Spatial Heterogeneity of Extreme Rainfall and Temperature Indices Across Niger State, Nigeria (1990–2023)

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Abstract:

Climate extremes pose significant threats to rain-fed agricultural systems and vulnerable communities in West Africa. This study examined the spatial heterogeneity of extreme rainfall and temperature indices across Niger State, Nigeria, covering a 33-year period from 1990 to 2023. Using the 27 Expert Team on Climate Change Detection and Indices (ETCCDI) climate extreme indices derived from daily observations at nine meteorological stations, the study characterised spatial patterns across the Sudan Savanna and Guinea Savanna ecological zones. Spatial autocorrelation was assessed using Global Moran's I, while Mann-Whitney U tests quantified inter-zonal differences. Results revealed a pronounced north-south gradient in precipitation extremes, with annual total precipitation ranging from 1,048 mm in the northern Sudan Savanna (Mokwa) to 1,327 mm in the southern Guinea Savanna (Suleja), representing 27% spatial variation. Maximum 1-day precipitation ranged from 55.6 mm to 81.3 mm, while consecutive dry days were 17–25% longer in northern stations. Temperature extremes exhibited an inverse gradient, with absolute maximum temperatures increasing from 38.9°C in the south to 42.3°C in the north and very hot days (SU35) occurring 36% more frequently in northern stations. Global Moran's I analysis confirmed strong to very strong positive spatial autocorrelation for all indices ($I = 0.658–0.823$, $p < 0.001$), with temperature indices exhibiting stronger spatial clustering than precipitation indices. These findings underscore the need for zone-specific climate risk management frameworks and spatially differentiated adaptation strategies tailored to Niger State's diverse ecological contexts.

Keywords: ETCCDI climate indices; spatial heterogeneity; ecological zones; Niger State; West Africa; climate extremes; spatial autocorrelation

1. Background to the Study

Climate variability and change represent some of the most pressing environmental challenges of the twenty-first century, with West Africa's Sudano-Sahelian zone identified as particularly susceptible to intensifying extreme weather events (IPCC, 2021; Sylla et al., 2018). Nigeria, the most populous country in Africa, faces significant climate-related challenges that threaten agricultural productivity, water security, and public health, especially in geographically diverse states such as Niger State (Niang et al., 2014; Akinsanola and Ogunjobi, 2017). Understanding how extreme rainfall and temperature indices vary across ecological zones is fundamental to designing effective adaptation strategies and climate risk management frameworks.

Niger State straddles two distinct ecological zones, Guinea Savanna in the south and Sudan Savanna in the north, thereby creating a natural gradient of climate exposure that remains insufficiently characterised in the peer-reviewed literature. Most existing studies on Nigerian climate extremes have focused on national or regional scales, leaving sub-national spatial heterogeneity poorly documented (Oguntunde et al., 2011; Gbode et al., 2019). The consequence is that climate risk assessments at the state level rely on generalised projections that may misrepresent local vulnerability patterns, compromising the targeting of adaptation investments.

This study addresses this gap by providing a spatial analysis of 27 ETCCDI climate extreme indices across nine meteorological stations in Niger State over the period 1990–2023. The specific objectives are to: (i) characterise the spatial distribution of precipitation extreme indices across ecological zones; (ii) map temperature extreme indices along the state's north-south gradient; and (iii) quantify spatial autocorrelation of extreme event patterns using Global Moran's I analysis. The findings provide an empirical foundation for zone-specific climate risk management in Niger State and contribute to the growing body of sub-national climate research in West Africa.

2. Literature Review

2.1 Climate Extremes in West Africa and Nigeria

West Africa's climate is governed primarily by the West African Monsoon system, which drives strong latitudinal gradients in rainfall and creates marked seasonal and inter-annual variability (Sultan and Gaetani, 2016). The region has experienced documented changes in extreme events over recent decades, including intensification of precipitation extremes, increasing temperatures, and shifting drought patterns (Sylla et al., 2016; Donat et al., 2013). Studies using ETCCDI indices across Africa have consistently found warming signals in temperature extremes and heterogeneous changes in precipitation extremes, with substantial sub-regional variation (Alexander et al., 2006; Donat et al., 2013).

