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Potential consequences for rising temperature trends in the Oti River Basin, West Africa

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Introduction: One of the ways that climate change manifest itself is through temperature changes. Though the Oti River basin has been grappling with drought incidents, there has been little or no emphasis on analyzing temperature fluctuations in the basin. This study aimed to analyze the mean annual and seasonal temperature for the observed (1981–2010) and future periods (2021–2050) over the Oti River basin.

Methods: Historical data were obtained from meteorological stations and the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER). Data quality assessment was conducted, and the NASA POWER temperature was validated against the stations' temperature. Ensemble of eight models acquired from the Coordinated Regional Climate Downscaling Experiment (CORDEX–Africa) under two Representative Concentration Pathways (RCP4.5 and RCP8.5), were used for the future projection. The mean annual and seasonal temperatures were analyzed for 1981–2010 and 2021–2050 (under RCPs 4.5 and 8.5 scenarios). The Modified Mann–Kendall test was used for trend analysis at 5% significant level.

Results and discussion: In the near-future, temperature is anticipated to increase at the mean monthly scale in the ranges of +0.88°C in October to +2.65°C in January under the RCP4.5 scenario, while the RCP8.5 predicts increases between +2.71°C in July and +6.48°C in January. The annual mean temperature change for the entire basin is projected at +1.47°C (RCP4.5) and +4.2°C (RCP8.5). For the rainy season period, the RCP4.5 projects annual mean temperature changes in the ranges of −0.72°C and +1.52°C while the RCP8.5 predicts changes between +1.06°C and +4.45°C. Concerning the dry season period, the anticipated changes in the annual mean temperature under the RCP4.5 would range from −0.43°C to +2.78°C whereas that of RCP8.5 would be between +1.97°C and 7.25°C. The Modified Mann–Kendall test revealed significantly increasing trends for temperature projections in the basin under both the RCPs 4.5 and 8.5 in the basin. The study provides significant contribution to the comprehension of temperature patterns in time and space which is necessary for the sustenance of rainfed agriculture and water resources within the basin.

KEYWORDS

Oti River Basin, temperature, climate change, RCP4.5 scenario, West Africa, NASA POWER, RCP8.5

1. Introduction

One of the ways that climate change shows itself is through temperature changes. According to the Intergovernmental Panel on Climate Change, IPCC (2018), the world's temperature (from 2015 to 2019), which was 1.1°C higher than it was in pre-industrial times, is expected to continue warming through 2052 and is likely to reach 1.5°C higher. Most of the time, the emission of greenhouse gases enhances global temperatures, which affects evapotranspiration and rainfall (Bates et al., 2008). It was estimated by the Food and Agriculture Organization and Economic Commission for Africa (2018) that between 2006 and 2016, agriculture (crops, livestock, fisheries, aquaculture, and forestry) sustained well over 26% of all damages and losses inflicted by extreme weather conditions and close to 80% of those resulting from drought globally. Catastrophic events, glacier retreat, and decreased sea ice quantity have all been linked to elevated temperatures (Huss et al., 2017). Although these trends are not anticipated to be consistent, both locally and globally, the intensity and frequency of climatic changes are likely to expand (Agyekum et al., 2018; Kruger et al., 2019; Choi et al., 2021).

West Africa has been identified as one of the areas of the globe that will be increasingly vulnerable to droughts, resulting in an increased loss of life-sustaining activities (Ndehedehe et al., 2016). Due to the region's involvement in climate-sensitive sectors such as agriculture, policymakers are particularly interested in how vulnerable the West African sub-region is toward climate change. Approximately 95% of the region's fertile land is used for agriculture, which employs 65% of the workforce and generates 30%−70% of the region's Gross Domestic Product (Blanc, 2012; Akumaga and Tarhule, 2018). Climate change has caused nearly all countries in West Africa to experience a rise in mean annual temperature over the years (Iheonu et al., 2022). For example, Aziz and Obuobie (2017) found a considerable rise in the annual average temperature of 0.9°C in the Black Volta Basin part of Burkina Faso and anticipated variation in average rainfall volume (ranging from −16 and +6%) for the late 21st century (2050–2075) under the Representative Concentration Pathway 4.5 scenario.

In the same way, during the rainy season, Diba et al. (2019) noted a deepening of the tropical night and a decrease in the frequency of thermal extremes across the Sahel. Extreme temperature in the Sahel portion of the region decreases feed consumption, causes energy shortages, and lowers animal production, while drought can lower calving rates. In addition, it causes the disappearance of conventional grazing and water sources, which changes the pastoralists' migratory habits (Lafia N'gobi et al., 2022). The Sahara Desert region of Niger is already under significant pressure on water supplies and agricultural production due to the increase in temperature and excessive rains, according to the African Development Bank (2018).

Temperature and rainfall fluctuations impact watershed environments, which alter freshwater supplies, thereby increasing the occurrence of hydrologic extremes such as flooding and drought (Awotwi et al., 2021; Gurara et al., 2023). For instance, even though the Volta River basin in West Africa supports the region's economy, the sub-region experiences harsh weather events that cause deaths and widespread damage (Annor et al., 2017; Agyekum et al., 2018). Regrettably, climate change is anticipated to worsen severe drought trends and prolonged rainfall start in the basin (van de Giesen et al., 2010; Yeboah et al., 2022) and in the Oti basin (Kwawuvi et al., 2022b). Under high-emission scenarios, it is expected that by 2040, West Africa may experience more frequent instances of excessive heat than it does now (Russo et al., 2016). West Africa is expected to experience persistent and increased heating due to climate change (up to ∼6.5°C), exceeding the estimated mean temperature worldwide of 1.5°C by 2100 (Sylla et al., 2016). These projections are likely true as trends in global drying triggered by climate change will eventually modify the hydrology of the land surface (Ndehedehe et al., 2016).

Although several other climate change impact studies have been conducted in the West African region, none of these studies have specifically performed a spatiotemporal analysis of temperature across the Oti basin to know the temperature patterns in this basin. For instance, Kwawuvi et al. (2022a) analyzed the variations in rainfall at both temporal and spatial scales in the basin and projected a decline in rainfall for the period 2021–2050 under both the RCP4.5 and RCP8.5 scenarios. Additionally, Klassou and Komi (2021) examined the extreme rainfall across the central portion of ORB. Their research showed that while the majority of the heavy rainfall indices they examined showed a decline, the dry spell index showed a rising tendency across a sizable part of the basin. Komi et al. (2017) estimated the magnitude of flood hazard in the Togo portion of the Oti basin. In the Kara basin, a sub-basin of the Oti basin, Badjana et al. (2014) also investigated land-cover changes. They indicated that between 1972 and 2000, the area underwent a transformation in its land cover, with a noticeably large loss of its native forests. Within the same Kara basin, Badjana et al. (2017) examined the long-term patterns in yearly precipitation, its length, and the yearly maximum precipitation for seven stations from 1950 to 2010. According to their findings, the mean annual precipitation significantly dropped at several stations, while the interannual variability of annual precipitation decreased over time at all the stations studied. However, they also noted an increase in the length of annual precipitation, suggesting that precipitation was more frequent but less intense in areas where annual precipitation had decreased. In all these studies, temperature was not the main emphasis even though it is one of the main climatic factors for determining climate change, and its oscillations could influence water availability. Analyzing the spatial and temporal fluctuations in temperature in the basin for the past (1981–2010) and the future (2021–2050) is therefore essential for determining how the climate is changing in the basin since most communities rely on its water for farming and fishing for subsistence. The outcomes of this study could help policymakers comprehend the basin's temperature trend and determine the most effective strategies to manage the basin's water supplies.

