

Research Article

Spatial and Temporal Characteristics of Wet and Dry Spells During the Kiremt Season Over Ethiopia

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Abstract

The understanding of changes of rainfall patterns and climate extremes are crucial factors for addressing agricultural risks and sustaining water resources in Ethiopia. This study aims to investigate baseline rainfall climatology (1991-2020) and long-term spatiotemporal changes (1981-2022) of Kiremt seasonal rainfall totals (PRCPTOT) and selected ETCCDI-based rainfall indices across Ethiopia. The daily rainfall was analyzed using the Mann-Kendall test and Sen's slope estimator to examine changes of wet and dry spell frequencies (NWS and NDS), spell durations (MWSL and MDSL) and total wet and dry days (TWD and TDD) from gridded and gauge-based datasets. The baseline climatology reveals a clear rainfall gradient with seasonal totals over 800 mm and more than 80 wet days in western highlands, while less than 400 mm and maximum dry spells over 80 days observed in the eastern lowlands. Kiremt rainfall significantly increased at a national scale by 2.56 mm/year ($p = 0.004$), specifically the central, western and northern highlands. However, the wet- and dry-spell frequencies increased while the maximum wet-spell duration showed no consistent trend while the total wet days declined recently. These changes suggest greater intra-seasonal rainfall variability with concentrated rainfall and frequent dry spells influencing risks of soil erosion, runoff, and water stress and crop yields. Therefore, it requires soil-moisture conservation, rainwater harvesting and climate-smart agricultural practices.

Keywords

Kiremt Rainfall, Rainfall Variability, Wet and Dry Spells, Extreme Precipitation Indices, Trend Analysis, Ethiopia

1. Introduction

Rainfall is one of the key elements of Ethiopia's climatic system with significant agricultural, water, ecosystem and livelihood implications. Due to its dependence on rainfall for agriculture, the amount, timing and distribution of rainfall are critical determining factors for crop production and food security. Rainfall variability is reflected not only in seasonal and annual totals but also in the occurrence and persistence of wet and dry spells which can influence soil moisture, crop development, water availability and climate-related hazards [7, 10].

Wet and dry spells provide information on the temporal distribution of rainfall that seasonal totals cannot capture. Prolonged dry spells can reduce soil moisture and constrain crop growth while persistent wet spells may increase waterlogging, erosion, flooding and crop damage. Understanding their frequency, duration and timing is therefore important for agricultural planning, water-resource management, and drought-monitoring and flood-risk reduction. Previous studies have reported substantial spatial and seasonal differences in rainfall-spell characteristics across Ethiopia [1, 15].

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Ethiopia experiences strong spatial and temporal rainfall variability due to its complex topography, seasonal migration of the Inter-Tropical Convergence Zone and interactions among regional and large-scale atmospheric systems. The Belg (February-May) and Kiremt (June-September) seasons are particularly important despite their rainfall contribution and characteristics varying considerably across the country [7, 10, 12]. Seasonal rainfall totals may therefore mask important variations in the timing and persistence of wet and dry conditions.

This study investigates the spatiotemporal characteristics and trends of wet and dry spells across Ethiopia using daily rainfall observations. It examines their frequency, duration, spatial distribution and temporal changes, providing information relevant to agricultural planning, drought and flood risk assessment, water-resource management and climate early-warning services.

2. Materials and Methods

2.1. Study Area

Ethiopia, located in Horn of Africa between approximately

3° – 15° N and 33° – 48° E covers about 1.1 million km². Its highly varied topography from about 125 m below sea level in the Afar Depression to over 4,500 m above sea level in the Simien Mountains strongly influences the spatial and temporal distribution of rainfall and temperature [8].

Ethiopia's climate is influenced by complex interactions of topography and large-scale atmospheric systems like the Inter-tropical Convergence Zone (ITCZ), Tropical Easterly Jet (TEJ), Somali Low-Level Jet (SLLJ) and El Niño-Southern Oscillation (ENSO), resulting in substantial seasonal and interannual rainfall variability [3, 7, 11]. The country has three major rainfall regimes; Kiremt (June-September) the main rainy season over western, central and northern Ethiopia; Belg (February-May) an important secondary season in central and northeastern areas; and bimodal rainfall in the south and southeast, mainly during March-May and October-December [16, 17].

Since Ethiopian agriculture is rain-fed, the variability in occurrence, duration and frequency of wet and dry spells has significant implications for crop production, drought, floods and water resources. Understanding these variations is therefore essential for agricultural planning, drought monitoring and climate adaptation [3, 8, 13].

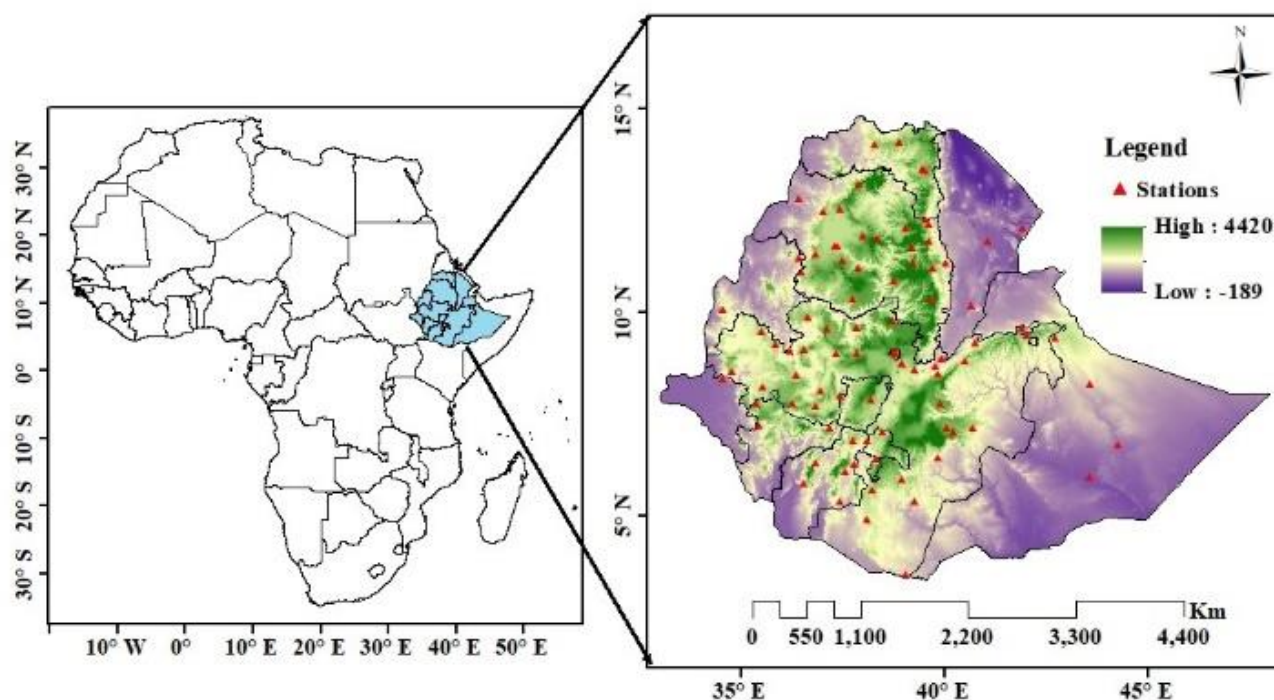


Figure 1. Study area map.

