

## Investigation the Cause of Drought Conditions Over Afghanistan with Consideration of Climate Trends and Indices

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### ABSTRACT

Global warming significantly intensifies drought conditions, posing severe threats to vulnerable, agriculturally dependent nations like Afghanistan. Existing research often lacks a systematic framework for selecting and validating representative extreme climate indices (ECIs) to capture regional hydroclimatic variability in data-scarce environments accurately. This study addresses this gap by investigating the relationships between drought severity and extreme temperature and precipitation events across Afghanistan during 1975–2014. Methodologically, twenty-seven ETCCDI-defined ECIs were initially examined. A robust subset of eight representative indices was systematically selected through correlation analysis and Variance Inflation Factor (VIF) diagnostics, ensuring VIF values below 2.0 to minimize multicollinearity. The Standardized Precipitation Evapotranspiration Index (SPEI), derived from ERA5 reanalysis data, was used to characterize drought. The Mann–Kendall test and Sen’s slope estimator were applied to determine the statistical significance ( $P < 0.05$ ) and magnitude of long-term trends, followed by correlation analysis. Results indicate that temperature-related ECIs exhibit consistent and statistically significant upward trends across Afghanistan, with TX90P and TN90P increasing by 2–4% per decade. These temperature indices showed strong negative correlations with SPEI, ranging from approximately -0.5 to -0.65, indicating that rising temperatures are directly linked to intensified drought. The SPEI itself revealed a statistically significant decreasing trend ( $P < 0.05$ ), notably shifting from near-zero values pre-1999 to consistently below -1 for lower elevations post-1999. Conversely, precipitation-related ECIs showed no significant long-term variation and exhibited only weak, inconsistent correlations with SPEI (0.0–0.25), confirming their lesser role. These findings underscore the dominant influence of temperature extremes on the development of drought in Afghanistan.

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## INTRODUCTION

Climate extremes such as heatwaves, heavy precipitation, and prolonged droughts exert far greater impacts on human societies and natural ecosystems than average climatic conditions. According to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), the global mean surface temperature has increased by approximately 1.1°C since the beginning of the twentieth century (Alexander, 2016; Chen et al., 2023; Legg, 2021). This persistent warming has altered the frequency, intensity, duration,

and spatial extent of extreme climatic events (Abel et al., 2019; Safi et al., 2024). A growing body of research has revealed that such extremes have become more frequent and severe over the last century and are expected to intensify further throughout the twenty-first century (Safi et al., 2024).

Among these extremes, drought represents one of the most complex and damaging natural hazards, primarily caused by prolonged water scarcity and elevated temperatures under a changing climate (Alami et al., 2017; Aliyar et al., 2022). Extreme climatic conditions play a crucial role in shaping drought characteristics by affecting precipitation patterns, surface water availability, and evapotranspiration rates (Habib et al., 2021; Jahish et al., 2021). To quantify these effects, climate extreme indices (ECIs) have been widely applied to assess the contribution of temperature and precipitation extremes to regional drought variability (Rahimi et al., 2024; Rousta et al., 2020).

However, despite numerous studies linking climate extremes to drought, there remains a significant methodological gap in selecting and validating indices that effectively represent the spatial and temporal variability of extreme events within a given region (Chen et al., 2023; Jahish et al., 2025). South Asia, one of the most climatically diverse and densely populated regions of the world, is highly vulnerable to climate extremes such as floods, heatwaves, and droughts (Aliyar et al., 2022; Baig et al., 2020). The dependence of its economy on agriculture further amplifies the impacts of such events (Zaki, 2023). Afghanistan, situated in the heart of South Asia, faces even greater vulnerability due to its socio-economic fragility and limited adaptive capacity (Peroz & Farhat, 2025). With more than 80% of its population relying on agriculture for livelihoods and food security, the country is particularly exposed to drought and temperature extremes (Chen et al., 2023; Rahimi, 2024). For instance, the severe drought of 2011 pushed millions of Afghans into poverty and food insecurity (Dost & Kasiviswanathan, 2023). Although a few studies have examined the relationship between drought and climate extremes in Afghanistan, most lack a comprehensive methodological framework for identifying and analyzing representative extreme climate indices (Hayat, 2022). To address this challenge, the Expert Team on Climate Change Detection and Indices (ETCCDI) has defined 27 standardized precipitation- and temperature-based indices to capture changes in the frequency and intensity of climate extremes (Jahish et al., 2025; Sidiqi et al., 2023). These indices have been successfully applied across various regions, including South Asia, to evaluate long-term climate trends (Jahish et al., 2024; Noori & Singh, 2021; Parry, 2007).

