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Predicting Standardized Precipitation Evapotranspiration Index for Fada N'Gourma by 2050 Using CMPI-6 Outputs under SSPs Scenarios

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Abstract: Extreme weather events, such as floods and droughts, are expected to rise significantly worldwide as a result of climate change. Investigating future drought patterns is therefore a key approach for elaborating anticipatory water resources management responses to climate change. In this paper, future meteorological drought conditions are investigated based on the SPEI (Standardised Precipitation Evapotranspiration Index). This study makes use of observed and projected data. The simulated data were retrieved from the CMIP6 (Coupled Model Intercomparison Project Phase 6) over the period 2025-2050, and the Delta change method was adopted to remove the bias in the dataset. Then SPEI at various scales has been estimated under four future scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5). The trend analysis of the projected SPEI was performed at $p < 0.05$ using the MMK (Modified Mann-Kendall) test in order to detect the statistically significant trend of the drought against the null hypothesis of no trend. Results show large variability in the magnitude of drought in the past and future. Based on SPEI at 24 months accumulation, the result shows that under SSP1-2.6, the basin will experience a wet period during the first decade (SPEI = 0.60), the second decade will be dry (SPEI24 = -0.43). The remaining years will be also dry (SPEI = -0.34). Under SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios, the district will experience a wet period during the first two decades with SPEI ranging from 0.38 to 0.59. This wet period will be followed by a dry period under these scenarios ranging from -0.14 to -0.06. Overall, under SSPs scenarios, two main periods characterized by a rainfall recovery spanning from followed by a moderately prolonged drought are identified within the study area. The findings of this study may provide valuable information for developing proactive measures to reduce water insecurity in Fada N'Gourma through effective drought mitigation.

Key words: Climate change, drought index, CMPI-6, Fada N'Gourma, SSP-scenarios.

1. Introduction

Under climate change, water availability, accessibility, and mobilisation for present and future purposes related to agriculture, economic development, and sanitation are worrying governments, researchers, and the population worldwide. Indeed, a great proportion of the world's population experiences severe water scarcity for at least part of the year [1-3]. The UNEP (UN Environment Programme) [4] reported that globally, 2.2 billion people lack access to safe water. According to Otto et al. [5], currently twenty-five percent of the world population faces extremely high water stress. Extreme events, including floods and droughts, remain among the most devastating water-related disasters. Indeed, over the period 2002-2021, floods caused nearly 100,000 deaths, with an additional 8,000 in 2022. This creeping phenomenon affected another 1.6 billion people and caused US $832 billion in economic losses [6, 7]. In the case of Burkina Faso, located in western Africa, Crawford et al. [8] stated that droughts are the most regular meteorological phenomena. Indeed, since

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the significant alteration in climate patterns in the 1970s, Burkina Faso has experienced chronic drought, with the most critical phases being the years 1973-1974 and 1983-1984 [9]. Moreover, since 1991, the country has experienced about seven major drought events. Recent drought episodes have been detected in 2011, 2012, 2014, and 2020 [10]. Gautier et al. [11] revealed that droughts that have been experienced by the country have resulted in production losses. This has induced food prices and food shortages with consequences for malnutrition [12-14]. According to USAID [13], during the 2011-2012 drought, farmers lost an estimated 25%-75% of their farm income and their livestock income. The number of undernourished people in the country increased from 3.8 million (2008-2010) to 4.4 million (2011-2013). Moreover, the drought left 450,000 children under the age of five in a situation of severe malnutrition and 100,000 in a situation of acute malnutrition. In recent decades, historical and future drought assessments over Burkina Faso have gained attention among scholars. Mbaye et al. [15] investigated drought magnitude over Burkina Faso based on SPEI (Standardised Precipitation Evapotranspiration Index) estimation. In addition, Omondi et al. [16] applied the effective reconnaissance drought index approach to handle projected changes in agricultural drought over Gourma Province in Burkina Faso. They identified mild and ephemeral agricultural drought events in 1983 and 2008. Diasso et al. [17] studied the signature of future drought over West Africa based on RegCM4 and WRF simulations under RCP4.5 scenario. They indicated that reforestation over the Savanna could increase the daily rainfall by 0.8 to 1.2 mm. In addition, Sawadogo et al. (2024) investigated the impacts of climate change for Burkina Faso based on NEX-GDDP-CMIP6 models (25 km) by 2100. Results show that under the SSP5-8.5, precipitation will increase by 30%. The aim of this paper is to forecast drought characteristics based on the SPEI across Fada N'Gourma, under the SSPs (Shared Socioeconomic Pathways) scenarios by 2050. SPEI is a meteorological drought index that expresses anomalies at various time scales. It estimates anomalies based on climatic water balance. This study is organized within three sections. Section 1 presents the study area, the observed and simulated data, the methods deployed to bias correct the Regional Climate Model (RCMs) data, and to estimate the SPEI. Results and discussion are reported in Section 2, while the main conclusions and perspectives are summarized in Section 3.

2. Methods and Datasets

2.1 Presentation of the Study Area

In the present study, future drought patterns are analyzed for the district of Fada N'Gourma. The watershed is located in the eastern part of Burkina Faso confined with longitude 1°25′ East and latitude 11°55′ North (Fig. 1). Covering 3,400.2 km^2, the area is affected by the Soudano Sahelian climate, which is characterized by a hot semi-arid climate and a short rainy season. Indeed, the rainfall over the study area displays a unimodal regime with a rainy season in May to September (MJJAS) and a long dry season spanning from October to April (ONDJFMA). The annual precipitation varies from 290 mm to 2,050 mm. The mean annual temperature is averaging 28.9 ℃, and the annual mean relative humidity is about 50.4%. Three main soil groups are present within the study area, which are tropical ferruginous soils. The vegetation is dominated by tree and shrub savanna.

