Analysis of rainfall and temperature trends in Eswatini from 1981 to 2020: A perspective of climate change and variability

AUTHORS:
Thandeka Ndlela[1]
Lungile S. Sifundza[2]
Heinz Beckedahl[1,3]
Thandi Kapwata[4,5]
Tracey L. Laban[5,6]
Nomfundo Mahlangeni[7]
Caradee Y. Wright[1,5,6]

AFFILIATIONS:
[1]Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Pretoria, South Africa
[2]Department of Agricultural and Biosystems Engineering, University of Eswatini, Luyengo, Eswatini
[3]Department of Geography, Environmental Science and Planning, Centre for Climate Change and Sustainability Research, University of Eswatini, Kwaluseni, Eswatini
[4]Environment and Health Research Unit, South African Medical Research Council, Johannesburg, South Africa
[5]Department of Environmental Health, University of Johannesburg, Johannesburg, South Africa
[6]Environment and Health Research Unit, South African Medical Research Council, Pretoria, South Africa
[7]Environment and Health Research Unit, South African Medical Research Council, Cape Town, South Africa

CORRESPONDENCE TO:
Thandeka Ndlela

EMAIL:
thandekavndlela@gmail.com

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Rainfall and temperature are key climatic indicators essential for monitoring climate variability and change. Understanding long-term trends in these parameters is crucial for evidence-based policy formulation, particularly in vulnerable regions. We examined rainfall and temperature trends in Eswatini over a 40-year period (1981–2020) using meteorological data from five physiographic regions. Trends in monthly, seasonal and annual rainfall, alongside minimum and maximum temperatures, were analysed using the Mann–Kendall test and Sen's slope estimator. The results reveal high interannual variability and shifting seasonal precipitation patterns, with an overall decline in annual rainfall. Statistically significant declines were noted in June and October, especially in the Lowveld and Highveld regions, whereas certain summer months (December to February) recorded increasing rainfall trends at some stations. Temperature analysis indicated significant warming trends in maximum temperature at four stations (Big Bend, Mbabane, Malkerns and Nhlangano), with increases in minimum temperature most evident in Mbabane and Big Bend. A cooling trend was observed at Mhlume in the Western Lowveld, highlighting geographic temperature variability. These findings align with regional studies that have reported increased climate variability across southern Africa. The results emphasise the urgency of implementing adaptive strategies, including improved water resource management and the development of early warning systems. This research provides a foundation for informed climate policy interventions in Eswatini.

Significance:

This study provides a detailed assessment of long-term rainfall and temperature trends in Eswatini based on meteorological station data from 1981 to 2020. The findings show a general decline in rainfall and rising temperatures, with important seasonal and geographical differences across the country's physiographic regions. These changes have implications for water availability, ecological function and the vulnerability of climate-sensitive ecosystems. By linking observed trends to broader regional patterns and known climate drivers such as the El Niño-Southern Oscillation, the study offers a baseline for national climate planning and contributes to a better understanding of climate variability in southern Africa.

Introduction

Rainfall and temperature are fundamental climatic variables that serve as primary indicators of climate variability and long-term change. Globally, numerous studies have documented significant shifts in these parameters, with implications for ecosystem functioning, agricultural productivity and human well-being.[1,2] Increasing climatic variability has heightened concerns regarding the vulnerability of small countries like the Kingdom of Eswatini, a landlocked nation whose diverse ecosystems are highly sensitive to shifts in rainfall and temperature.[3,4] Despite its modest size, Eswatini faces severe and recurring climate-related challenges, including prolonged dry spells, erratic rainfall and rising temperatures.[5,6] These trends have contributed to water scarcity and increased ecological and social vulnerability.[4,6] In 2021, for example, Cyclone Eloise triggered devastating flooding that displaced thousands and damaged critical infrastructure, highlighting the country's exposure to extreme weather events.[7]

Regional climate model evaluations (e.g. the Coordinated Regional Climate Downscaling Experiment Africa regional climate models) demonstrate skill in reproducing rainfall variability, providing a foundation for understanding how combined warming and rainfall reduction may exacerbate drought severity in arid and semi-arid regions across southern Africa.[8] Historical temperature data from Eswatini between 1961 and 2020 show a warming trend, particularly in daily minimum temperatures (Tmin), which is consistent with broader regional patterns.[3,9] Rainfall trends, however, remain more complex and spatially heterogeneous, with studies reporting changes in the timing, intensity and duration of rainfall events, including delayed onset of the rainy season and increased frequency of intra-seasonal dry spells.[10] These rainfall fluctuations are influenced in part by large-scale climate drivers such as the El Niño-Southern Oscillation (ENSO), which has been linked to major drought events in Eswatini, including those between 1991–1992 and 2015–2016.[11]

Physiographic regions in Eswatini experience different levels of climatic variability. The Lowveld is characterised by high rainfall variability (up to 34%), whereas the Highveld and Middleveld record slightly lower but still significant interannual fluctuations of 25% and 23%, respectively.[12] These fluctuations affect water resources and hydrologically sensitive ecosystems, especially in rural areas where reliable rainfall supports livelihoods and ecological stability. For example, some wetlands can be highly sensitive to variability in precipitation. Changes in rainfall timing and intensity can disrupt their hydrological balance, with consequences for vegetation composition, soil development and the ecosystems they provide.[13-15]