Nevertheless, applying all 27 indices is often redundant, as several exhibit high inter-correlation. Prior studies recommend selecting a subset of representative indices that can capture the full variability of extreme climate conditions while minimizing redundancy (Noori & Singh, 2021). For example, Seo et al. (2019) identified key indices through cross-correlation and variance inflation factor (VIF) analysis. However, in regions with complex topography and heterogeneous climatic conditions—such as Afghanistan—the spatial variability of these indices must also be carefully considered (Chen et al., 2023; Peroz & Farhat, 2025; Tayfur et al., 2025; Zaki, 2023). In this context, high-resolution reanalysis datasets such as ERA5,

provided by the Copernicus Climate Change Service (C3S), offer valuable long-term and spatially consistent climate data (Rahimi et al., 2024). Previous evaluations have confirmed the superior performance of ERA5 data in South Asia, particularly for Afghanistan (Hayat, 2022). Leveraging these data, the present study aims to fill the existing research gaps by developing a systematic approach to select and analyze representative ECIs and assess their relationship with drought conditions. Specifically, the objectives of this study are to:

1. Identify the optimal set of temperature- and precipitation-based ECIs for Afghanistan's different climatic regions using correlation and collinearity diagnostics.
2. Examine the spatial and temporal trends in drought severity and extreme climate indices using the modified Mann–Kendall test and Sen's slope estimator.
3. Evaluate the relationship between selected ECIs and drought variability using correlation analysis.

This research provides a robust methodological framework for assessing the influence of extreme climate events on drought conditions in Afghanistan, thereby offering new insights into regional hydroclimatic dynamics under a warming climate.

## **MATERIALS AND METHODS**

### ***Data Sources***

The ERA5 reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) was used in this study because there is a limited and uneven network of in situ meteorological stations throughout Afghanistan. Previous research has confirmed the accuracy of ERA5 data in Afghanistan's difficult topography, a crucial factor for our investigation. Research by Hayat (2022) and Sediqi et al. (2019) established it as a reliable high-resolution source for hydroclimatic analysis, confirming its consistent performance against local ground-truth data. The following preparatory steps were taken to prepare the data for the 1975–2014 analysis period: hourly ERA5 temperature and precipitation data were combined to create a daily time series. The daily average, maximum, and minimum temperatures were determined from the hourly data, and the daily total precipitation was computed by adding the hourly numbers. The integrity of the ensuing analysis was strengthened by the ERA5 reanalysis product's completeness, which guaranteed a continuous, gap-free record and eliminated the need for imputation for missing variables. The Standardized Precipitation Evapotranspiration Index (SPEI) for a 12-month period and at  $0.5^\circ \times 0.5^\circ$  spatial resolution was obtained from the Global SPEI Database to describe interannual drought variability.

### ***Selection Of Key Climate Extreme Indices***

This study began with the 27 standardized indices from the Expert Team on Climate Change Detection and Indices (ETCCDI) to examine how climate extremes affect drought. Using all these indicators would lead to statistical redundancy and multicollinearity, as many of them

exhibit strong correlations. As a result, a methodical, two-step process was used to choose a representative but economical subset of indices.