2.2. Data

This study utilized daily rainfall data obtained from the En-

hancing National Climate Services (ENACTS) dataset developed by the Ethiopian Meteorological Institute (EMI). The dataset provides high-resolution gridded rainfall estimates by combining quality-controlled station observations with satellite-derived rainfall information.

The analysis covered the 1991-2020 periods, to represent a standard 30-year climatological baseline. Daily rainfall data with a spatial resolution of approximately 4 km × 4 km were used to characterize wet and dry spell variability during the Kiremt (June-September) rainy season across Ethiopia.

2.3. Methodology

2.3.1. Definition of Wet and Dry Spells

Wet and dry spells were identified from daily rainfall observations using a threshold-based approach widely used in climatological studies over Ethiopia and the Greater Horn of Africa. A wet day was defined as a day receiving at least 1 mm of rainfall, while a dry day was defined as a day receiving less than 1 mm of rainfall [5, 6]. A wet spell consists of consecutive wet days, while a dry spell consists of consecutive dry days. Similar 1-mm thresholds have also been applied in recent analyses of wet days and dry spells across the IGAD region [9].

The analysis was performed for each grid cell across Ethiopia during the Kiremt season (June-September) for each year from 1981 to 2022. The resulting wet- and dry-spell characteristics were used to calculate the Number of Wet Spells (NWS), Number of Dry Spells (NDS), Maximum Wet Spell Length (MWSL), Maximum Dry Spell Length (MDSL), Total Wet Days (TWD), and Total Dry Days (TDD).

2.3.2. Wet and Dry Spell Indices

Several indices were calculated to characterize the frequency and persistence of wet and dry spells during the study season. Daily rainfall observations were first classified into wet and dry days using a predefined rainfall threshold. A wet day was defined as a day receiving rainfall equal to or greater than the selected threshold, while a dry day was defined as a day receiving rainfall below the threshold. Consecutive wet or dry days were then grouped into individual wet or dry spells. For each year, the number and duration of wet and dry spells were calculated, including the maximum and mean spell durations. Similar wet- and dry-spell indices have been widely applied in rainfall variability and climate-extreme studies [4, 6, 9].

Number of wet spells (NWS): represents the total number of distinct wet spells occurring during the season in a given year. A new wet spell was counted whenever a sequence of consecutive wet days began following a dry day.

Mean wet spell duration (MWSD): represents the average duration, in days, of all wet spells occurring during the season. It was calculated by dividing the total number of wet days within all identified wet spells by the number of wet spells.

Maximum wet spell duration (MaxWSD): represents the longest consecutive sequence of wet days observed during the season. This index indicates the persistence of wet conditions and is particularly useful for assessing periods of sustained rainfall.

Dry spell indices

Number of dry spells (NDS): represents the total number of distinct dry spells occurring during the season. A new dry spell was counted whenever a sequence of consecutive dry days began following a wet day.

Mean dry spell duration (MDSD): represents the average duration, in days, of all dry spells occurring during the season. It was calculated as the total number of dry days within all identified dry spells divided by the number of dry spells.

Maximum dry spell duration (MaxDSD): represents the longest consecutive sequence of dry days observed during the season. This index provides an indication of the persistence and severity of within-season rainfall deficits.

For each station and year, these indices were calculated separately for the study season. The resulting annual time series were subsequently used to assess temporal variability and trends in the frequency and persistence of wet and dry conditions.

2.3.3. Trend Analysis

Temporal trends in the wet and dry spell indices were assessed using the non-parametric Mann-Kendall (MK) test. The MK test was chosen because it does not require the data to follow a normal distribution and is therefore suitable for time series that may contain non-normality and outliers. The test was applied independently to the annual seasonal time series of MDSL, MWSL, NDS, NWS, TDD, TWD, and PRCPTOT for each station.

The magnitude of each trend was estimated using the Sen's slope estimator. The Sen's slope represents the median rate of change in an index per year, with positive values indicating an increasing trend and negative values indicating a decreasing trend. Statistical significance was evaluated at the 5% significance level ($\alpha = 0.05$). Trends with p-values less than 0.05 were considered statistically significant, while trends with p-values ≥ 0.05 were considered non-significant.

2.3.4. Wet and Dry Year Classification

Wet and Dry Year Classification of the Kiremt rainfall variability was assessed using the Standardized Anomaly Index (SAI). The SAI was calculated by subtracting the long-term mean rainfall from the rainfall recorded in each year and dividing the result by the standard deviation over the study period. Positive SAI values indicate wetter-than-normal conditions, while negative values indicate drier-than-normal conditions. Years were classified as extremely wet, very wet, moderately wet, near normal, moderately dry, very dry, or extremely dry based on predefined SAI thresholds. The rainfall anomaly for year i was calculated as:

$$SAI_i = \frac{P_i - \bar{P}}{\sigma} \quad (1)$$

Where: P_i is seasonal rainfall for year i ,
 $\bar{P}$ is the long-term mean seasonal rainfall,

σ is the standard deviation.

2.3.5. Spatial Analysis

Spatial distributions of all wet and dry spell indices were produced using Python. The resulting maps illustrate the geographical variability of spell characteristics across Ethiopia. Spatial patterns were interpreted in relation to Ethiopia's topography and rainfall climatology.

Table 1. Definitions, calculation methods, and interpretations of rainfall spell and precipitation indices used in this study.