Given these dynamics, characterising long-term trends in rainfall and temperature is essential for formulating evidence-based climate adaptation and mitigation strategies. Although several national and regional reports have highlighted climate risks in Eswatini, there is limited empirical analysis that systematically evaluates historical rainfall and temperature trends across physiographic regions. In this study, therefore, we aimed to analyse trends in monthly, seasonal and annual rainfall and temperature between 1981 and 2020, using meteorological station-level

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observations and robust statistical methods. The results offer insights into spatial and temporal patterns of climate change in Eswatini and inform policy responses in water management, ecosystem resilience and disaster risk reduction. Although the analysis does not explicitly examine the influence of the ENSO, the observed trends are interpreted in the context of known regional climate drivers, including ENSO-linked drought years.

Study area

The study was conducted in Eswatini, located in southern Africa between latitudes 25°43′S and 27°19′S and longitudes 31°47′E and 32°08′E.[16] The country is landlocked by the Republic of South Africa and Mozambique (Figure 1) and covers a total land surface area of 17 360 km^2.[17] Eswatini is characterised by a subtropical climate with cold, dry winters and warm, wet summers.[5,9] As such, most of the precipitation, approximately 75–83%, falls between October and March.[18]

The country is divided into six distinct physiographic regions based on elevation, terrain, climate, geology and soil: the Highveld (33%), Upper Middleveld (14%), Lower Middleveld (14%), Western Lowveld (20%), Eastern Lowveld (11%) and Lubombo Plateau (8%).[19,20] These regions range from cool and mountainous areas in the Highveld to hot and dry areas in the Lowveld. The Highveld, situated at the highest elevations, receives between 850 mm and 1500 mm of rainfall annually and has a mean temperature of approximately 17 °C. The Middleveld experiences intermediate conditions, with rainfall ranging from 650 mm to 1000 mm and mean temperatures of 20–21 °C. The Lowveld, which occupies the lowest elevations, is the driest and warmest region, receiving between 550 mm and 725 mm of rainfall and recording average temperatures of around 22 °C. The Lubombo Plateau, a narrow upland area along the eastern border, receives between 700 mm and 825 mm of rainfall annually, with a mean temperature of approximately 19 °C.[19-21]

Materials and methods

Rainfall and temperature data

Rainfall and temperature data were obtained from the Eswatini Meteorological Service. Monthly rainfall records were available for 14 stations across the six physiographic regions for the full period (1981–2020). However, due to gaps and missing values, temperature data (minimum temperature [Tmin] and maximum temperature [Tmax]) were limited in temporal coverage, with usable records available for only eight stations. Tmin and Tmax values refer to the average monthly minimum and maximum temperatures, rather than absolute extremes, thereby reducing the influence of outliers on trend estimation. For four stations, complete temperature records only began in 2000, constraining the temperature trend analysis to the 2000–2020 period for those sites. To ensure data reliability, only stations with at least a data completeness of 90% were included in the analysis (Table 1). Data completeness was assessed at a monthly level, such that stations were retained only if at least 90% of monthly observations within the analysis period contained valid records. Although this approach may limit representativeness, care was taken to ensure that most physiographic regions were reflected in the final data set. In addition, the annual series was visually inspected and checked for the persistence of repeated values. One rainfall station (Siteki, located in the Lubombo Plateau) contained an extended block of near-identical annual totals, which is implausible for the region and indicates a non-climatic artefact. Because this span dominated the record and could not be reliably corrected, Siteki was excluded from the analysis. Consequently, no rainfall or temperature station data were available for the Lubombo Plateau.

