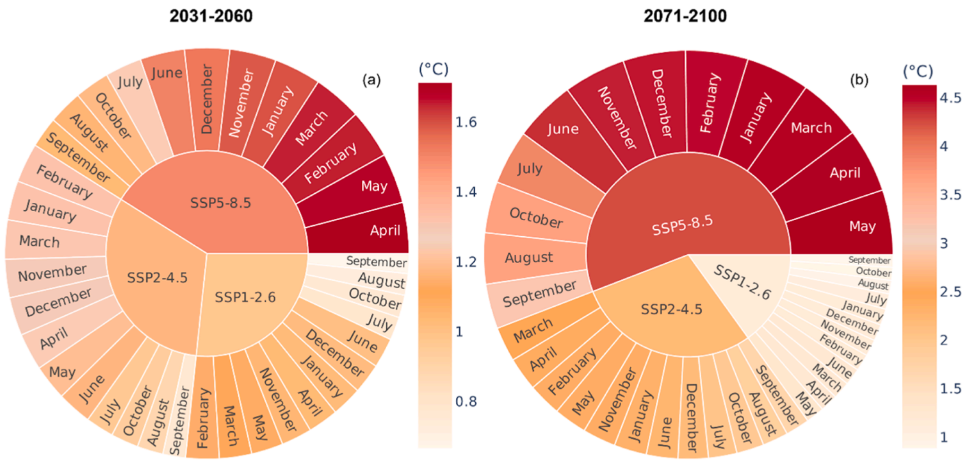

Fig. 6. Projected annual and monthly air temperature changes for Burkina Faso illustrated as pie chart for the based on the ensemble mean of statistically downscaled CMIP6 scenarios. Panel (a) indicates the change in near future (2031–2060), while panel (b) shows the change in far future (2071–2100).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

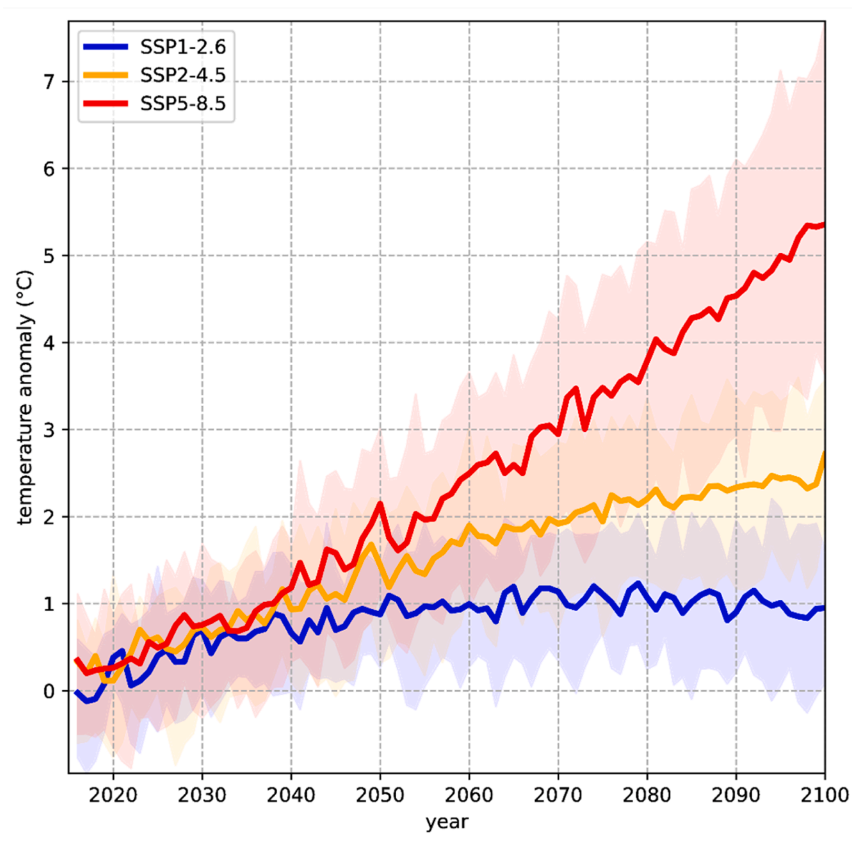

Fig. 7. Temporal change in mean annual air temperature for Burkina Faso from 2015 to 2100 compared to the reference period (1985 to 2014) based on statically downscaled CMIP6 scenarios. The blue, orange, and red lines indicate the ensemble mean for the SSP1–2.6, SSP2–4.5, and SSP5–8.5 scenarios, respectively.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

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. 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. Notably, GHG emissions are the factors influencing 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