2. Materials and methods

2.1. Study area

Four West African countries share the Oti River basin (Ghana, Burkina Faso, Togo, and Benin) and are located between longitudes 6°W and 2°E and latitudes 0° and 15°N (Figure 1). It is a part of the West African Volta basin system and has a surface size of ∼72,000 km^2 (Barry et al., 2005; Kasei, 2009). The intertropical discontinuity (ITD) movement and interactions with the corresponding West African Monsoon determine the basin's climate. The annual rainfall varies from 1,010 to 1,400 mm, with 2,540 mm of pan evaporation and 254 mm of runoff (Kasei, 2009). August is the wettest month in the basin, with a uniform rainfall distribution. The wet season lasts from April to October, whereas the dry season lasts from November to March (Klassou and Komi, 2021). The typical annual temperature ranges from 25.9 to 34°C. The steep topography of the basin and abundant rainfall aid surface runoff, which contributes to ∼25% of the annual total flow to Volta Lake (Barry et al., 2005). According to climate projections, under the RCP8.5 and RCP 4.5 emission scenarios, the basin might see very wet (+1.91) rainfall in 2028 and extremely wet (+2.12) rainfall in 2037 (Kwawuvi et al., 2022a). Developing adaptation measures that would be resilient to the extremes in climate requires knowledge of the distribution of temperature projections at the annual and seasonal scales.

2.2. Sources of data

2.2.1. Station and models data

The Ghana Meteorological Agency, the National Meteorological Service of Togo, and the Benin Meteorological Department provided daily maximum and minimum temperature data for eight climate stations within the Oti basin for the years 1981 to 2010. Additionally, due to the basin's limited spatial distribution of climate stations, gridded daily minimum and maximum temperature data for 22 gridded points were extracted from the National Aeronautics and Space Administration Prediction of Worldwide Energy Resource (NASA POWER) project for the period 1981–2010 (Stackhouse et al., 2018) (Table 1). The daily maximum and minimum temperature data were extracted for each gridded location using the respective geographic coordinates of 22 gridded points that had been previously used to extract rainfall data across the basin (Kwawuvi et al., 2022b). The temperature data were obtained in MS Excel (.csv) format. The NASA POWER datasets have been used throughout the region and have been verified to be universally consistent with ground data (Lizumi et al., 2014; Joseph et al., 2020).

To project the future temperature in the Oti basin, the outputs of an ensembled mean of eight Global Circulation Models (GCMs) under the Coordinated Regional Climate Downscaling Experiment (CORDEX-Africa) were used (Table 2). These GCMs were downscaled by the Rossby Center regional atmospheric model (RCA4) at a spatial resolution of 0.44° × 0.44° (∼50 km × 50 km) (Samuelsson et al., 2011; Kjellström et al., 2016). The reliability of the chosen Regional Climate Models (RCMs) and GCMs have been assessed, and the models showed reasonable levels of accuracy in replicating the Oti basin's temperature pattern (Kwawuvi et al., 2022b). The RCMs have already been bias-corrected using the quantile-quantile mapping procedure in Kwawuvi et al. (2022b). Daily simulated maximum and minimum temperature data for the period 2021–2050 under the Representative Concentration Pathways, RCP4.5, and RCP8.5 scenarios make up the output used in this study.

2.3. Models and station data quality control and assessment

Data quality for the eight stations was examined (Natitingou, Kete-Krachi, Yendi, Dapaong, Kara, Mango, Niamtougou, and Sokode). Four stations including Yendi, Dapaong, Kara, and Mango were found to have complete data for the period 1981–2010 and hence considered for validation. The validation exercise was done on a monthly scale. For each validation, the gridded and extracted values of NASA POWER temperature data were compared with the temperature data at the four stations that had complete data for 1981–2010. The validation of the NASA POWER temperature data was examined using commonly employed statistical indicators such as the Pearson correlation coefficient (r), bias, root-mean-square error (RMSE), and Nash–Sutcliffe efficiency (NSE). The position of the NASA POWER temperature data within the acceptable range of the time-series metric [(r = −1 to 1), (bias = 0 to ∞, with 1 being the perfect fit), (RMSE = 0 to ∞, with 0 being the perfect fit), and (NSE = − ∞ to 1, with 1 being the perfect fit)] demonstrated the accuracy of temperature data (Moriasi et al., 2007; Dembélé and Zwart, 2016; Bessah et al., 2020). After validation, a total of 22 grid points data were extracted for the work including four points that used a complete station observed data and four other points (Natitingou, Kete-Krachi, Niamtougou, and Sokode stations) that had station observed data but had their missing gaps filled with data from the NASA POWER extracted data as it has been previously demonstrated in Aguilar et al. (2009), Larbi et al. (2018), and Kwawuvi et al. (2022b). The statistical indicators were calculated as follows:

$$r = \frac{\sum_{i=1}^{n}\left(G_i - \overline{G}\right)\left(S_i - \overline{S}\right)}{\sqrt{\sum_{i=1}^{n}\left(G_i - \overline{G}\right)^2}\sqrt{\sum_{i=1}^{n}\left(S_i - \overline{S}\right)^2}}, \quad (1)$$

$$Bias = \frac{\sum_{i=1}^{N} S_i}{\sum_{i=1}^{N} G_i}, \quad (2)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(S_i - G_i\right)^2}, \quad (3)$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}\left(S_i - G_i\right)^2}{\sum_{i=1}^{N}\left(\overline{G} - G_i\right)^2}, \quad (4)$$

where G_i and S_i are observed and NASA POWER data, respectively; $\bar{G}$ and $\bar{S}$ are mean values of observed and satellite data; and N is the number of data pairs.

To evaluate the efficiency of the RCMs and their ensemble, the simulated temperature was compared with the observed temperature at the mean monthly scale. These have been performed and documented in a previous study by Kwawuvi et al. (2022b). It was found that the correlation between the raw models' ensemble mean and the observation was 0.82 and had an NSE of −0.38. However, after bias correcting the models, the correlation between the models' ensemble mean and the observation improved to 1.00 with an improved NSE of 0.99.