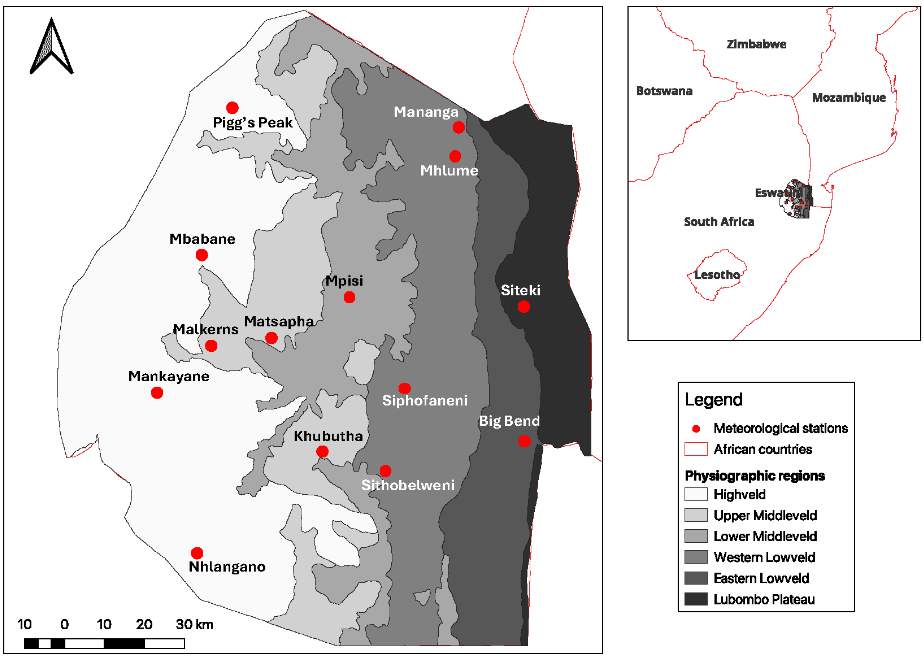

Figure 1: The six physiographic regions of Eswatini and the locations of meteorological stations. Siteki (Lubombo Plateau) is shown but was excluded from the analysis due to data quality issues. The inset map indicates the location of Eswatini within southern Africa.

Table 1: Summary of meteorological stations used in the study, including geographic location, physiographic region and data availability for rainfall and temperature (1981–2020). Only stations with a data completeness of ≥90% were included.

Physiographic region	Station	Latitude (S)	Longitude (E)	Parameters analysed	Temperature data available (years)
Highveld	Mankayane	−26.6753	31.0553	*R*	–
	Mbabane	−26.3171	31.1335	*R* and *T*	1981–2020
	Pigg's Peak	−25.8266	31.4267	*R* and *T*	2000–2020
	Nhlangano	−27.1277	31.2012	*R* and *T*	2000–2020
Upper Middleveld	Khubutha	−26.8667	31.4833	*R*	–
	Malkerns	−26.5567	31.8783	*R* and *T*	2000–2020
	Matsapha	−26.5332	31.3018	*R* and *T*	2000–2020
Lower Middleveld	Mpisi	−26.4322	31.5313	*R*	–
Western Lowveld	Mananga	−26.0005	31.7533	*R* and *T*	1981–2020
	Mhlume	−26.0333	31.1550	*R* and *T*	1981–2020
	Siphofaneni	−26.6733	31.6833	*R*	–
	Sithobelweni	−26.8865	31.6257	*R*	–
Eastern Lowveld	Big Bend	−26.8517	31.8763	*R* and *T*	1981–2020

R, rainfall data available; T, temperature data available

Rainfall records span the full study period (1981–2020); temperature data availability varies by station.

Data analysis

The analysis categorised each year into two hydrological seasons: the dry, cool season (April to September) and the wet, warm season (October to March). To detect trends in rainfall and temperature over time, two non-parametric statistical tests were applied: the Mann–Kendall trend test and Sen's slope estimator, using XLSTAT (2021), version 2.2.1141. These non-parametric methods were selected due to their robustness against non-normal distributions, which are common in climate data.[22] They are also well-suited for time-series analysis because they are relatively insensitive to outliers.[23,24]

The Mann–Kendall test[25,26] is commonly used in the trend detection of variables in the fields of meteorology and hydrology.[27] However, it gives the direction of the trend but not the magnitude of the trend. The Mann–Kendall test statistic S is calculated using the following formula:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i), \qquad \text{Equation 1}$$

where n is the total number of data points; x_i and x_j are the data values in the time series i and j, respectively ($j > i$); and $sgn(x_j - x_i)$ is the sign function, which is computed as follows:

$$sgn(x_j - x_i) = \{+1, \text{ if } x_j - x_i > 0;\ 0, \text{ if } x_j - x_i = 0;\ -1, \text{ if } x_j - x_i < 0\}. \qquad \text{Equation 2}$$

The variance is computed as

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(t_i - 1)(2t_i + 5)}{18}, \qquad \text{Equation 3}$$

where n is the number of data points, that is, the number of tied groups, and t_i refers to the number of data points in the ith group (with zero difference between compared values) to the extent i.

The values of S and $Var(S)$ are used to compute the test statistic Z_s as follows:

$$Z_s = \left\{ \frac{S-1}{\sqrt{Var(S)}}, \text{ if } S > 0;\ 0, \text{ if } S = 0;\ \frac{S+1}{\sqrt{Var(S)}}, \text{ if } S < 0 \right\}. \qquad \text{Equation 4}$$

The presence of a statistically significant trend is evaluated using the Z_s value. A positive value of Z_s indicates an upward trend whilst its negative value indicates a downward trend. In this study, a 95% confidence level was used to detect statistically significant trends, although lower percentages were used to see whether the correlation was significant.

To determine the magnitude of the rate of change of the trend, Sen's slope estimator was employed.[28] Sen's slope is first computed for N pairs of data as follows:

$$Q_i = \frac{x_j - x_k}{j - k} \text{ for } i = 1, \ldots, N \qquad \text{Equation 5}$$

where x_j and x_j are data values at times j and k ($j > k$), respectively.

If there is only one datum in each period, then $N = \frac{n(n-1)}{2}$, where n is the number of periods. If there are multiple observations in one or more time periods, then $N < \frac{n(n-1)}{2}$, where n is the total number of data points.