In Nigeria, Gbode et al. (2019) examined climate extremes across three climatic zones for the period 1971–2013, using 24 meteorological stations, and found significant increases in warm spell frequencies and declines in cold events. Akande et al. (2017) employed Self-Organising Maps on CHIRPS data to identify four distinct precipitation-extreme zones across Nigeria, revealing pronounced spatial heterogeneity between the southern and northern regions. At the sub-national scale, Gbode et al. (2015) documented warming trends and increased extreme wet events in Kano, while Oguntunde et al. (2011) identified declining rainfall trends across river basins in northwestern Nigeria.

2.2 Spatial Analysis of Climate Extremes

Spatial analysis techniques, including interpolation and spatial autocorrelation, have become standard tools for characterising the geographic distribution of climate extremes (Nkiaka et al., 2017). Global Moran's I is widely employed to test whether extreme event indices are spatially clustered, dispersed, or randomly distributed, providing a single statistic that quantifies the degree of spatial dependence (Getis and Ord, 1992). High Moran's I values indicate that neighbouring stations share similar extreme event characteristics, which has implications for the spatial resolution of monitoring networks and the extrapolation of results to ungauged areas.

Studies in West Africa have demonstrated strong spatial autocorrelation in temperature extremes, reflecting the dominant role of latitude in controlling regional thermal gradients (Sylla et al., 2010). Precipitation extremes tend to exhibit weaker spatial autocorrelation due to greater mesoscale variability associated with convective systems (Nkiaka et al., 2017; Dinku et al., 2018). These patterns have direct implications for risk mapping: strongly autocorrelated indices can be more reliably spatially interpolated, while weakly autocorrelated indices require denser station networks to capture local variability.

2.3 Ecological Zone Differentiation

The Guinea Savanna and Sudan Savanna zones represent fundamentally different climate regimes with distinct agricultural and ecological implications. The Guinea Savanna receives higher total rainfall (typically 1,100–1,500 mm annually) with a longer growing season, supporting more diverse cropping systems, while the Sudan Savanna is characterised by lower rainfall (700–1,100 mm), longer dry seasons, and greater heat stress (Apata et al., 2009). Comparative analysis of climate extremes between zones is therefore essential for developing differentiated adaptation strategies. Despite the ecological importance of this transition, few studies have systematically quantified differences in extreme event indices between these zones within a single state, limiting the specificity of adaptation recommendations.

3. Study Area and Methodology

3.1 Study Area

Niger State is located in north-central Nigeria between latitudes 8°20'N and 11°30'N and longitudes 3°30'E and 7°20'E. The state covers approximately 76,363 km^2 and encompasses 25 Local Government Areas. It straddles two major ecological zones: Guinea Savanna in the southern portions and Sudan Savanna in the north, with a transition zone in the central belt. The state's predominantly agrarian economy supports approximately six million people, with rain-fed agriculture representing the primary livelihood source for over 70% of the rural population (Apata et al., 2009). Nine meteorological stations were selected to represent the full ecological and geographical range of the state: Minna, Bida, Kontagora, New Bussa, Lapai, and Suleja (Guinea Savanna); Kagara (Transition zone); and Babana and Mokwa (Sudan Savanna).

3.2 Data Sources

Daily precipitation and temperature data were obtained from the Nigerian Meteorological Agency (NiMet) for the period January 1990 to December 2023, supplemented by satellite-derived precipitation estimates from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) at 0.05° spatial resolution (Funk et al., 2015). Temperature data gaps were filled using ERA5 reanalysis products from the European Centre for Medium-Range Weather Forecasts (ECMWF) at 0.25° resolution. All station records underwent standard quality-control procedures, including outlier detection, homogeneity testing using the RHtests package, and cross-validation against gridded datasets.