To determine the degree of relationship between all 27 indices, a cross-correlation study was first conducted. This functioned as an initial screening to comprehend their connections. Second, a stepwise diagnostic utilizing the Variance Inflation Factor (VIF) was used to reduce multicollinearity formally. The VIF measures the degree of multicollinearity in a regression study. A precise and strict criterion served as the basis for the selection process: starting with a preselected group of 18 indices, the index with the highest VIF was successively eliminated until all remaining indices had VIF values below 2.0. The resulting set of indices is robust for trend and correlation analyses, as this conservative criterion ensures that they are statistically independent and represent distinct aspects of climatic variability.

$$VIF = \frac{1}{1-r^2} \quad (1)$$

where r is the correlation between the ETCCDI indices in the multiple regression model.

### **Correlation and Trend Analysis**

The rate of variation in the Extreme Climate Indices (ECIs) and the Standardized Precipitation Evapotranspiration Index (SPEI) was evaluated using the Sen's slope estimator (Sen, 1968), while the Mann-Kendall (MK) test (Mann, 1945; Kendall, 1957) was applied to determine the statistical significance of the observed trends at the 95% confidence level. The MK test, as a nonparametric approach, is particularly effective for detecting monotonic trends in climatic and hydrological datasets because it does not assume normality and is resistant to outliers and missing observations.

$$Q_{med} = \left\{ \begin{array}{l} Q_{\lfloor \frac{N+1}{2} \rfloor} \text{ if } N \text{ is odd} \\ \frac{Q_{\lfloor \frac{N}{2} \rfloor} + Q_{\lfloor \frac{N+2}{2} \rfloor}}{2} \text{ if } N \text{ is even} \end{array} \right. \quad (2)$$

The Mann-Kendall test statistic (S) for a time series x with n data points is calculated as follows.

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^n \text{sign}(x_i - x_k) \quad (3)$$

Where

$$\text{sign}(x_i - x_k) = \begin{cases} +1 & \text{when } (x_i - x_k) > 0 \\ 0 & \text{when } (x_i - x_k) = 0 \\ -1 & \text{when } (x_i - x_k) < 0 \end{cases} \quad (4)$$

The significance of the trend is calculated by using Z statistics as follows.

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{when } S > 0 \\ 0 & \text{when } S = 0 \\ \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{when } S < 0 \end{cases} \quad (5)$$

where Var (S) is the variance of S

$|Z| \geq 1.64$  indicates that the confidence level in the current test was >95% ( $p < 0.05$ ).

## FINDINGS and DISCUSSION

### Selection of Key Climate Extreme Indices

The preliminary analysis involved examining the cross-correlation matrix of 27 ETCCDI indices for regions across Afghanistan, specifically differentiating between areas below and above 2000 m in elevation (Rahimi, 2024). This process, illustrated in Figure S1 for areas below 2000m, revealed strong intercorrelations among precipitation-based extreme indices. Conversely, the associations between temperature-related and precipitation-related indices were generally weak, suggesting distinct drivers. Notably, some temperature indices exhibited internal correlations, such as between PRCPTOT and R10MM, and between TX10P and TN10P.

To mitigate multicollinearity and identify a parsimonious set of representative indices, a systematic screening process was employed (Sidiqi et al., 2023). Initially, eighteen indices were pre-selected (Table 1). A stepwise Variance Inflation Factor (VIF) diagnostic was then applied, progressively removing indices with the highest VIF values. For instance, indices like TN10P (VIF = 51.3), R20MM (VIF = 34.5), and TNN (VIF = 31.5) were among the first to be removed due to excessive multicollinearity. This rigorous statistical approach ultimately yielded a refined subset of eight representative indices (highlighted in bold in Table 1), all exhibiting VIF values below 2.0 (e.g., CDD: 1.5, R95P: 1.3, R10MM: 1.7, RX5DAY: 1.5, TN90P: 1.3, TX90P: 1.6, TXN: 2.0, TXX: 1.9), ensuring that the selected variables effectively capture distinct climatic variability for further trend and correlation analyses (Peroz & Farhat, 2025).

