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CONTRIBUTION OF CLIMATE INDICES TO THE CHARACTERIZATION OF CLIMATE VARIABILITY : CASE OF THE PORO REGION IN NORTHERN CÔTE D'IVOIRE

Climate Change

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ABSTRACT

The objective of this study is to characterize climate variability in the Poro region using four climate indices. To this end, daily rainfall, maximum temperature, and minimum temperature data covering a 41-year observation period (1982–2022) were used. These data were analyzed and processed using the RClimdex software, which enables climate data quality control and the calculation of climate indices. The results highlight a progressive modification of climatic conditions in the Poro region between 1982 and 2022, characterized by increasing temperatures, irregular rainfall patterns, and contrasting changes in drought sequences across localities. Thus, the analysis of the CDD index shows an increasing trend in the number of consecutive dry days in several localities of the region, notably Guiembé, Dikodougou, Korhogo, and M'Bengué, as indicated by the respective positive trend slopes of 0.0146 day/year, 0.1341 day/year, 0.2267 day/year, and 0.5082 day/year.The PRCPTOT index reveals strong variability in annual precipitation across the region. Indeed, the stations of M'Bengué, Korhogo, and Sirasso show increasing trends in annual rainfall totals, with respective trends of 6.5257 mm/year, 2.9212 mm/year, and 0.0231 mm/year, whereas the stations of Dikodougou and Guiembé exhibit decreasing annual rainfall amounts, with slopes of −1.2707 mm/year and −0.0142 mm/year, respectively. Regarding the thermal indices Tx and Tn, the results indicate a generalized increase in both maximum and minimum temperatures throughout the region, with respective increases of 3.153 °C and 2.17 °C over the study period. Overall, these changes reflect a trend toward climate warming and drier conditions in the Poro region, which may have long-term impacts on natural resources as well as on the socio-economic activities of local populations.

KEYWORDS

Climate Indices, Climate Variability, Poro Region, Precipitation, Temperatures.

INTRODUCTION

Climate change currently constitutes one of the major environmental challenges worldwide due to its increasing impacts on natural resources, ecosystems, and socio-economic activities (IPCC, 2023). It is notably manifested through disruptions in rainfall regimes, rising temperatures, and the intensification of extreme climatic events such as droughts, floods, and heat waves (O'Gorman, 2015; Fowler et al., 2021). In West Africa, several studies have highlighted a general decline in rainfall between the 1960s and 1990s, accompanied by strong climate variability (Hubert et al., 1989; Mahé and Olivry, 1995; Bricquet et al., 1997; Servat et al., 1999). This situation has led to a significant reduction in water resources, particularly in the Sudanian and Sahelian regions that are highly dependent on climatic conditions.

In Côte d'Ivoire, the effects of climate change are reflected in increasing rainfall irregularity and a gradual rise in temperatures. Several studies have reported the existence of a persistent rainfall deficit since the 1970s, affecting both water resources and agricultural and environmental systems (Servat et al., 1999; Brou et al., 1998; N'go et al., 2017). More recent studies also confirm an increase in extreme temperatures as well as strong spatio-temporal variability in rainfall across several regions of the country (Kouman et al., 2022; Gone, 2024).

The northern regions of the country, particularly the Poro region, appear to be among the areas most vulnerable to climate fluctuations. Over recent decades, this region has experienced severe episodes of droughts and floods, resulting in significant disturbances to water resources, agricultural production, and the living conditions of local populations (Soro et al., 2011; Kouakou et al., 2017; Kouman et al., 2022). The work of Brou (2005) also highlights that the northern regions of Côte d'Ivoire are particularly exposed to rainfall variability and increasing temperatures, with direct consequences for agro-pastoral systems and water resources.

Furthermore, the global increase in temperatures contributes to enhanced evapotranspiration processes and reduced water resource availability (IPCC, 2007). These changes directly affect environmental balances and reinforce the vulnerability of tropical regions to climatic hazards. In this context, the analysis of climate indices appears to be an essential approach for better characterizing the evolution of climatic parameters and assessing the magnitude of changes observed at the local scale.