The median of the N values of Q_i is Sen's slope estimator of the slope of the best-fit line and is calculated as follows:

$$\beta = Median = \left(\frac{x_j - x_k}{j - k}\right), j > k \qquad \text{Equation 6}$$

where β is Sen's slope estimator of the rate of change. $\beta < 0$ indicates a downward trend in the given time period, whereas $\beta > 0$ points towards an upward trend in the time series. For this study, trends were considered significant at a 95% confidence level.

The coefficient of variation (CV) was used to assess the interannual variability of rainfall. Following Hare[29], CV values were classified as follows: <20% (low variability), 20–30% (moderate), 30–40% (high), 40–70% (very high) and >70% (extremely high).

Results

Overview of national-scale rainfall and temperature patterns

Figure 2 shows national-scale patterns in annual rainfall and Tmin and Tmax, based on spatially averaged values from all the meteorological stations used in the study. The analysis of long-term climatic data from 1981 to 2020 revealed a modest but consistent decreasing trend of the mean annual rainfall in Eswatini ($R^2 = 0.0456$), indicating high interannual variability and the limited explanatory power of the linear model (Figure 2A). Rainfall values fluctuated from year to year, with pronounced maxima. The highest total annual rainfall was recorded in 2000 at 1281.6 mm, followed by 1984 with 1215.6 mm. In contrast, the lowest totals occurred in 2015 and 1982, with 499 mm and 575.5 mm, respectively. Notably, some of the driest years, such as 1982 and 2015, coincide with strong El Niño events, whereas years of high rainfall, such as 2000, are associated with regional flood events.[5,6] Temperature records from 2000 to 2020 indicated a general warming trend, with Tmax increasing at a steeper rate than Tmin (Figures 2B and 2C). The lowest average Tmin values (14 °C) were recorded in 2000 and 2018, whereas the highest (17 °C) occurred in 2020. For Tmax, the lowest average (24.8 °C) was recorded in 2000, with the highest (27.7 °C) also occurring in 2020. These trends suggest a decline in cooler days and an increase in heat extremes. Linear regression results indicated positive slopes of 0.028 °C per year for Tmin and 0.054 °C per year for Tmax, with R^2 values of 0.0732 and 0.2025, respectively. Although only 20% of Tmax variability is explained by the model, the consistent upward trends suggest increasing thermal stress and a reduction in cooler days.

The inconsistency in trends across stations contributed to low statistical significance, reflecting the diverse climatic regimes across the country's physiographic regions.

Rainfall patterns across physiographic regions

Analysis of annual rainfall across Eswatini, based on the statistics presented in Table 2, revealed geographical and temporal variability. Stations located in the Highveld, particularly Mbabane and Pigg's Peak, recorded the highest mean annual rainfall of 1416 mm and 1149 mm, respectively. In contrast, Big Bend in the Eastern Lowveld exhibited the lowest average annual rainfall at 550 mm (Table 2). Seasonal patterns followed expected trends, with the wet season (October to March) accounting for approximately 75% of total annual rainfall. Wet season totals ranged from 450 mm to 1173 mm, whereas dry season (April to September) totals ranged from 100 mm to 356 mm. The national long-term average annual rainfall between 1981 and 2020 was calculated to be 827.6 mm. Rainfall variability, expressed as the CV, was consistently higher during the dry season. Dry season CVs ranged from 38% to 97%, with the highest values at Khubutha (97%) and Mpisi (95%). Wet season CVs were lower, ranging from 21% to 46%, indicating more stable but still variable rainfall during the main rainfall period. Annual CVs were relatively high at several stations in the Lowveld, where they ranged from 29% to 35%, whereas Mbabane, located in the Highveld recorded the lowest interannual variability (CV < 20%).

Supplementary figure 1 shows the annual rainfall trends for the 13 meteorological stations across Eswatini from 1981 to 2020. Year-to-year fluctuations were evident, with 2000 recorded as the wettest year (1282 mm) and 2015 as the driest (499 mm), both aligning with recorded regional episodes. Declining linear trends in annual rainfall at 12 of the 13 stations were also observed (Supplementary figure 1). The steepest declines were observed at stations such as Mhlume, Khubutha and Matsapha. However, low R^2 values (typically <0.1) suggest that these trends are weakly linear and probably moderated by strong interannual variability. This high variability may reflect the influence of large-scale atmospheric processes and episodic events, such as droughts and tropical storms. Stations in the Eastern Lowveld (Big Bend) and the Western Lowveld (Sithobelweni) displayed relatively