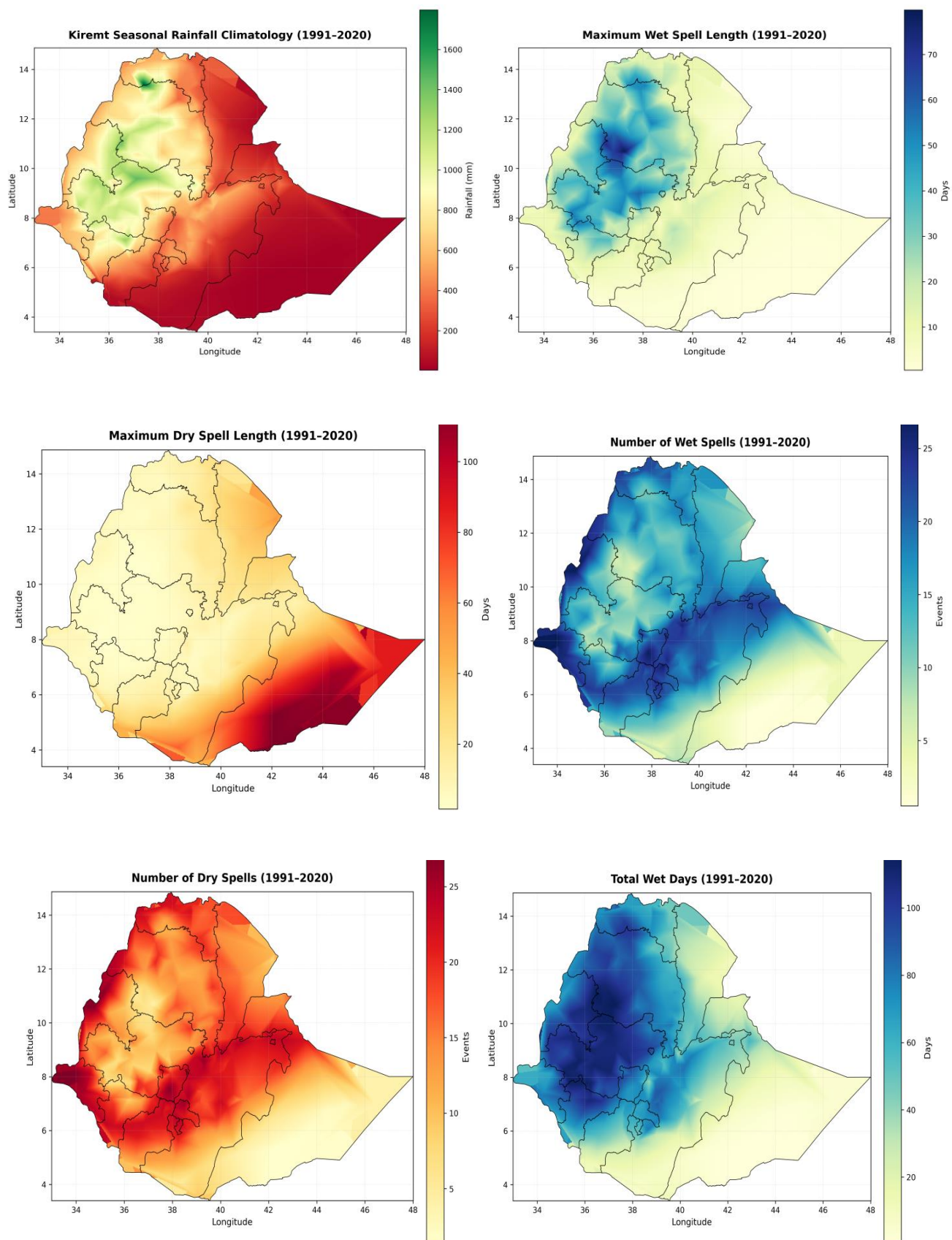
Index	Full name	Definition / Calculation	Interpretation
MDSL	Maximum Dry Spell Length	The longest consecutive number of dry days in a season/year (dry day = rainfall below a selected threshold, usually <1 mm/day)	Indicates the severity of drought periods. Increasing MDSL means longer rainless periods and higher agricultural water stress.
MWSL	Maximum Wet Spell Length	The longest consecutive number of wet days (rainfall ≥ threshold, usually ≥1 mm/day)	Represents persistence of rainfall. Increasing MWSL indicates longer continuous rainy periods and potential flood/soil moisture benefits.
NDS	Number of Dry Spells	Total number of dry spell events during a season/year	Shows the frequency of rainfall interruptions. Higher NDS means rainfall is more fragmented and unreliable.
NWS	Number of Wet Spells	Total number of wet spell events during a season/year	Indicates the frequency of rainfall events. Higher NWS means more frequent rainfall episodes.
TDD	Total Dry Days	Total number of days with rainfall below the dry-day threshold in a season/year	Measures overall dryness. Increasing TDD indicates longer seasonal dry conditions.
TWD	Total Wet Days	Total number of days with rainfall ≥ wet-day threshold in a season/year	Represents rainfall occurrence frequency. Increasing TWD indicates more days with rainfall activity.
PRCPTOT	Total Precipitation	Sum of precipitation on all wet days (usually rainfall ≥1 mm/day)	Measures total seasonal rainfall amount. Higher PRCPTOT indicates wetter conditions; decreasing trends indicate drying.

3. Results and Discussion

3.1. Climatology of Kiremt Wet and Dry Spells

The spatial distribution of total Kiremt seasonal rainfall demonstrates a pronounced east-to-west gradient across Ethiopia. The central and southwestern highlands receive the highest seasonal Rainfall totals, ranging from 800 mm to over 1,400 mm in core high-elevation zones (Figure 2). In contrast, the eastern and southeastern lowlands (primarily Afar and northern Somali regions) exhibit arid to semi-arid conditions, with cumulative seasonal rainfall generally remaining below 200-400 mm. The western, central, and southwestern regions experience a high frequency of wet spell events (15 to >25 discrete events) (Figure 2), reflecting frequent convective activity and recurring rain-bearing systems during the season. Western and central highland areas also register a elevated

number of dry spell occurrences (15-25 events). This pattern indicates that precipitation in the highlands is highly episodic, characterized by short dry breaks alternating with wet events. Lowland regions display fewer distinct dry spell events primarily because dry conditions persist uninterrupted rather than breaking into separate events. Continuous wet episodes are longest over the western and northwestern highlands, where maximum wet spell durations reach 40 to >70 consecutive days. Towards the eastern and southern borders, MWSL sharply drops to <10-20 days. The southeastern lowlands face severe dry persistence, with peak continuous dry spells extending beyond 80 to 100+ consecutive days. Conversely, MDSL in the central and western highlands rarely exceeds 15-25 days. The western and central highlands record the maximum number of rainy days, ranging between 80 and 110+ wet days per season. The eastern half and southern borders are dominated by dry conditions, recording 100 to >120 total dry days out of the seasonal period.