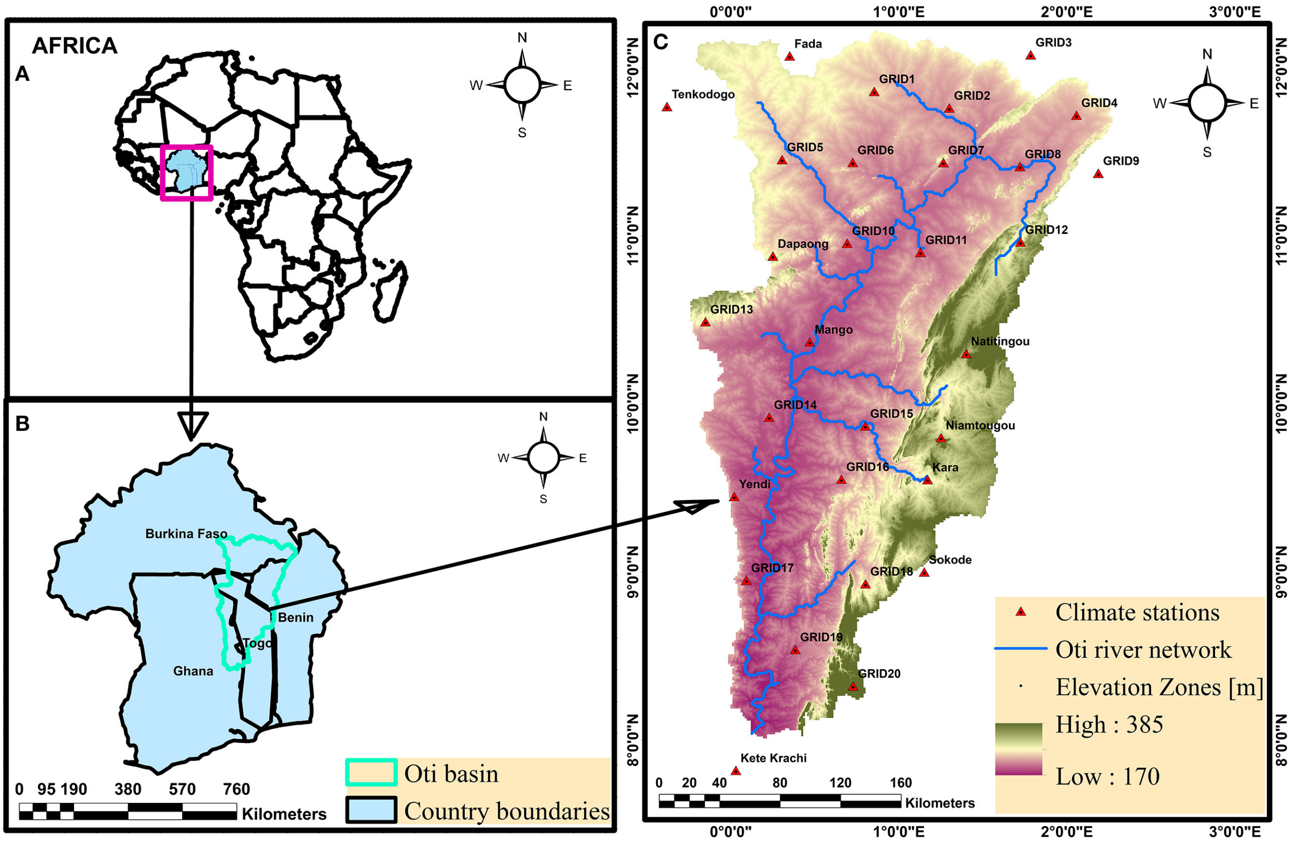

FIGURE 1
Map of the study area showing **(A)** location of Oti Riparian countries in Africa highlighted, **(B)** Oti River Basin (in green) shared by Ghana, Burkina Faso, Togo, and Benin, and **(C)** climate stations, elevation zones, and river network in the Oti basin.

TABLE 1 **Observed and virtual climate locations used for the study (1981–2010).**

Details	GRID1	GRID2	GRID3	GRID4	GRID5	GRID6	GRID7	GRID8
Long	0.85	1.3	1.78	2.06	0.31	0.73	1.26	1.72
Lat	11.86	11.76	12.08	11.72	11.45	11.44	11.44	11.41
Data	Virtual	Virtual	Virtual	Virtual	Virtual	Virtual	Virtual	Virtual
	GRID9	GRID10	GRID11	GRID12	GRID13	GRID14	GRID15	GRID16
Long	2.19	0.69	1.13	1.72	−0.15	0.23	0.8	0.66
Lat	11.37	10.96	10.9	10.96	10.49	9.92	9.87	9.55
Data	Virtual	Virtual	Virtual	Virtual	Virtual	Virtual	Virtual	Virtual
	GRID17	GRID18	GRID19	GRID20	Niamtougou	Sokode		
Long	0.09	0.8	0.38	0.73	1.25	1.15		
Lat	8.95	8.93	8.54	8.32	9.8	9		
Data	Virtual	Virtual	Virtual	Virtual	Station	Station		
	Natitingou	Fada	Tenkodogo	Kete-Krachi	Yendi	Dapaong	Kara	Mango
Long	1.4	0.35	−0.38	0.03	0.02	0.25	1.17	0.47
Lat	10.3	12.07	11.77	7.82	9.45	10.88	9.55	10.37
Data	Station	Virtual	Virtual	Station	Station	Station	Station	Station

Long, longitude; Lat, latitude.

TABLE 2 RCA4-downscaled Global Climate Models (GCMs) used in this study.

Model center	Short name	GCM name
Canadian Center of Climate Modeling and Analysis	CanESM2	CCCma-CanESM2
Center National de Recherches Météorologiques-Groupe d'études de l'Atmosphère Météorologique and Center Européen de Recherche et de Formation Avancée	CNRM-CM5	CNRM-CERAFACS-CNRMCM5
Consortium of European Research Institution and Researchers	EC-EARTH	ICHEC-EC-EARTH
Institut Pierre-Simon Laplace	IPSL-CM5A-MR	IPSL-IPSL-CM5A-MR
National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	MIROC-MIROC5
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-ESM-LR	MPI-M-MPI-ESM-LR
The Norwegian Climate Center	NorESM1-M	NCC-NorESM1-M
NOAA Geophysical Fluid Dynamics laboratory	GFDL-ESM2M	NOAA-GFDL-GFDL-ESM2M

2.4. Mean temperature distribution in the basin

The mean annual temperature was analyzed from the daily maximum and minimum temperature data. The mean annual temperature was determined as the yearly average temperature for 30 stations in the basin for the observed period (1981–2010) and the future period (2021–2050). The standard deviation was also estimated for the observed and future periods. The standard deviation was estimated as

$$SD = \sqrt{\frac{\sum (X_i - \overline{X})^2}{N}}, \quad (5)$$

where represents each value from the data, $\overline{X}$ is the data mean, and N is the size of the data.

The seasonal temperature averages were calculated based on the rainy season (AMJJASO) and the dry season (NDJFM) periods in the basin. The mean temperature projections over the Oti River basin were analyzed using the ensemble mean of eight RCMs. According to Luhunga et al. (2016), using the ensemble mean of RCMs improves the result of climate change scenario estimates. The future (2021–2050) temperature analyses considered the RCP4.5 and 8.5 scenarios. The estimated differences in annual means between the observed (1981–2010) and the near-future periods (2021–2050) reflect how much the yearly mean temperature will vary compared to past and future times. The projected changes in the mean temperature were obtained by subtracting the observed mean temperature from the anticipated mean temperature under both RCP4.5 and RCP8.5.

2.5. Spatial distribution analysis and the modified Mann–Kendall trend test

The analyzed mean annual temperature across the basin was spatially plotted using the inverse distance weighted (IDW) interpolation approach (Diodato and Ceccarelli, 2005; Lu and Wong, 2008).

To evaluate trends in mean annual temperature over the Oti River basin (ORB), the study used the modified Mann–Kendall (MK) trend statistics. It is a non-parametric trend test that serves as a tool for detecting monotonic trends within time series data (Mann, 1945; Sen, 1968; Kendall, 1975). The trends were computed in R software with the modified MK package and tested at a 0.05 significance level. Hence, a p-value of ≤ 0.05 shows a significant trend, whereas a p-value of >0.05 demonstrates a non-significant trend. The MK test contrasts the alternative hypothesis (H_1) that there is a trend with the null hypothesis (H_o) that there is none (Önöz and Bayazit, 2003). The positive MK test results suggest rising tendencies, while negative ones reveal declining trends. All time series were initially examined for autocorrelation. When auto-correlated data were present, the time series were pre-whitened before trend computation using Eqs (6) to (11) (Pingale et al., 2016; Saini and Sahu, 2021). In situations where a time series exhibits positive autocorrelation, there is a tendency to underestimate the variance. Using the significant values of ρk, the correction factor for the variance $\frac{n}{n_s^*}$ is calculated (Pingale et al., 2016).

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} \Sigma_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2) \rho_s(i), \quad (6)$$

where n is the total observations, n_s^* is the "effective" observations to consider for the autocorelation in the time series, and $\rho_s(i)$ is the autocorrelation function of the ranks of the observations.

$$\rho_s(i) = \sin^{-1}\left(\frac{\rho(i)}{2}\right), \quad (7)$$

where $\rho(i)$ is the parent autocorrelation function of rank of the observation.

The corrected variance is calculated as

$$V^*(S) = V(S) \cdot \frac{n}{n_s^*}, \quad (8)$$

where $V(S)$ is the variance of the simple Mann–Kendall trend test (Kendall, 1975), and it is estimated as

$$S = \Sigma_{k=1}^{n-1} sgn(x_j - x_k), \quad (9)$$

$$V(S) = \frac{\left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)\right]}{18}, \quad (10)$$

where $(x_j - x_k)$ is the signum function and S is the test statistic.