Therefore, the objective of this study is to demonstrate the contribution of climate indices to the characterization of climate change in the Poro region using daily rainfall, maximum temperature, and minimum temperature data over the period 1982–2022. The study also aims to highlight the climatic trends observed in the different localities in order to contribute to a better understanding of regional climate dynamics and to provide decision-support elements for climate change adaptation strategies.

Study Area

The Poro region is located in northern Côte d'Ivoire, within the Savanes District, between latitudes 8.50° and 10.20° North and longitudes 6.00° and 5.00° West. Its administrative capital is the city of Korhogo, which constitutes the main urban and economic hub of northern Côte d'Ivoire. The region notably includes the departments of Korhogo, Sinématiali, M'Bengué, and Dikodougou.

The Poro region belongs to the Sudanian climatic zone, characterized by an alternation between a rainy season and a dry season dominated by the Harmattan wind (Brou, 2005). Annual rainfall generally ranges between 1,000 and 1,400 mm, with strong interannual variability (Servat et al., 1999; Kouman et al., 2022). Temperatures remain high throughout the year and may exceed 35 °C during the dry season.

From a hydrographic perspective, the region is drained by the Bandama River and several tributaries, including the Lokpoho, Solomougou, Yoréloro, Badénou, and Lofigué rivers, which constitute essential water resources for agricultural and pastoral activities.

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Figure 1 Location of the Selected Stations in the PORO Region.

1. MATERIALS AND METHODS
1.1. Materials
1.1.1. Climate Data
This study required the use of daily rainfall, maximum temperature, and minimum temperature data covering the period 1982–2022 from the stations of Dikodougou, Sirasso, Guiembé, Korhogo, Sinématiali, and M'Bengué in order to assess climate variability in these localities. The climate data analyzed were obtained from the National Aeronautics and Space Administration (NASA) website: NASA POWER Project.

1.1.2. Software and Computer Tools
Several software programs were used in this study:
- Excel 2019 spreadsheet software was used to organize daily data into monthly and annual datasets and to produce maps illustrating climate variability and climate evolution within the study area.
- The R statistical software was used for the calculation of climate indices.
- The RHtests software package was used to perform homogeneity tests on climate data.
- ClimPACT2 Master was used to calculate daily climate indices. These programs are accessible through the website of the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI). ClimPACT2 Master is a software package specifically designed for climate studies, developed and recommended by the World Meteorological Organization (WMO), and operating within the R software environment (Alexander and Herold, 2016; N'Guessan Bi et al., 2018).
- ArcGIS 10.8 software was used for the spatial analysis and mapping of climate indices.

1.2. Methods
The methodology adopted in this study to characterize climate variability is based on climate indices (Hountondji et al., 2011; N'Guessan Bi et al., 2018) proposed by the Expert Team on Climate Change Detection and Indices (ETCCDI) through the ClimPACT2 Master program. These experts defined twenty-seven (27) climate indices, including eleven (11) rainfall indices and sixteen (16) indices related to temperature extremes (Xuelin and Yang, 2004). These indices describe specific characteristics of rainfall and temperature extremes, including the frequency, intensity, and persistence of rainfall events (Taïbi, 2016). According to Xuelin and Yang (2004), these indices can be grouped into four major categories:
1. Duration-based indices;
2. Intensity indices;
3. Percentile-based indices;
4. Threshold indices.

The four rainfall and temperature indices considered in this study include one intensity index, namely total annual rainfall (PRCPTOT), and one duration-based index, namely consecutive dry days (CDD). The other two indices are temperature-based and correspond to daily maximum temperatures and daily minimum temperatures (Xuelin and Yang, 2004).

The calculation of climate indices was carried out in three stages:
- Quality control (QC) of the data used;
- Homogeneity testing of climate data;
- Calculation of climate indices.

Before calculating the indices, data quality was checked and data homogeneity was tested.

The analysis was therefore conducted according to the following methodology:
- Data quality control using the RClimDex software;
- Homogeneity testing of climate data;
- Calculation of climate indices;
- Climate indices calculated using RClimDex;
- Fixed-threshold indices;
- Variable-threshold indices;
- Statistical analyses of the calculated index series;
- Analysis using RClimDex.