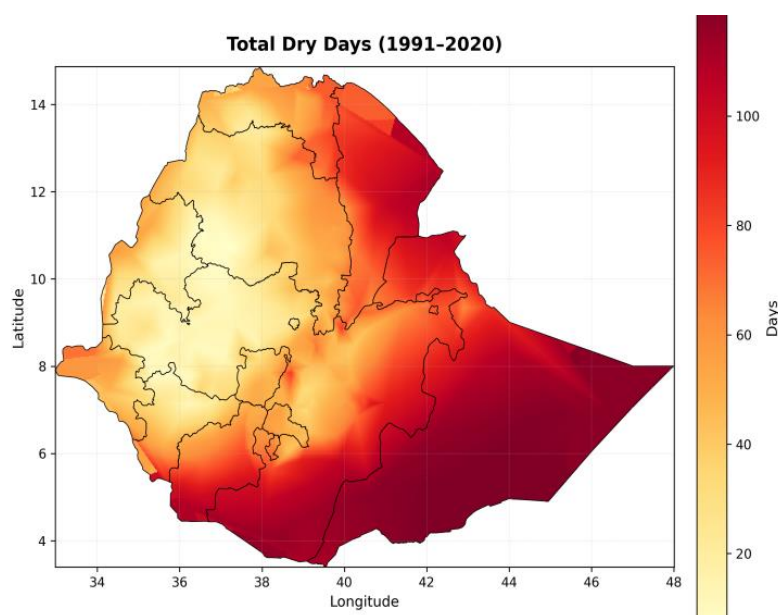


Figure 2. Spatial distribution of seasonal rainfall climatology and rainfall extreme indices over Ethiopia during the Belg season (1991-2020): Total seasonal rainfall (PRCPTOT, mm); Total wet days (TWD, days); Total dry days (TDD, days); Number of wet spells (NWS, events); Number of dry spells (NDS, events); Maximum wet spell length (MWSL, days); and Maximum dry spell length (MDSL, days).

3.2. Temporal Trends and Variability of Seasonal Rainfall and Extreme Indices

Seasonal rainfall (PRCPTOT) exhibits a statistically significant increasing trend over the 42-year period, with an estimated Sen's slope of +2.56 mm/year ($p = 0.004$). Despite considerably interannual variability, with seasonal rainfall ranging from approximately 440 mm during dry years to more than 700 mm during wet years, the overall seasonal rainfall amount has increased.

Maximum Dry Spell Length (MDSL) (Figure 3a) shows a slight decreasing tendency of -0.04 days/year, although the trend is not statistically significant ($p = 0.156$). Maximum dry-spell duration generally varied between about 13 and 20 days throughout the study period.

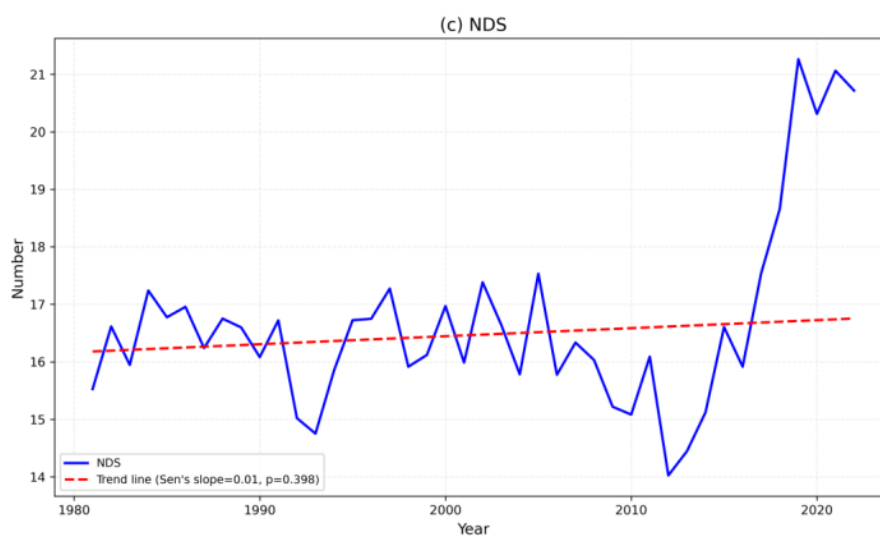
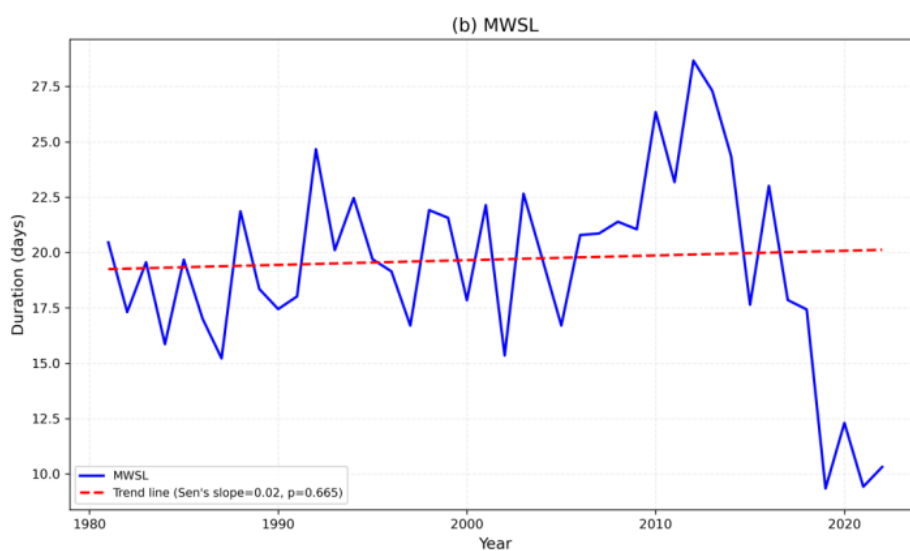
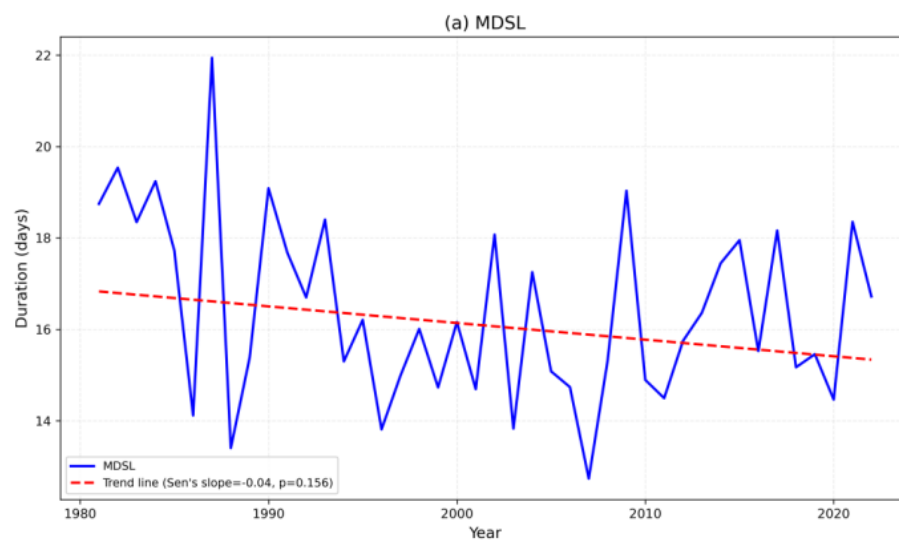
Maximum Wet Spell Length (MWSL) (Figure 3b) shows a very weak and statistically non-significant increase of $+0.02$ days/year ($p = 0.665$). Considerable interannual variability is evident, with maximum wet-spell durations reaching approximately 28 days around 2012-2013 before declining to below 12 days in recent years.