2.2 Observed and Simulated Climate Dataset

The observed and simulated climatic dataset used in this research includes monthly maximum temperature ($T_{\max}$), monthly minimum temperature ($T_{\min}$), and monthly rainfall (Prcp). As shown in Table 1, monthly observed temperature and precipitation measurements for the period 1981-2021 were provided by the ANM (National Meteorological Agency). The simulated datasets were collected from CMPI-6 outputs.

The descriptive statistics of the observed climate dataset correlation coefficient are summarized in Table 2.

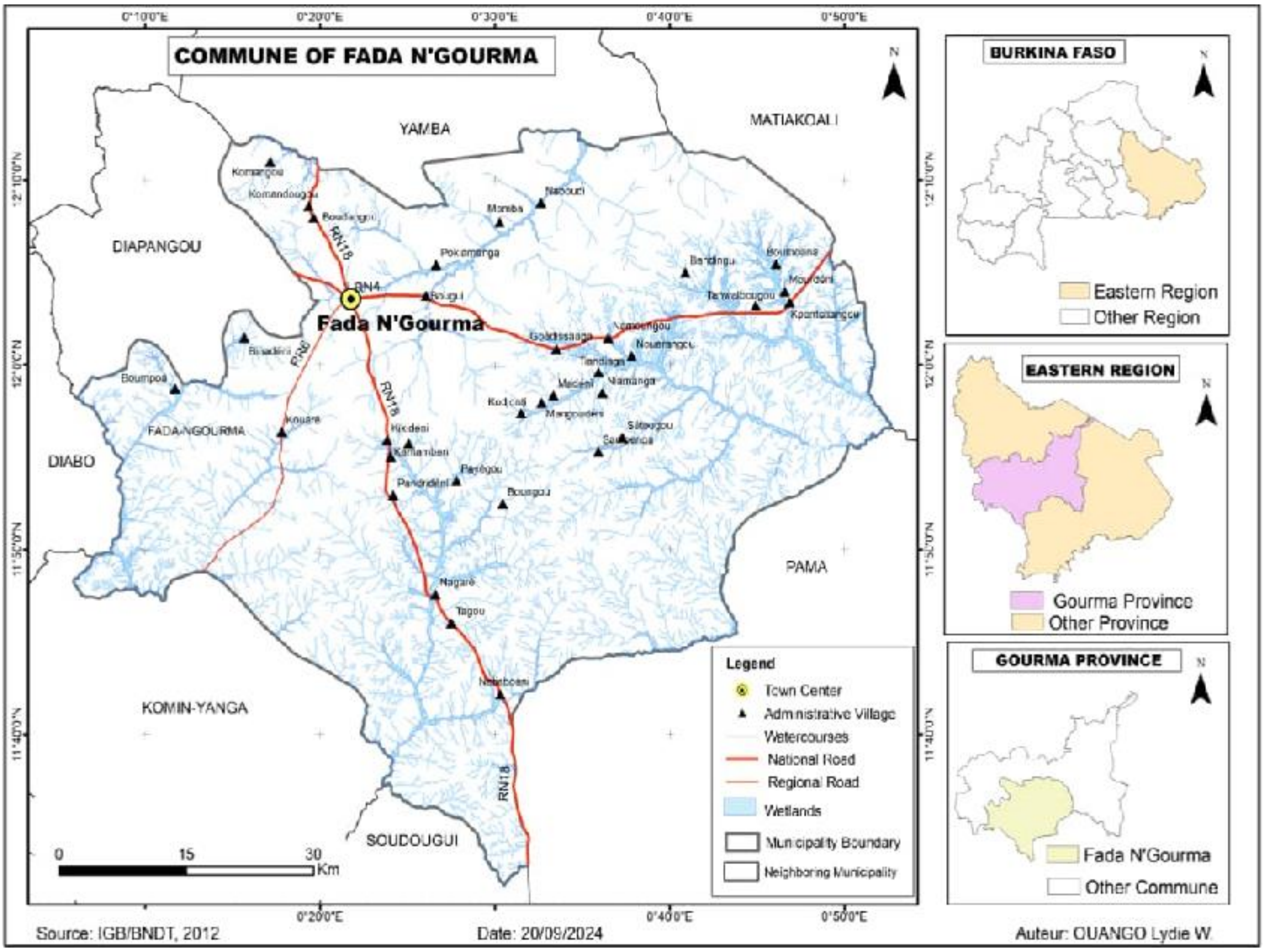


Fig. 1 Presentation of the study area.

Table 1 Data sets and sources used in the study.

Data type	Data description	Time period	Scale	Source
Observed data	T_{max}, T_{min}, Precipitation	1981-2021	Monthly	ANM
Simulated data	T_{max}, T_{min}, Precipitation	-2050	Monthly	CMPI-6

Table 2 Basic characteristics of observed rainfall and temperature (Fada N'Gourma).

	Year	Month	Prcp	T_{max}	T_{min}
Min	1981	1.00	0.00	29.34	14.95
1st Qu	1991	3.75	0.00	32.60	20.44
Medain	2001	6.50	24.35	35.30	22.64
Mean	2001	6.50	68.19	35.31	22.39
3rd Qu	2011	9.25	120.70	37.69	24.34
Max	2021	12.00	416.00	41.40	28.99

2.3 Bias Correction of CMPI6 Output

The availability of reliable projected climatic data is very important for the optimal application in future climate-related studies. However, projected data are bound by bias that needs to be corrected before using in models. To address this concern, the Delta change method is applied to remove the bias for better analysis. According to Dessu et al. [18], the Delta method is a downscaling technique that estimates the difference (delta) between the Global Climate Model (GCM) data and observed data over a specific historical period. Furthermore, this delta is applied to the GCM projections to adjust and refine the climate data, providing more accurate and localized information.

The formula of the downscaled data is given by:

$$P_{SD}^{Delta} = P_{GCMrcp} * \frac{\bar{\bar{P}}_{obs}}{\bar{P}_{GCMhist}}$$

$$T_{SD}^{Delta} = T_{GCMrcp} + (\bar{T}_{obs} - \bar{T}_{GCMhist})$$

where, P_{SD}^{Delta} stands for downscaled data of precipitation.