The modified Mann–Kendall test statistic Z_{mmk} is determined as

$$Z_{mmk} = \begin{cases} \frac{S-1}{\sqrt{V^*(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{V^*(S)}} & if\ S < 0 \end{cases} \tag{11}$$

3. Results and discussion

3.1. Validation of NASA POWER data against station data

Table 3 presents the validation results of NASA POWER temperature against observed temperature data at four stations in the basin from 1981 to 2010. The statistics show a good agreement with the station temperature data owing to the high correlation (r = 0.71–0.99) recorded; an acceptable bias within the range of 0.99–1.12; fairly low RMSE values between 0.01 and 0.92; and acceptable NSE values of 0.50 at Dapaong and 0.99 at Mango stations, whereas that of Yendi (−0.55) and Kara (−0.03) showed poor performances at the mean monthly scale. Yendi and Kara's NSE values are negative, which suggests that the measured value at these stations is a better predictor than the estimated values. These estimations agree with those made by Larbi et al. (2018) and Okafor et al. (2021), who also employed NASA POWER temperature and found a good correlation with NSE values when it was compared with local station data in the region. In summary, the outcomes of the evaluations suggest that the NASA POWER data matches the temperature pattern of the stations in the basin and, therefore, was used for subsequent investigation.

TABLE 3 Mean monthly statistics of stations and NASA POWER temperature in Oti basin (1981–2010).

Monthly scale	Yendi	Dapaong	Kara	Mango
Pearson correlation co-efficient (r)	0.92	0.71	0.93	0.99
Bias	0.93	0.99	1.12	0.99
Root-mean-square error (RMSE)	0.67	0.49	0.92	0.01
Nash-Sutcliffe Efficiency (NSE)	−0.55	0.50	−0.03	0.99

3.2. Mean monthly distribution of temperature in the basin

The annual cycle of mean monthly temperature in the basin for the observed (1981–2010) and future periods (2021–2050) are shown in Figure 2. The mean temperature in the basin was found to likely increase in near future and under both climate change emission scenarios. For the observed period, mean temperature was the highest in April (30.49°C) and lowest (25.25°C) in December. However, in near future, the highest mean annual temperature would be recorded in March, at ∼31.70 and 34.86°C under RCP4.5 and RCP8.5 scenarios, respectively, whereas the lowest mean temperature would be ∼26.58°C (RCP4.5) and 28.26 (RCP8.5) in August. This trend change in future scenarios may be due to the non-linear responses of the climatic system to anthropogenic forcings such as an increase in greenhouse gas levels (Intergovernmental Panel on Climate Change, 1996). An increase in mean monthly temperature is anticipated from January to December. This increase is expected to be from +0.88°C (October) to +2.65°C (January) under RCP4.5 and from +2.71°C (July) to +6.48°C (January) under the RCP8.5 scenario. These outcomes align with the findings of Dembélé et al. (2022) who observed a clear rise in mean temperature between +0.6°C and +4.4°C under RCPs 2.6, 4.5, and 8.5, and at all months within the Volta Basin, during the period of 2021–2100. The basin's projection indicates a prospective exacerbation of aridity under both emission scenarios during the dry season (November–March) within the basin (Ankomah-Baffoe et al., 2021).

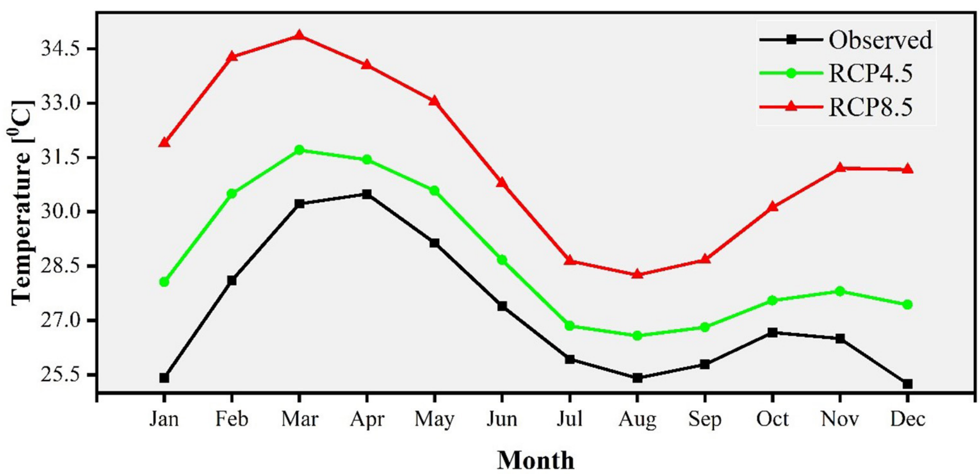

FIGURE 2
Annual cycle of mean monthly temperature during the observed (1981–2010) and future period (2021–2050).

TABLE 4 Mean annual temperature and standard deviation in the Oti River basin.

Station	Observed		RCP4.5		RCP8.5	
	Mean	SD	Mean	SD	Mean	SD
GRID1	27.68	±0.43	29.59	±0.28	29.85	±0.46
GRID2	27.76	±0.44	29.57	±0.27	33.00	±0.46
GRID3	27.78	±0.43	29.82	±0.29	33.39	±0.48
GRID4	27.69	±0.47	29.61	±0.28	33.09	±0.47
GRID5	27.28	±0.42	29.10	±0.27	32.35	±0.45
GRID6	27.44	±0.41	29.27	±0.27	32.53	±0.45
GRID7	27.60	±0.42	29.44	±0.27	32.79	±0.45
GRID8	27.29	±0.44	29.25	±0.28	32.63	±0.47
GRID9	27.29	±0.43	29.23	±0.27	32.63	±0.46
GRID10	27.05	±0.41	28.75	±0.25	31.88	±0.42
GRID11	26.74	±0.41	28.55	±0.26	31.73	±0.44
GRID12	26.53	±0.41	28.45	±0.27	31.72	±0.45
GRID13	26.84	±0.46	28.54	±0.25	28.78	±0.41
GRID14	26.89	±0.48	28.61	±0.25	31.56	±0.41
GRID15	26.82	±0.48	28.61	±0.25	31.62	±0.43
GRID16	26.82	±0.48	28.61	±0.25	31.62	±0.43
GRID17	26.41	±0.43	28.08	±0.24	28.31	±0.39
GRID18	25.88	±0.43	27.68	±0.25	30.53	±0.42
GRID19	26.41	±0.43	28.14	±0.26	30.85	±0.42
GRID20	25.39	±0.38	27.10	±0.23	29.76	±0.39
Natitingou	26.51	±3.08	27.95	±0.26	28.21	±0.43
Fada	27.72	±0.41	29.71	±0.28	33.26	±0.48
Tenkodogo	27.48	±0.47	29.42	±0.28	32.85	±0.47
Kete Krachi	28.06	±0.35	27.46	±0.22	29.69	±0.36
Yendi	28.14	±0.37	28.51	±0.26	31.38	±0.42
Dapaong	28.13	±0.45	28.60	±0.25	31.71	±0.42
Kara	27.39	±0.51	27.86	±0.26	30.95	±0.44
Mango	28.91	±0.47	28.50	±0.25	31.51	±0.41
Niamtougou	26.63	±0.36	27.86	±0.26	30.95	±0.44
Sokode	26.84	±0.36	27.64	±0.26	30.70	±0.44
Basin	27.18	±0.33	28.65	±0.26	31.38	±0.43

SD, standard deviation.