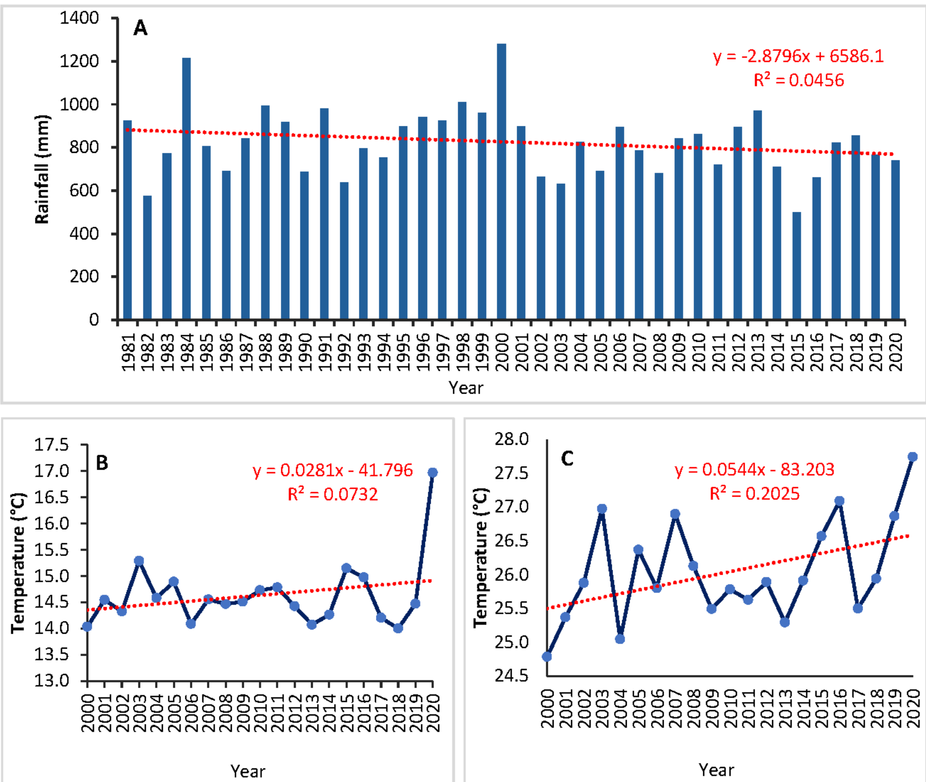

Figure 2: Temporal variation in (A) mean annual rainfall (1981–2020), (B) mean annual minimum temperature (Tmin) (2000–2020) and (C) mean annual maximum temperature (Tmax) (2000–2020).

stable rainfall with minimal trend direction, highlighting the heterogeneity of climate variability across the physiographic regions.

Temperature patterns across physiographic regions

Table 3 lists the statistical summaries of Tmin and Tmax, including mean values, standard deviations and CVs. Highveld stations (Mbabane, Nhlangano and Pigg's Peak) recorded the lowest average temperatures, consistent with their elevation and cooler climate. Interannual variability in temperature was relatively low, with CVs for Tmin ranging from 2.4% to 13.0% and those for Tmax ranging from 2.7% to 6.8%. The highest variability in Tmin occurred at Big Bend during the dry season, whereas Tmax variability remained uniformly low across all stations.

Table 2: Summary of rainfall statistics for 13 meteorological stations in Eswatini (1981–2020), showing mean, standard deviation (SD) and coefficient of variation (CV) for the dry season (April–September), wet season (October–March) and annual totals

Station	Dry season (April–September)			Wet season (October–March)			Annual		
	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)	Mean (mm)	SD (mm)	CV (%)
Big Bend	100.13	71.29	71	449.96	146.80	33	550.1	181.6	33.0
Khubutha	316.34	308.24	97	515.83	236.38	46	832.2	255.0	30.6
Malkerns	145.72	56.88	39	797.74	215.52	27	938.7	219.9	23.4
Mananga	110.96	49.38	45	567.19	199.30	35	678.1	208.1	30.7
Mankayane	129.55	49.53	38	686.06	190.39	28	815.6	198.9	24.4
Matsapha	133.72	63.83	48	694.42	186.58	27	833.3	207.8	24.9
Mbabane	243.18	99.46	41	1173.19	243.01	21	1416.4	275.3	19.4
Mhlume	123.07	55.18	45	555.56	198.10	36	678.6	218.4	32.2
Mpisi	204.77	194.86	95	490.21	204.85	42	695.0	245.9	35.4
Nhlangano	140.71	72.75	52	656.07	180.18	27	796.8	212.2	26.6
Pigg's Peak	355.85	225.75	63	792.93	251.81	32	1148.8	306.7	26.7
Siphofaneni	111.16	63.44	57	528.70	207.04	39	639.9	222.7	34.8
Sithobelweni	126.23	60.26	48	484.65	164.89	34	610.9	181.2	29.7

Table 3: Summary of minimum (Tmin) and maximum (Tmax) statistics for eight meteorological stations in Eswatini, showing mean, standard deviation (SD) and coefficient of variation (CV) for the dry season (April–September), wet season (October–March) and annual totals