T_{SD}^{Delta} refers to downscaled data of temperature.

$\bar{\bar{P}}_{obs}$ represents the average of observed precipitation.

$\bar{P}_{GCMhist}$ is the mean simulation of GCM historical precipitation.

$\bar{\bar{T}}_{obs}$ represents the average of observed temperature.

$\bar{T}_{GCMhist}$ is the mean simulation of GCM historical temperature.

2.4 Estimation of Historical and Future SPEI

The SPEI is a multiscale meteorological drought index developed in 2010 by Vicente-Serrano et al. SPEI is computed as the difference between precipitation and PET (Potential Evapotranspiration). In this study, the Hargreaves equation suggested by Hargreaves et al. [19] is adopted to estimate the PET based on data availability due to the adaptability of the formula to dry areas. The PET formula is expressed by:

$$PET = 0.0135k_{R_s}\frac{R_a}{\lambda}\sqrt{T_{max} - T_{min}}(T - 17.8)$$

where R_a corresponds to the extraterrestrial radiation, which is related to the latitude of the study area as stated by Allen et al. [20], λ stands for the latent.

The second step in SPEI calculation is the estimation of the climatic water balance, which detects the water deficit or surplus. Furthermore, the SPEI is provided as the aggregation of the water balance at various time scales.

According to Beguer ía et al. [21], the water balance is expressed as:

$$D_i = P_i - PET_i$$

where D_i *stands for the water balance for the month i*, P_i represents the precipitation for month *i* and PET_i refers to the potential evapotranspiration at month *i*.

Table 3 details the different grades of droughts related to the SPEI values according to the classification provided by Wang et al. [22].

2.5 Trend Analysis

The trend detection analysis was performed using the MMK (Modified Mann-Kendall) test. The MMK test performs statistically significant decreasing or increasing trend in time series [23-25].

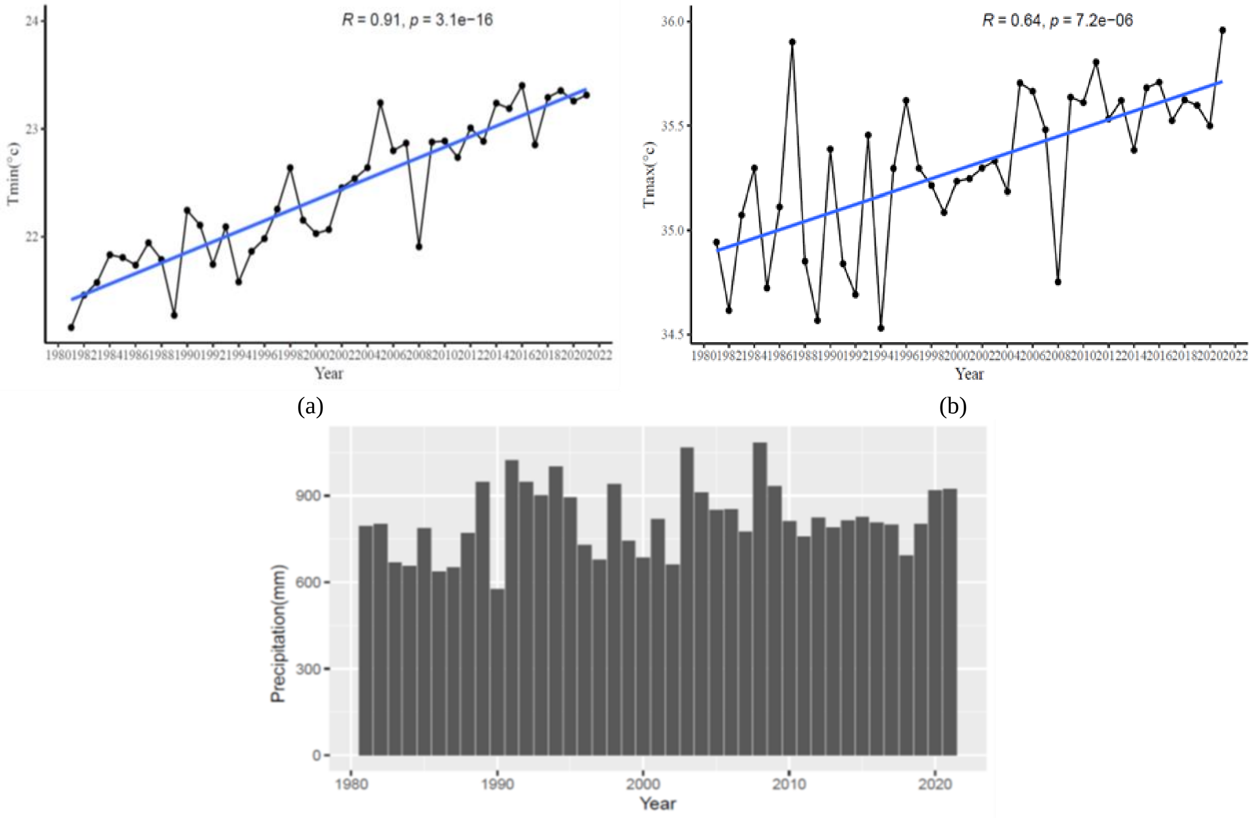
3. Results

3.1 Changes in Historical Annual Temperature and Rainfall

Fig. 2 presents the trend of observed rainfall and minimum and maximum temperature within Fada N'Gourma. Over the historical period (1981-2021), a continuous increase in annual temperature is identified. The minimum temperature is increasing at a faster rate (R = 0.91) than the maximum temperature (R = 0.64). Similar patterns of temperature across Burkina Faso have been reported by many scholars [26-28]. The annual precipitation shows high variability over years. During the period of the study, 2008 is the year with the

Table 3 Categorization of drought grade by the SPEI.