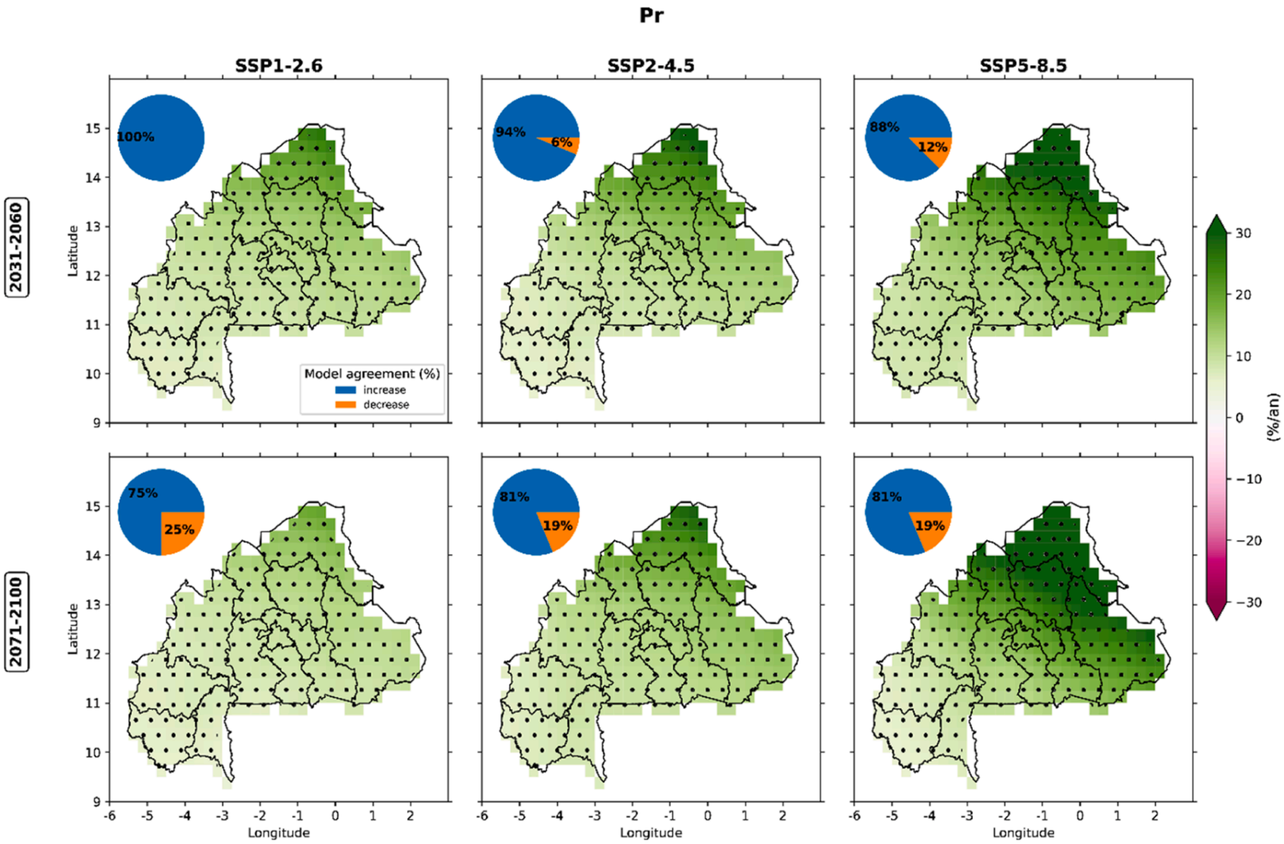

Fig. 8. Similar as in Fig. 5, but for mean annual precipitation amount. The projected precipitation changes are indicated as relative values. Green area corresponds to an increase of the annual precipitation amount over Burkina Faso and therefore wetter conditions.

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 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). However, the EnsMean also projects a significant and robust increase in ET_0 among all SSPs and time periods (Fig.SI.1). 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) contributing 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.

3.2.3. RX5days and RX1day

Fig. 10 shows the annual projected changes in RX5days in Burkina Faso. Similar to rainfall, the EnsMean projects an increase in RX5days in all scenarios and 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. Other studies also reported an increase in RX5days in some parts of West Africa, including Burkina Faso (Worou et al., 2023; Akinsanola and Zhou, 2019; Diallo et al., 2016). Similar to RX5days. the projected changes in RX1day shows a significant increase in all the scenarios across Burkina Faso (Fig. 11). These expected changes are more pronounced under the SSP5–8.5 scenario and at the end of century. Under this scenario, the expected increase in RX1day could reach 40 %, notably in the northern and eastern parts of the country.

Additionally, the number of heavy rainfall events in the country is likely to increase (Fig.SI.2; Supporting Information). The increase in RX5days, RR20mm and RX1day 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). 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.

3.2.4. Heat stress (HI)

Fig. 12 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. 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

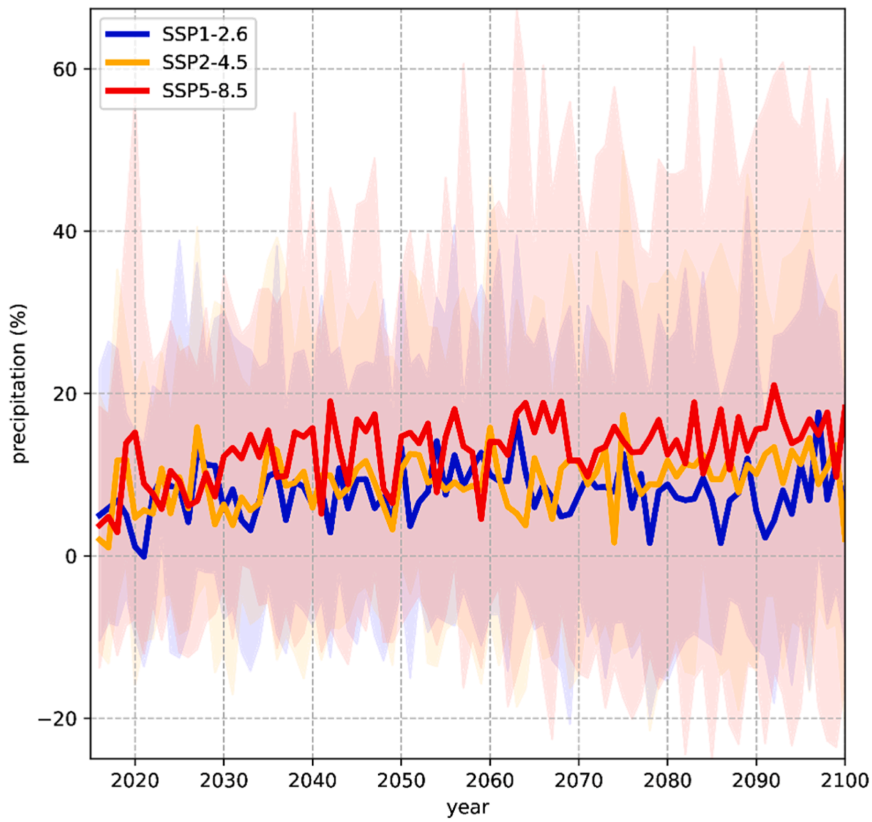

Fig. 9. Similar as in Fig. 7, but for the annual precipitation amount. The projected precipitation changes are indicated as relative values. A positive value indicates an increase of the precipitation amount.

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.

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. 13). 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.

Table 1 presents the results of the trend analysis for various climate indices considered in this study across Burkina Faso for different climate scenarios at 5 % significant level. RS exhibits no trend under the SSP1–2.6 and SSP2–4.5 scenarios. However, a notable and statistically significant increasing trend is observed under the SSP5–8.5 scenario. Conversely LRS does not display any trend across all scenarios. Significant increasing trends are identified in HI, DI, ET_0, and CDD. Particularly, SSP5–8.5 reveals a high significant increase, with ET_0 having the highest statistically significant trend, characterized by a slope value of 5.8244. On the other hand, only tas exhibits a statistically significant decreasing trend under SSP1–2.6, suggesting a projected decrease in temperature over time. This finding aligns with Fig. 7. Nonetheless, a statistically significant increasing trend in temperature is evident under SSP2–4.5 and SSP5–8.5 scenarios. Our results are consistent with the findings of Ilori and Ajayi (2020), who reported a statistically significant increasing trend in tas under RCP4.5 and RCP8.5 scenarios in the Sahel region using CORDEX data. Similar increasing trends are observed in Pr, RX1day, RX5days and RR20mm under SSP2–4.5 and SSP5–8.5, while no trend is noted under SSP1–2.6. Pr shows the smallest slope values of 0.0013 and 0.0018 under SSP2–4.5 and SSP5–8.5, respectively, implying a relatively lower increasing trend in precipitation across Burkina Faso.