1.2.1. Quality Control (QC)
The main objective of data quality control is to identify data recording errors or "outliers" (values located outside a user-defined interval, generally defined as follows):
[mean - 4 × standard deviation; mean + 4 × standard deviation]

The most common errors encountered include negative rainfall values, negative temperatures (when the study concerns West African countries), and maximum temperatures lower than minimum temperatures. These errors are transformed into missing data by the RClimDex software; however, it is ultimately the user's responsibility to validate or correct the detected errors.

The percentage of missing data is also checked during this stage because it must remain below 25%, which is a necessary condition for the software to compute climate indices.

The quality control of our data was performed using the RClimDex package in R, and no errors were detected.

1.2.2. Homogeneity Testing of Climate Data
Data homogeneity was verified using the RHtests software developed by the Canadian Meteorological Service (Zhang et al., 2005) and implemented within the R statistical and programming environment. This procedure is based on a double regression model (Wang, 2003).

1.2.3. Calculation of Climate Indices
Climate Indices Calculated by RClimDex
After data quality control and homogeneity testing, the next step consisted of calculating climate indices. The validation of calculated index values followed the following criteria:
- The estimation error of the slope resulting from linear regression must be lower than the estimated slope value;
- The p-value resulting from the associated significance test must be lower than 0.05 (p-value < 0.05).

Thus, the obtained trend is considered statistically significant at a 95% confidence level (Sensoy et al., 2013).

Threshold Definition (POT)
The calculation of extreme indices using RClimDex first requires the identification and introduction of threshold values (upper and lower temperature thresholds and rainfall thresholds). The POT (Peak Over Threshold) approach is used to select these threshold values. The principle of this method is to choose a sufficiently high threshold value and analyze the values exceeding this threshold.

1.2.4. Statistical Analysis
We used the RClimDex statistical tool to analyze climate index time series.
- RClimDex

Following the calculation of climate indices, RClimDex computes trend slopes for these indices using the least squares method. The significance level of the trends is evaluated using the Mann–Kendall test, which calculates the p-value (Seyners, 1990).

In this study, a trend is considered statistically significant when it is significant at the 90% confidence level, that is, when the p-value is lower than 0.1.

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Figure 2 : RClimDex 1.0 Software Interface and Selection of Climate Indices.

2. RESULTS

2.1. Statistical Analysis of Climate Indices

2.1.1. CDD Index (Maximum Number of Consecutive Dry Days) from 1982 to 2022

The CDD index determines the maximum number of consecutive dry days. Figure 3 presents the interannual evolution of the CDD index between 1982 and 2022 at the stations of Dikodougou, Sirasso, Guiembé, Korhogo, and M'Bengué. The curves reveal a progressive increase in the number of dry days as well as strong annual variability in dry sequences, with values ranging from 20 to more than 140 consecutive dry days depending on the year in most stations. The highest CDD values were recorded at M'Bengué and Korhogo. The linear regression lines observed on the graphs indicate an increasing trend in CDD values, with respective coefficients of 0.5082 day/year and 0.2267 day/year. This situation reflects an intensification of drought periods in these localities.

Furthermore, at Dikodougou and Guiembé, the regression lines also show increasing trends in CDD values, although weaker, with respective coefficients of 0.1341 and 0.0146. This also indicates an evolution of dry sequences in these localities.

In contrast to the other stations, Sirasso shows a slight decreasing trend in the CDD index. The regression coefficient is negative (-0.1293), suggesting a relative reduction in the number of consecutive dry days in this locality.

These results indicate a modification of climatic regimes in the Poro region, characterized by increasing rainfall irregularity and longer dry periods, which are likely to affect water resources and agricultural activities.