Categorization	SPEI values	Categorization	SPEI values
Extremely wet	SPEI ≥ 2	Normal	-0.5 ≤ SPEI ≤ 0.5
Severely wet	1.5 ≤ SPEI < 2	Mild drought	-1 < SPEI < -0.5
Moderately wet	1 ≤ SPEI < 1.5	Moderate drought	-1.5 < SPEI ≤ -1
Mildly wet	0.5 < SPEI < 1	Severe drought	-2 < SPEI ≤ -1.5
		Extreme drought	SPEI ≤-2



(a) (b)

(c)

Fig. 2 (a) Annual minimum temperature of Fada N'Gourma (1981-2021); (b) Annual maximum temperature of Fada N'Gourma (1981-2021); (c) Annual rainfall of Fada N'Gourma (1981-2021).

highest cumulative rainfall amount record. A slight rainfall recovery is noticed from 2019 to 2021. This finding is in agreement with the study of Nouaceur et al. [29].

3.2 Historical SPEI at Various Time Scale for Fada N'Gourma

A SPEI of the 3-months, 6-months, 12-months, and 24-months based on historical observed data (1981-2021) over Fada N'Gourma is illustrated in Fig. 3. The SPEI investigation indicated a high variability of meteorological drought at all scales. The left and right top panels of Fig. 3 exhibit a pattern of continued mild wetness from 1981 to 1990. SPEI patterns at the 12- and 24-month scales illustrated respectively at the left and right bottom panels present a normal condition from 1991 to 2015 with minor drought occurrence in some years. The period 2016 to 2021, however, sows drought conditions. The most severe drought situations occurred during 1985, 2015, and 2020. Additionally, Omondi et al. [16] investigated changes in agricultural drought over Gourma Province in Burkina Faso. Results show that agricultural drought events of 1983 and 2008 are mild and ephemeral, while the 1999-2006 event is severe and protracted.

3.3 Accuracy of Climate Data Simulated

Fig. 4 displays correlations between observed and historical CMPI6 climate data based on the Pearson approach. Remarkably, the historical CMPI6 data exhibit strong ability in reproducing the observed climate variables over Fada N'Gourma. Indeed, the value of 0.66 is detected as a correlation coefficient value of the precipitation. A value of 0.78 is observed as the correlation coefficient between the observed maximum temperature of Fada N'Gourma and historical CMPI-6 maximum temperature, while 0.84 is identified as the rate of correlation as far as minimum temperature is concerned.

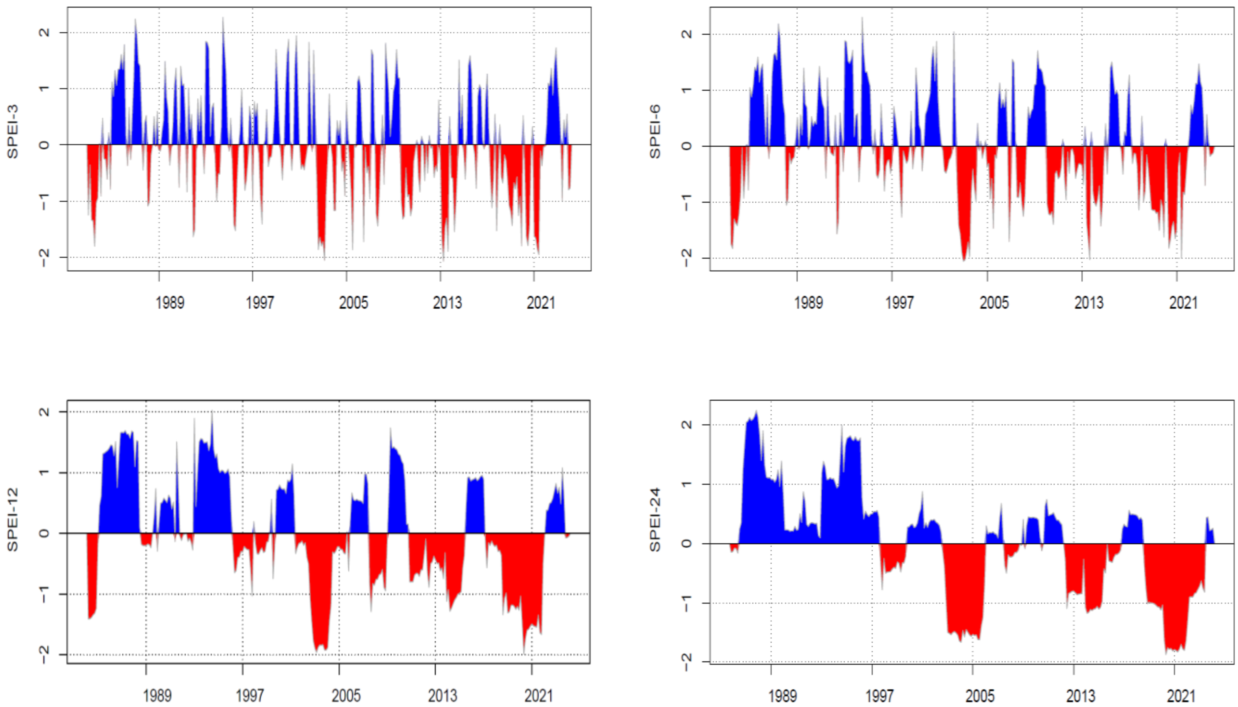


Fig. 3 SPEI calculated from observed precipitation and temperature data from Fada N'Gourma at different accumulation periods.

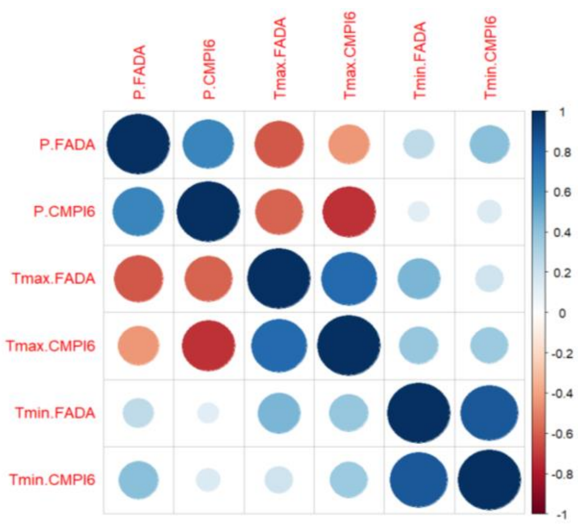


Fig. 4 Correlation graph for observed and historical CMIP-6 climate data.