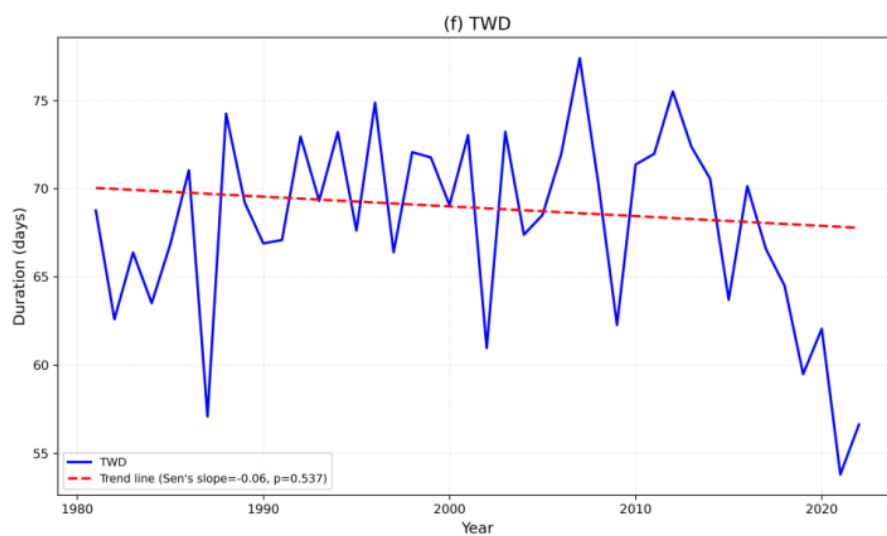
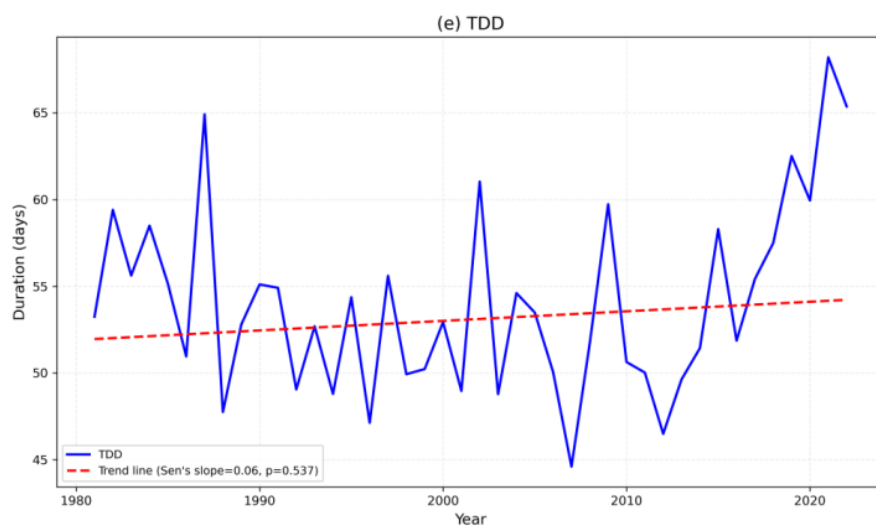
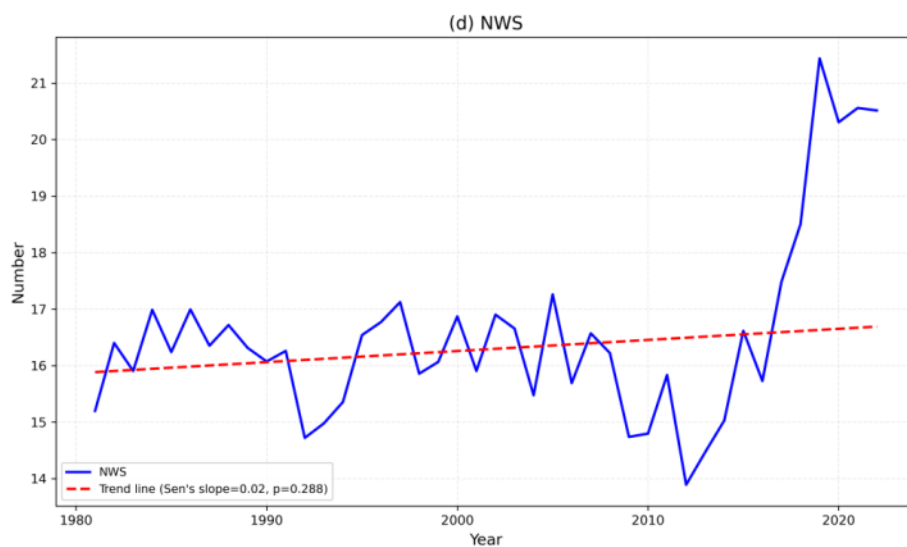
Number of Dry Spells (NDS) and Number of Wet Spells

(NWS) (Figure 3c-d) both show weak positive tendencies. NDS increased by $+0.01$ events/year ($p = 0.398$), while NWS increased by $+0.02$ events/year ($p = 0.288$); however, neither trend is statistically significant. Both indices show more noticeable year-to-year increases after approximately 2015.

Total Dry Days (TDD) and Total Wet Days (TWD) (Figure 3e-f) show opposite but statistically non-significant tendencies. TDD increased slightly by $+0.06$ days/year, while TWD decreased by -0.06 days/year ($p = 0.537$ for both). A more pronounced change is observed after 2018, when TDD increased toward approximately 68 days while TWD declined to below 58 days.

Overall, while Kiremt seasonal rainfall (PRCPTOT) increased significantly over 1981-2022, the wet- and dry-spell characteristics did not show statistically significant monotonic trends over the full study period. Nevertheless, the recent increase in both wet- and dry-spell frequencies, together with a decline in total wet days, suggests greater irregularity in the intra-seasonal distribution of rainfall. This finding is consistent with previous research showing that Kiremt rainfall characteristics are influenced not only by seasonal totals but also by the frequency and duration of intervening dry periods [2, 11, 14].





