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Research Article

Spatio-Temporal Variability of Climate Extremes in the Nouhao Sub-Basin, Burkina Faso: A Comprehensive Analysis of Trends and Spatial Patterns (1981-2020)

Noba

Independent Scholar

A R T I C L E I N F O

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A B S T R A C T

Extreme weather events are attracting growing scientific interest due to their profound and often devastating impacts on natural ecosystems and socio-economic systems, particularly in regions where livelihoods depend heavily on climate-sensitive activities such as rain-fed agriculture. However, despite the vulnerability of the Sahel to climate variability and change, relatively few studies have focused specifically on the detailed analysis of extreme weather events in the sub-national basins of Burkina Faso, a landlocked Sahelian country in West Africa facing significant water resource challenges. This study addresses this gap by providing a comprehensive analysis of the spatio-temporal variability and trends of climate extremes, focusing on both precipitation and temperature parameters, in the Nouhao sub-basin over the forty-year period from 1981 to 2020. The analysis is based on a combination of observational station data obtained from the National Meteorological Agency of Burkina Faso and high-resolution ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts. A set of core climate extreme indices, carefully selected from the suite defined by the Expert Team on Climate Change Detection and Indices, was calculated using the specialized RClimdex software package. These indices include consecutive dry days, consecutive wet days, maximum one-day precipitation, and maximum five-day precipitation for rainfall, as well as the percentage of cool nights, warm nights, cool days, and warm days for temperature. Statistical trend analysis was performed using the non-parametric Mann-Kendall test to assess the significance of observed changes, complemented by Sen's slope estimator to quantify the magnitude of these trends. The spatial structure and distribution of the climate extremes across the basin were analyzed using geostatistical interpolation techniques, specifically kriging, implemented within a Geographic Information System framework.

The study reveals a complex and nuanced picture of climate variability in the Nouhao sub-basin. The analysis of extreme precipitation indices demonstrates strong decadal variability throughout the study period, but no clear, consistent, or monotonic long-term trend emerges for any of the rainfall-based indices over the full forty years. This suggests that the rainfall regime in this part of the Sahel is characterized more by multi-decadal oscillations and high interannual variability than by a simple, unidirectional shift towards drier or wetter conditions. In stark contrast, the analysis of extreme temperature indices reveals a much clearer and more consistent signal, pointing towards a gradual but definitive warming of the temperature regime across the basin. The findings show a general and statistically discernible trend towards a decrease in cold extremes, as evidenced by declining frequencies of cool nights and cool days, and a concurrent increase in hot extremes, reflected in rising frequencies of warm nights and warm days. This warming trend is particularly pronounced for nighttime temperatures, with the frequency of warm nights showing a statistically significant increase in the most recent decade. The spatial analysis further illustrates these changes, showing how the patterns of temperature extremes have evolved across the basin over the four decades. These results constitute a critical climate signal for the Nouhao sub-basin, providing essential scientific evidence that can inform and guide sustainable water resource management strategies, support the development of effective climate change adaptation plans for local communities, and contribute to broader efforts to enhance resilience in the face of a changing climate.

1. INTRODUCTION

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Climate change stands as one of the most profound and far-reaching challenges of the twenty-first century, with its impacts reverberating across natural ecosystems, human societies, and global economies. The climate system, which represents the complex and dynamic integration of meteorological phenomena over time, serves as an essential indicator of the state and health of the entire biosphere, influencing everything from agricultural productivity and water availability to biodiversity patterns and human settlement. Since the onset of the industrial revolution in the mid-nineteenth century, the relentless increase in atmospheric concentrations of greenhouse gases, primarily carbon dioxide, methane, and nitrous oxide, has driven a discernible warming of the global climate system. This warming is unequivocal, and its consequences are increasingly visible and measurable, including rising global mean sea levels, a significant reduction in the extent and thickness of snow and ice cover, and profound and consequential changes in the frequency, intensity, and spatial distribution of climate extremes across the globe.

Extreme weather events, such as intense rainfall leading to devastating floods, prolonged dry spells causing agricultural drought, and record-breaking heatwaves, are attracting rapidly growing scientific and public attention due to their disproportionate and often catastrophic impacts on both natural and human systems. Unlike gradual changes in mean climate conditions, extremes can push socio-ecological systems beyond their coping thresholds, causing irreversible damage to infrastructure, triggering food and water crises, displacing populations, and undermining decades of development progress. The characteristics of these extremes, particularly precipitation patterns, are fundamentally shaped by an uneven and highly complex distribution in both time and space, making their analysis and prediction a formidable scientific challenge. Understanding how these extremes are changing at the local and regional scale is therefore not merely an academic exercise but a critical prerequisite for effective climate risk management and adaptation planning.