3.3. Spatial distribution of temperature in the basin

The result depicts that the mean annual temperature across the entire basin was 27.18°C (±0.33°C) which varied between 25.39°C at GRID 20 and 28.91°C at Mango during the observed historical period (1981–2010). In near future and under the RCP4.5 scenario, the mean annual temperature is anticipated to be ∼28.65°C (±0.26°C) and would vary from 27.1°C at GRID20 to 29.82°C at GRID3. The future mean annual temperature is expected to be ∼31.38°C (±0.43°C) and would vary between 28.21°C at Natitingou and 33.39°C at GRID3 under the RCP8.5 emission scenario (Table 4). This corroborates The New Humanitarian's (2013) assertion that rising average yearly temperature is one of the basin's most important signs of approaching climate change. Volta basin's yearly temperature pattern was found to be rising at all examined sites by Kabo-Bah et al. (2016). These temperature rises have led to a higher rate of water loss in the basin.

It is observed that the spatial variability of mean temperature is low in the southern part of the basin as compared to the central and northern parts for the observed and future periods (Figure 3). As we proceed from the stations in the basin's southern part to the northern region, the mean temperature appears to increase. During the observed period, stations that exhibited elevated average temperature values of 28.14°C, 28.13°C, and 28.91°C were Yendi, Dapaong, and Mango, respectively. According to the RCP4.5 scenario, it is expected that the average temperature of the basin will undergo a significant increase in near future, with the northern parts experiencing the greatest temperature rise. Similarly, the RCP8.5 predicts a generally high increase in mean annual temperature except for stations such as GRID1, where the expected temperature elevation would be moderate, whereas GRID13, GRID17, and Natitingou anticipate a relatively lower mean temperature (Figure 3).

Table 5 shows the outcomes of the modified Mann–Kendall test at a significance level of 0.05 for the mean annual temperature. As portrayed, the basin recorded a mixture of increasing and decreasing trends during the observed period. Stations such as Kete-Krachi, Yendi, Mango, Niamtougou, and Sokode had a significantly increasing trends, whereas GRID1 to GRID11, GRID13 to GRID17, GRID19, Fada, Tenkodogo, Dapaong, and Kara recorded non-significantly decreasing trends. GRID12, GRID18, GRID20, and Natitingou had decreasing trends with only the trend at Natitingou being significant. The entire basin had a non-significantly increasing trend with a mean magnitude of 0.011°C. This trend confirms the considerable warming signals that occurred in the basin between 1983 and 2010 (Sylla et al., 2016). The results align with those of Aziz and Obuobie (2017), who discovered a statistically significant rise in mean temperature in the Black Volta River Basin between 1981 and 2010 at a 5% significance level and with a 0.03 magnitude of increase. In near future, under the RCP4.5 and RCP8.5, all the stations in the basin are projected to have significantly increasing trends. The magnitude of these trends could range from 0.018 to 0.027 under the RCP4.5, whereas that of RCP8.5 would be between 0.034 and 0.051. Ilori and Ajayi (2020) also discovered that the magnitude of change in temperature over West Africa was predicted to range from 0.025 to 0.033 under RCP4.5 and from 0.057 to 0.063 under RCP8.5. A large rise in the mean annual temperature could accompany this change.

3.4. Seasonal temperature distribution across the basin

An increase was seen northward of the basin from the south according to the seasonal distribution of mean temperature during

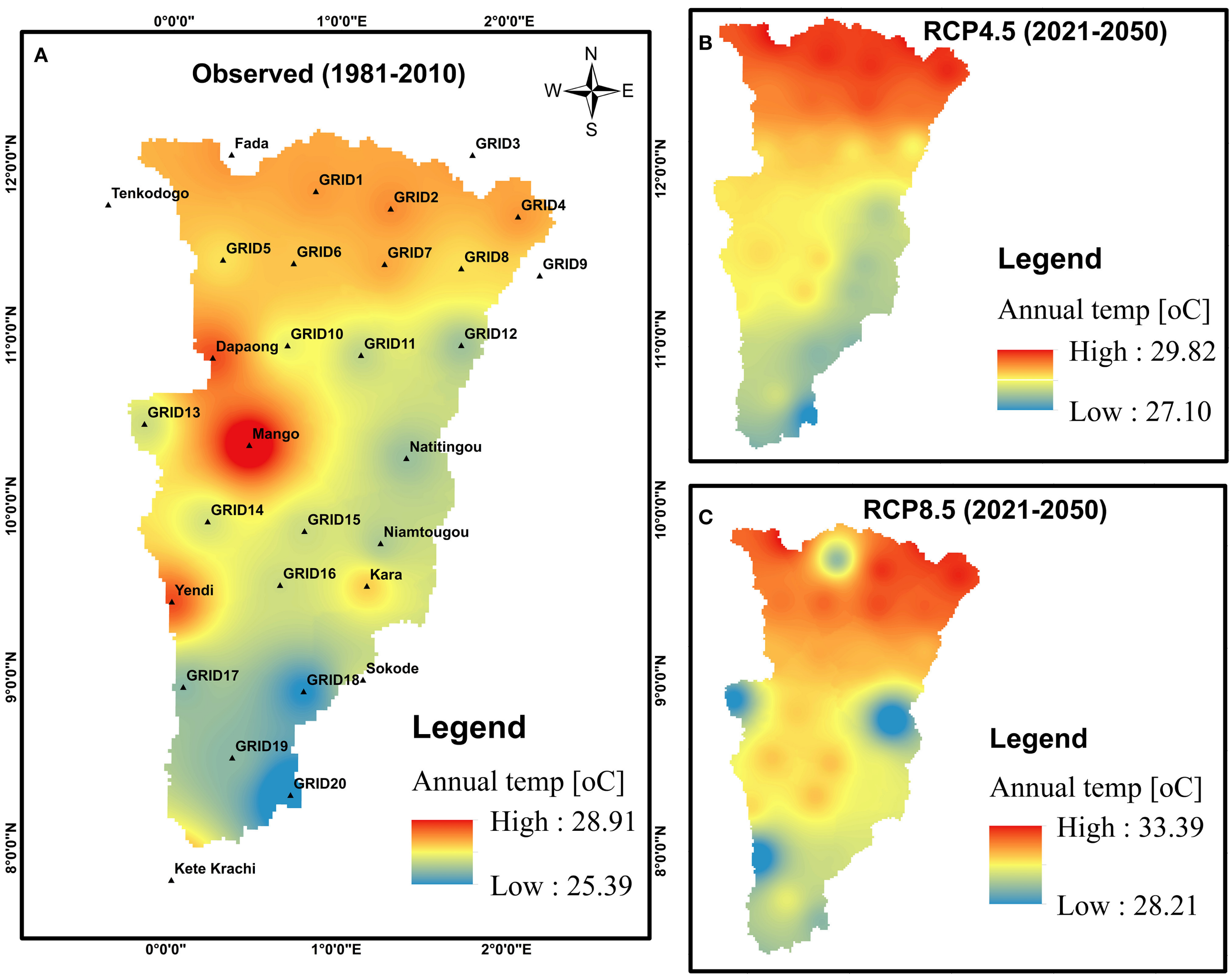

FIGURE 3
Spatial trends in mean annual temperature in the Oti River basin for **(A)** the observed period (1981–2010) and future period (2021–2050), **(B)** RCP4.5 scenario, and **(C)** RCP8.5 scenario.

the observed period (Figure 4). The rainy season's mean annual temperature is projected to be the highest at GRID3 (30.26°C) and the lowest at GRID20 (26.52°C), with a basin mean of 28.35°C under the RCP4.5 scenario. Under the RCP8.5, temperature would range between GRID17 (27.62°C) and GRID3 (33.19°C) with a basin mean of 30.93°C. In the dry season, the RCP4.5 projects the highest temperature to occur at GRID7 (29.78°C) while the lowest would be at GRID20 (27.94°C) with a basin mean of 29.1°C. Under the RCP8.5, temperature would range between 28.9°C at Natitingou and 34.18°C at GRID7, with a basin mean of 33.22°C. Warmer temperatures expected during both the wet and dry seasons could shorten the agricultural cycle and decrease food production in the basin (Roudier et al., 2011; Sultan et al., 2013).