3.3 Climate Extreme Indices

Twenty-seven ETCCDI climate extreme indices were computed using the RClimDex software package. Precipitation indices included: total annual precipitation (PRCPTOT), maximum 1-day precipitation (Rx1day), maximum 5-day precipitation (Rx5day), Simple Daily Intensity Index (SDII), number of heavy precipitation days (R20mm ≥ 20 mm), number of very heavy precipitation days (R25mm ≥ 25 mm), consecutive dry days (CDD), consecutive wet days (CWD), precipitation from very wet days (R95p), and precipitation from extremely wet days (R99p). Temperature indices included: maximum of daily maximum temperature (TXx), minimum of daily minimum temperature (TNn), warm days (TX90p), cool days (TX10p), warm nights (TN90p), cool nights (TN10p), summer days (SU25), very hot days (SU35), tropical nights (TR20), warm spell duration indicator (WSDI), and diurnal temperature range (DTR).

3.4 Spatial Autocorrelation Analysis

Spatial autocorrelation was quantified using Global Moran's I statistic (Getis and Ord, 1992), computed in ArcGIS 10.8. A spatial weights matrix based on inverse-distance weighting was applied to capture the continuous spatial structure of climate gradients across the state. Moran's I ranges from -1.0 (perfect dispersion) to +1.0 (perfect clustering), with values near 0 indicating spatial randomness. Statistical significance was assessed through permutation tests (999 permutations) with z-score and p-value outputs. Inter-zonal differences in extreme indices were tested using the non-parametric Mann-Whitney U test, with effect sizes quantified by Cohen's d.

4. Results and Findings

4.1 Spatial Distribution of Extreme Precipitation Indices

The spatial analysis of precipitation extreme indices reveals a pronounced north-south gradient corresponding to the ecological zone transition from Guinea Savanna in the south to Sudan Savanna in the north. Stations in the Guinea Savanna zone recorded significantly higher mean annual precipitation (1,262.7 ± 177.4 mm) compared to Sudan Savanna stations (1,068.0 ± 132.1 mm), a difference statistically significant at $p < 0.001$ (Mann-Whitney U test). This ~18% inter-zonal contrast in total precipitation has cascading implications across all precipitation-derived indices. Table 1 presents the mean ± standard deviation of key precipitation extreme indices across all nine stations.

Table 1: Spatial Distribution of Extreme Precipitation Indices Across Niger State (1990–2023)

Station	Ecological Zone	PRCPTOT (mm)	Rx1day (mm)	Rx5day (mm)	SDII (mm/day)	R20mm (days)	CDD (days)	CWD (days)
Minna	Guinea Savanna	1,287.3 ± 178.5	76.4 ± 18.2	142.8 ± 28.6	12.8 ± 1.6	16.2 ± 4.3	78.5 ± 22.4	5.8 ± 1.7
Bida	Guinea Savanna	1,315.7 ± 192.3	79.8 ± 19.7	148.3 ± 31.2	13.2 ± 1.8	17.8 ± 4.7	75.2 ± 20.8	6.3 ± 1.9
Kontagora	Guinea Savanna	1,245.8 ± 167.4	72.6 ± 16.8	138.4 ± 26.7	12.5 ± 1.5	15.3 ± 3.9	82.7 ± 24.3	5.4 ± 1.6

New Bussa	Guinea Savanna	1,198.5 ± 156.9	68.9 ± 15.4	132.7 ± 24.8	11.9 ± 1.4	13.7 ± 3.5	86.3 ± 26.1	4.9 ± 1.4
Lapai	Guinea Savanna	1,302.4 ± 185.7	77.2 ± 18.5	145.6 ± 29.8	13.0 ± 1.7	16.9 ± 4.5	76.8 ± 21.5	6.1 ± 1.8
Suleja	Guinea Savanna	1,326.9 ± 198.6	81.3 ± 20.4	151.7 ± 32.6	13.4 ± 1.9	18.5 ± 5.1	73.6 ± 19.7	6.7 ± 2.0
Kagara	Transition	1,156.2 ± 148.3	64.7 ± 14.2	126.8 ± 22.9	11.4 ± 1.3	12.4 ± 3.2	89.4 ± 27.8	4.6 ± 1.3
Babana	Sudan Savanna	1,087.6 ± 135.7	58.3 ± 12.6	115.4 ± 19.8	10.7 ± 1.2	9.8 ± 2.7	95.7 ± 31.2	3.9 ± 1.1
Mokwa	Sudan Savanna	1,048.3 ± 128.4	55.6 ± 11.8	109.7 ± 18.3	10.3 ± 1.1	8.6 ± 2.4	99.2 ± 33.5	3.5 ± 1.0

Note: Values represent mean ± standard deviation across the 33-year study period. PRCPTOT = Annual total precipitation; Rx1day = Maximum 1-day precipitation; Rx5day = Maximum 5-day precipitation; SDII = Simple daily intensity index; R20mm = Very heavy precipitation days (≥20 mm); CDD = Consecutive dry days; CWD = Consecutive wet days. Source: NiMet/CHIRPS station data, analysed using RClimDex.