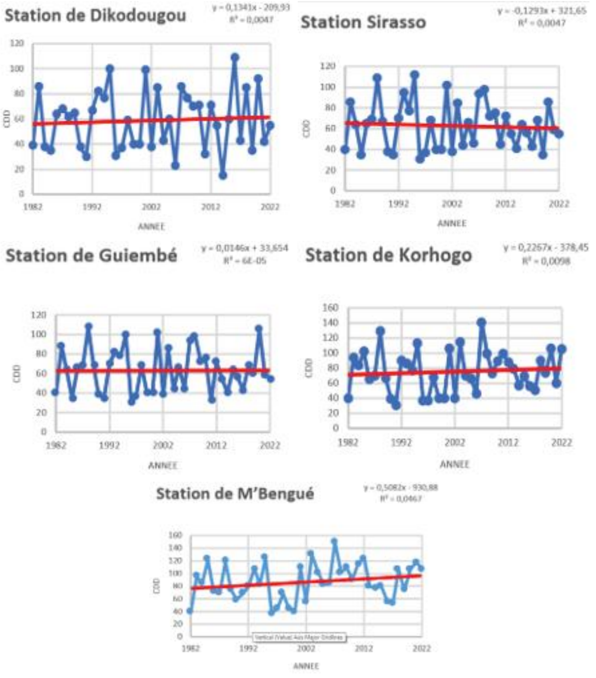


Figure 3: Maximum Annual Consecutive Dry Days from 1982 to 2022 in the Poro Region.

2.1.2. PRCPTOT Index (Total Annual Rainfall) from 1982 to 2022

Annual rainfall totals are presented in Figure 4. The curves reveal significant fluctuations in annual rainfall across all the studied stations, with values ranging between 700 and 1600 mm depending on the year.

The regression curve shows an increasing trend in the PRCPTOT index in the localities of Sirasso, Korhogo, and M'Bengué, with respective coefficients of 0.0231 mm, 2.9212 mm, and 6.5257 mm per year. This situation indicates a gradual increase in annual rainfall in these localities during the study period. In contrast, at the Dikodougou and Guiembé stations, the regression lines show a decreasing trend in the PRCPTOT index. The trends are estimated at -1.2707 mm/year for Dikodougou and -0.0142 mm/year for Guiembé. This suggests a moderate decline in rainfall totals in these localities over the observation period.

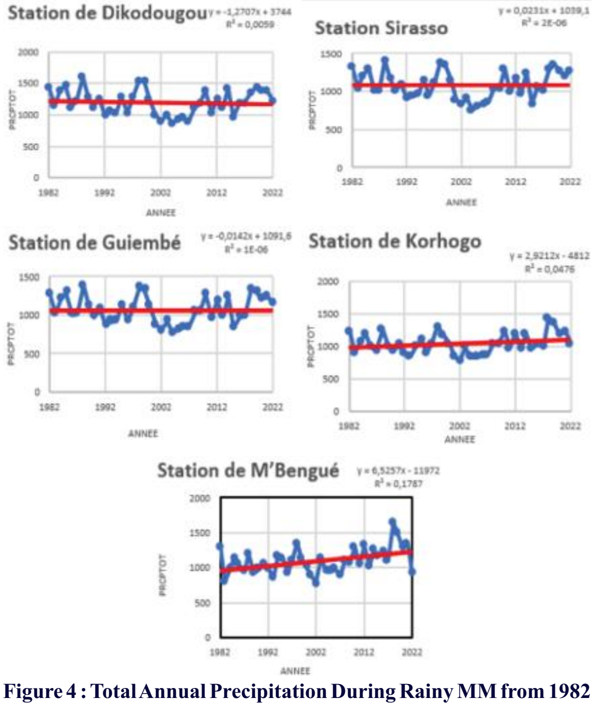
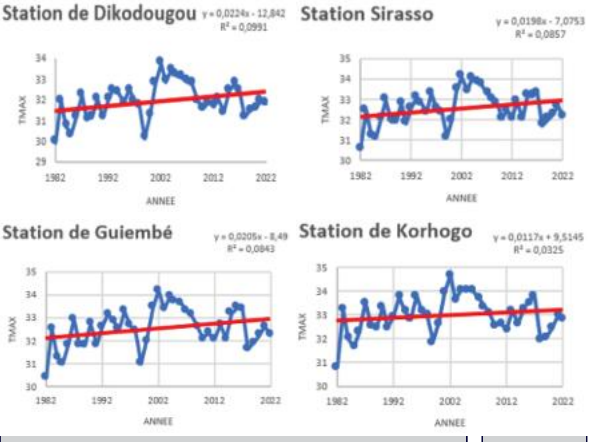


Figure 4 : Total Annual Precipitation During Rainy MM from 1982 to 2022 in the Poro Region.