From Figure 5, the mean annual temperature in the basin is projected to increase at the temporal scale (2021–2050). The models' mean ensemble projected the hottest year of 28.88°C mean temperature for 2049 under the RCP4.5 and in the rainy season (AMJJASO). For the RCP8.5 scenario, the hottest year would be 2048 and would have a mean temperature of ∼31.28°C. Concerning the dry season (NDJFM) period, 2049 would be the warmest with a mean temperature of ∼29.72°C under the RCP4.5, while the RCP8.5 predicts that the hottest mean temperature of 33.71°C occur in 2048. The increase in warm climatic conditions within the basin may have implications for a variety of ecosystem services, including the production of crops (Shrestha and Roachanakanan, 2021) during the rainy season.

3.5. Distribution of the basin's projected yearly mean temperature

With respect to the basin's projected yearly mean temperature, Kete-Krachi and Mango were the only two out of the thirty stations which could have a reduced mean temperature by ∼-0.6 and −0.41°C, respectively, in the future period 2021–2050. All of the stations projected a temperature increase for both RCP4.5 and RCP8.5. Under the RCP4.5, the change in mean temperature

TABLE 5 Trend test statistics in mean annual temperature for the observed (1981–2010) and future period (2021–2050).

Station	Observed (1981–2010)			RCP4.5 (2021–2050)			RCP8.5 (2021–2050)		
	Z-value	Pw Sen's slope	*P*-value	*Z*-value	Pw Sen's slope	*P*-value	*Z*-value	Pw Sen's slope	*P*-value
GRID1	1.249	0.013	0.212	5.196	0.026	0.000	5.421	0.042	0.000
GRID2	1.356	0.012	0.175	5.233	0.025	0.000	5.571	0.047	0.000
GRID3	1.407	0.014	0.159	5.271	0.027	0.000	5.534	0.051	0.000
GRID4	1.182	0.013	0.237	5.346	0.026	0.000	5.571	0.048	0.000
GRID5	0.678	0.007	0.498	5.008	0.024	0.000	5.496	0.045	0.000
GRID6	0.749	0.007	0.454	5.271	0.024	0.000	5.459	0.045	0.000
GRID7	0.678	0.008	0.498	5.346	0.025	0.000	5.609	0.047	0.000
GRID8	0.642	0.005	0.521	5.196	0.027	0.000	5.646	0.050	0.000
GRID9	0.892	0.010	0.372	5.233	0.026	0.000	5.571	0.048	0.000
GRID10	0.214	0.002	0.830	5.196	0.022	0.000	5.571	0.044	0.000
GRID11	0.143	0.001	0.887	5.121	0.024	0.000	5.646	0.046	0.000
GRID12	−0.071	0.000	0.943	5.121	0.024	0.000	5.721	0.049	0.000
GRID13	0.571	0.006	0.568	4.671	0.020	0.000	5.646	0.042	0.000
GRID14	1.035	0.014	0.301	4.558	0.018	0.000	5.759	0.045	0.000
GRID15	0.571	0.007	0.568	4.633	0.020	0.000	5.609	0.045	0.000
GRID16	0.571	0.007	0.568	4.633	0.020	0.000	5.609	0.045	0.000
GRID17	0.749	0.007	0.454	5.046	0.022	0.000	5.534	0.038	0.000
GRID18	−0.036	−0.001	0.972	5.083	0.023	0.000	5.233	0.039	0.000
GRID19	0.749	0.007	0.454	5.083	0.025	0.000	5.083	0.038	0.000
GRID20	−0.464	−0.005	0.643	5.196	0.024	0.000	5.008	0.036	0.000
Natitingou	−2.391	−0.025	0.017	4.483	0.019	0.000	5.684	0.044	0.000
Fada	1.332	0.012	0.183	5.158	0.025	0.000	5.609	0.048	0.000
Tenkodogo	0.732	0.007	0.464	5.046	0.024	0.000	5.646	0.048	0.000
Kete Krachi	3.318	0.024	0.001	4.896	0.021	0.000	4.971	0.034	0.000
Yendi	3.658	0.029	0.000	4.933	0.021	0.000	5.496	0.043	0.000
Dapaong	1.294	0.009	0.196	5.121	0.021	0.000	5.646	0.044	0.000
Kara	1.820	0.016	0.069	4.371	0.019	0.000	5.421	0.043	0.000
Mango	4.408	0.042	0.000	4.821	0.020	0.000	5.571	0.044	0.000
Niamtougou	2.284	0.020	0.022	4.371	0.019	0.000	5.421	0.043	0.000
Sokode	4.033	0.029	0.000	5.046	0.025	0.000	5.271	0.041	0.000
Basin	1.534	0.011	0.125	5.121	0.023	0.000	5.646	0.044	0.000

Pw Sen's Slope is Pre-whitened Sen's slope.

could vary between −0.6 and +2.04°C and is anticipated to vary between +1.63 and +5.61°C under the RCP8.5 scenario. In the entire basin, mean temperature is predicted to increase by +1.47°C (RCP4.5) and +4.20°C (RCP8.5) relative to the baseline period (Table 6). Additionally, it should be emphasized that the warming trend is greater under the RCP8.5 scenario than under the RCP4.5 scenario. The warmer climate projected in the basin under both RCP4.5 and RCP8.5 is consistent with the IPCC (2013) report which stated that warmer climate would be experienced in the late end of the 21st century. Aziz and Obuobie (2017) also discovered in their study that the anticipated temperature increase in the Black Volta River basin was significant. Toward the end of the 21st century, the surface temperature worldwide may have risen by more than 1.5°C compared to the pre-modern temperature, and it may have risen even more or less depending on the location according to the IPCC's fifth assessment report (IPCC, 2014).

The spatial distribution of mean temperature in the basin shows that in near future and under the RCP4.5 scenario, mean annual temperature is anticipated to increase in the northern