The West African Sahel, a semi-arid region stretching across the continent just south of the Sahara Desert, is widely recognized as one of the most vulnerable areas in the world to climate variability and change. Since the devastating droughts of the 1970s, the Sahel has been synonymous with climate vulnerability. Burkina Faso, a landlocked country at the heart of the Sahel, has been profoundly affected by this high climate variability, characterized by dramatic alternations between dry and wet periods that have reshaped the country's rainfall regimes, hydrological systems, and consequently, its socio-economic landscape. This succession of contrasting climatic episodes has had a decisive influence on national food security, which is heavily dependent on rain-fed agriculture, on the availability of surface and groundwater resources for domestic and productive use, and on the overall stability of fragile ecosystems. This climate dynamic, often amplified by the increasing frequency or intensity of extremes, directly impacts the recharge of dams and reservoirs, the flow of rivers, the productivity of crops and pastures, and the living conditions of the predominantly rural population.

Within Burkina Faso, the Nouhao sub-basin, a tributary of the Nakanbé River located in the central-eastern part of the country, presents a particularly pertinent case study for analyzing climate extremes. Like other areas in the Sahelian zone, rainfall and temperature extremes in the Nouhao sub-basin play a central and decisive role in the dynamics of surface water resources, the successful recharge of small dams and reservoirs that are vital for local water supply and irrigation, and the overall sustainability of livelihoods for communities engaged in agro-pastoral activities. Given the pronounced variability of the climate and the potential for the intensification of extremes under global warming, a deep and nuanced understanding of local climate trends is absolutely essential. Such understanding is the cornerstone upon which to build sound strategies for integrated water resource management, to guide agricultural planning and risk reduction, and to develop effective and context-appropriate climate change adaptation measures that can enhance the resilience of local populations.

The rigorous and standardized analysis of climate extremes is made possible by a suite of indices developed by the Expert Team on Climate Change Detection and Indices, a joint initiative of the World Meteorological Organization and other international bodies. These ETCCDI indices provide a robust, internationally recognized, and consistent framework for quantifying the frequency, intensity, duration, and persistence of extreme events. By applying these indices to long-term, high-quality time series of daily precipitation and temperature data, researchers can systematically track changes in extremes over time and compare findings across different regions of the world. The objective of this study is to apply this powerful analytical framework to the Nouhao sub-basin. Specifically, this research aims to analyze, based on a combination of observed station data and state-of-the-art ERA5 reanalysis data, the spatio-temporal evolution of key climate extremes over the forty-year period from 1981 to 2020. More precisely, it seeks to examine the trends in carefully selected rainfall and temperature indices in order to comprehensively assess the risks associated with droughts, floods, and interannual precipitation variability in this sensitive and economically important area of Burkina Faso. By providing a detailed and localized assessment of climate trends, this study aims to generate actionable scientific knowledge that can directly support policymakers, water resource managers, and local communities in their efforts to adapt to a changing and increasingly variable climate.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The Nouhao sub-basin, an integral part of the larger Nakanbé River basin, is situated in the central-eastern region of Burkina Faso, a landlocked country in the heart of West Africa. Its geographical position is defined by latitudes extending between 10 degrees 55 minutes and 12 degrees 35 minutes north, and longitudes stretching from 1 degree 00 minutes west to 0 degrees 45 minutes east, covering a total surface area of approximately four thousand and fifty square kilometers. This basin is characteristic of the Sudano-Sahelian climatic zone, which represents a transitional environment between the more humid Sudanian zone to the south and the arid Saharan zone to the north. The climate of the area is defined by a distinct alternation of two principal seasons each year: a single rainy season typically lasting from May to October, during which the region receives the vast majority of its annual precipitation, followed by a prolonged dry season from November to May, characterized by the influence of the dry and dusty harmattan wind. Annual rainfall in the Nouhao sub-basin is generally variable, typically ranging between six hundred and nine hundred millimeters, but this total is subject to very high interannual and interdecadal variability, a hallmark of the Sahelian climate regime. Temperatures across the basin exhibit a wide annual range, with average minimum temperatures fluctuating between eighteen and twenty-two degrees Celsius, often during the cooler months of December and January, while average maximum temperatures frequently exceed thirty-five degrees Celsius during the hottest period, typically just before the onset of the rains in March, April, and May. From a socio-economic perspective, the Nouhao basin is predominantly rural, and its economy is heavily dominated by agro-pastoral activities, including the cultivation of staple food crops like sorghum, millet, and maize, and the rearing of livestock such as cattle, goats, and sheep. In addition to agriculture, there are also burgeoning but crucial sectors such as local trade, artisanal crafts, road transport, and the harvesting of non-timber forest products, all of which are sensitive to climate variability.