Parameter	Station	Dry season (April–September)			Wet season (October–March)			Annual		
		Mean (°C)	SD (°C)	CV (%)	Mean (°C)	SD (°C)	CV (%)	Mean (°C)	SD (°C)	CV (%)
Tmin	Big Bend	11.4	1.48	12.98	19.35	0.79	4.06	15.4	1.3	8.45
	Malkerns	11.22	0.62	5.54	17.07	0.41	2.39	14.12	0.45	3.2
	Mananga	13.15	0.67	5.1	19.41	0.48	2.48	16.28	0.49	2.98
	Matsapha	12.32	0.66	5.36	18.02	0.66	3.67	15.16	0.68	4.48
	Mbabane	9.76	1.07	11.01	14.83	0.66	4.46	12.27	0.79	6.41
	Mhlume	12.84	0.78	6.09	19.05	0.6	3.16	15.96	0.58	3.63
	Nhlangano	9.99	0.64	6.38	14.9	0.71	4.73	12.42	0.57	4.59
	Pigg's Peak	11.89	1.03	8.66	15.43	0.93	6.03	13.68	0.95	6.93
Tmax	Big Bend	27.66	1.18	4.27	31.02	1.49	4.8	29.38	1.48	5.05
	Malkerns	24.55	0.95	3.86	26.87	0.95	3.54	25.72	0.85	3.29
	Mananga	26.68	0.97	3.62	30.06	0.83	2.77	28.37	0.77	2.71
	Matsapha	24.73	0.73	2.96	27.53	1	3.62	26.2	0.73	2.79
	Mbabane	21.27	0.98	4.61	24.36	0.72	2.95	22.79	0.71	3.1
	Mhlume	26.14	0.88	3.35	29.62	1.04	3.52	27.89	0.86	3.08
	Nhlangano	21.98	1.49	6.78	25.09	1.06	4.23	23.65	1.09	4.59
	Pigg's Peak	21.5	1.25	5.82	24.29	1.08	4.43	22.91	0.97	4.22

Annual temperature trends across Eswatini showed heterogeneity across physiographic regions and over time. Of the eight stations with sufficient data, only four (Big Bend, Mananga, Mbabane and Mhlume) had continuous temperature records extending back to 1981 (Supplementary figure 2). Among these stations, Big Bend, Mananga and Mbabane showed gradual increases in both Tmin and Tmax, with Mbabane showing the strongest warming trend in mean temperature ($R^2 = 0.48$). In contrast, Mhlume in the Western Lowveld showed a decreasing trend in Tmax over the full period, with a negative slope ($y = -0.056x$) and relatively strong model fit ($R^2 = 0.75$), suggesting a localised cooling pattern. For the remaining four stations (Malkerns, Matsapha, Nhlangano and Pigg's Peak), temperature data were available from 2000 to 2020 (Supplementary figure 2). During this shorter period, all stations except Pigg's Peak recorded increasing trends in both Tmin and Tmax. Malkerns and Nhlangano displayed relatively strong increases in mean temperature, with R^2 values of 0.46 and 0.19, respectively. Nhlangano recorded the lowest Tmin (11.4 °C) in 2000, whereas Matsapha registered the highest Tmax (27.8 °C) in 2008. Pigg's Peak, located in the cooler Highveld region, showed a slight cooling trend in both parameters, although the R^2 values were low, suggesting a weak and potentially localised signal.

Trend analysis of rainfall and temperature

Monthly, seasonal and annual rainfall trends

Rainfall trend analysis was conducted at monthly, seasonal and annual scales using the Mann–Kendall (*Z*-value) test and Sen's slope estimator. The Mann–Kendall results for monthly, seasonal and annual rainfall are presented in Supplementary table 1, whereas the corresponding Sen's slope estimates are provided in Supplementary table 2. Positive *Z* and slope values indicate increasing trends, whereas negative values reflect decreasing trends. Sen's slope estimator quantifies the rate of change in millimetres per year, offering insight into the magnitude of observed changes. At the monthly time scale, rainfall trends varied by season. Summer months, particularly January, February and December, showed positive *Z*-values at most stations. December showed increasing trends at 80% of stations, with a statistically significant rise observed at Khubutha. In contrast, October showed widespread declines, with 12 of 13 stations showing negative *Z*-values. Significant reductions were noted at Matsapha and Mbabane, suggesting a shift in the onset of the rainy season. Similarly, declining trends in April were observed at Malkerns, Mbabane and Nhlangano, whereas June recorded statistically significant decreases at Big Bend, Mpisi and Sithobelweni.

No statistically significant trends were observed at the seasonal time scale, although 12 stations showed negative *Z*-values for dry season rainfall, indicating a general tendency towards reduced winter rainfall. Malkerns and Siphofaneni were the only stations with positive, but non-significant, trends during the dry season. For the wet season, nine stations (primarily in the Highveld) recorded decreasing rainfall trends, whereas the remaining five exhibited increasing trends, further highlighting the geographical heterogeneity of rainfall patterns. At the annual time scale, most stations recorded non-significant declines in total rainfall from 1981 to 2020. Only Malkerns and Sithobelweni displayed slight positive trends, but these were not statistically significant.

Monthly, seasonal and annual temperature trends

Tmin and Tmax trends were also assessed using the Mann–Kendall and Sen's slope tests across monthly, seasonal and annual scales. The Mann–Kendall and Sen's slope results for Tmin are presented in Supplementary tables 3 and 4, respectively, whereas those for Tmax are provided in Supplementary tables 5 and 6. The analysis revealed geographically variable trends, particularly for Tmin, whereas Tmax showed more consistent increases across stations. In the Highveld, Mbabane exhibited consistent monthly increases in Tmin, with statistically significant trends observed in multiple months. In contrast, Nhlangano, also in the Highveld, showed decreasing Tmin trends between January and March, suggesting localised differences despite geographic proximity. For Tmax, both Mbabane and Nhlangano recorded statistically significant warming trends from June to September, indicating pronounced warming during the dry season. In the Lowveld, Big Bend displayed warming trends in Tmin during February, March and April, whereas Tmax showed moderate increases across the year. Mhlume, however, presented a contrasting pattern, with statistically significant declines in Tmax during January, March and April, indicating potential local cooling effects. The month of June showed the most consistent warming trend, with multiple stations across different physiographic regions recording significant increases in both Tmin and Tmax. These mid-winter changes may reflect broader shifts in baseline temperatures during the cooler season.