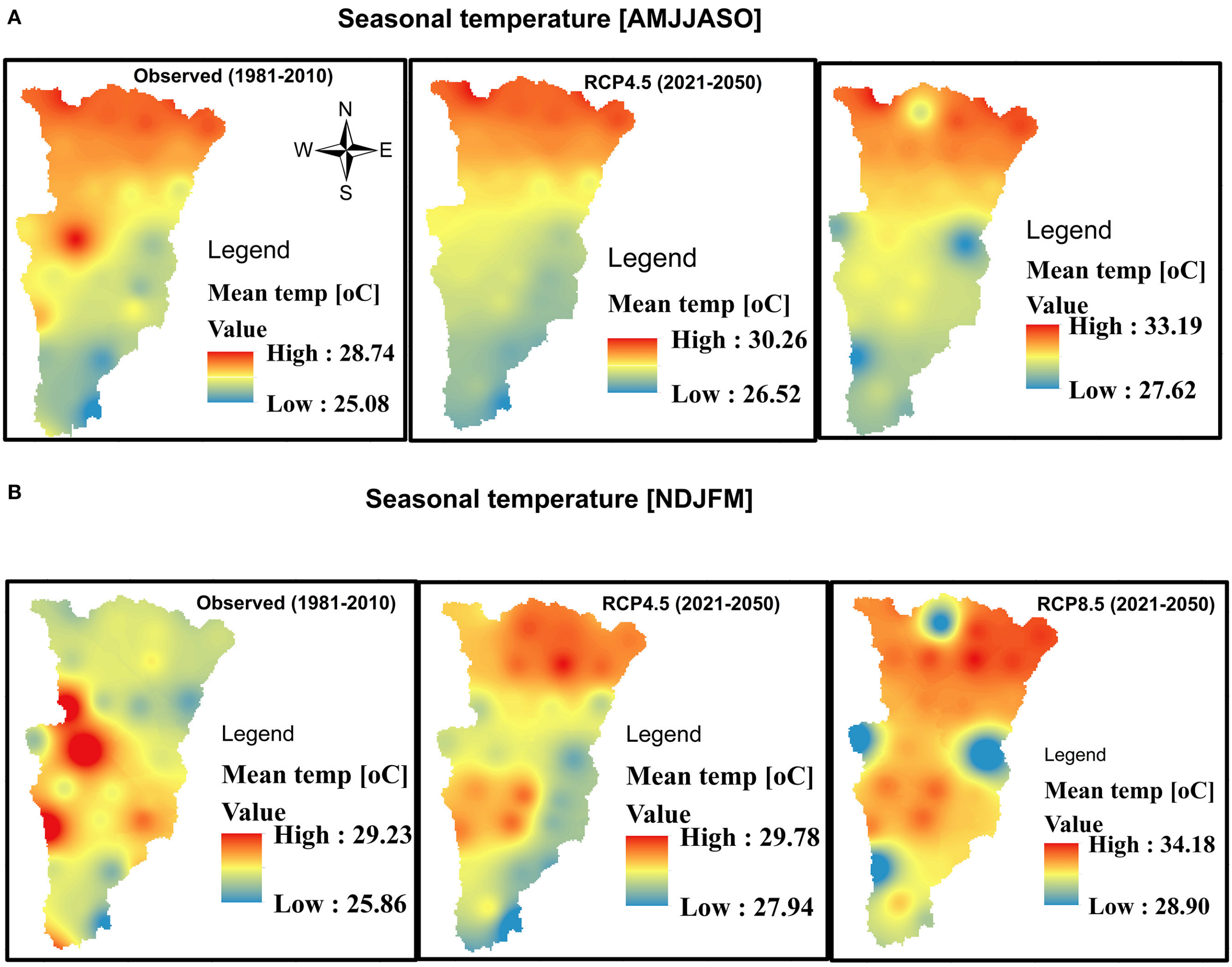

FIGURE 4
Spatial trends in mean annual temperature for **(A)** rainy season and **(B)** dry season in the Oti River basin.

part of the basin and with significant changes also expected in the southern part (Figure 6). The changes would increase from the south toward the northern part of the basin. The RCP4.5 projects a majority of the stations to the increase in mean annual temperature with the highest increase expected to be ∼+2.04°C which would occur at GRID3, except Kete-Krachi and Mango, where the mean annual temperature is expected to be ∼-0.41 and −0.6°C, respectively. The mean annual temperature in the entire basin is expected to increase by ∼+1.47°C. Under the RCP8.5 scenario, an increase in mean annual temperature is projected at all stations in the basin, and the highest increase would be ∼+5.61°C which is anticipated to occur at GRID3, while the lowest increase of ∼+1.63°C is expected to occur at Kete-Krachi. In the entire basin, the mean annual temperature is expected to increase by ∼+4.2°C. These findings align with the study of Sylla et al. (2016), who found that the air temperature over West Africa had increased significantly and was expected to continue to do so up to 6.5°C. Additionally, it supports the findings of Ofori et al. (2021), who found that the average temperature on the African continent is expected to increase by 3–6°C by the end of the century, which is higher than the worldwide mean value. Furthermore, Dembélé et al. (2022) maintain that a 5% increase in the yearly mean temperature results in a corresponding elevation of ∼3% in potential evaporation, and this could subsequently result in reduced surface and subsurface runoff, diminished groundwater retention, and complications in water management (Maček et al., 2018).

4. Implications of the basin's predicted temperature trends

The projected increasing trends in mean temperature over the basin could have severe consequences on the basin. During the onset of dry seasons when limited or no rainwater accumulates, a rise in temperature results in increased rates of evapotranspiration and increasing water demand (Das et al., 2022). In Africa and West Asia, the production of crops that relied on atmospheric temperature variation was reduced by 15%−35%, while a decrease of between 25 and 35% in the Middle East, respectively, was

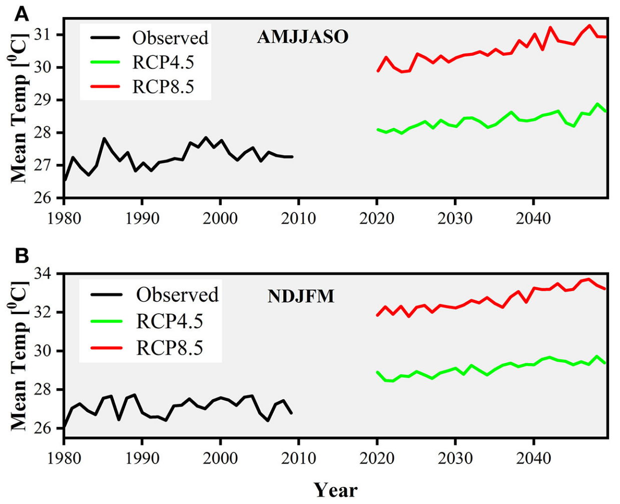

FIGURE 5
Temporal trends in mean annual temperature for **(A)** rainy (AMJJASO) season and **(B)** dry (NDJFM) season in the Oti basin.

TABLE 6 Projected changes in mean annual temperature (°C) in 2021–2050.

Station	Observed	RCP4.5	RCP8.5	RCP4.5 change	RCP8.5 change
GRID1	27.68	29.59	29.85	+1.91	+2.17
GRID2	27.76	29.57	33.00	+1.81	+5.24
GRID3	27.78	29.82	33.39	+2.04	+5.61
GRID4	27.69	29.61	33.09	+1.92	+5.4
GRID5	27.28	29.1	32.35	+1.82	+5.07
GRID6	27.44	29.27	32.53	+1.83	+5.09
GRID7	27.6	29.44	32.79	+1.84	+5.19
GRID8	27.29	29.25	32.63	+1.96	+5.34
GRID9	27.29	29.23	32.63	+1.94	+5.34
GRID10	27.05	28.75	31.88	+1.7	+4.83
GRID11	26.74	28.55	31.73	+1.81	+4.99
GRID12	26.53	28.45	31.72	+1.92	+5.19
GRID13	26.84	28.54	28.78	+1.7	+1.94
GRID14	26.89	28.61	31.56	+1.72	+4.67
GRID15	26.82	28.61	31.62	+1.79	+4.8
GRID16	26.82	28.61	31.62	+1.79	+4.8
GRID17	26.41	28.08	28.31	+1.67	+1.9
GRID18	25.88	27.68	30.53	+1.8	+4.65
GRID19	26.41	28.14	30.85	+1.73	+4.44
GRID20	25.39	27.1	29.76	+1.71	+4.37
Natitingou	26.51	27.95	28.21	+1.44	+1.7
Fada	27.72	29.71	33.26	+1.99	+5.54
Tenkodogo	27.48	29.42	32.85	+1.94	+5.37
Kete Krachi	28.06	27.46	29.69	−0.6	+1.63
Yendi	28.14	28.51	31.38	+0.37	+3.24
Dapaong	28.13	28.6	31.71	+0.47	+3.58
Kara	27.39	27.86	30.95	+0.47	+3.56
Mango	28.91	28.5	31.51	−0.41	+2.6
Niamtougou	26.63	27.86	30.95	+1.23	+4.32
Sokode	26.84	27.64	30.7	+0.8	+3.86
Basin	27.18	28.65	31.38	+1.47	+4.20

attributed to a rise in mean temperature from 2 to 4°C (Food and Agricultural Organization, 2001). One of the main factors affecting agricultural output is the climate, which includes elements such as rainfall, temperature, sunshine, wind speed, and direction [Food and Agriculture Organization (FAO), 2017]. Consequently, significant changes to these elements could threaten sectors, notably agriculture (Raza et al., 2019). The expected temperature fluctuations might adversely affect the Oti River basin as it provides revenue and a means of subsistence to many different nations. The expected rise in the average annual temperature and its upward pattern might result in less water being available for farming, reducing agricultural output (Bessah et al., 2020). In particular, increased soil aridity could result from the expected rise in temperature which might pose as a risk to plants such as vegetables cultivated in the basin (Diallo et al., 2016; Monerie et al., 2016). It is known that in regions such as the Sahel in West Africa, many plants typically thrive under temperatures that are at the optimum. Therefore, further temperatures rise could result in poorer agricultural output (Amuji et al., 2020), particularly when excessive temperatures occur during a crucial period of plant development (Firmansyah and Argosubekti, 2020). This is supported by the study of Lobell et al. (2008), who discovered that in the coming 20 years, Northern China's main agricultural outputs are anticipated to decline as a result of rising temperatures. In addition to causing the spread of livestock illnesses and parasites from increased temperatures, the amount and value of fodder, grain, and pasture could also be affected in the basin (Henrietta et al., 2020).