The negative impacts of climate change on the Sudan-Sahel Region have been observed for the last decades and it will be strengthened with the ongoing global warming for all SSPs. Moreover, these negative impacts are not homogeneous, but rather distributed over the administrative regions of the country. We also provided in supporting information the projected changes of the eleven indices for the 13 administrative regions. From this perspective, urgent adaptation measures can be prioritized in the most vulnerable administrative regions. Moreover, the international community must recognize that the impacts of climate change in this vulnerable country are not isolated and affecting food security, water resources, and the livelihoods of the population. Therefore, appropriate measures are needed to improve the resilience of the population and the respect of the Paris Agreement signed by all Parties to reduce GHG emissions is essential to mitigate

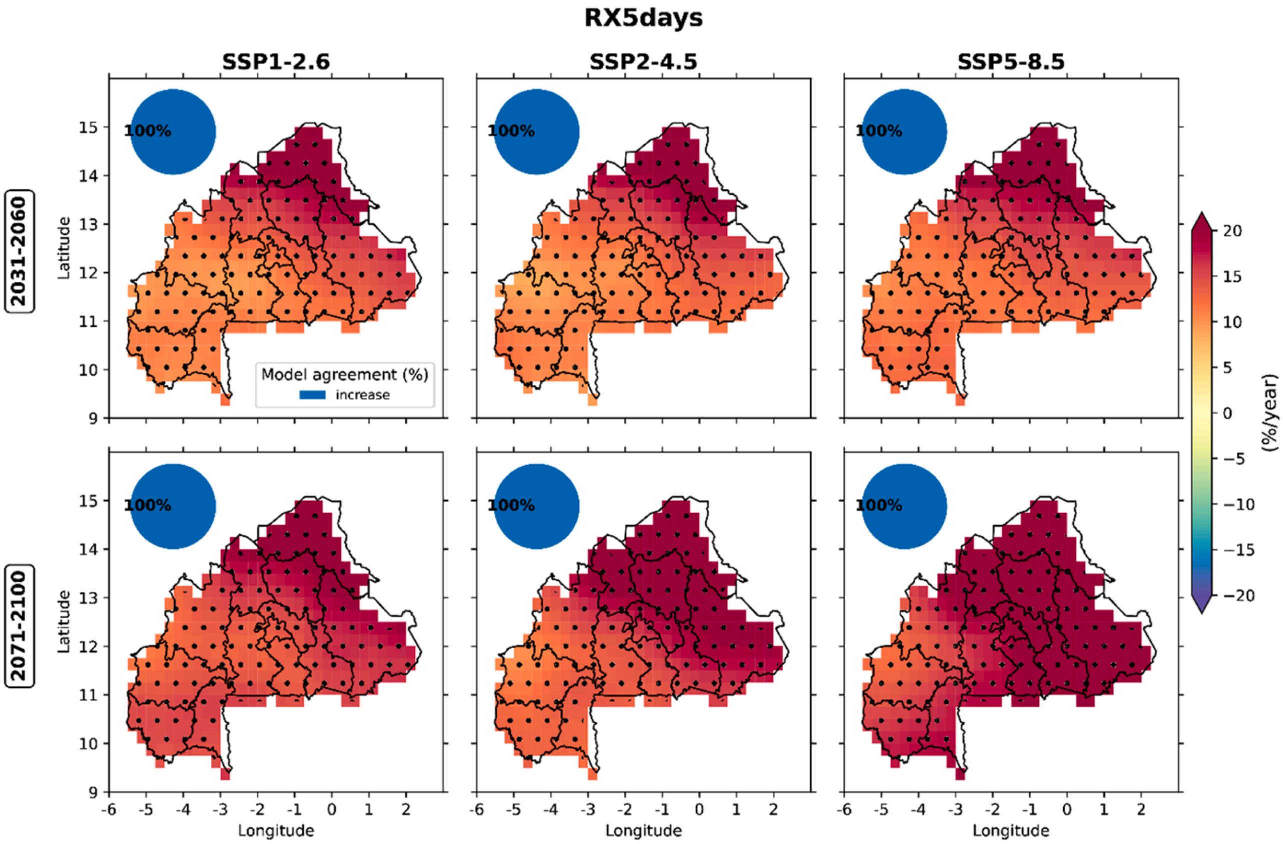

Fig. 10. Similar as in Fig. 5, but for the maximum of five-day precipitation amount (RX5days). The projected RX5days changes are indicated as relative values. Red areas correspond to an increase of the five-day precipitation amount over Burkina Faso and therefore to wetter and more extreme conditions during the monsoon period.

these impacts and secure a more sustainable future for all.

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.
- While annual precipitation may increase up to 30 %, a 20 % rise in evapotranspiration could lead to water stress, impacting off-season agriculture and water resource management.
- The length of the rainy season could potentially increase by up to 10 days under the SSP5–8.5 scenario, increasing flood risk, and heat stress, and cooling degree days are expected to rise across all scenarios and time periods.
- Most of the projected climate indices indicate a statistically significant increasing trend over time under SSP2–4.5 and SSP5–8.5 scenarios.

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 socioeconomic pathways SSP1–2.6 and SSP2–4.5. Thus, the timely implementation of mitigation measures could significantly reduce climate change effects for this vulnerable region. These findings align with previous studies on the West Africa region, mainly in the Sudan-Sahel, where most climate indices are amplified by global warming (Diba et al., 2022; Vogel et al., 2020; Diasso and Abiodun, 2018). 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 NAP every five years to mitigate the impacts of climate change in their respective countries. The results of this study offer valuable insights into the climate change impacts specific to Burkina Faso, drawing 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 also serve as an

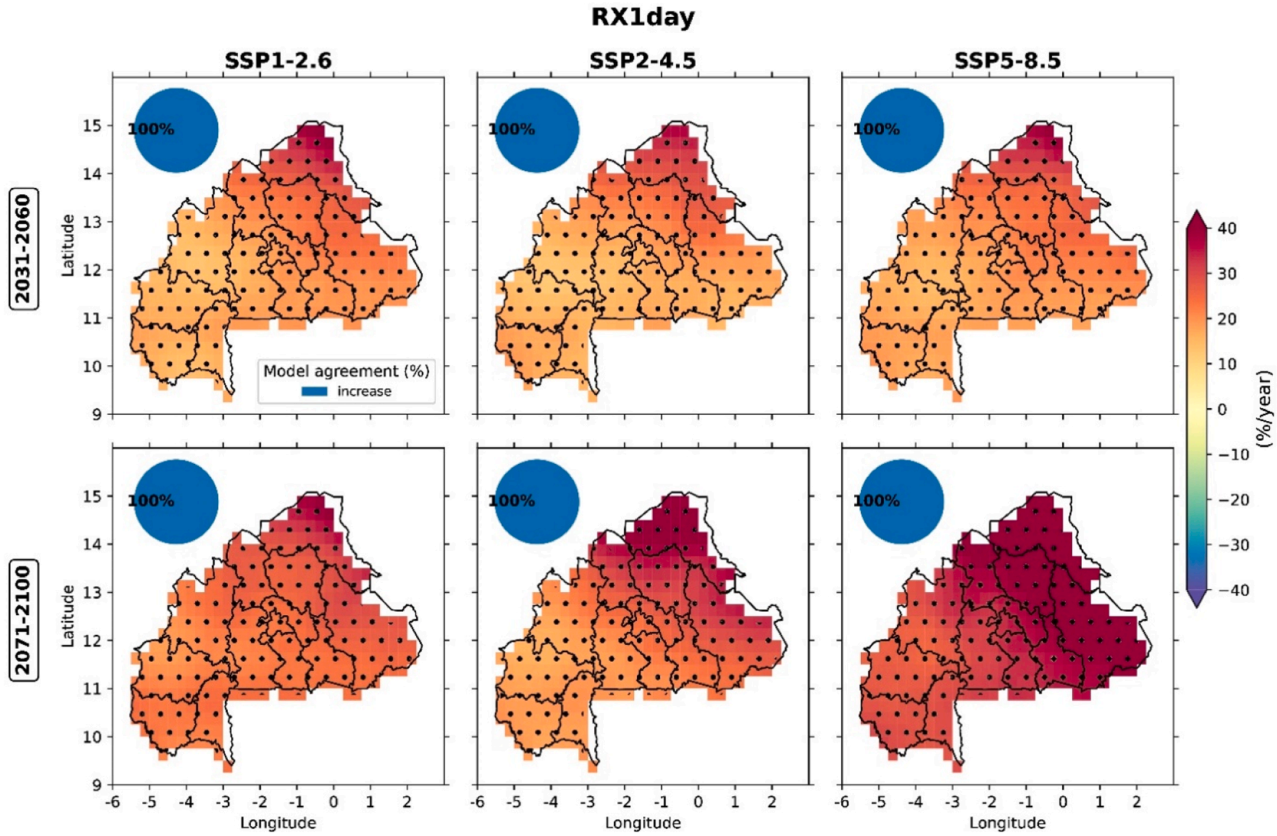

Fig. 11. Similar as in Fig. 5, but for maximum daily precipitation (RX1day).