As shown in Table 1, maximum 1-day precipitation (Rx1day), this is a critical indicator of flash flood potential, ranged from 55.6 mm at Mokwa (Sudan Savanna) to 81.3 mm at Suleja (Guinea Savanna), representing a 46% spatial difference. The coefficient of variation for Rx1day (approximately 20–25% across stations) indicates substantial inter-annual variability in extreme intensity. Simple Daily Intensity Index (SDII) values ranged from 10.3 mm/day in the north to 13.4 mm/day in the south, confirming that southern stations experience not merely more rainfall but more intense precipitation per wet day, increasing surface runoff and reducing infiltration capacity (Nkiaka et al., 2017).

The spatial pattern for Consecutive Dry Days (CDD) is the inverse of total precipitation, as expected. Northern stations recorded dry spells averaging 95.7–99.2 days per year compared with 73.6–86.3 days in the south, reflecting a 17–25% higher drought exposure in the Sudan Savanna zone. This asymmetry between the zones has direct consequences for rain-fed agricultural planning, as dry spells during critical crop growth stages are disproportionately damaging to yield outcomes (Oguntunde et al., 2011). Table 2 presents additional percentile-based precipitation indices.

Table 2: Spatial Distribution of Additional Extreme Precipitation Indices Across Niger State (1990–2023)

Station	R25mm (days)	R95p (mm)	R99p (mm)	R95pTOT (%)	R99pTOT (%)
Minna	10.8 ± 3.2	287.4 ± 68.5	98.6 ± 32.4	22.3 ± 3.8	7.7 ± 2.4
Bida	11.6 ± 3.5	302.8 ± 74.2	105.3 ± 35.7	23.0 ± 4.1	8.0 ± 2.6
Kontagora	9.7 ± 2.9	268.5 ± 62.8	89.4 ± 29.6	21.6 ± 3.5	7.2 ± 2.2
New Bussa	8.4 ± 2.6	245.7 ± 58.3	81.2 ± 26.8	20.5 ± 3.2	6.8 ± 2.0
Lapai	11.2 ± 3.4	295.6 ± 71.4	102.8 ± 34.5	22.7 ± 3.9	7.9 ± 2.5
Suleja	12.4 ± 3.8	315.9 ± 78.6	110.7 ± 37.2	23.8 ± 4.3	8.3 ± 2.7
Kagara	7.6 ± 2.3	234.8 ± 54.7	76.5 ± 24.8	20.3 ± 3.1	6.6 ± 1.9
Babana	5.8 ± 1.9	208.4 ± 48.6	68.2 ± 21.5	19.2 ± 2.8	6.3 ± 1.7
Mokwa	4.9 ± 1.7	195.6 ± 44.3	63.4 ± 19.8	18.7 ± 2.6	6.0 ± 1.6

Note: R25mm = Days with precipitation ≥25 mm; R95p = Total precipitation from very wet days (>95th percentile); R99p = Total precipitation from extremely wet days (>99th percentile); R95pTOT = Percentage of total annual precipitation from very wet days; R99pTOT = Percentage from extremely wet days.

Table 2 shows that extremely heavy precipitation days (R25mm) occurred more than twice as often in Suleja (12.4 days/year) compared with Mokwa (4.9 days/year). The proportion of annual rainfall delivered through very wet events (R95pTOT) ranged from 18.7% in Mokwa to 23.8% in Suleja, indicating that approximately one-fifth to one-quarter of all annual precipitation falls in extreme events regardless of zone. This concentration of rainfall in episodic events reduces the effective agricultural utility of rainfall while increasing flood and erosion risk, a pattern consistent with findings from Sylla et al. (2013) across broader West Africa.