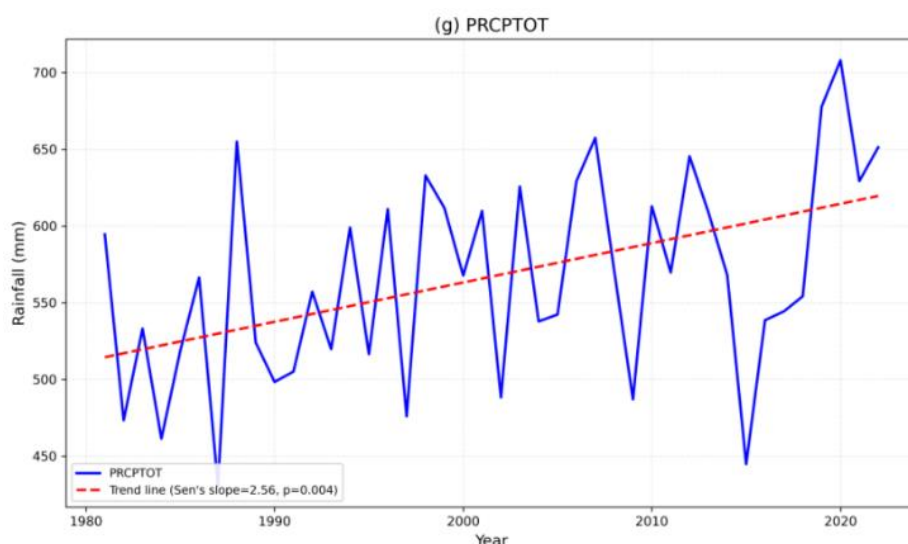
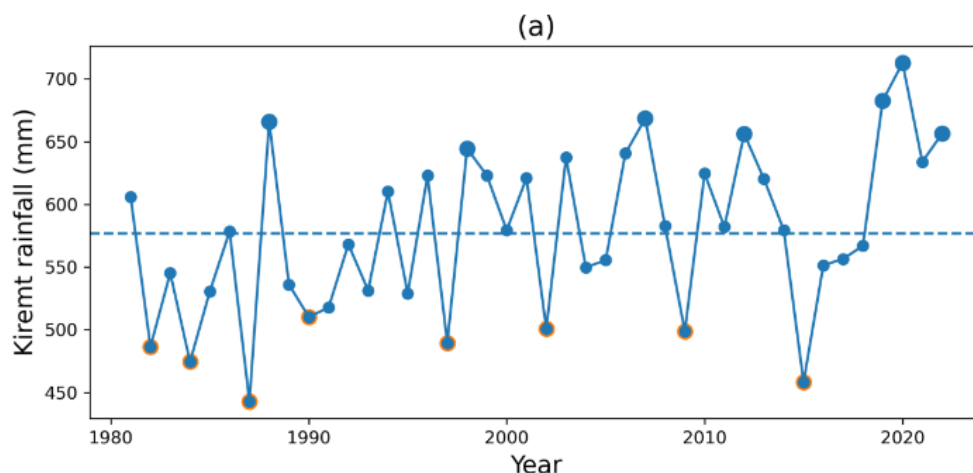


Figure 3. Long-term temporal trends and interannual variability of seasonal rainfall totals and extreme climate indices from 1981 to 2022: (a) Maximum Dry Spell Length (MDSL, days); (b) Maximum Wet Spell Length (MWSL, days); (c) Number of Dry Spells (NDS, events); (d) Number of Wet Spells (NWS, events); (e) Total Dry Days (TDD, days); (f) Total Wet Days (TWD, days); and (g) Total Seasonal Rainfall (PRCPTOT, mm). Blue solid lines represent annual observed values, and red dashed lines depict non-parametric trend lines derived from Sen's slope estimator; with Mann-Kendall p-values reported in legends.

3.3. Wet-Dry Variability and Trends in Kiremt Rainfall

The interannual variability of Kiremt seasonal rainfall across Ethiopia during 1981–2022 shows marked fluctuations around the long-term mean of 576.9 mm. Seasonal rainfall totals varied from below 450 mm to more than 700 mm during the study period (Figure 4a). This pronounced year-to-year variability is consistent with earlier studies that have documented substantial interannual and multi-decadal variability in Ethiopian Kiremt rainfall [2, 11]. The time series also indicates distinct periods of predominantly negative and positive

rainfall anomalies. From 1981 to around 2010, negative anomalies occurred relatively frequently, while the period after 2015 was characterized by more frequent positive anomalies. In particular, 2019, 2020, and 2022 recorded rainfall totals substantially above the long-term mean, with 2020 representing the highest value in the study period (Figure 4b). The occurrence of contrasting wet and dry periods agrees with previous findings showing strong temporal variability in Kiremt rainfall over Ethiopia and the wider East African region [2, 11].



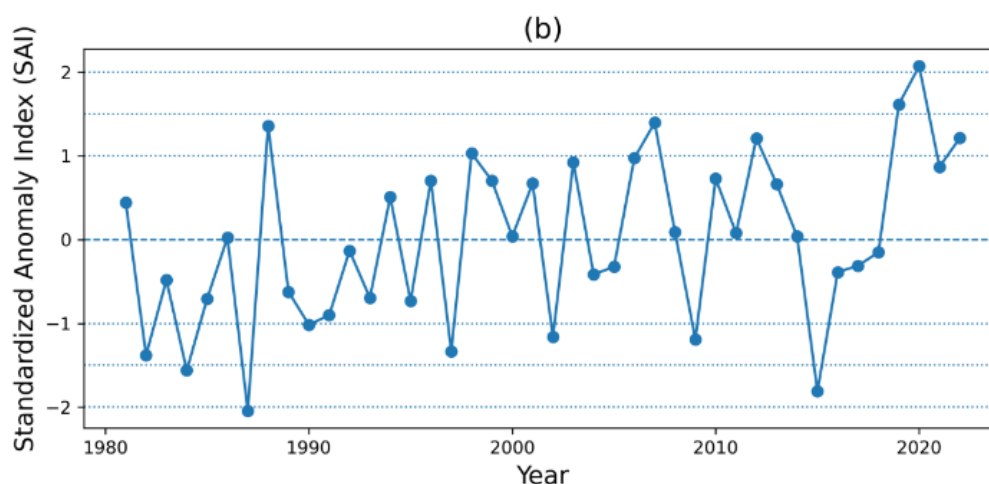


Figure 4. Interannual variability and standardized anomalies of Kiremt seasonal rainfall across Ethiopia (1981–2022). (a) Time series of total seasonal rainfall (mm) relative to the long-term mean of 576.9 mm (dashed line). Circles indicate wet years ($SAI \geq 1.0$) and dry years ($SAI \leq -1.0$). (b) Standardized Anomaly Index (SAI) showing annual departures from the long-term mean in standard deviation units. Dotted lines indicate the SAI thresholds of ± 1.0 and ± 2.0 .