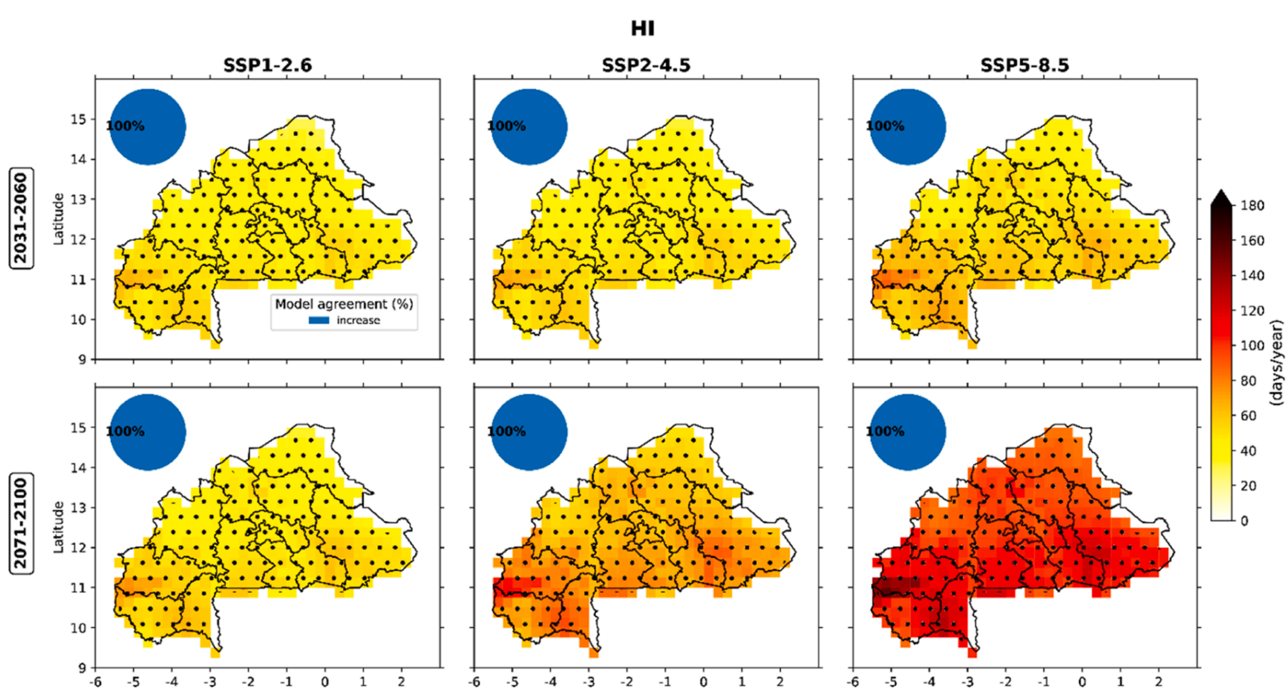

Fig. 12. Similar as in Fig. 5, but for heat stress index (HI).

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.

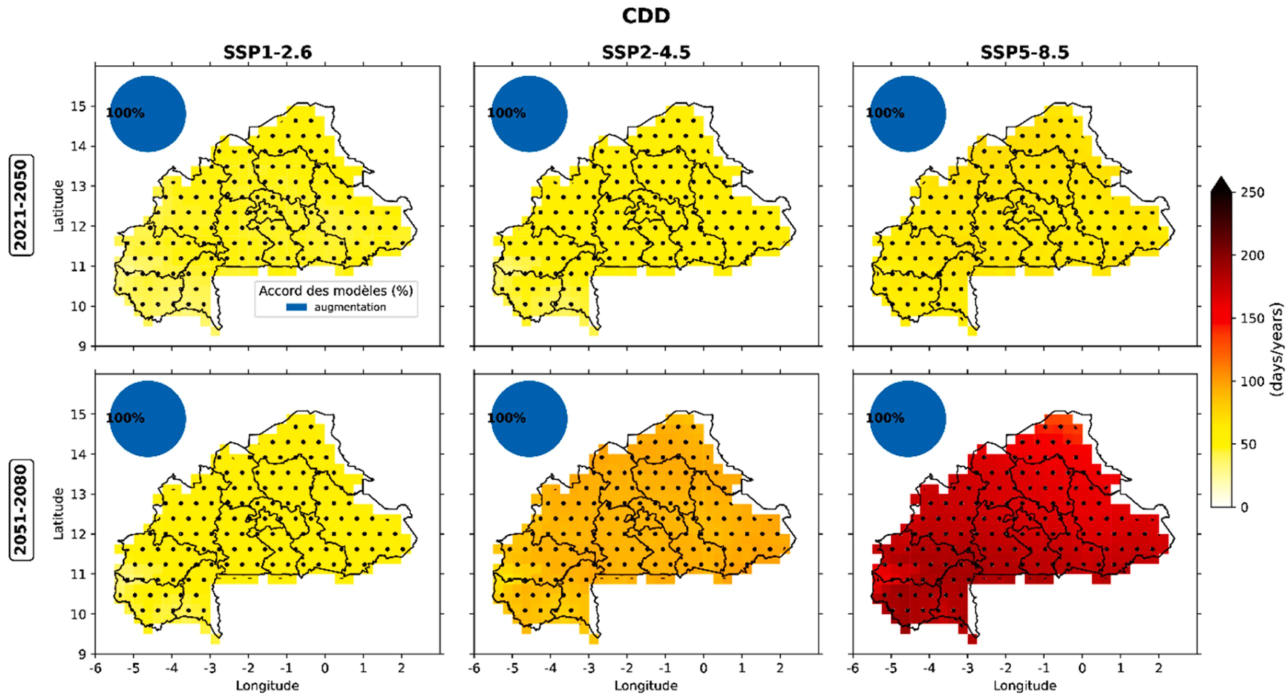

Fig. 13. Similar as in Fig. 5, but for cooling degree days (CDD).