At the seasonal time scale, Mbabane showed statistically significant warming in Tmin during both the dry and wet seasons. Big Bend recorded dry season warming in Tmin, whereas Nhlangano showed a decline during the wet season. For Tmax, the dry season was the period with the strongest warming trends, with significant increases recorded at several stations, including Mbabane, Malkerns and Nhlangano. Annual trends in Tmin showed statistically significant increases at Mbabane and Big Bend. For Tmax, four stations (Big Bend, Mbabane, Malkerns and Nhlangano) recorded significant warming trends. Mhlume was the only station to exhibit a statistically significant annual decline in Tmax. The geographic distribution of stations with significant warming (across the Highveld, Middleveld and Lowveld) points to the widespread nature of the observed temperature increases, even if the magnitude and timing vary locally.

Discussion

Understanding climate variability in Eswatini is critical for designing context-specific adaptation strategies, especially for a country characterised by diverse physiographic regions and limited resilience to climate extremes. This study analysed rainfall and temperature trends across five physiographic regions in Eswatini using monthly, seasonal and annual data from 1981 to 2020 and 2000 to 2020. The results revealed significant differences among stations and over time in both variables, emphasising the significance of localised climate planning and sustainable land management.

The analysis showed a general decline in annual rainfall across Eswatini, although the trend was not spatially uniform. Approximately 85% of the stations recorded decreasing rainfall during the study period, with pronounced declines in the key transitional months such as October and June. October, which traditionally marks the onset of the rainy season, exhibits delayed and reduced rainfall at multiple stations, suggesting a shift in the onset to November or even December. This pattern is consistent with the findings of Roffe et al.[30], who identified later and more concentrated rainfall seasons across southern Africa, as well as Kruger and Nxumalo[31], who reported increased intra-seasonal dry spells in the region. Although some stations recorded increased rainfall during peak summer months (December to February), these trends were localised and not statistically significant. Interannual variability was also evident, with the driest years (such as 2015) corresponding to strong El Niño events. The ENSO exerts a major influence on the rainfall patterns by suppressing early summer rainfall and shortening the wet season.[32,33] Studies in Eswatini have shown that El Niño episodes are often linked to delayed rainfall onset and prolonged dry spells, particularly in the early stages of the rainy season.[34] These ENSO-related disruptions to rainfall timing have direct implications for water resources and rainfall-dependent ecosystems.

In the southern African region, rainfall declines have been attributed to reductions in the number of rainfall days, rather than rainfall intensity.[35,36] Similarly, although some areas in northern South Africa have shown increasing rainfall trends, these have generally not reached statistical significance.[31] At a global scale, trends in annual precipitation remain mixed, with increases in some regions and decreases in others, reflecting the complexity of climate system responses.[37] The spatially variable trends observed in Eswatini may similarly reflect the influence of large-scale atmospheric circulation patterns, which drive interannual rainfall variability. These broader-scale drivers likely interact with Eswatini's elevation-driven microclimates, producing highly localised and heterogeneous rainfall responses across physiographic regions.

Rainfall variability was most pronounced during the dry season, particularly in the Lowveld and Middleveld, where CVs exceeded 70% at certain stations. These areas, characterised by lower elevation, high evapotranspiration and minimal influence from terrain-driven rainfall, are more susceptible to frequent and severe droughts. This observation aligns with that of Mlenga and Jordaan[34], who used the Standard Precipitation Index to identify the Lowveld and Middleveld as the most drought-prone regions in Eswatini, predominantly during the 2015–2016 El Niño-linked drought. In contrast, although the Highveld receives more rainfall due to its elevation and cooler conditions, this region also showed signs of delayed seasonal onset, potentially increasing exposure to mid-season dry spells. The wet season exhibited more moderate variability overall, but its reliability has declined in recent decades. These findings highlight the importance of investing in drought preparedness strategies, which are priorities also highlighted in Eswatini's Initial Adaptation Communication to the United Nations Framework Convention on Climate Change.[3] Historically, the wettest year was 2000 and the driest was 2015, both of which were associated with major regional hydroclimatic anomalies. Notable flood events were recorded in 1984 and 2000, whereas severe droughts occurred in 1982, 1992, 2002, 2003 and 2015[34,38], many of which are linked to ENSO phases.