**Table 1.** Variance inflation factor (VIF) values of pre-selected ETCCDI indices

ETCCDI indices	Variance inflation factor (VIF)			
	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>
CDD	2.2	1.7	1.6	1.5
R95P	2.2	2.1	1.4	1.3
SDII	4.9	3.1	2.4	remove
R10MM	5.2	3.4	1.8	1.7
RX1DAY	8.6	6.5	remove	remove
RX5DAY	7.3	4.1	2.0	1.5
R20MM	34.5	remove	remove	remove
TN90P	5.1	3.1	1.8	1.3
CWD	3.8	3.5	2.8	remove
TNN	31.5	remove	remove	remove

IDo	27.4	remove	remove	remove
TN10P	51.3	remove	remove	remove
TX90P	5.3	3.5	1.9	1.6
TXN	9.7	3.2	1.8	2.0
FDo	9.3	4.5	4.1	remove
TNX	13.5	7.7	remove	remove
TXX	8.0	4.6	1.8	1.9
CSDI	8.5	5.4	remove	remove

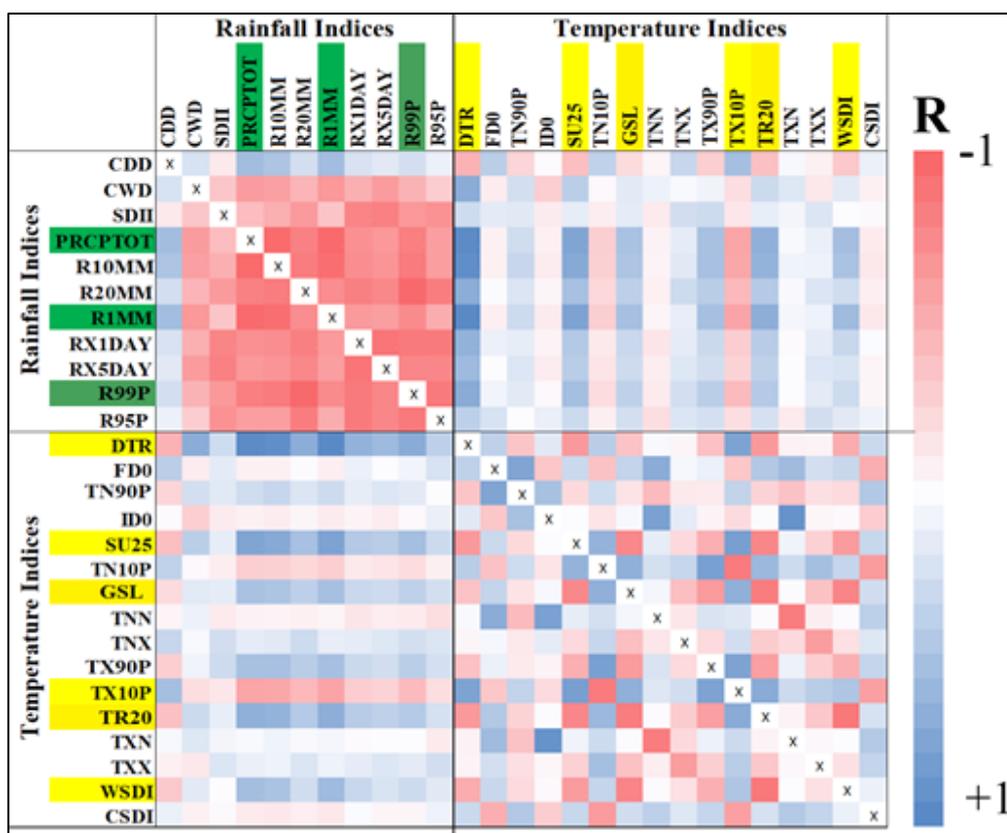


Figure S1. Cross-correlation table of the 27 ETCCDI indices for Afghanistan from 1976 to 2015

### Spatial and Temporal Trend In SPEI Drought Index

The spatial characteristics of the SPEI drought index across Afghanistan from 1975 to 2014, as depicted in Figure S2, reveal a clear gradient of aridity changing from the northeast to the southwest. A significant decrease in SPEI, indicating increasing drought severity, was observed, particularly in the southwestern desert region.