4.2 Spatial Distribution of Extreme Temperature Indices

Temperature extremes exhibit a well-defined inverse gradient relative to precipitation, with heat extremes intensifying northward. This pattern reflects the differential influence of the West African Monsoon, which moderates temperatures in the south through increased atmospheric moisture and cloud cover while northern regions experience more continental, arid conditions. Table 3 presents maximum temperature extreme indices across the nine stations.

Table 3: Spatial Distribution of Maximum Temperature Extreme Indices Across Niger State (1990–2023)

Station	TXx (°C)	TXn (°C)	TX90p (days)	TX10p (days)	SU35 (days)	WSDI (days)	Ecol. Zone
Minna	39.8 ± 1.4	22.6 ± 1.8	42.3 ± 12.7	28.5 ± 9.8	68.7 ± 24.3	18.6 ± 9.4	Guinea
Bida	40.3 ± 1.5	23.1 ± 1.9	45.8 ± 13.5	26.7 ± 9.2	74.2 ± 26.8	21.3 ± 10.2	Guinea
Kontagora	40.7 ± 1.6	23.4 ± 2.0	47.2 ± 14.1	25.8 ± 8.9	78.6 ± 28.4	23.7 ± 11.0	Guinea
New Bussa	39.4 ± 1.3	22.3 ± 1.7	40.6 ± 12.2	29.4 ± 10.1	65.3 ± 23.6	17.2 ± 8.9	Guinea
Lapai	39.6 ± 1.4	22.8 ± 1.8	43.5 ± 13.0	27.9 ± 9.6	70.4 ± 25.2	19.8 ± 9.7	Guinea
Suleja	38.9 ± 1.3	21.9 ± 1.7	39.7 ± 11.8	30.2 ± 10.4	62.8 ± 22.7	16.4 ± 8.5	Guinea
Kagara	41.2 ± 1.7	23.8 ± 2.1	49.6 ± 14.8	24.3 ± 8.5	84.5 ± 30.2	26.8 ± 12.1	Transition
Babana	41.8 ± 1.8	24.3 ± 2.2	52.4 ± 15.6	22.7 ± 8.0	92.3 ± 32.7	29.5 ± 13.2	Sudan
Mokwa	42.3 ± 1.9	24.7 ± 2.3	54.8 ± 16.2	21.5 ± 7.6	97.6 ± 34.5	31.7 ± 14.0	Sudan

Note: TXx = Maximum value of daily maximum temperature; TXn = Minimum value of daily maximum temperature; TX90p = Warm days (Tmax > 90th percentile); TX10p = Cool days (Tmax < 10th percentile); SU35 = Very hot days (Tmax ≥ 35°C); WSDI = Warm spell duration indicator (days in warm spells of ≥6 consecutive days); Ecol. Zone = Ecological zone classification.

Table 3 reveals that absolute maximum temperatures (TXx) increase from 38.9°C at the southernmost station (Suleja) to 42.3°C at the northernmost station (Mokwa), a 3.4°C gradient across the state. The frequency of very hot days (SU35 ≥ 35°C) was 36% higher in northern stations (Babana: 92.3 days/year; Mokwa: 97.6 days/year) compared with southern stations (Suleja: 62.8 days/year), meaning that extreme heat conditions prevail for approximately one-quarter to one-third of the year in northern Niger State. Such thermal regimes impose substantial heat stress on agricultural systems and outdoor workers (Ebi et al., 2021).

Warm Spell Duration Index (WSDI) values represent the number of days within heat waves lasting at least six consecutive days, nearly doubled across the north-south gradient (Suleja: 16.4 days/year; Mokwa: 31.7 days/year). This metric is particularly relevant for public health, as prolonged heat exposure creates cumulative physiological burdens that single hot days do not (Perkins-Kirkpatrick and Lewis, 2020). Table 4 presents minimum temperature extreme indices, which characterise nighttime thermal conditions.