2.2 Data Sources and Acquisition

For the purposes of this study, two complementary types of observational data were utilized to ensure both accuracy and spatial coverage. The first category consists of in-situ field observation data. Daily precipitation records were obtained from four meteorological stations strategically located within and in the immediate vicinity of the Nouhao sub-basin, providing essential ground truth for rainfall analysis. These stations include Dialgaye, Ouargaye, Sangha, and Tenkodogo. For temperature analysis, daily maximum and minimum temperature series were primarily sourced from the Fada synoptic station, which is the main meteorological station whose observational footprint adequately covers the basin in terms of reliable temperature measurements. All field observation data were officially acquired from the National Meteorological Agency of Burkina Faso, which is responsible for maintaining and disseminating the country's meteorological archives. The second category of data comprises reanalysis products, specifically the ERA5 reanalysis. ERA5 is the fifth generation of atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), covering the period from January 1940 to the present day. It represents a significant advancement over previous reanalyses, utilizing a more advanced forecasting system and data assimilation techniques, and it is widely recognized for its ability to skillfully reproduce most meteorological variables, particularly temperature, across data-sparse regions like West Africa. ERA5 reanalysis data were obtained from the Copernicus Climate Change Service, accessible through their dedicated online data portal. The complete period considered for analysis in this study spans forty years, from 1981 to 2020, providing a sufficiently long baseline for robust trend analysis.

2.3 Selection and Calculation of Climate Extremes Indices

The analysis of climate extremes was conducted using a standardized set of indices developed and recommended by the Expert Team on Climate Change Detection and Indices. The ETCCDI has defined a comprehensive suite of twenty-seven core indices, designed to capture different facets of climate extremes, with sixteen indices relating to temperature and the remainder focusing on precipitation. These indices are broadly categorized into four main groups based on their defining characteristics: percentile-based indices, which identify extremes relative to a local climatological distribution; absolute indices, which represent maximum or minimum values; duration indices, which measure the length of spells or periods; and threshold-based indices, which count days above or below fixed absolute values.

For this study, a focused selection of eight core climate indices was made, comprising four indices dedicated to the analysis of precipitation extremes and four indices dedicated to the analysis of temperature extremes. The selection was guided by the relevance of each index to the key climate-related risks and concerns in the Sahelian context, such as drought, flood, and heat stress. The selected precipitation indices include the Consecutive Dry Days index, which represents the maximum number of consecutive days in a year with daily precipitation less than one millimeter, serving as a key indicator of drought risk and dry spell length. The Consecutive Wet Days index represents the maximum number of consecutive days with daily precipitation greater than or equal to one millimeter, indicating the persistence of wet conditions. The maximum one-day precipitation amount, RX1day, captures the intensity of extreme daily rainfall events, while the maximum five-day precipitation amount, RX5day, provides a measure of prolonged heavy rainfall that can lead to flooding. For temperature, the selected indices include the percentage of cool nights, which counts days when the daily minimum temperature falls below the tenth percentile of the climatological distribution for that calendar day; the percentage of warm nights, which counts days when the minimum temperature exceeds the ninetieth percentile; the percentage of cool days, for maximum temperature below the tenth percentile; and the percentage of warm days, for maximum temperature above the ninetieth percentile. All index values were calculated using the specialized RClimdex software package, which incorporates the standardized, peer-reviewed calculation methods endorsed by the ETCCDI and the World Meteorological Organization, ensuring the reproducibility and international comparability of the results.