Table 1
Trend analysis of different climate indices of the ensemble mean in the reference period and under different climate change scenarios over Burkina Faso at 5 % significant level.

climate indices	Scenario								
	SSP1–2.6			SSP2–4.5			SSP5–8.5		
	trend	pvalue	slope	trend	pvalue	slope	trend	pvalue	slope
ORS	no trend	0.8883	−0.0019	no trend	0.6680	0.0059	increasing	0.0058	0.0455
CRS	no trend	0.4410	0.0053	increasing	0.0249	0.0142	increasing	0.0000	0.0432
LRS	no trend	0.8346	0.0029	no trend	0.9425	−0.0011	no trend	0.9304	−0.0021
Pr	no trend	0.4592	0.0003	increasing	0.0007	0.0013	increasing	0.0000	0.0018
RX5days	no trend	0.7759	0.0044	increasing	0.0018	0.0615	increasing	0.0000	0.1096
RR20mm	no trend	0.8644	0.0005	increasing	0.0000	0.0119	increasing	0.0000	0.0299
RX1day	no trend	0.6625	−0.0062	increasing	0.0000	0.0617	increasing	0.0000	0.1279
tas	decreasing	0.0204	−0.0056	increasing	0.0000	0.0148	increasing	0.0000	0.0148
HI	increasing	0.0000	0.2319	increasing	0.0000	0.6694	increasing	0.0000	1.2510
DI	increasing	0.0000	0.3487	increasing	0.0000	1.0470	increasing	0.0000	2.4832
ET	increasing	0.0000	1.1250	increasing	0.0000	2.9938	increasing	0.0000	5.8244
CDD	increasing	0.0000	0.321	increasing	0.0000	1.0704	increasing	0.0000	2.4279

CRediT authorship contribution statement

Windmanagda Sawadogo: Conceptualization, Investigation, Methodology, Writing – original draft. **Tiga Neya:** Methodology, Writing – review & editing. **Idrissa Semde:** Writing – review & editing. **Joël Awouhidia Korahiré:** Writing – review & editing. **Alain Combasséré:** Writing – review & editing. **Do Etienne Traoré:** Writing – review & editing. **Pamoussa Ouedraogo:** Writing – review & editing. **Ulrich Jacques Diasso:** Writing – review & editing. **Babatunde J Abiodun:** Methodology, Writing – review & editing. **Jan Bliefernicht:** Methodology, Writing – review & editing. **Harald Kunstmann:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work in this article.

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). The data used in this study are available online.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2024.100860.

References

Ahmed, K.F., Wang, G., Yu, M., Koo, J., You, L., 2015. Potential impact of climate change on cereal crop yield in West Africa. Clim. Change 133 (2), 321–334. https://doi.org/10.1007/s10584-015-1462-7.

Ajibola, F.O., Zhou, B., Tchalim Gnitou, G., Onyejuruwa, A., 2020. Evaluation of the performance of CMIP6 HighResMIP on West African precipitation. Atmosphere (Basel) 11 (10), 1053. https://doi.org/10.3390/atmos11101053.

Akinsanola, A.A., Zhou, W., 2019. Projections of West African summer monsoon rainfall extremes from two CORDEX models. Clim. Dyn. 52 (3–4), 2017–2028. https://doi.org/10.1007/s00382-018-4238-8.

Alduchov, O.A., Eskridge, R.E., 1996. Improved magnus form approximation of saturation vapor pressure. J. App. Meteorol. 35 (4), 601–609. https://doi.org/10.1175/1520-0450(1996)035<0601:IMFAOS>2.0.CO;2.

Almazroui, M., Saeed, F., Saeed, S., Islam, Nazrul, M, Ismail, M, Klutse, N, A.B., Siddiqui, M.H, 2020. Projected Change in Temperature and Precipitation Over Africa from CMIP6. Earth. Syst. Environ. 4 (3), 455–475. https://doi.org/10.1007/s41748-020-00161-x.

Andrade, C., Mourato, S., Ramos, J., 2021. Heating and cooling degree-days climate change projections for portugal. Atmosphere (Basel) 12 (6), 715. https://doi.org/10.3390/atmos12060715.

Arisco, N.J., Sewe, M.O., Bärnighausen, T., Sié, A., Zabre, P., Bunker, A., 2023. The effect of extreme temperature and precipitation on cause-specific deaths in rural Burkina Faso: a longitudinal study. Lancet Planet. Health 7 (6), e478–e489. https://doi.org/10.1016/S2542-5196(23)00027-X.

Bellomo, K., Angeloni, M., Corti, S., von Hardenberg, J., 2021. Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. Nat. Commun. 12 (1), 3659. https://doi.org/10.1038/s41467-021-24015-w.

Biasutti, M., 2013. Forced Sahel rainfall trends in the CMIP5 archive. Atmospheres 118 (4), 1613–1623. https://doi.org/10.1002/jgrd.50206.

Bliefernicht, J., Berger, S., Salack, S., Guug, S., Hingerl, L., Heinzeller, D., Mauder, M., Steinbrecher, R., Steup, G., Bossa, A.Y., others, 2018. The WASCAL hydrometeorological observatory in the Sudan Savanna of Burkina Faso and Ghana. Vadose Zone Journal 17 (1).

Bliefernicht, J., Salack, S., Waongo, M., Annor, T., Laux, P., Kunstmann, H., 2021. Towards a historical precipitation database for West Africa: overview, quality control and harmonization. Internat. J. Climat.

Cheng, W., Chiang, J.C.H., Zhang, D., 2013. Atlantic Meridional overturning circulation (AMOC) in CMIP5 models: RCP and historical simulations. J. Clim 26 (18), 7187–7197. https://doi.org/10.1175/JCLI-D-12-00496.1.

Crawford, A., Price-Kelly, H., Terton, A., & Echeverr\'\ia, D. (2016). *Review of current and planned adaptation action in Burkina Faso*.

Daron, :.J.D, 2014. Regional climate messages: west Africa. Scient. report. CARIAA Adaptat.Scale Semi-Arid Regions (ASSAR) Project.

de Hipt, F., 2018. Modeling climate and land use change impacts on water resources and soil erosion in the dano catchment. Universitäts-und Landesbibliothek Bonn, Burkina Faso, West Africa.

De Longueville, F., Hountondji, Y.C., Kindo, I., Gemenne, F., Ozer, P., 2016. Long-term analysis of rainfall and temperature data in Burkina Faso (1950-2013). Internat. J. Climat. 36 (13), 4393–4405. https://doi.org/10.1002/joc.4640.

Dembélé, M., Vrac, M., Ceperley, N., Zwart, S.J., Larsen, J., Dadson, S.J., Mariéthoz, G., Schaefli, B., 2022. Contrasting changes in hydrological processes of the Volta River basin under global warming. Hydrol. Earth. Syst. Sci. 26 (5), 1481–1506. https://doi.org/10.5194/hess-26-1481-2022.

Diallo, I., Giorgi, F., Deme, A., Tall, M., Mariotti, L., Gaye, A.T., 2016. Projected changes of summer monsoon extremes and hydroclimatic regimes over West Africa for the twenty-first century. Clim. Dyn. 47 (12), 3931–3954.

Diarra, A., Barbier, B., Yacouba, H., others, 2017. Impact of climate change on cotton production in Burkina Faso. Afr. J. Agric. Res. 12 (7), 494–501.

Diasso, U., Abiodun, B.J., 2018. Future impacts of global warming and reforestation on drought patterns over West Africa. Theor. Appl. Climatol. 133 (3), 647–662. https://doi.org/10.1007/s00704-017-2209-3.