A change in the water cycle could emerge from rising temperatures because the atmosphere's ability to hold more water would rise, and consequently, lead to worldwide mean rainfall increment (He et al., 2017; Ahmed et al., 2020; Hu et al., 2020). Depending on the location, temperature rise could decrease rainfall due to the deepening of the seasonal cycle and an increased prevalence of catastrophic incidents according to Piani et al. (2010). Thus, many places may face droughts because of elevated levels of evaporation and altering wind conditions, while other areas may suffer flooding (Ahmed et al., 2020). According to estimates, the length and regularity of the hot summer days have increased in several regions of the world (Ahmed et al., 2020). For instance, at a 2°C increase in temperature in Africa, the amount of water available is likely to decline by 20%–30% (Brahic, 2007). Given that rising temperatures would cause evaporation to rise and could result in droughts, it could also have a detrimental

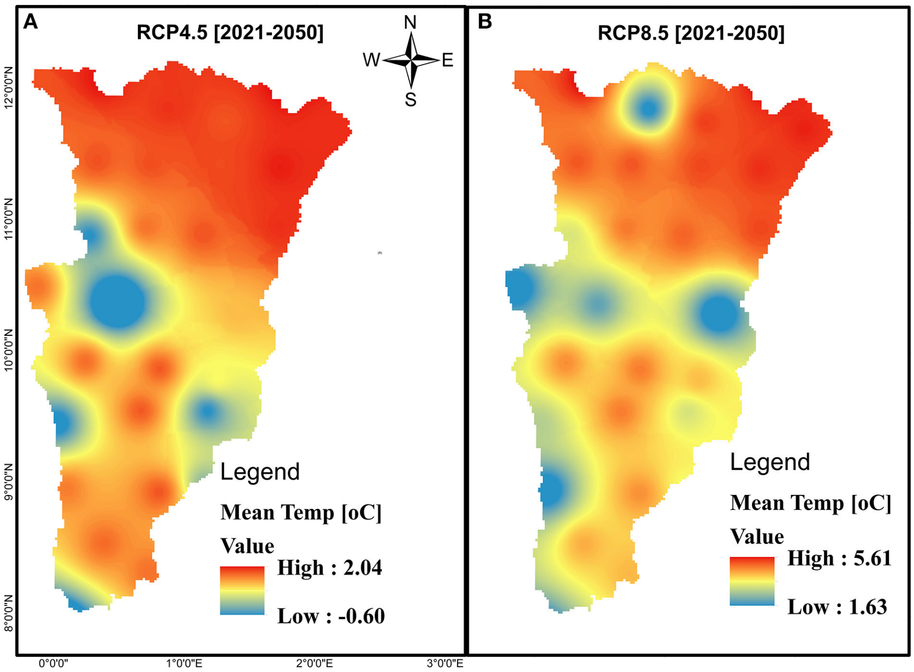

FIGURE 6
Spatial change of future mean annual temperature in the Oti River basin in the future period (2021–2050) under **(A)** RCP4.5 scenario and **(B)** RCP8.5 scenario.

impact on the basin's regular flows (Gulacha and Mulungu, 2016; Karam et al., 2022). Higher evaporation levels, decreased river discharge, and more frequent water deficits are all effects of elevated temperatures (Stagl et al., 2014; Miller et al., 2021). Water shortages brought on by warming temperatures could alter the basin's operational activities and pose risks to water supply facilities (Kundzewicz et al., 2008; Howard et al., 2016).

Along with the effects already described, the coastal people may also experience hardship due to the expected temperature increase because they depend largely on the basin for household tasks. The accessibility of usable water for domestic use by the inhabitants may decrease due to flooding and drought conditions that may be brought on by an increase in temperature (Abedin et al., 2019). According to Hunter et al. (2010), a number of water-borne diseases are also linked to the lack of safe water supplies for domestic use. For instance, Lama et al. (2004) reported that warmer temperatures are linked to water-borne diseases, such as diarrhea, and the breakout and spread of diseases (Elderd and Reilly, 2014). According to Brahic (2007), a rise in temperature of 2°C exposes between 40 and 60 million individuals in Africa to malaria. Additionally, the organic carbon dynamics of soils may be impacted by the anticipated elevated temperatures of +1.47 and +4.2°C in the basin (Biswas et al., 2018). This is supported by Crowther et al. (2016) whose investigation reveals that carbon would be lost from the top soil strata at a rate ranging from 30 to 203 petagrams for every degree Celsius of soil temperature rise (0–15 cm).

5. Conclusion

This study offers perspectives on the anticipated temperature patterns within West Africa's Oti River basin for the period 2021–2050. It did so by using an ensemble mean of eight RCA4 models from the CORDEX-Africa project (Coordinated Regional Climate Downscaling Experiment), under RCP4.5 and RCP8.5 emission scenarios. The study also evaluated the observed temperature trends for the period 1981–2010, using temperature data from meteorological stations and the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER). The study identified changes in annual temperature within the basin as well as for the rainy season (April–October) and the dry season (November–March) in the basin for the future period (2021–2050).

The study revealed that the annual cycle of mean monthly temperature was the highest in the month of April at 30.49°C, while the lowest of 25.25°C occurred in December during the observed period. However, the highest mean monthly temperature in the future is expected to be recorded in March (31.70°C) while the lowest (26.58°C) is anticipated in August under the RCP4.5 scenario. Similarly, the RCP8.5 scenario projects the highest mean temperature to be in March (34.86°C) and the lowest to be in August (28.26°C). Moreover, the study projected the mean annual temperature changes in the basin to range between −0.6 and +2.04°C (RCP.45) and +1.63 and +5.61°C (RCP8.5), while the mean annual temperature for the entire basin is projected to be +1.47 and +4.2°C under the RCP4.5 and RCP8.5 emission scenarios, respectively. In addition, the mean annual temperature in the observed period was the highest at 28.74 and the lowest at

25.08°C. The RCP4.5 scenario projects the highest mean annual temperature to be 30.26°C and the lowest to be 26.52°C, whereas the RCP8.5 predicts the highest to be 33.19°C and the lowest to be 27.62°C.

The anticipated changes in temperature could present challenges to agricultural productivity within the basin wherein crop cultivation, animal husbandry, and fishing activities underpin the livelihoods of the surrounding communities. It is plausible that alterations within the hydrological cycle may transpire, an event that could lead to both droughts and flooding within the basin. Such occurrences could have consequential effects on agricultural pursuits and stifle the natural flow of the basin. As a way of adapting to the anticipated changes in temperature in the basin, farmers could engage in cultivating crop varieties that are drought-tolerant or require higher temperatures. Policymakers could also implement measures to conserve water particularly, during times of unassigned and wet conditions, to preserve and enhance the hydrological functions of the basin. This initiative will enable the dispensation of water for agricultural and other vital purposes amidst the adverse climate conditions.

Data availability statement

The datasets generated for this study can be found in CORDEX-Africa (https://climate4impact.eu) and NASA POWER (https://power.larc.nasa.gov/data-access-viewer/). Further inquiries on the stations can be directed to the corresponding author.

Author contributions

DK developed the idea and completed the majority of the analysis and writings. DM, SA, and EB supervised the manuscript writing and reviewed it. GY and WA helped with the data analysis and review. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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