2.4 Statistical Trend Analysis

The variability of the calculated climate extreme indices was analyzed using multiple complementary approaches. Decadal variability was examined by constructing graphical representations of the annual average index values for the Nouhao sub-basin over the full forty-year period, often smoothed to highlight longer-term fluctuations. To determine the statistical significance of any observed trends in the time series, the non-parametric Mann-Kendall test was employed. This test is widely recommended for hydro-climatic trend analysis because it does not assume any particular distribution for the data and is robust to the presence of outliers, which are common in extreme value series. The test was applied to the annual average values of each index, with a significance threshold set at five percent, meaning that a p-value less than or equal to 0.05 indicates a statistically significant trend. While the Mann-Kendall test indicates whether a trend is present and its significance, it does not provide an estimate of the trend's magnitude. Therefore, Sen's slope estimator was also calculated for each index. Sen's slope provides a robust, non-parametric estimate of the rate of change over time, representing the median slope among all lines passing through pairs of data points. This combined approach of using the Mann-Kendall test for significance and Sen's slope for magnitude is a standard and highly recommended methodology, aligning with World Meteorological Organization guidelines and widely adopted in contemporary hydro-climatic research. To obtain spatially representative average values of the climate extreme indices for the entire Nouhao sub-basin, the Thiessen polygon method was employed. This geometric technique assigns a weight to each meteorological station based on its area of influence within the basin, allowing for a weighted average that accounts for the spatial distribution of the stations. The Thiessen polygons were constructed and the weights calculated using ArcGIS software.

2.5 Spatial Distribution Analysis

To complement the temporal trend analysis, the spatial distribution of the climate extremes across the Nouhao sub-basin was also investigated. This spatial analysis was performed on a decadal basis over the full 1981-2020 period, allowing for the visualization of how the patterns of extremes have evolved in space over time. The spatial distribution maps were generated through geostatistical interpolation of the gridded ERA5 reanalysis data. The chosen interpolation method was ordinary kriging, a powerful and flexible geostatistical technique that predicts values at unmeasured locations based on a weighted average of surrounding measured values. Kriging is particularly well-suited for climate data as it not only generates a prediction surface but also accounts for the spatial autocorrelation structure of the data, providing a measure of the uncertainty associated with the predictions. The kriging process begins by creating an empirical semivariogram, which models how the variance between data points changes as a function of the distance separating them. A theoretical model is then fitted to the empirical semivariogram, and this model is used to determine the optimal weights for interpolation. The result is a continuous surface or contour map of the estimated index values across the basin. In this study, kriging interpolation was performed using the geostatistical analyst extension within ArcGIS mapping software, which provides a comprehensive suite of tools for spatial analysis and visualization.

3. RESULTS

3.1 Temporal Variability and Trends in Extreme Precipitation Indices

The analysis of the four selected extreme precipitation indices for the Nouhao sub-basin over the 1981 to 2020 period reveals a complex picture dominated by strong interannual and interdecadal variability, with no single, clear monotonic trend applying uniformly across the entire four decades. The Consecutive Dry Days index, which measures the maximum length of dry spells each year, shows marked fluctuations from one decade to the next. A slight and statistically insignificant downward trend was observed during the first decade from 1981 to 1990, suggesting a minor tendency towards shorter dry spells. This was followed by a moderate and also non-significant increase between 1991 and 2000, indicating a return to longer dry periods. The decade spanning 2001 to 2010 was characterized by near stability, with only a very slight, non-significant negative trend. However, the most recent decade, from 2011 to 2020, shows a more pronounced increase in the CDD, with a Sen's slope of 2.70, although this trend also remains below the threshold for statistical significance due to high interannual variability. This recent tendency, while not definitive, hints at a possible recent lengthening of dry sequences.

The Consecutive Wet Days index, which tracks the maximum duration of wet spells, similarly confirms these contrasting decadal dynamics. A slight decline was noted in the 1981-1990 period, followed by a moderate increase in 1991-2000. The 2001-2010 decade displayed a more pronounced negative trend, suggesting that wet spells were becoming shorter during that time. In a reversal, the 2011-2020 decade shows an upward recovery in the CWD. This pattern of alternating increases and decreases reflects the significant variability in wet sequences, but like the CDD, there is no statistically significant long-term trend over the full forty-year period, indicating that the average duration of wet spells has not undergone a consistent unidirectional change.