Temporal analysis of the regionally averaged SPEI for both elevation zones (Figure 1a for elevations < 2000 m and Figure 1b for elevations > 2000 m) confirms a statistically significant decreasing trend at the 95% confidence level ( $P < 0.05$ ). For elevations below 2000 m (Figure 1a), the SPEI values show a marked decline, often reaching -1, especially in the later period. The regression analysis for this zone yielded an  $R^2$  value of 0.2244, suggesting a moderate explanatory power for the linear trend. Similarly, for elevations greater than 2000 m (Figure 1b), a decreasing SPEI trend is also evident ( $P < 0.05$ ), though with a lower  $R^2$  of 0.0434, indicating weaker linearity than at lower elevations.

A critical observation from both time series is the profound impact of a prolonged drought period from 1999 to 2002 (Alami et al., 2017). The average SPEI values from 1975 until 1998 were near zero, reflecting largely drought-free conditions. In stark contrast, the average SPEI from 1999 to 2014 consistently remained below -1 at lower elevations, indicating a shift toward moderate drought conditions.

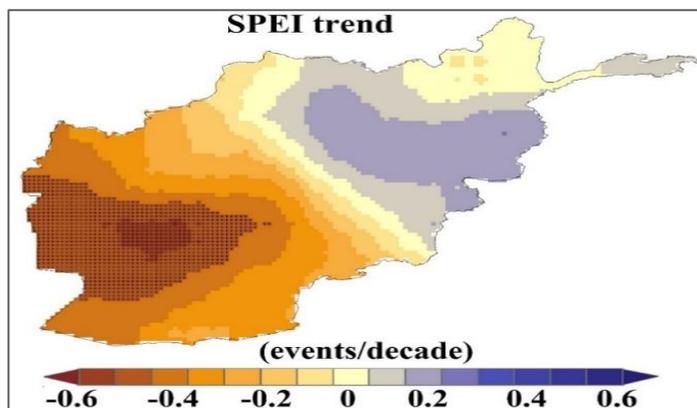


Figure S2. Trend of the SPEI index over Afghanistan from 1975 to 2014

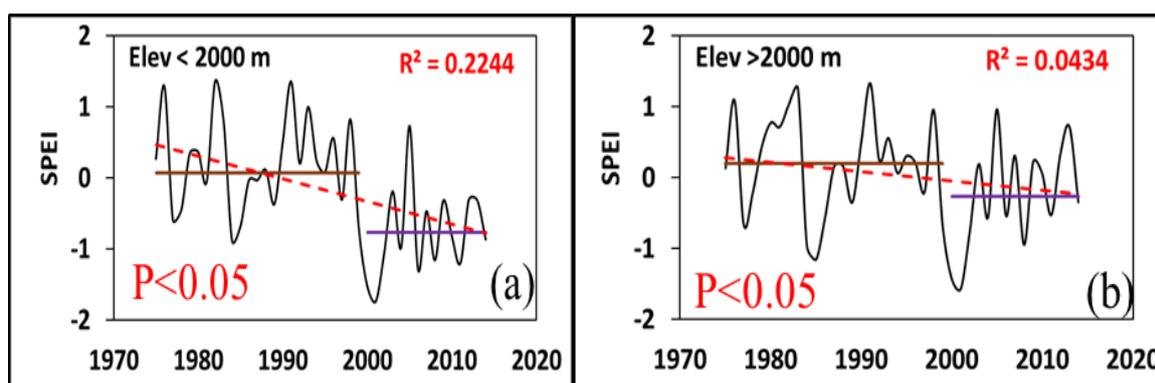


Figure 1a, 2b. Time series of the SPEI index over Afghanistan

### Spatial and Temporal Distribution of Extreme Indices

The linear trends of extreme climate events in Afghanistan (1975–2014) exhibit distinct spatial and temporal patterns, differentiating significantly between temperature- and precipitation-related indices (Safi et al., 2024).