3.4. Spatial Distribution of Trends in Kiremt Season Rainfall and Extreme Climate Indices

Total seasonal rainfall (PRCPTOT) shows widespread increasing trends across the central, western, and northern highlands (Figure 5). A large cluster of stations in the northwestern and central regions exhibits statistically significant increases, represented by dark green triangles.

In contrast, the isolated stations in the central-western and southern regions show significant decreases, indicated by blue inverted triangles.

The Number of Wet Spells (NWS) (Figure 5) shows widespread increasing trends, with statistically significant increases mainly distributed across the western, central, and northern regions. This spatial pattern is broadly consistent with the increase in PRCPTOT, suggesting a greater frequency of distinct wet periods during the Kiremt season. Similarly, the Number of Dry Spells (NDS) exhibits significant increases at several stations across the northern, western, and south-central highlands. The concurrent increase in both wet- and dry-spell frequencies indicates greater intra-seasonal variability, characterized by more frequent transitions between wet and dry periods.

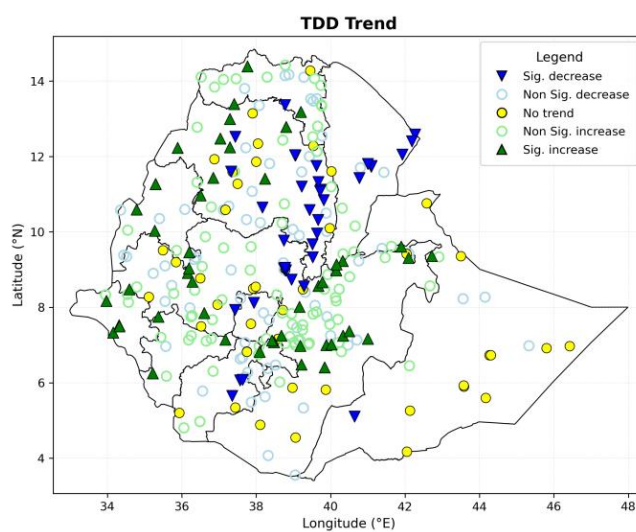
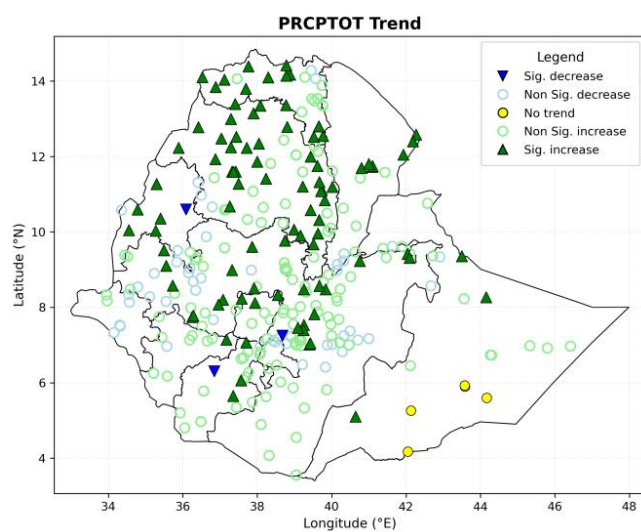
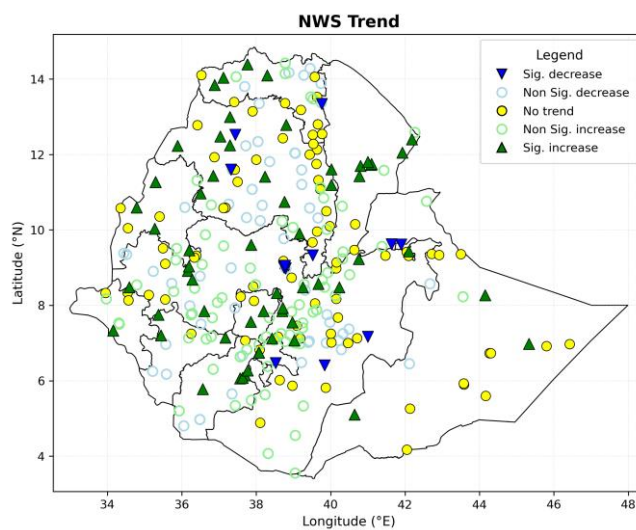
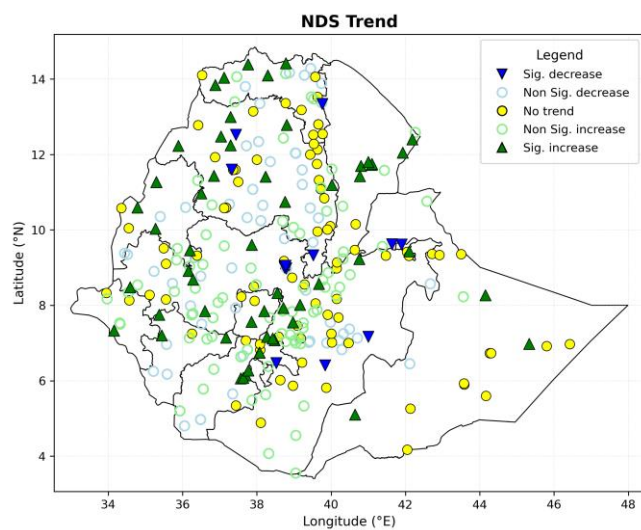
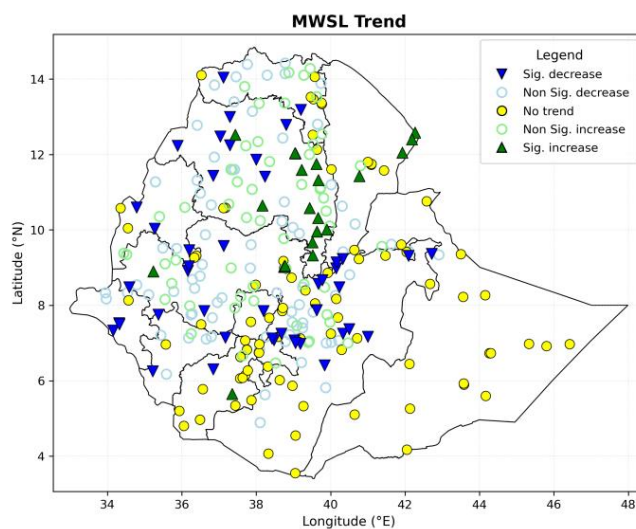
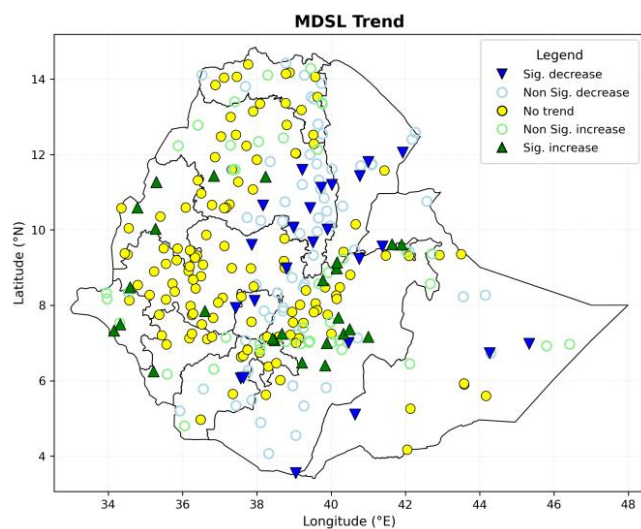
The Maximum Wet Spell Length (MWSL) shows a mixed spatial pattern. Significant increases are mainly confined to localized areas along the northeastern and eastern margins of