3.4 Hstorical SPEI Distribution for Fada N'Gourma

Fig. 5 shows the PDF (Probability Density Function) as estimated by the KDE (Kernel Density Estimation). The kernel estimates of the SPEI display two modes that lie between -3 and +3 which depicts moderate drought of the region. KDE is a nonparametric method that estimates the PDF of a random variable from a given sample of data. It provides a smooth curve representation of the data's distribution and helps determine the shape and spread of the density estimate around any specific point. Common kernel functions used in KDE include Gaussian, Epanechnikov, and rectangular [30, 31].

3.5 SPEI Patterns over Fada N'Gourma by 2050 under SSP1-2.6 Scenarios

The SPEI at 3, 6, 12, and 24-month accumulation for a given year in Fada N'Gourma is illustrated in Fig. 6. The SPEI investigation indicated a high variability of meteorological drought over years. Under SSP1-2.6 scenarios at 24 months accumulation, the basin will experience a wet period during the first decade (SPEI = 0.60), the second decade will be dry (SPEI = -0.43). These findings align with previous research highlighting potential rainfall recovery in the Sahel region based on

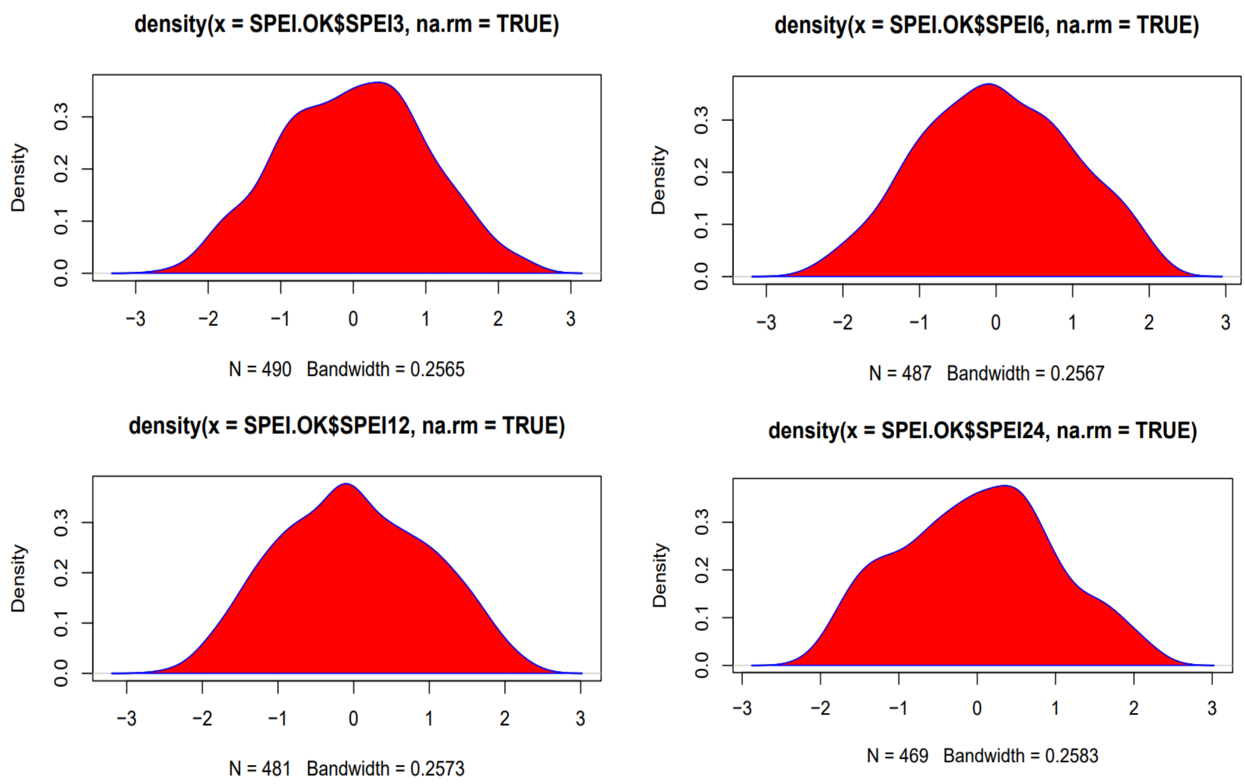


Fig. 5 Kernel distribution of SPEI over Fada N'Gourma.