Temperature-related indices (Figure S3): These indices generally indicate an increasing trend in aridity, particularly pronounced in the southwest region, where trends pass the 95% significance test. For example, maps for TXx (Annual maximum value of Tmax), TX90P (Warm days), TN90P (Warm nights), and TXn (Annual minimum value of Tmax) all show widespread increases (from red to dark red), especially across the central and southwestern parts of the country. TX90P and TN90P show increases often exceeding 2-4% per decade, while TXx and TXn also display notable warming trends in these regions. Conversely, the absolute temperature indices (TXx and TXn) exhibited a weaker trend in the northeast of Afghanistan. The temporal distribution (Figure S5) further confirms a general increase in temperature-related extreme weather events, particularly evident in the southwest.

Precipitation-related indices (Figure S4): These indices present a more varied and less statistically significant picture. While the desert region showed a decreasing trend in some precipitation indices, few areas passed the 95% significance test. For instance, CDD (Consecutive dry days) shows increasing trends (up to 30 days/decade) in parts of the southwest, implying longer dry spells. However, R95P (Very wet days) indicates decreases in the south but increases in the northeast. R10MM (Number of heavy rainfall days) and RX5DAY (Annual maximum 5-day rainfall) exhibit mixed spatial trends, with generally lower magnitudes and less widespread statistical significance than temperature indices. Temporally (Figure S5), precipitation-related extreme indices exhibit frequent alternation between decreasing and increasing patterns, suggesting a less consistent long-term trend.