Diba, I., Diedhiou, A., Famien, A.M., Camara, M., Fotso-Nguemo, T.C., 2022. Changes in compound extremes of rainfall and temperature over West Africa using CMIP5 simulations. Environ. Res. Commun. 4 (10), 105003 https://doi.org/10.1088/2515-7620/ac9aa7.

Dieng, D., Laux, P., Smiatek, G., Heinzeller, D., Bliefernicht, J., Sarr, A., Gaye, A.T., Kunstmann, H., 2018. Performance analysis and projected changes of agroclimatological indices across West Africa based on high-resolution regional climate model simulations. Atmospheres. https://doi.org/10.1029/2018JD028536.

Engel, T., Fink, A.H., Knippertz, P., Pante, G., Bliefernicht, J., 2017. Extreme precipitation in the West African Cities of Dakar and Ouagadougou: atmospheric dynamics and implications for flood risk assessments. J. Hydrometeorol. 18 (11), 2937–2957. https://doi.org/10.1175/JHM-D-16-0218.1.

Ezeife, N.D., 2014. Projected impact of global warming on West Africa: case for regional and transnational adaptive measures. Ann. Surv. Int'l \& Comp. L. 20, 101.

Fan, X., Duan, Q., Shen, C., Wu, Y., Xing, C., 2020. Global surface air temperatures in CMIP6: historical performance and future changes. Environmental Research Letters 15 (10), 104056. https://doi.org/10.1088/1748-9326/abb051.

Faye, A., Akinsanola, A.A., 2022. Evaluation of extreme precipitation indices over West Africa in CMIP6 models. Clim. Dyn. 58 (3–4), 925–939. https://doi.org/10.1007/s00382-021-05942-2.

Fischer, E.M., Sedláček, J., Hawkins, E., Knutti, R., 2014. Models agree on forced response pattern of precipitation and temperature extremes. Geophys. Res. Lett. 41 (23), 8554–8562. https://doi.org/10.1002/2014GL062018.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. data 2 (1), 1–21.

Gaetani, M., Flamant, C., Bastin, S., Janicot, S., Lavaysse, C., Hourdin, F., Braconnot, P., Bony, S., 2017. West African monsoon dynamics and precipitation: the competition between global SST warming and CO2 increase in CMIP5 idealized simulations. Clim. Dyn. 48 (3–4), 1353–1373. https://doi.org/10.1007/s00382-016-3146-z.

Gbode, I.E., Babalola, T.E., Diro, G.T., Intsiful, J.D., 2023. Assessment of ERA5 and ERA-Interim in Reproducing Mean and Extreme Climates over West Africa. Adv. Atmos. Sci. 40 (4), 570–586. https://doi.org/10.1007/s00376-022-2161-8.

Guan, K., Sultan, B., Biasutti, M., Baron, C., Lobell, D.B., 2015. What aspects of future rainfall changes matter for crop yields in West Africa? Geophys. Res. Lett. 42 (19), 8001–8010. https://doi.org/10.1002/2015GL063877.

Hagedorn, R., Doblas-Reyes, F.J., Palmer, T.N., 2005. The rationale behind the success of multi-model ensembles in seasonal forecasting—I. Basic concept. Tellus A 57 (3), 219–233.

Ritchie, Hannah, R, M., P, R, 2020. CO_2 and Greenhouse Gas Emissions. Published Online at OurWorldInData.Org. https://ourworldindata.org/co2-and-greenhouse-gas-emissions.

Hardiman, S.C., Dunstone, N.J., Scaife, A.A., Smith, D.M., Comer, R., Nie, Y., Ren, H.L., 2022. Missing eddy feedback may explain weak signal-to-noise ratios in climate predictions. NPJ. Clim. Atmos. Sci. 5 (1), 57. https://doi.org/10.1038/s41612-022-00280-4.

Heinzeller, D., Dieng, D., Smiatek, G., Olusegun, C., Klein, C., Hamann, I., Salack, S., Bliefernicht, J., Kunstmann, H., 2018. The WASCAL high-resolution regional climate simulation ensemble for West Africa: concept, dissemination and assessment. Earth. Syst. Sci. Data. https://doi.org/10.5194/essd-10-815-2018.

Hersbach, H., Bell, B., Berrisford, P., Horányi, A., Sabater, J.M., Nicolas, J., Radu, R., Schepers, D., Simmons, A., Soci, C., Dee, D., 2019. Global reanalysis: goodbye ERA-Interim, hello ERA5. ECMWF Newsletter.

Ibrahim, B., Karambiri, H., Polcher, J., Yacouba, H., Ribstein, P., 2014. Changes in rainfall regime over Burkina Faso under the climate change conditions simulated by 5 regional climate models. Clim. Dyn. 42 (5–6), 1363–1381. https://doi.org/10.1007/s00382-013-1837-2.

Ilori, O.W., Ajayi, V.O., 2020. Change detection and trend analysis of future temperature and rainfall over West Africa. Earth. Syst. Environ. 4 (3), 493–512. https://doi.org/10.1007/s41748-020-00174-6.

IPCC. (2021). *Summary for policymakers.* In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change* Masson-Delmotte,V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, https://doi.org/10.1017/9781009157896.001.

Jones, C.A., 1990. Crop growth models. Manage. Farm Irrigated Syst.

Kendall, M.G., 1975. Rank correlation methods. Oxford University Press, New York, NY.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15 (3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Kumi, N., Abiodun, B.J., 2018. Potential impacts of 1.5°C and 2°C global warming on rainfall onset, cessation and length of rainy season in West Africa. Environ. Res. Lett. 13 (5), 55009.

Lorenz, M., Bliefernicht, J., Kunstmann, H., 2022. Bias correction of daily precipitation for ungauged locations using geostatistical approaches: a case study for the <scp>CORDEX-Africa</scp>ensemble. Internat. J. Climatol. 42 (12), 6596–6615. https://doi.org/10.1002/joc.7649.

Mann, H.B., 1945. Nonparametric Tests Against Trend. Econometrica 13 (3), 245. https://doi.org/10.2307/1907187.

Maslin, M.A., Lang, J., Harvey, F., 2023. A short history of the successes and failures of the international climate change negotiations. UCL Open Environ. 5 https://doi.org/10.14324/111.444/ucloe.000059.

Meinshausen, M., Nicholls, Z.R.J., Lewis, J., Gidden, M.J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J.G., Daniel, J.S., John, A., Krummel, P.B., Luderer, G., Meinshausen, N., Montzka, S.A., Rayner, P.J., Reimann, S., Wang, R.H.J., 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci. Model. Dev. 13 (8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020.

Monerie, P.A., Sanchez-Gomez, E., Boé, J., 2017. On the range of future Sahel precipitation projections and the selection of a sub-sample of CMIP5 models for impact studies. Clim. Dyn. 48 (7–8), 2751–2770. https://doi.org/10.1007/s00382-016-3236-y.

Monerie, P.A., Wilcox, L.J., Turner, A.G., 2022. Effects of anthropogenic aerosol and greenhouse gas emissions on northern hemisphere monsoon precipitation: mechanisms and uncertainty. J Clim 35 (8), 2305–2326. https://doi.org/10.1175/JCLI-D-21-0412.1.

Mounkaila, M.S., Abiodun, B.J., 'Bayo Omotosho, J., 2015. Assessing the capability of CORDEX models in simulating onset of rainfall in West Africa. Theor. Appl. Climatol. 119 (1–2), 255–272. https://doi.org/10.1007/s00704-014-1104-4.