The indices related to precipitation intensity reveal a more contrasting and perhaps more telling trend. The maximum one-day precipitation amount, RX1day, shows a slight, non-significant increase during the first two decades, 1981-1990 and 1991-2000. However, this pattern reverses in the subsequent decades. The 2001-2010 decade shows a gradual decrease in RX1day, a trend that becomes slightly more pronounced in the 2011-2020 decade. This suggests a recent reduction in the intensity of the most extreme daily rainfall events, although the trends remain statistically insignificant due to high variability. The pattern for the maximum five-day precipitation amount, RX5day, is even more striking. A slight increase in the 1980s is followed by a more marked and comparatively stronger increase during the 1990s, with a Sen's slope of 4.19. This suggests that prolonged heavy rainfall events were becoming more intense at the end of the twentieth century. However, the trend reverses dramatically after the turn of the millennium. A clear negative trend is observed from 2001 to 2010, which becomes even more pronounced and approaches the threshold of statistical significance in the 2011-2020 decade, with a Sen's slope of -5.78 and a p-value of 0.0736. This finding, while not quite statistically significant at the five percent level, strongly suggests a gradual and potentially important decrease in the intensity of episodes of prolonged extreme rainfall over the last two decades.

3.2 Temporal Variability and Trends in Extreme Temperature Indices

In stark contrast to the precipitation indices, the analysis of the four extreme temperature indices reveals a much clearer, more consistent, and statistically significant signal, pointing towards a gradual but definitive warming of the temperature regime across the Nouhao sub-basin over the 1981-2020 period. The TN10p index, which represents the frequency of cool nights, shows an overall downward trend throughout the study period. A moderate, non-significant decrease was observed in the 1980s, followed by near stability in the 1990s. The downward trend resumed in the 2000s and became more marked in the most recent decade of 2011-2020, with a Sen's slope of -0.35. While this recent trend is not statistically significant on its own, the overall pattern across the four decades strongly suggests a gradual but consistent decrease in the occurrence of cool nights, consistent with a warming trend in nighttime minimum temperatures.

Conversely, the TN90p index, which indicates the frequency of warm nights, shows a clear and statistically significant upward trend, particularly in the most recent decade. A moderate increase was observed as early as the 1980s, with a Sen's slope of 0.37, which was close to the significance threshold. The 1990s and 2000s were characterized by relative stability in the frequency of warm nights. However, the decade from 2011 to 2020 shows a dramatic and highly significant increase, with a Sen's slope of 0.80 and a p-value of 0.0491. This statistically significant result confirms a recent and marked intensification of nighttime warming, with a rapid increase in the number of nights where the minimum temperature exceeds the historical ninetieth percentile.

The indices related to maximum temperatures, or daytime extremes, reveal a somewhat more nuanced picture but one that also supports an overall warming trend. The TX10p index, representing the frequency of cool days, shows high interannual variability with no clear or significant trend over the full period. There were weak positive trends in some decades and slight decreases in others, but no consistent pattern emerges, suggesting that the frequency of cool daytime temperatures has remained relatively stable. In contrast, the TX90p index, which measures the frequency of extremely warm days, reveals a more consistent upward trend. Increases were observed in the 1980s and 1990s, followed by relative stability in the 2000s. The most recent decade, 2011-2020, shows a resumption of this upward trend. Although none of these decadal trends for TX90p are individually statistically significant, the overall pattern across the forty years, assessed through the Sen's slope, indicates a gradual but discernible increase in the occurrence of extremely hot days, confirming a warming trend in daytime maximum temperatures as well.

3.3 Spatial Distribution of Extreme Precipitation Indices

The spatial distribution of the average values for the four extreme precipitation indices, analyzed decade by decade, reveals a complex and evolving geographical pattern across the Nouhao sub-basin. For the Consecutive Dry Days index, during the 1981-1990 decade, dry spells were relatively shorter in the northern part of the basin, while the southern zone experienced longer dry periods. This pattern shifted during the 1991-2000 decade, with areas of high dry persistence expanding into the center and south, reflecting an intensification of arid conditions in those areas. Between 2001 and 2010, the southeast continued to experience the longest dry spells, while a slight decrease in CDD was observed in the northwest. Finally, for the 2011-2020 period, a distinct spatial redistribution is evident, with the northwest experiencing shorter dry spells and the center and south maintaining the longest dry periods, suggesting an increased concentration of drought risk in the southern and central parts of the basin in recent years.

The spatial pattern for Consecutive Wet Days also evolved over time. The 1980s showed longer wet durations in the northwest. In the 1990s, a homogenization of CWD values was observed across the central and southern parts. The 2000s saw a small area in the west retaining the longest wet periods. However, the most recent decade, 2011-2020, shows a new pattern where the entire basin exhibits relatively high CWD values, indicating a possible recent intensification or expansion of prolonged rainy episodes across the whole sub-basin.