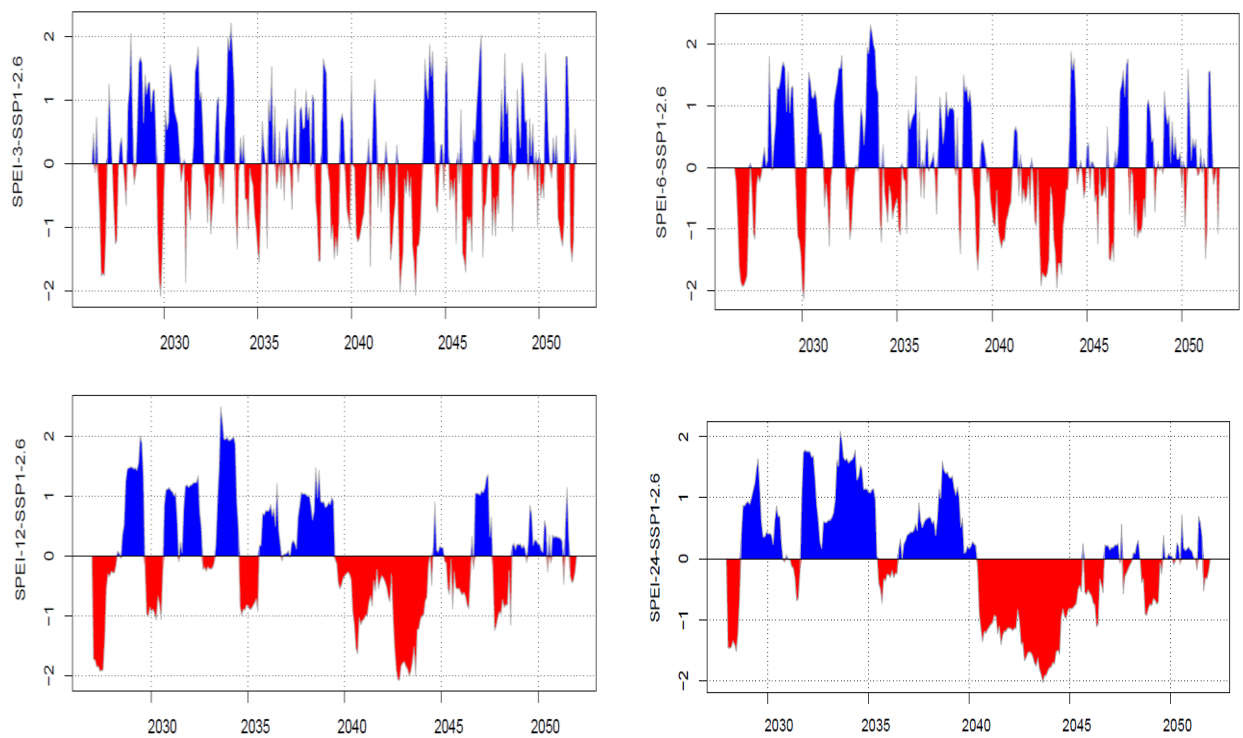


Fig. 6 Projected SPEI for Fada N'Gourma at different time scale accumulation from 1925 to 2050 under SSP1-2.6 scenarios.

Table 4 Values of the Mann Kendall test for monthly SPEI by 2050 under SSP1-2.6 scenarios.

	z	*p*-value	MKtau
SPEI-3-SSP1-2.6	-1.5309	0.1258	-5.831872e-02
SPEI-6-SSP1-2.6	-1.2819	0.1999	-4.907283e-02
SPEI-12-SSP1-2.6	-2.2974	0.0216	-8.881506e-02
SPEI-24-SSP1-2.6	-6.1155	9.624e-10	-2.413014e-01

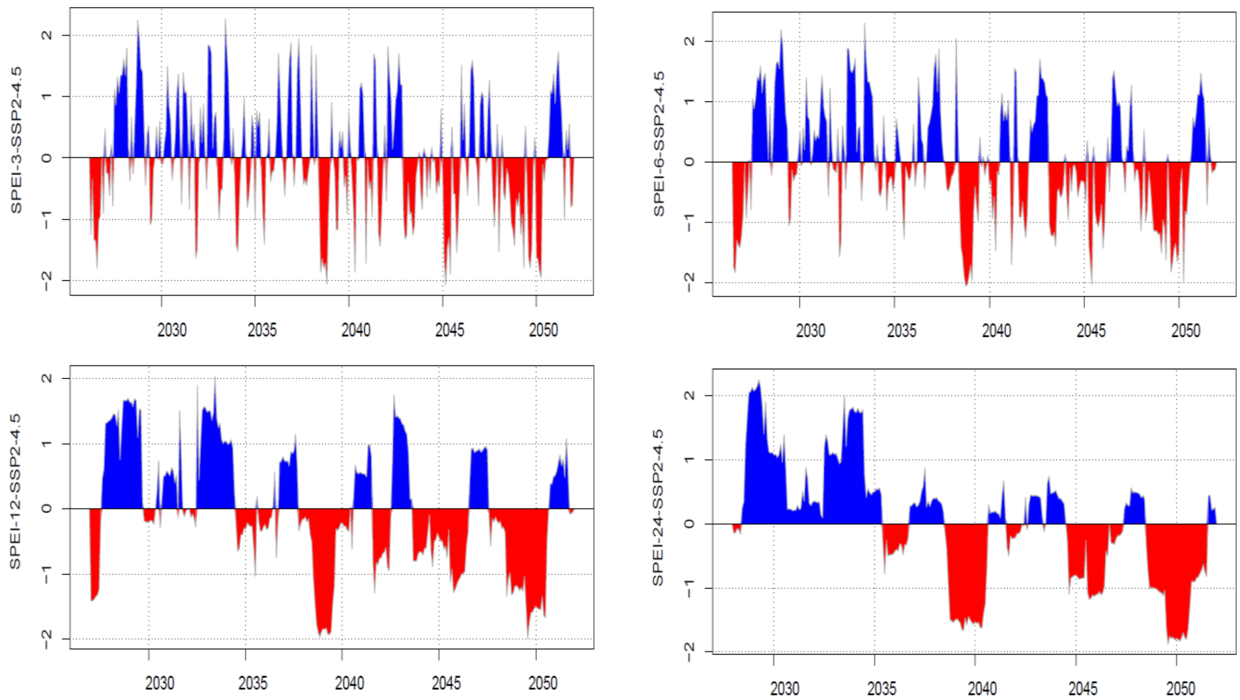


Fig. 7 Projected SPEI for Fada N'Gourma at different time scale accumulations from 1925 to 2050 under SSP2-4.5 scenarios.

Table 5 Values of the Mann Kendall for monthly SPEI by 2050 under SSP2-4.5 scenarios.

	z	*p*-value	MKtau
SPEI-3-SSP2-4.5	-3.2483	0.001161	-1.237081e-01
SPEI-6-SSP2-4.5	-4.4576	8.288e-06	-1.705946e-01
SPEI-12-SSP2-4.5	-3.2483	0.001161	-1.237081e-01
SPEI-24-SSP2-4.5	-10.094	< 2.2e-16	-3.982603e-01

projected data [32, 33]. This expected recovery period will be followed by a prolonged drought. Indeed, a moderate drought is anticipated to persist from 2041 to 2047.