Ngoungue Langue, C.G., Lavaysse, C., Vrac, M., Flamant, C., 2023. Heat wave monitoring over West African cities: uncertainties, characterization and recent trends. Nat. Hazards Earth Syst.Sci. 23 (4), 1313–1333. https://doi.org/10.5194/nhess-23-1313-2023.

Nicholson, S.E., Fink, A.H., Funk, C., 2018. Assessing recovery and change in West Africa's rainfall regime from a 161-year record. Internat. J. Climatology 38 (10), 3770–3786.

Nkrumah, F., Vischel, T., Panthou, G., Klutse, N.A.B., Adukpo, D.C., Diedhiou, A., 2019. Recent trends in the daily rainfall regime in southern West Africa. Atmosphere (Basel) 10 (12), 741. https://doi.org/10.3390/atmos10120741.

Odou, O.D.T., Ursula, H.H., Adamou, R., Godjo, T., Moussa, M.S., 2023. Potential changes in cooling degree day under different global warming levels and shared socioeconomic pathways in West Africa. Environ. Res. Lett. 18 (3), 034029 https://doi.org/10.1088/1748-9326/acbc8f.

Okafor, G.C., Larbi, I., Chukwuma, E.C., Nyamekye, C., Limantol, A.M., Dotse, S.Q., 2021. Local climate change signals and changes in climate extremes in a typical Sahel catchment: the case of Dano catchment, Burkina Faso. Environ. Chall. 5, 100285 https://doi.org/10.1016/j.envc.2021.100285.

Okoro, U.K., Chen, W., Nath, D., Nnamchi, H.C., 2020. Variability and trends of atmospheric moisture in recent West African monsoon season and the coordinated regional downscaling experiment-Africa projected 21st century scenarios. Internat. J. Climatology 40 (2), 1149–1163. https://doi.org/10.1002/joc.6261.

Omotosho, J.B., Balogun, A.A., Ogunjobi, K., 2000. Predicting monthly and seasonal rainfall, onset and cessation of the rainy season in West Africa using only surface data. Internat. J. Climat. 20 (8), 865–880. https://doi.org/10.1002/1097-0088(20000630)20:8<865::AID-JOC505>3.0.CO;2-R.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environ. Change 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

O'Neill, B.C., Tebaldi, C., van Vuuren, D.P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.F., Lowe, J., Meehl, G.A., Moss, R., Riahi, K., Sanderson, B.M., 2016. The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci. Model. Dev. 9 (9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016.

Ouedraogo, M., 2020. Emergence of agriculture against season in the central region of burkina faso: an alternative for food security?, 3. Université Paul-Valéry-Montpellier.

Quenum, G.M.L.D., Nkrumah, F., Klutse, N.A.B., Sylla, M.B., 2021. Spatiotemporal changes in temperature and precipitation in West Africa. Part i: analysis with the CMIP6 historical dataset. Water. (Basel) 13 (24), 3506. https://doi.org/10.3390/w13243506.

Rameshwaran, P., Bell, V.A., Davies, H.N., Kay, A.L., 2021. How might climate change affect river flows across West Africa? Clim. Change 169 (3–4), 21. https://doi.org/10.1007/s10584-021-03256-0.

Reliefweb. (2009). *Burkina faso: 2009 flooding situation report No.1*. https://reliefweb.int/report/burkina-faso/burkina-faso-2009-flooding-situation-report-no1.

Romanovska, P., Gleixner, S., Gornott, C., 2023. Climate data uncertainty for agricultural impact assessments in West Africa. Theor. Appl. Climatol. 152 (3–4), 933–950. https://doi.org/10.1007/s00704-023-04430-3.

Rothfusz, L.P., Headquarters, N.W.S.S.R., 1990. The heat index equation (or, more than you ever wanted to know about heat index). Fort Worth, Texas: National Oceanic and Atmospheric Administration. National Weather Service, Office of Meteorology, p. 9023.

Roudier, P., Sultan, B., Quirion, P., Berg, A., 2011. The impact of future climate change on West African crop yields: what does the recent literature say? Global Environ. Change 21 (3), 1073–1083. https://doi.org/10.1016/j.gloenvcha.2011.04.007.

Salack, S., Klein, C., Giannini, A., Sarr, B., Worou, O.N., Belko, N., Bliefernicht, Jan, Kunstman, H., 2016. Global warming induced hybrid rainy seasons in the Sahel. Environ. Res. Lett. 11 (10), 104008 https://doi.org/10.1088/1748-9326/11/10/104008.

Sawadogo, B., 2022. Drought impacts on the crop sector and adaptation options in burkina faso: a gender-focused computable general equilibrium analysis. Sustainability. 14 (23), 15637. https://doi.org/10.3390/su142315637.

Sawadogo, W., Abiodun, B.J., Okogbue, E.C., 2019. Impact of global warming on photovoltaic power generation over West Africa. Renew. Energy. https://doi.org/10.1016/j.renene.2019.11.032.

Schmidt, M.W., Chang, P., Parker, A.O., Ji, L., He, F., 2017. Deglacial tropical atlantic subsurface warming links ocean circulation variability to the West African monsoon. Sci. Rep. 7 (1), 15390. https://doi.org/10.1038/s41598-017-15637-6.

Semde, I., Yonkeu, S., Badolo, M., & Pare, S. (2021). *indicative elements for improving the resilience of food security to climate risks in Burkina Faso*.

Semmler, T., McGrath, R., Steele-Dunne, S., Hanafin, J., Nolan, P., Wang, S., 2009. Influence of climate change on heating and cooling energy demand in Ireland. International J. Climatol. https://doi.org/10.1002/joc.1997 n/a-n/a.

Sissoko, K., van Keulen, H., Verhagen, J., Tekken, V., Battaglini, A., 2011. Agriculture, livelihoods and climate change in the West African Sahel. Reg. Environ. Change 11 (S1), 119–125. https://doi.org/10.1007/s10113-010-0164-y.

Sorgho, R., Jungmann, M., Souares, A., Danquah, I., Sauerborn, R., 2021a. Climate change, health risks, and vulnerabilities in burkina faso: a qualitative study on the perceptions of national policymakers. Int. J. Environ. Res. Public Health 18 (9), 4972.

Sorgho, R., Jungmann, M., Souares, A., Danquah, I., Sauerborn, R., 2021b. Climate change, health risks, and vulnerabilities in Burkina Faso: a qualitative study on the perceptions of national policymakers. Int. J. Environ. Res. Public Health 18 (9), 4972. https://doi.org/10.3390/ijerph18094972.

Sougué, M., Merz, B., Sogbedji, J.M., Zougmoré, F., 2023. Extreme rainfall in southern Burkina Faso, West Africa: trends and links to Atlantic sea surface temperature. Atmosphere (Basel) 14 (2), 284. https://doi.org/10.3390/atmos14020284.

Stalled, R.R.H., 2012. A climate trend analysis of Burkina Faso. Sci Chang World 3084.

Stern, R.D., Dennett, M.D., Garbutt, D.J., 1981. The start of the rains in West Africa. J. Climatology 1 (1), 59–68. https://doi.org/10.1002/joc.3370010107.