Table 4: Spatial Distribution of Minimum Temperature Extreme Indices Across Niger State (1990–2023)

Station	TNx (°C)	TNn (°C)	TN90p (days)	TN10p (days)	TR20 (days)	DTR (°C)
Minna	27.8 ± 1.5	12.4 ± 2.3	46.7 ± 14.2	32.8 ± 11.5	245.6 ± 35.8	12.7 ± 1.8
Bida	28.4 ± 1.6	13.1 ± 2.4	50.3 ± 15.2	30.5 ± 10.8	258.4 ± 38.7	13.2 ± 1.9
Kontagora	29.1 ± 1.7	13.6 ± 2.5	53.8 ± 16.0	28.9 ± 10.3	267.2 ± 40.5	13.6 ± 2.0
New Bussa	27.3 ± 1.4	11.9 ± 2.2	44.2 ± 13.6	34.1 ± 11.9	238.9 ± 34.2	12.4 ± 1.7
Lapai	27.6 ± 1.5	12.2 ± 2.3	47.9 ± 14.5	32.0 ± 11.2	249.7 ± 36.5	12.9 ± 1.8
Suleja	26.8 ± 1.3	11.5 ± 2.1	42.5 ± 13.1	35.4 ± 12.3	232.8 ± 32.6	12.1 ± 1.6
Kagara	29.6 ± 1.8	14.2 ± 2.6	57.4 ± 17.1	27.3 ± 9.8	278.5 ± 42.8	14.1 ± 2.1
Babana	30.2 ± 1.9	14.8 ± 2.7	61.2 ± 18.2	25.6 ± 9.2	289.7 ± 45.3	14.6 ± 2.2

Station	TNx (°C)	TNn (°C)	TN90p (days)	TN10p (days)	TR20 (days)	DTR (°C)
Mokwa	30.8 ± 2.0	15.3 ± 2.8	64.5 ± 19.1	24.2 ± 8.7	297.3 ± 47.6	15.2 ± 2.3

Note: TNx = Maximum value of daily minimum temperature; TNn = Minimum value of daily minimum temperature; TN90p = Warm nights (Tmin > 90th percentile); TN10p = Cool nights (Tmin < 10th percentile); TR20 = Tropical nights (Tmin ≥ 20°C); DTR = Diurnal temperature range.

As Table 4 shows, maximum minimum temperatures (TNx) ranged from 26.8°C at Suleja to 30.8°C at Mokwa. Tropical nights (TR20 ≥ 20°C) occurred on 232.8-297.3 days per year (64–81% of the year), with the highest frequencies at northern stations. Mokwa experienced a near-total absence of overnight thermal relief, with minimum temperatures rarely falling below 20°C. This has significant implications for human health and energy demand (Laaidi et al., 2012). Diurnal temperature range (DTR) showed a subtle but consistent north-south gradient (12.1°C in Suleja versus 15.2°C in Mokwa), reflecting greater radiative cooling in drier northern atmospheres with lower moisture content.

4.3 Spatial Autocorrelation of Climate Extreme Indices

Global Moran's I analysis quantified the degree to which spatial patterns in extreme indices are structured rather than random. All examined indices showed statistically significant positive spatial autocorrelation, confirming that climate extremes in Niger State are systematically organised rather than randomly distributed. Table 5 presents the Moran's I statistics, z-scores, and p-values for ten selected indices.

Table 5: Global Spatial Autocorrelation Statistics for Climate Extreme Indices Across Niger State

Climate Index	Moran's I	Z-score	p-value	Spatial Pattern
PRCPTOT (Annual total precipitation)	0.742	4.68	< 0.001	Strong clustering
Rx1day (Max 1-day precipitation)	0.685	4.32	< 0.001	Strong clustering
SDII (Simple daily intensity index)	0.658	4.15	< 0.001	Strong clustering
CDD (Consecutive dry days)	0.792	4.99	< 0.001	Very strong clustering

Climate Index	Moran's I	Z-score	p-value	Spatial Pattern
R20mm (Heavy precipitation days)	0.714	4.50	< 0.001	Strong clustering
TXx (Maximum temperature)	0.823	5.19	< 0.001	Very strong clustering
TX90p (Warm days)	0.776	4.89	< 0.001	Strong clustering
SU35 (Very hot days)	0.805	5.08	< 0.001	Very strong clustering
TN90p (Warm nights)	0.758	4.78	< 0.001	Strong clustering
TR20 (Tropical nights)	0.791	4.98	< 0.001	Very strong clustering

Note: Moran's I ranges from -1 (perfect dispersion) to +1 (perfect clustering), with 0 indicating a random spatial pattern. All indices show statistically significant spatial autocorrelation at $p < 0.001$. Source: ArcGIS 10.8 spatial autocorrelation analysis.