2.1.3. Tx Index (Annual Maximum Temperature) from 1982 to 2022

Figure 5 presents the interannual evolution of the Tx index between 1982 and 2022 at the stations of Dikodougou, Sirasso, Guiembé, Korhogo, and M'Bengué. The curves reveal a progressive increase in annual maximum temperatures, with values ranging between 29 and more than 34 °C depending on the year in most stations. The average maximum temperature recorded across the stations is 32 °C.

The figure highlights a generalized increase in annual maximum temperatures throughout the region, as indicated by the linear regression lines. The regression coefficients are 0.0224 °C/year for Dikodougou, 0.0198 °C/year for Sirasso, 0.0205 °C/year for Guiembé, 0.0117 °C/year for Korhogo, and 0.0025 °C/year for M'Bengué. These results indicate that maximum temperatures are increasing in all the studied localities.



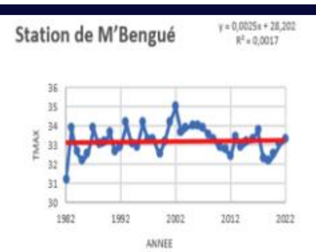


Figure 5 : Trend in Annual Maximum Temperatures (Tx) from 1982 to 2022 in the Poro Region.

2.1.4. Tn Index (Annual Minimum Temperature) from 1982 to 2022

Figure 6 presents the interannual evolution of the Tn index between 1982 and 2022 at the stations of Dikodougou, Sirasso, Guiembé, Korhogo, and M'Bengué. The curves reveal a continuous increase in minimum temperatures, with values ranging between 19 and more than 21 °C depending on the year in most stations. The average minimum temperature recorded across the stations is 21 °C. The regression lines indicate an increasing trend in annual minimum temperatures at all the studied stations (Dikodougou, Sirasso, Guiembé, Korhogo, and M'Bengué), with respective coefficients of 0.0057 °C, 0.0094 °C, 0.0127 °C, 0.0122 °C, and 0.0134 °C per year. These results indicate that minimum temperatures have increased in all the studied localities.

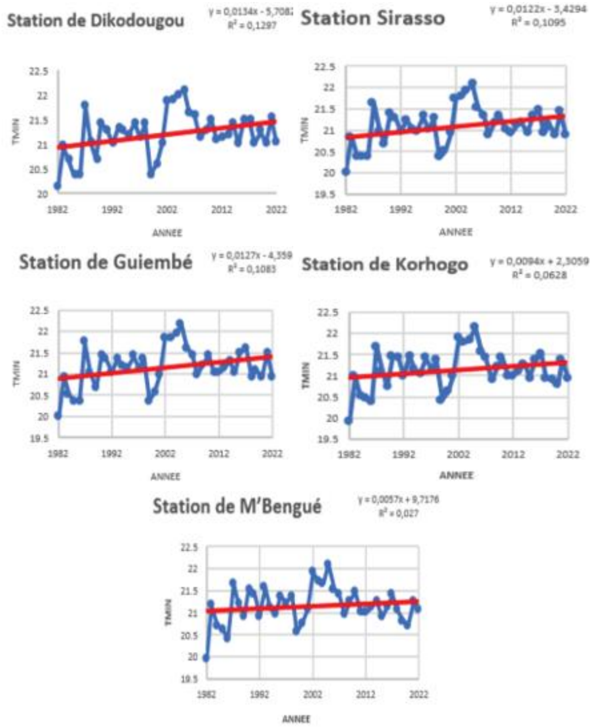


Figure 6 : Trend in Annual Minimum Temperatures (Tn) from 1982 to 2022 in the Poro Region.

2.2. Spatial Distribution of Climate Indices

2.2.1. Spatial Distribution of the CDD Index (Consecutive Dry Days) from 1982 to 2022

Figure 7 highlights the map showing the spatio-temporal evolution of the decadal average values of the CDD index in the Poro region. It makes it possible to identify the areas most exposed to prolonged dry sequences within the region.