Stouffer, R.J., Eyring, V., Meehl, G.A., Bony, S., Senior, C., Stevens, B., Taylor, K.E., 2017. CMIP5 Scientific Gaps and Recommendations for CMIP6. Bull. Am. Meteorol. Soc. 98 (1), 95–105. https://doi.org/10.1175/BAMS-D-15-00013.1.

Sultan, B., Defrance, D., Iizumi, T., 2019. Evidence of crop production losses in West Africa due to historical global warming in two crop models. Sci. Rep. 9 (1), 12834. https://doi.org/10.1038/s41598-019-49167-0.

Sun, Q., Miao, C., Hanel, M., Borthwick, A.G.L., Duan, Q., Ji, D., Li, H., 2019. Global heat stress on health, wildfires, and agricultural crops under different levels of climate warming. Environ. Int. 128, 125–136. https://doi.org/10.1016/j.envint.2019.04.025.

Sylla, M.B., Elguindi, N., Giorgi, F., Wisser, D., 2016a. Projected robust shift of climate zones over West Africa in response to anthropogenic climate change for the late 21st century. Clim. Change 134 (1), 241–253. https://doi.org/10.1007/s10584-015-1522-z.

Sylla, M.B., Faye, A., Giorgi, F., Diedhiou, A., Kunstmann, H., 2018a. Projected heat stress under 1.5°C and 2°C global warming scenarios creates unprecedented discomfort for humans in West Africa. Earth's Future 6 (7), 1029–1044. https://doi.org/10.1029/2018EF000873.

Sylla, M.B., Giorgi, F., Coppola, E., Mariotti, L., 2013. Uncertainties in daily rainfall over Africa: assessment of gridded observation products and evaluation of a regional climate model simulation. Internat. J. Climatology 33 (7), 1805–1817. https://doi.org/10.1002/joc.3551.

Sylla, M.B., Nikiema, P.M., Gibba, P., Kebe, I., Klutse, N.A.B., 2016b. Climate change over West Africa: recent trends and future projections. In Adaptation to Climate Change and Variability in Rural West Africa. Springer, pp. 25–40.

Sylla, M.B., Pal, J.S., Faye, A., Dimobe, K., Kunstmann, H., 2018b. Climate change to severely impact West African basin scale irrigation in 2°C and 1.5°C global warming scenarios. Sci. Rep. 8 (1), 14395. https://doi.org/10.1038/s41598-018-32736-0.

Talib, J., Taylor, C.M., Klein, C., Harris, B.L., Anderson, S.R., Semeena, V.S., 2022. The sensitivity of the West African monsoon circulation to intraseasonal soil moisture feedbacks. Q. J. R. Meteorol. Soc. 148 (745), 1709–1730.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93 (4), 485–498.

Tazen, F., Diarra, A., Kabore, R.F.W., Ibrahim, B., Bologo/Traoré, M., Traoré, K., Karambiri, H., 2019. Trends in flood events and their relationship to extreme rainfall in an urban area of Sahelian West Africa: the case study of Ouagadougou, Burkina Faso. J. Flood. Risk. Manage 12, e12507.

Tebaldi, C., Knutti, R., 2007. The use of the multi-model ensemble in probabilistic climate projections. Philosophical Transact. Royal Society A 365 (1857), 2053–2075. https://doi.org/10.1098/rsta.2007.2076.

Theokritoff, E., Lise D'haen, S.A., 2022. How is science making its way into national climate change adaptation policy? Insights from Burkina Faso. Clim. Dev. 14 (9), 857–865. https://doi.org/10.1080/17565529.2021.2018985.

Thrasher, B., Wang, W., Michaelis, A., Melton, F., Lee, T., Nemani, R., 2022. NASA Global Daily Downscaled Projections, CMIP6. Sci. Data 9 (1), 262. https://doi.org/10.1038/s41597-022-01393-4.

Trenberth, K.E., 2018. Climate change caused by human activities is happening and it already has major consequences. J. Energy Nat. Resources Law 36 (4), 463–481. https://doi.org/10.1080/02646811.2018.1450895.

Ukey, R., Rai, A.C., 2021. Impact of global warming on heating and cooling degree days in major Indian cities. Energy Build. 244, 111050 https://doi.org/10.1016/j.enbuild.2021.111050.

UNFCCC. (2015). *Burkina Faso national climate change adaptation plan (NAP)*. https://www4.unfccc.int/sites/NAPC/Documents/Parties/Burkina-Faso-NAP_English.pdf.

Vargas Zeppetello, L.R., Raftery, A.E., Battisti, D.S., 2022. Probabilistic projections of increased heat stress driven by climate change. Commun. Earth. Environ. 3 (1), 183. https://doi.org/10.1038/s43247-022-00524-4.

Visser, S.M., Leenders, J.K., Leeuwis, M., 2003. Farmers' perceptions of erosion by wind and water in northern Burkina Faso. Land. Degrad. Dev. 14 (1), 123–132. https://doi.org/10.1002/ldr.530.

Vogel, M.M., Hauser, M., Seneviratne, S.I., 2020. Projected changes in hot, dry and wet extreme events' clusters in CMIP6 multi-model ensemble. Environ. Res.Lett. 15 (9), 094021 https://doi.org/10.1088/1748-9326/ab90a7.

Wainwright, C.M., Black, E., Allan, R.P., 2021. Future changes in wet and dry season characteristics in CMIP5 and CMIP6 simulations. J. Hydrometeorol. https://doi.org/10.1175/JHM-D-21-0017.1.

Wang, F., Harindintwali, J.D., Yuan, Z., Wang, M., Wang, F., Li, S., Yin, Z., Huang, L., Fu, Y., Li, L., Chang, S.X., Zhang, L., Rinklebe, J., Yuan, Z., Zhu, Q., Xiang, L., Tsang, D.C.W., Xu, L., Jiang, X., Chen, J.M., 2021. Technologies and perspectives for achieving carbon neutrality. Innovation 2 (4), 100180. https://doi.org/10.1016/j.xinn.2021.100180.

Wang, H., Chen, Q., 2014. Impact of climate change heating and cooling energy use in buildings in the United States. Energy Build. 82, 428–436. https://doi.org/10.1016/j.enbuild.2014.07.034.

Weijer, W., Cheng, W., Garuba, O.A., Hu, A., Nadiga, B.T., 2020. CMIP6 models predict significant 21st century decline of the Atlantic meridional overturning circulation. Geophys. Res. Lett. (12), 47. https://doi.org/10.1029/2019GL086075.

WMO. (2019). *The global climate in 2015–2019*.

Wood, A.W., Leung, L.R., Sridhar, V., Lettenmaier, D.P., 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Clim. Change 62 (1–3), 189–216. https://doi.org/10.1023/B:CLIM.0000013685.99609.9e.

Worou, K., Fichefet, T., Goosse, H., 2023. Future changes in the mean and variability of extreme rainfall indices over the Guinea coast and role of the Atlantic equatorial mode. Weather Climate Dynamics 4 (2), 511–530. https://doi.org/10.5194/wcd-4-511-2023.

Xu, H., Chen, H., Wang, H., 2022. Detectable human influence on changes in precipitation extremes across China. Earth's Future 10 (2). https://doi.org/10.1029/2021EF002409.