Furthermore, temperature trends provide evidence of intensifying climate variability across Eswatini. Although differences across physiographic regions exist, a consistent warming trend, mostly in Tmax, was observed. Statistically significant increases in Tmax were recorded at stations located in the Highveld (Mbabane, Nhlangano), Middleveld (Malkerns) and Eastern Lowveld (Big Bend). These findings are consistent with regional climate projections, indicating that the interior of southern Africa is warming at approximately twice the global average, particularly under low mitigation scenarios.[39,40] These findings also align with the observed warming trends in the elevated regions of South Africa.[30,41] Importantly, although the Highveld has historically maintained cooler temperatures, it is now experiencing statistically significant increases in both Tmin and Tmax, suggesting a significant warming trend. These trends reflect a broader pattern of increasing heat extremes that have been documented across the region, including a rise in the frequency and duration of heat waves and hot days.[42] Conversely, Mhlume in the Western Lowveld exhibited a cooling trend, reflecting the geographic heterogeneity of temperature dynamics. This anomaly may be linked to local factors such as land-use change, vegetation cover or microclimatic effects associated with altitude and proximity to water bodies.

The geographic patterns of warming are particularly relevant for Eswatini's vulnerability profile.[3,6] The Lowveld, already the hottest and driest region, continues to record the highest Tmax values and is experiencing an increase in heat extremes. These trends have critical implications for vulnerable ecosystems such as wetlands, for agricultural productivity and for water availability, especially in rural areas where adaptive capacity remains limited. Rising temperatures also elevate evapotranspiration rates, further reducing soil moisture and surface water availability and compounding the impacts of declining rainfall. These findings are supported by broader regional studies that document a rise in mean temperatures, along with more frequent and intense heatwaves and drought events across southern Africa.[40,42,43] The climate trends observed in Eswatini are consistent with a wider regional shift towards greater climate variability and compound extremes. Southern Africa is recognised as a global climate-change hotspot, with warming occurring at twice the global average. In this context, Eswatini's Initial Adaptation Communication to the United Nations Framework Convention on Climate Change identifies agriculture, water and biodiversity as key sectors at risk, mainly in physiographic regions such as the Lowveld and Middleveld.[3] This study contributes new empirical evidence from a relatively underrepresented region and highlights the urgent need for downscaled climate assessments. It also demonstrates how physiographic diversity and climate drivers, such as the ENSO, interact to create distinct vulnerability profiles across the landscapes in Eswatini.

Limitations of the study

Even though this study provides an empirical assessment of long-term climate trends across Eswatini's physiographic regions, it is not without limitations. One key constraint is the incomplete temperature data set, with several stations only having usable records between 2000 and 2020. This shortened time limits the ability to detect longer-term warming trends or to make direct comparisons with the full 1981–2020 rainfall record. In addition, although rainfall data were available from more stations, only those with at least 90% data completeness were included. Importantly, the Lubombo Plateau had no rainfall or temperature station data after quality control was carried out, leaving this physiographic region unrepresented in the analysis. This absence reduces spatial coverage and limits the generalisability of national results. Future work should recover/validate historical data (e.g. from Siteki) or establish independent gauges to improve coverage in the Lubombo Plateau. Furthermore, the Mann–Kendall test, although widely used, can be sensitive to short-term fluctuations and may not fully capture nonlinear or episodic patterns. Finally, the low R^2 values in many of the rainfall trend regressions reflect high interannual variability, which can obscure long-term trends. These limitations highlight the importance of expanding and maintaining consistent meteorological monitoring to improve the robustness of future climate analyses.

Conclusion

We examined rainfall and temperature trends across Eswatini from 1981 to 2020, using data from meteorological stations spanning five physiographic regions. The results reveal a general decline in annual rainfall, accompanied by shifts in monthly and seasonal distributions. Statistically significant reductions were observed in June and October – months critical for water availability – suggesting a delayed onset of the rainy season and a reconfiguration of intra-seasonal rainfall patterns. Although some summer months show localised increases in rainfall, these increases are not statistically significant. Rainfall variability is particularly high during the dry season, which could heighten drought risk and reduce the reliability of rain-dependent ecosystems. Temperature analysis indicates a warming trend, especially in Tmax, across most physiographic regions. Notably, significant increases were recorded in both the Highveld and Lowveld, highlighting the spatial extent of warming. However, localised cooling at Mhlume reflects the potential influence of land-use dynamics, topography and microclimates. The combination of declining rainfall, rising temperatures and increased climatic variability highlights the urgency of implementing targeted adaptation strategies in Eswatini. Key priorities include improved water resource management and watershed protection, strengthening of early warning systems and climate services to better anticipate extreme events, sustained investment in long-term climate monitoring to address data gaps, and integration of climate risk into land-use planning, particularly in vulnerable regions.

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Data availability

The data supporting the results of this study have not been made available by the authors in any format.

Declarations

We have no competing interests to declare. We have no AI or LLM use to declare.

Authors' contributions

T.N.: Conceptualisation, methodology, investigation, sample analysis, formal analysis, validation, data curation, writing – original draft, writing – review and editing. L.S.S.: Conceptualisation, methodology, investigation, data curation, writing – original draft. H.B.: Supervision, writing – review and editing. T.K.: Writing – review and editing. T.L.L.: Writing – review and editing. N.M.: Writing – review and editing. C.Y.W.: Writing – review and editing. All authors read and approved the final manuscript.

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