For the RX1day index, representing maximum daily precipitation, the 1980s showed higher values in the center and south. The 1990s witnessed a general increase in daily maximum rainfall across the entire basin. The 2000s saw a more uniform spatial distribution of high values. In the last decade, the southeast consistently shows the highest values, suggesting an intensification of heavy daily rainfall events in the southern part of the basin. The spatial distribution of the RX5day index, for five-day cumulative rainfall, generally follows a similar pattern, with the central and southern parts of the basin consistently showing the highest cumulative precipitation amounts across most decades, although the spatial gradients and intensity have varied over time, with a relative homogenization of values across the north and south in the most recent decade.

3.4 Spatial Distribution of Extreme Temperature Indices

The spatial analysis of extreme temperature indices powerfully illustrates the changes in both minimum and maximum temperatures across the Nouhao sub-basin over the 1981-2020 period. For the percentage of cool nights, the maps show that during the first three decades, values fluctuated across the basin, but the most recent decade, 2011-2020, displays a general and spatially widespread decrease in TN10p, particularly evident in the center and north. This visual pattern corroborates the temporal trend analysis, confirming a basin-wide decline in the frequency of cold nights. The complementary evolution of the TN90p index, for warm nights, is even more striking. While the early decades show a moderate frequency of warm nights with some spatial heterogeneity, the maps for the 2001-2010 and especially the 2011-2020 decades show a clear increase. The most recent decade exhibits the highest values of the entire series across most of the basin, visually confirming the marked and widespread increase in exceptionally warm nights.

The spatial patterns for the daytime indices provide a complementary view. For cool days, the maps show a general decrease in TX10p over time, particularly in the southern part of the basin in the most recent decades, aligning with the trend of decreasing cool daytime extremes. Conversely, the spatial distribution of the hot day index, TX90p, powerfully illustrates the intensification of daytime heat. The early 1980s show moderate values, but subsequent decades, particularly 2001-2010 and 2011-2020, show a clear and progressive expansion of areas with higher TX90p values. The latest decade shows the highest values across most of the basin, with a notable intensification in the northeast and south, reflecting a continuous and spatially widespread increase in the number of exceptionally hot days.

4. DISCUSSION

The findings of this study provide a detailed and nuanced understanding of how climate extremes have evolved in the Nouhao sub-basin over the past forty years, revealing a distinct dichotomy between the behavior of precipitation and temperature. The analysis of extreme precipitation indices demonstrates the dominant influence of strong multi-decadal variability, a characteristic feature of the Sahelian climate. The absence of a clear, monotonic trend for indices like consecutive dry days, consecutive wet days, and maximum one- and five-day rainfall over the full 1981-2020 period indicates that the rainfall regime in this part of Burkina Faso is not undergoing a simple, unidirectional shift towards either aridity or pluvial conditions. Instead, it is characterized by significant oscillations between wetter and drier phases on decadal timescales, which aligns with the well-documented history of the Sahel, including the severe droughts of the 1970s and 1980s and the partial recovery or "regreening" observed in some areas since the 1990s.

However, despite the lack of a long-term monotonic trend, the data do reveal potentially important decadal-scale changes. The suggestion of a recent increase in the length of dry spells in the last decade, coupled with the more pronounced and nearly significant decline in the intensity of five-day maximum rainfall since the early 2000s, points to a possible shift in the nature of the rainfall regime. This pattern, where rainfall may be becoming less frequent but with events that are potentially less intense in terms of prolonged heavy rainfall, could have significant implications for water resource management. It could mean longer dry periods between rainfall events, increasing crop water stress, while the reduced intensity of prolonged wet spells might lessen the risk of large-scale flooding. These observations are broadly consistent with findings from other recent studies in West Africa, which have noted changes in the structure of the rainy season and a tendency towards more intense but shorter-duration rainfall events in some locations, although the spatial patterns are complex and highly variable. The contrasting trends observed between the RX1day and RX5day indices in the most recent decades also underscore the importance of analyzing multiple facets of extreme rainfall, as daily and multi-day extremes may respond differently to large-scale climatic drivers.