Under SSP1-2.6 scenarios, the SPEI at 3, 6, 12, and 24 monthly accumulations is decreasing with a respective *z* value of -1.5309, -1.2819, -2.2974, and -6.1155. Thus, under SSP1-2.6 scenarios, drought will slightly decrease over Fada N'Gourma. The estimated decrease in drought magnitude for future conditions in eastern Burkina Faso is in full agreement with the findings of Mudelsee et al. [34], who found a significant upward trend in precipitation for Burkina Faso.

3.6 SPEI Patterns over Fada N'Gourma by 2050 under SSP2-4.5 Scenarios

Under SSP2-4.5, the projected SPEI at 3, 6, 12, and 24-month accumulation for a given year over Fada N'Gourma is illustrated in Fig. 7. The SPEI investigation indicated a high variability of meteorological drought at all scales. Based on the SPEI-24 index, two distinct periods are projected: A rainfall recovery phase until 2035 (SPEI = 0. 59), followed by an almost continuous drought period that will last until 2050 (SPEI = -0.14).

Under SSP2-4.5 scenarios, the SPEI at 3, 6, 12, and 24 monthly accumulations is decreasing with a respective *z*-value -3.2483, -4.4576, -3.2483, and -10.094. Thus, under these climate scenarios, drought will decrease over Fada N'Gourma basin. This outcome is consistent with the analysis of Sawadogo et al. [35] which shows a significant increase of the annual rainfall amount in Burkina Faso by 2100 under all SSP scenarios.

3.7 SPEI Patterns over Fada N'Gourma by 2050 under SSP3-7.0 Scenarios

Under SSP3-7.0, the projected SPEI at 3, 6, 12, and 24-month accumulation for a given year over Fada N'Gourma is illustrated in Fig. 8. The SPEI investigation indicated a high variability of meteorological drought at all scales. Under the SSP3-7.0 scenario at 24 months of accumulation, the analysis indicates that the first two decades will be wet (SPEI = 0.38) and the remaining years will be dry (SPEI= -0.06).

Under SSP3-7.0 scenarios, the SPEI at 3, 6, 12, and 24 monthly accumulations is decreasing with a respective *z*-value -1.3182, -1.2273, -1.6785, and -1.2614. Thus, under this climate scenario, drought will decrease over the Fada N'Gourma basin.

Under SSP3-7.0 scenarios, the SPEI at 3, 6, 12, and 24 monthly accumulations is decreasing with a respective *z*-value -1,3182, -1.2273, -1.6785 and -1.2614. Thus, under these climate scenarios, drought will decrease over Fada N'Gourma basin. This implies that by 2050, Fada N'Gourma may experience rainfall recovery. This result is also similar to projections of rainfall in Burkina Faso for the next coming decades [36-38].

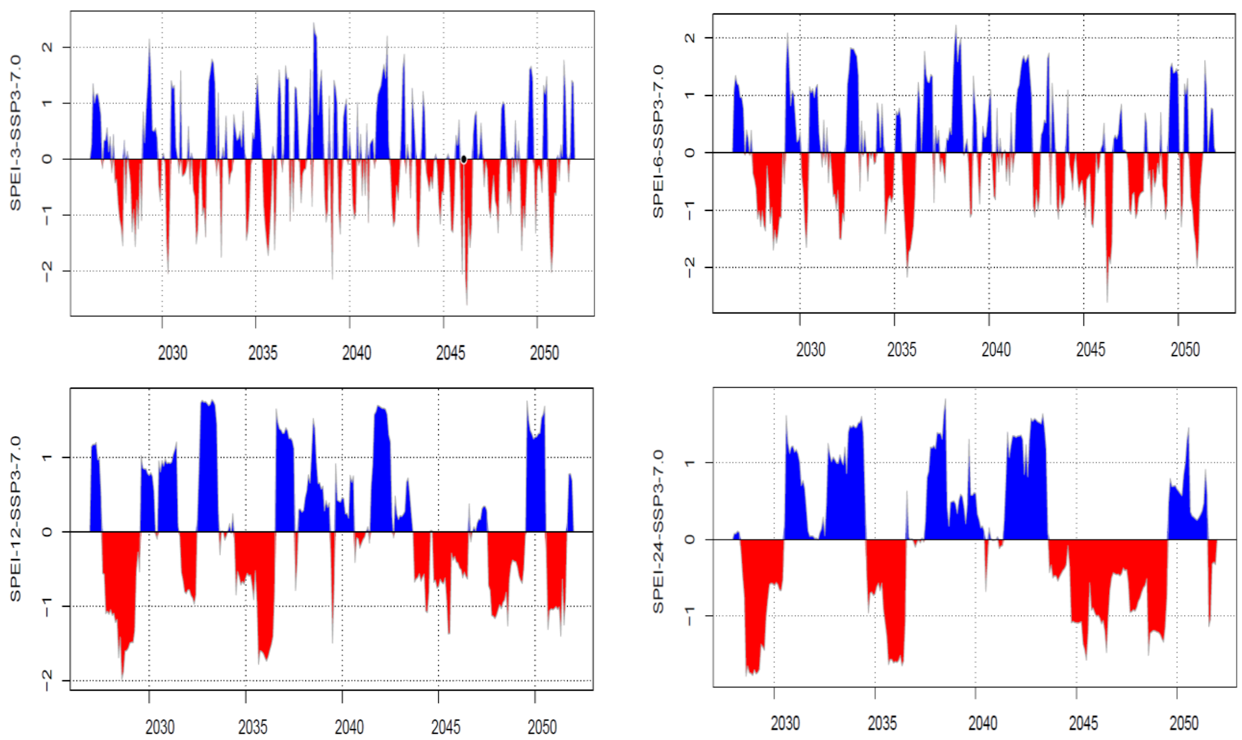


Fig. 8 Projected SPEI for Fada N'Gourma at different time scale accumulations from 2025 to 2050 under SSP3-7.0 scenarios.