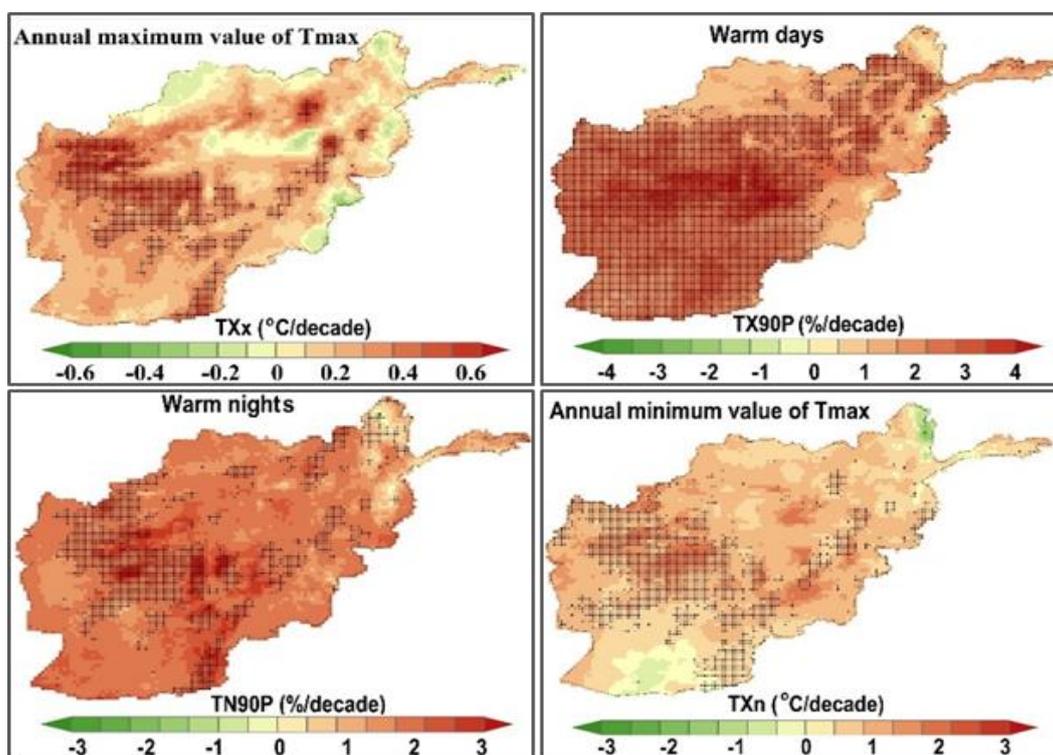


Figure S3. Trend of the extreme indices related to temperature over Afghanistan from 1975 to 2014

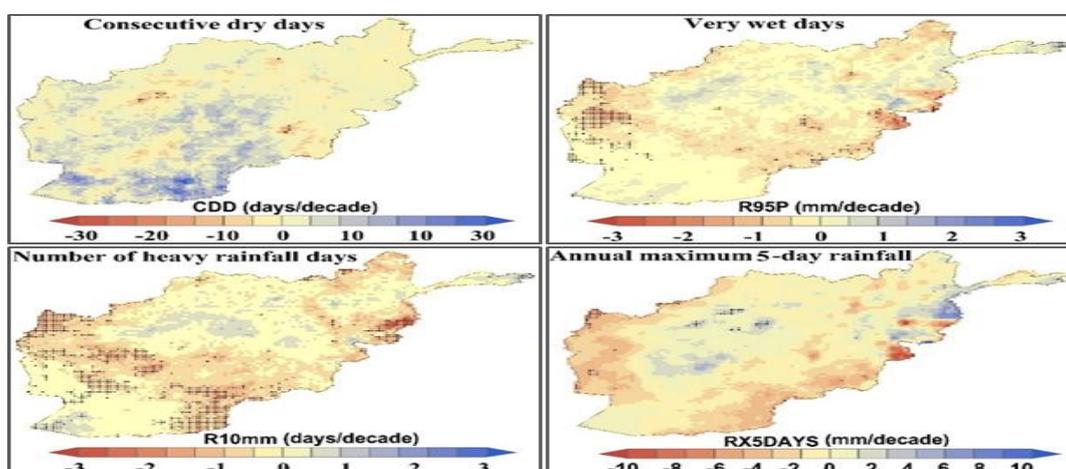


Figure S4. Trend of the extreme indices related to precipitation over Afghanistan from 1975 to 2014

### Correlation of Drought And Climate Factors

Figure 2 illustrates the correlation coefficients between the SPEI and the selected temperature and precipitation-related extreme climate indices for the 1975–2014 period. The analysis reveals a stark contrast in their relationship with drought severity (Parry, 2007).

The SPEI index exhibited significant negative correlations with temperature-related indices. For example, TN90P (warm nights), TX90P (warm days), TXN (annual minimum of daily maximum temperature), and TXX (annual maximum of daily maximum temperature) all showed strong negative correlation coefficients, ranging from approximately -0.5 to -0.65, particularly for elevations below 2000m. This statistically robust inverse relationship indicates that increasing temperature extremes are directly associated with intensified drought conditions (lower SPEI values).

In contrast, the SPEI index showed weak, often inconsistent correlations with precipitation-related indices. While CDD (consecutive dry days) showed a weak negative correlation (around -0.1 to -0.2), other precipitation indices, such as R10MM, R95P, and RX5DAY, exhibited only weak positive correlations (ranging from 0.0 to 0.25). This suggests that while precipitation certainly plays a role, its extreme events do not exert the same dominant influence on SPEI variability as temperature extremes (Nabizada et al., 2023; Nabizada & Köylü, 2025).

Therefore, the empirical evidence strongly supports the conclusion that the observed intensification of drought conditions in Afghanistan between 1975 and 2014 is predominantly related to rising temperatures rather than significant shifts in precipitation patterns.