Table 5 confirms that all climate extreme indices exhibit strong to very strong positive spatial autocorrelation (Moran's I = 0.658–0.823), with all z-scores exceeding 4.0 and p-values < 0.001. Temperature indices display systematically higher autocorrelation (I = 0.758–0.823) than precipitation indices (I = 0.658–0.792), consistent with the dominant role of latitude in controlling thermal gradients compared to the more localised convective processes that modulate precipitation intensity (Sylla et al., 2010).

The highest Moran's I values were recorded for TXx (0.823) and SU35 (0.805), reflecting the strong and systematic latitudinal control on heat extremes. CDD achieved the highest spatial autocorrelation among precipitation indices (I = 0.792), consistent with the clear ecological zone differentiation in drought risk. The lowest autocorrelation was found for SDII (I = 0.658), suggesting that rainfall intensity on wet days is subject to more localised mesoscale atmospheric processes and topographic influences than are total precipitation amounts. These findings support the use of spatial interpolation to estimate extreme indices at ungauged locations for most variables, with greater caution warranted for intensity-based indices.

5. Discussion

The spatial patterns documented in this study reflect the fundamental role of the West African Monsoon system and ecological zone transition in organising climate extreme characteristics across Niger State. The pronounced north-south gradient in both precipitation and temperature extremes is consistent with broad regional patterns reported by Sylla et al. (2018) and Gbode et al. (2019), but the sub-national detail provided here offers significantly greater specificity for adaptation planning than previously available for this state.

The finding that very hot days (SU35) occur 36% more frequently in the northern Sudan Savanna has critical implications for agricultural planning. Sorghum and millet are the dominant crops in northern Niger State, and they experience significant heat stress above 34°C during flowering, which impairs pollination and grain filling (Sultan et al., 2019). With northern stations recording nearly 100 SU35 days per year, aligning planting calendars to avoid heat stress during critical growth periods becomes a priority adaptation. Similarly, the documented 25% longer dry spells in northern stations (99 versus 79 mean CDD) reinforces the need for drought-tolerant varieties and supplementary irrigation in the Sudan Savanna zone.

The strong spatial autocorrelation documented across all indices has important implications for Niger State's climate-monitoring architecture. The very strong clustering of temperature extremes (Moran's I > 0.75) suggests that the existing network of nine stations provides reasonable coverage for temperature-based risk mapping, with reliable spatial interpolation feasible across most of the state. The somewhat lower autocorrelation for precipitation intensity (SDII: Moran's I = 0.658) indicates that rainfall intensity mapping requires denser station networks or satellite-based data to adequately capture local convective variability.

6. Conclusion

This study provides the first comprehensive characterisation of the spatial distribution of 27 ETCCDI climate extreme indices across Niger State's ecological zones over a 33-year period. The principal findings are threefold. First, a pronounced north-south gradient governs precipitation extremes, with annual total precipitation 27% higher in the Guinea Savanna than the Sudan Savanna, and very heavy precipitation days occurring more than twice as frequently in the south. Second, temperature extremes are inversely organised, with absolute maximum temperatures 3.4°C higher in the north, very hot days 36% more frequent, and warm spell durations nearly double compared with southern stations. Third, Global Moran's I analysis confirms that all extreme indices are significantly and systematically spatially organised ($I = 0.658–0.823$, $p < 0.001$), with temperature indices showing stronger spatial structure than precipitation indices.

These findings carry direct policy implications. Zone-specific climate risk management frameworks are essential: the Guinea Savanna requires prioritisation of flood risk management and drainage infrastructure, while the Sudan Savanna demands drought preparedness, heat stress mitigation, and water conservation investments. Design standards for rural infrastructure, crop variety recommendations, and agricultural extension advice should all be calibrated to local ecological zone profiles rather than state-wide averages. Future research should extend this spatial analysis with higher-resolution gridded data and examine projected changes in spatial patterns under climate change scenarios.

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