Table 6 Values of the Mann Kendall for monthly SPEI by 2050 under SSP3-7.0 scenarios.

	z	*p*-value	MKtau
SPEI-3-SSP3-7.0	-1.3182	0.1874	-5.021401e-02
SPEI-6-SSP3-7.0	-1.2273	0.2197	4.698644e-02
SPEI-12-SSP3-7.0	-1.6785	0.09325	-6.489480e-02
SPEI-24-SSP3-7.0	-1.2614	0.2072	-4.978854e-02

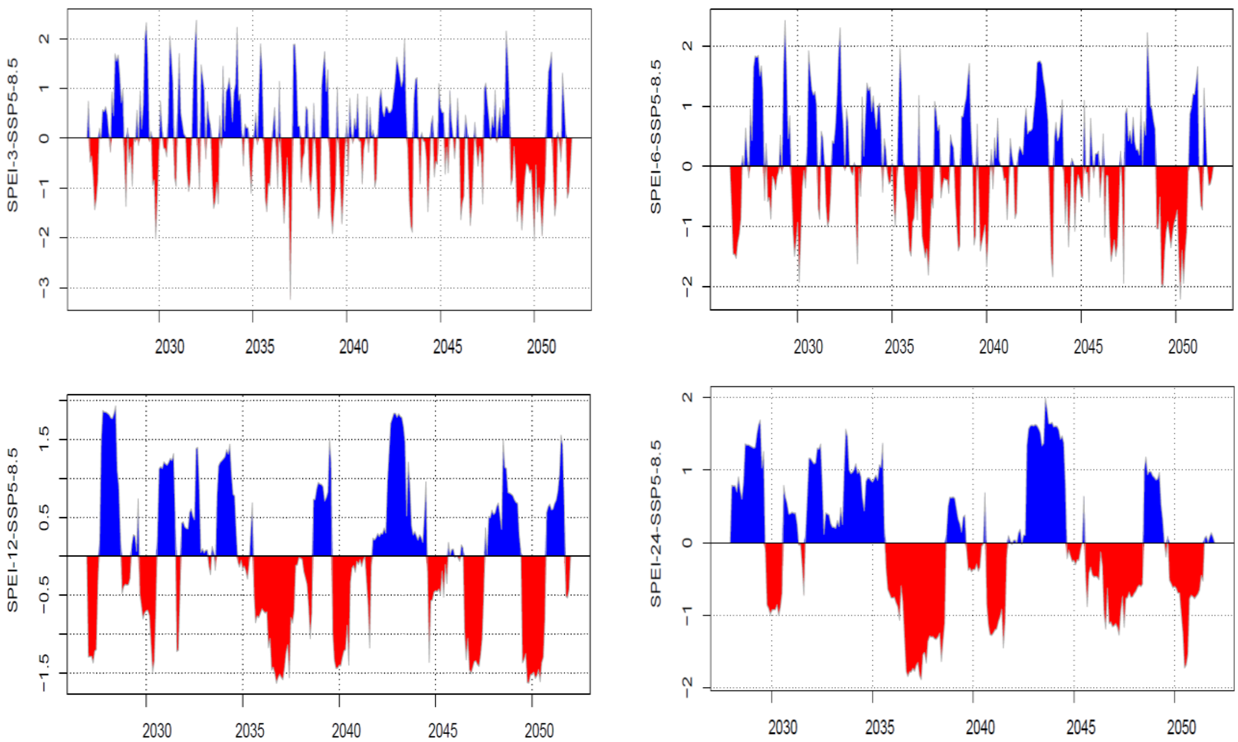


Fig. 9 Projected SPEI for Fada N'Gourma at different time scale accumulations from 2025 to 2050 under SSP5-8.5 scenarios.

Table 7 Values of the Mann Kendall for monthly SPEI by 2050 under SSP5-8.5 scenarios

	z	*p*-value	MKtau
SPEI-3-SSP5-8.5	-2.7833	0.005381	-1.060027e-01
SPEI-6-SSP5-8.5	-1.6413	0.1007	-6.282600e-02
SPEI-12-SSP5-8.5	-1.3702	0.1706	-5.297896e-02
SPEI-24-SSP5-8.5	-4.2299	2.338e-05	-1.669070e-01

3.8 SPEI Patterns over Fada N'Gourma by 2050 under SSP5-8.5 Scenarios

Under SSP5-8.5, the projected SPEI at 3, 6, 12, and 24-month accumulation for a given year over Fada N'Gourma is illustrated in Fig. 9. The SPEI investigation indicated a high variability of meteorological drought at all scales. Under SSP-585 scenarios at 24 months accumulation, the basin will experience a wet period during the first two decades with SPEI = 0.44 while a dry period will be experienced from 2045 to 2050 (SPEI = -0.06).

Under SSP5-8.5 scenarios, the SPEI at 3, 6, 12, and 24 monthly accumulations is decreasing with a respective *z*-value -2.7833, -1.6413, -1.3702, and -4.2299. Thus, under this climate scenario, drought will decrease over Fada N'Gourma basin. This finding corroborates the results of Sawadogo et al. [35] who found a significant increase of the annual rainfall amount in Burkina Faso by 2,100 under all SSP scenarios.

4. Conclusions

This study examined future drought patterns in the Fada N'Gourma under SSPs scenarios based on the SPEI. The Mann-Kendall and Sen Slope estimation tests were employed to identify drought trends and their severity. The study reveals a moderate rainfall recovery in the next two decades, followed by a prolonged moderate drought up to 2050. Rising temperatures are projected to intensify potential evapotranspiration rates, leading to a water deficit. Future research should investigate the primary climate factors contributing to the projected rainfall recovery and explore future dry spell occurrence and frequency.

Acknowledgements

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