the highlands, whereas non-significant or decreasing trends occur across much of the western and southern highlands. This suggests that, despite increases in wet-spell frequency in some areas, individual wet periods are generally not becoming longer.

Maximum Dry Spell Length (MDSL) exhibits widespread significant decreases, particularly along the central and north-eastern Rift Valley margins and parts of the central highlands. Significant increases are more sparsely distributed, mainly across the southwestern and south-central regions.

For Total Wet Days (TWD), significant increases are concentrated along the northeastern escarpment and eastern margins of the highlands, while several stations in the western and central regions show significant decreases. Total Dry Days (TDD) shows significant decreases along the northeastern Rift Valley corridor, whereas significant increases occur in parts of the western and central-southern highlands.

Overall, the spatial patterns indicate that increasing Kiremt seasonal rainfall in many parts of the Ethiopian highlands is accompanied by changes in its intra-seasonal distribution. The simultaneous increases in NWS and NDS, together with the absence of widespread increases in MWSL, suggest greater rainfall irregularity, with more frequent alternation between wet and dry periods rather than a consistent extension of wet spells. These changes highlight the importance of considering rainfall timing and persistence, in addition to seasonal totals, when assessing agricultural water availability and climate-related risks.



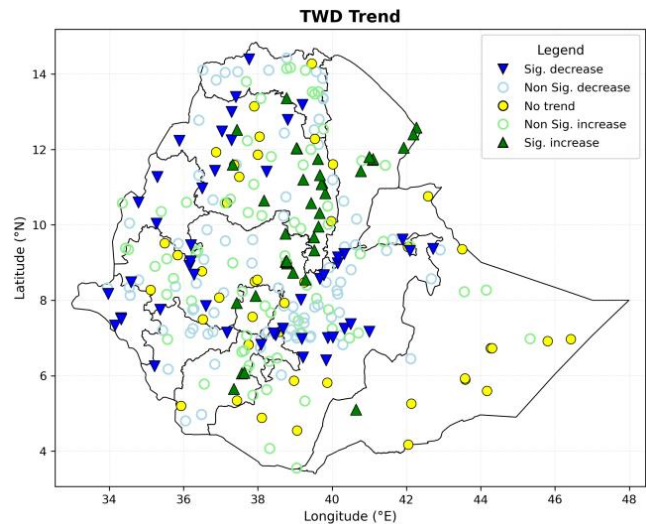


Figure 4. Station-level spatial distribution of Mann-Kendall trend test results for seasonal rainfall and extreme climate indices across Ethiopia: (a) Maximum Dry Spell Length (MDSL); (b) Maximum Wet Spell Length (MWSL); (c) Number of Dry Spells (NDS); (d) Number of Wet Spells (NWS); (e) Total Seasonal Rainfall (PRCPTOT); (f) Total Dry Days (TDD); and (g) Total Wet Days (TWD)($p < 0.05$).

4. Conclusion

This study examined the climatology, interannual variability, wet and dry years and long-term changes in Kiremt seasonal rainfall across Ethiopia during 1981-2022. The results showed a strong spatial rainfall gradient, with seasonal totals exceeding 800 mm and more than 80 wet days in the western highlands, compared with less than 400 mm and maximum dry spells exceeding 80 days in the eastern lowlands. Kiremt rainfall exhibited substantial interannual variability around the long-term mean of 576.9 mm, ranging from below 450 mm to above 700 mm. Negative anomalies were more frequent during the earlier part of the record, while positive anomalies became more common after 2015. The years 2019, 2020, and 2022 were notably wet, with 2020 recording the highest seasonal rainfall. Overall, Kiremt rainfall increased significantly at 2.56 mm/year ($p = 0.004$), particularly across the central, western, and northern highlands. However, increasing seasonal rainfall was accompanied by greater intra-seasonal variability, reflected in widespread increases in wet- and dry-spell frequencies, no consistent increase in maximum wet-spell length, and recent declines in total wet days. These changes may increase runoff, soil erosion, and flooding while also exposing crops to short dry periods and water stress. Strengthening rainwater harvesting, soil-moisture conservation, watershed management, and climate-informed agricultural practices is therefore important for managing increasing rainfall variability.

Abbreviations

ENACTS	Enhancing National Climate Services
EMI	Ethiopian Meteorological Institute

ETCCDI	Expert Team on Climate Change Detection and Indices
ENSO	El Niño-Southern Oscillation
ITCZ	Intertropical Convergence Zone
TEJ	Tropical Easterly Jet
SLLJ	Somali Low-Level Jet
SAI	Standardized Anomaly Index
MK	Mann-Kendall
PRCPTOT	Total Precipitation
NWS	Number of Wet Spells
NDS	Number of Dry Spells
MWSL	Maximum Wet Spell Length
MDSL	Maximum Dry Spell Length
TWD	Total Wet Days
TDD	Total Dry Days
MWSD	Mean Wet Spell Duration
MDSD	Mean Dry Spell Duration
MaxWSD	Maximum Wet Spell Duration
MaxDSD	Maximum Dry Spell Duration

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Author Contributions

Habtam Jenberu Wassie: Conceptualization, Data curation, Formal Analysis, Methodology, Software, Visualization, Writing – original draft
Samrawit Abebe Angasso: Conceptualization, Supervision, Validation, Writing – review & editing

Data Availability Statement

The high-resolution, station-satellite blended climate data analyzed in this study were obtained from the Enhancing National Climate Services (ENACTS) dataset, developed and managed by the Ethiopian Meteorological Institute (EMI). The ENACTS rainfall data were accessed through official data request procedures.

Conflicts of Interest

The authors declare no conflicts of interest.

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