During the first decade (1982–1991), the average CDD values ranged between 51.96 and 80.76 days. This decade was characterized by moderately humid M'Bengué remained the driest zones throughout the study period.

2.2.2. Spatial Distribution of the PRCPTOT Index (Total Annual Rainfall) from 1982 to 2022

Figure 8 presents the map of the spatio-temporal evolution of the decadal average values of the PRCPTOT index and helps identify the areas most exposed to low rainfall in the Poro region.

The first decade (1982–1991) shows that the average index values ranged between 1032.84 and 1347.01 mm of rainfall. This decade was characterized by wetter conditions (Figure 8). The wettest areas, corresponding to the highest PRCPTOT values, were located in the southern part of the region, particularly in the localities of Dikodougou and Boron.

The second decade (1992–2001) recorded average PRCPTOT values ranging between 1011.14 and 1235.39 mm of rainfall (Figure 8). The highest average PRCPTOT values were again observed in the southern part of the region. However, a slight northward extension of rainfall activity was observed within the study area. Nevertheless, the localities of Boron and Dikodougou remained those receiving the highest rainfall amounts during this decade. This increase may be related to the low rainfall recorded in northern localities.

The third decade (2002–2011) revealed average PRCPTOT values ranging between 932.17 and 1057.8 mm of rainfall. This decade was characterized by drier conditions (Figure 8). The wettest areas of the region were Boron in the south and Bougou and M'Bengué in the north. This decade was the driest over the entire observation period.

During the last decade (2012–2021), the average PRCPTOT values ranged between 1127.07 and 1322.18 mm of rainfall (Figure 8). This decade was wetter than the two previous decades. The localities of Bougou and M'Bengué in the north received the highest rainfall amounts, followed by Boron in the south.

2.2.3. Spatial Distribution of the Tx Index (Annual Maximum Temperature) from 1982 to 2022

Figure 9 presents the map of the spatio-temporal evolution of the decadal average values of the Tx index, which helps identify the areas most exposed to high maximum temperatures in the Poro region.

During the first decade (1982–1991), average Tmax values ranged between 31.17 and 33 °C. This decade was characterized by cooler conditions compared to the other decades (Figure 9). The hottest areas of the Poro region, corresponding to the highest Tx values, were located in the northern, northeastern, and northwestern sectors, particularly in the localities of Bougou, M'Bengué, Niofoin, and Sinématiali.

The Tx values for the decade 1992–2001 ranged between 31.88 and 33.4 °C (Figure 9). These values indicate that the entire region experienced heat waves, suggesting the onset of climate warming. The hottest areas remained located in the north, northeast, and northwest of the region, particularly in the localities of M'Bengué, Niofoin, Sinématiali, and Korhogo.

The Tx values for the decade 2002–2011 ranged between 32.69 and 33.84 °C (Figure 9). These values reveal that this decade was hotter than the previous one, indicating an intensification of climate warming throughout the region. The most affected areas were located in the northern, northeastern, and northwestern sectors of the Poro region, including the localities of Bougou and M'Bengué in the north, Niofoin in the northwest, and Sinématiali and Korhogo in the northeast.

During the decade 2012–2021, the average Tmax values ranged between 31.81 and 33.07 °C (Figure 9). The figure shows the establishment of slight cooling conditions within the region, accompanied by a gradual southward shift of heat waves from the northern part of the region. The locality least affected by climate warming was Boron, located in the southern part of the study area.

2.2.4. Spatial Distribution of the Tn Index (Annual Minimum Temperature) from 1982 to 2022

Figure 10 presents the map of the spatio-temporal evolution of the decadal average values of the Tn index, which helps identify the areas most exposed to high minimum temperatures in the Poro region. This index represents annual minimum temperature.

During the first decade (1982–1991), average Tn values ranged between 20.78 and 21.1 °C. This decade was characterized by relatively cooler conditions (Figure 10). The warmest areas of the region, corresponding to the highest Tn values, were located in the extreme northern and northwestern parts of the region, particularly in the localities of Bougou, M'Bengué, Sinématiali, and Komborodougou.