In stark contrast to the variable and non-linear behavior of precipitation, the temperature indices present a clear, consistent, and unambiguous signal of progressive warming. The significant increase in warm nights, particularly in the last decade, alongside the gradual decline in cool nights, and the corresponding increases in warm days, paint a coherent picture of a region undergoing sustained thermal intensification. The particularly strong and statistically significant trend in warm nights suggests that nighttime temperatures are rising faster than daytime temperatures, a phenomenon observed in many parts of the world and linked to factors such as increased atmospheric moisture and changes in cloud cover, which trap outgoing longwave radiation. This warming has profound implications. Increased nighttime temperatures can reduce the recovery period for both humans and crops from daytime heat stress, potentially impacting human health, particularly among vulnerable populations, and affecting critical physiological processes in plants, such as respiration, which can lead to lower crop yields. The increase in hot days directly increases heat stress on humans, livestock, and crops, raises evapotranspiration rates, and can exacerbate water scarcity.

The spatial analysis adds another critical layer to this understanding by revealing that these changes are not uniform across the basin. The spatial heterogeneity in both precipitation and temperature extremes highlights the importance of local factors, such as topography, land cover, and perhaps localized climate feedbacks, in modulating the expression of large-scale climate change. For instance, while the southern part of the basin appears to be experiencing an intensification of heavy daily rainfall, the central and northern areas show different patterns for dry spell length. This spatial variability has direct implications for adaptation planning. A one-size-fits-all approach will not be sufficient. Instead, interventions must be tailored to the specific risks and conditions of different localities within the basin. For water resource managers, these findings provide crucial evidence for scenario planning. The lack of a clear trend in total precipitation, combined with the warming temperatures, suggests that water availability will be increasingly stressed by higher evaporative demand, even if total rainfall does not change dramatically. The potential for longer dry spells interspersed with intense rainfall events points to a future with a more volatile hydrological cycle, demanding more flexible and resilient water storage and management systems.

5. CONCLUSION

This comprehensive study of climate extremes in the Nouhao sub-basin of Burkina Faso, spanning the forty-year period from 1981 to 2020, has yielded critical insights into the region's evolving climate, revealing a complex dichotomy between precipitation and temperature dynamics. The analysis of extreme precipitation indices demonstrates that the rainfall regime is characterized by profound multi-decadal variability rather than a simple, long-term monotonic trend. While no statistically significant long-term trend was detected for indices like consecutive dry days, consecutive wet days, or maximum one- and five-day rainfall, the data do reveal important decadal-scale fluctuations and a recent, near-significant decline in the intensity of prolonged heavy rainfall events. This suggests a potentially evolving rainfall regime where the risk of agricultural drought from longer dry spells may be increasing, while the threat of extreme flooding from sustained heavy rainfall may be showing a complex and non-linear trajectory. These findings underscore the persistent uncertainty inherent in Sahelian rainfall and the critical need for water resource management strategies that are robust to a wide range of possible conditions.

In stark contrast to the variability of rainfall, the analysis of extreme temperature indices reveals an unambiguous and powerful signal of progressive climatic warming. The results show a clear, consistent, and statistically significant trend towards a decrease in cold extremes, with fewer cool nights and cool days, and a concurrent, statistically significant increase in hot extremes, particularly a marked rise in the frequency of exceptionally warm nights over the last decade. This warming is not just a subtle shift in averages but a profound change in the thermal regime of the basin, with direct and far-reaching implications for human health, agricultural productivity, water resources, and ecosystem function. The spatial analysis further underscores that these changes are not uniform, highlighting the need for locally tailored adaptation responses.

Together, these results constitute a critical climate signal for the Nouhao sub-basin. They confirm the complexity of local hydroclimatic regimes and provide essential scientific evidence that can directly inform and support decision-making. The findings highlight an urgent need to integrate not only regional climate projections but also detailed, sectoral impact analyses into planning processes. Such integration is essential to better anticipate the future, multi-faceted effects of climate change, including the combined stresses of increased heat and potentially altered water availability. This evidence base is fundamental for supporting the development of robust and effective adaptation strategies that are tailored to the specific context of the Nouhao basin. These strategies must address both the immediate challenges of increasing heat stress and the long-term uncertainties surrounding water resources, ultimately aiming to build resilience and enhance the capacity of local communities and ecosystems to thrive in a changing climate. Future research should focus on refining these analyses with higher-resolution models, exploring the underlying drivers of the observed changes, and working directly with local stakeholders to translate these scientific findings into actionable, on-the-ground adaptation measures.

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