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The average Tn values for the decade 1992–2001 ranged between 20.95 and 21.22 °C (Figure 10). The Tn index values reveal the emergence of heat waves throughout the region. The region was already experiencing the effects of climate warming. The areas most affected by this phenomenon were located in the western part of the region, particularly the localities of Sinématiali, Korhogo, and Komborodougou.

The Tn index values for the decade 2002–2011 ranged between 21.45 and 21.63 °C (Figure 10). These values indicate that heat waves intensified throughout the region, extending toward the southern part of the region. The most affected areas were located in the western and southern sectors. The localities of Sinématiali, Korhogo, Komborodougou, Dikodougou, and Boron were the most affected.

During the 2012–2021 decade, the average values of the Tn index ranged between 21.05 and 21.33 °C (Figure 10). The new index values indicate a slight cooling of heat sequences throughout the study area. The warmest localities were located in the westernmost and southernmost parts of the region, namely Sinématiali, Komborodougou, Dikodougou, and Boron.

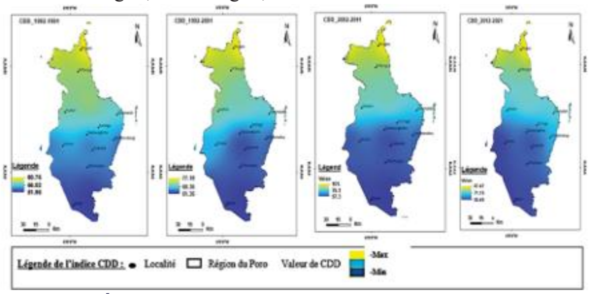

Figure 7 : Évolution Spatio-temporelle de l'indice CDD Dans la Région du Poro.

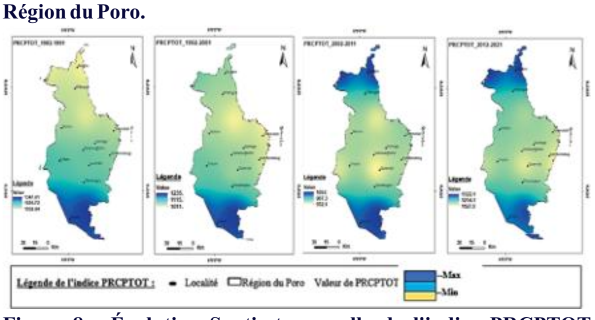

Figure 8 : Évolution Spatio-temporelle de l'indice PRCPTOT Dans la Région du Poro.

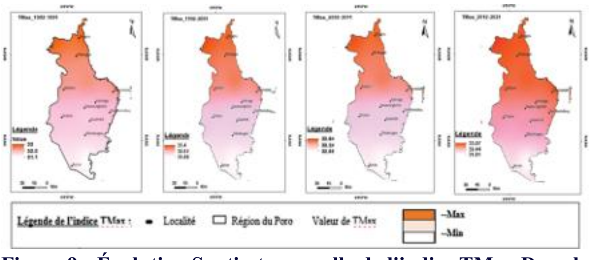

Figure 9 : Évolution Spatio-temporelle de l'indice TMax Dans la Région du Poro.

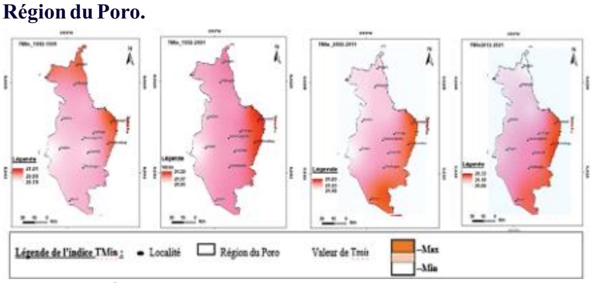

Figure 10 : Évolution Spatio-temporelle de l'indice TMin Dans la Région du Poro. 3.

DISCUSSION

The results obtained highlight a progressive modification of climatic conditions in the Poro region between 1982 and 2022, characterized by increasing temperatures, rainfall variability, and contrasting changes in dry sequences depending on the locality. These changes reflect climatic dynamics already observed across West Africa, particularly in Côte d'Ivoire (Servat et al., 1999; Brou, 2005; Kouman et al., 2022).

The analysis of the Consecutive Dry Days (CDD) index reveals an increase in dry sequences in several localities, particularly in Bougou, M'Bengué, Korhogo, Guiembé, and Dikodougou. This trend indicates a progressive extension of rainless periods and an intensification of drought episodes. These findings are consistent with those of Soro et al. (2011) and Kouakou et al. (2017), who reported an increase in drought frequency in northern Côte d'Ivoire associated with rainfall irregularity. The high CDD values observed in Bougou and M'Bengué indicate that northern areas are more exposed to water deficits, probably under the influence of dry Sahelian air masses and the variability of the West African monsoon.

Similar trends were also reported by Donat et al. (2013) in several regions worldwide, as well as by Balliet (2017), Danumah (2016), and Yapi et al. (2020) in Côte d'Ivoire using the RClimDex model. However, the decrease in dry days observed at Sirasso reflects a spatial heterogeneity of the climate that may be related to topographic conditions, vegetation cover, or the spatial redistribution of rainfall.

Furthermore, the PRCPTOT index highlights strong interannual and spatial rainfall variability within the Poro region. The increases observed in Bougou, M'Bengué, and Niofoin contrast with the slight decreases recorded in Boron, Dikodougou, and Sirasso. This situation may reflect the partial recovery of rainfall observed in West Africa since the 1990s, although this recovery remains irregular. These findings confirm the studies of Servat et al. (1999) and Brou et al. (1998), which showed that rainfall regimes in Côte d'Ivoire alternate between deficit periods and rainfall recovery phases.

They also corroborate the findings of New et al. (2006), Aguilar et al. (2009), Tramblay et al. (2013), and N'Guessan Bi et al. (2018), who highlighted decreasing rainfall and fewer rainy days in several African regions. Such rainfall irregularity may strongly affect agricultural yields, since crops are highly dependent on water availability. Spatial analysis also shows that the southern sectors of the region, particularly Dikodougou and Boron, remain the wettest areas under the influence of humid Guinean air masses, unlike the northern areas, which are subjected to drier Sahelian influences.

The decades 1992–2001 and 2002–2011 appear to be the most deficient periods, whereas the period 2012–2021 is characterized by a relative return to wetter conditions in some localities.

Regarding thermal indices, the results indicate a generalized increase in maximum (Tx) and minimum (Tn) temperatures throughout the region. This trend is consistent with the observations of the IPCC (2023) and the findings of Kouman et al. (2022), which indicate a significant increase in extreme temperatures in Côte d'Ivoire. The areas most affected are located in the northern, northeastern, and northwestern parts of the region, particularly Bougou, M'Bengué, Niofoin, and Sinématiali. This situation may be promoted by vegetation cover degradation and intensified solar radiation.

The increase in minimum temperatures also indicates that nights are becoming progressively warmer, which constitutes a major indicator of global warming (Fowler et al., 2021; IPCC, 2023). Finally, the spatial analysis of thermal indices reveals a slight decrease in heat waves during the 2012–2021 decade, probably related to the rainfall recovery observed in some localities.

CONCLUSION

The analysis of climate index evolution in the Poro region over the 41-year observation period revealed an increase in the number of consecutive dry days as well as rising maximum and minimum temperatures, induced by a continuous increase in the CDD, Tx, and Tn indices, with respective values of 0.15 day/year, 0.077 °C/year, and 0.053 °C/year.

The PRCPTOT index, on the other hand, shows strong rainfall variability, characterized by alternating deficit and surplus periods depending on the decades and localities within the region.

The climate index-based approach therefore made it possible to better

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identify the spatio-temporal dynamics of climate variability and to highlight the areas most vulnerable to climatic fluctuations. The results show that the Poro region, particularly the localities located in the northern part, remains highly exposed to the effects of climate change, notably recurrent droughts, heat waves, and rainfall irregularity, leading to environmental degradation and reduced agricultural productivity.

Consequently, integrating climate indices into environmental management and territorial planning policies appears essential to strengthen adaptation and resilience strategies in response to climate change in northern Côte d'Ivoire.

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