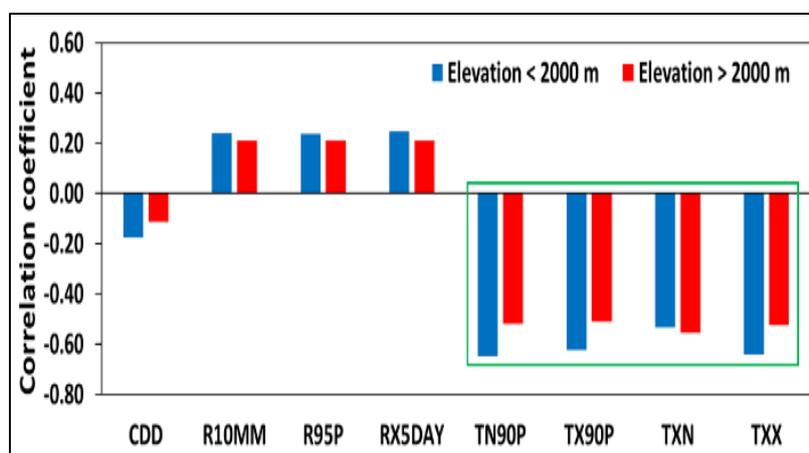


Figure 2. Correlation between SPEI and climate extreme indices

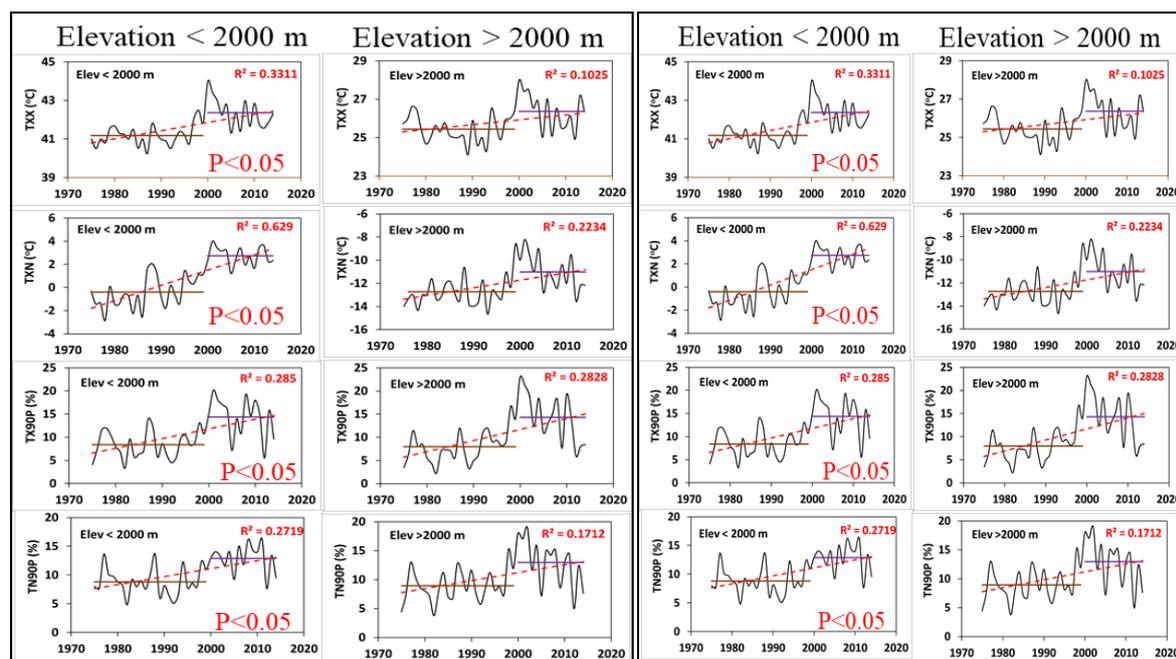


Figure S5. Time series of the extreme indices related to temperature over Afghanistan, and time series of the extreme indices related to precipitation over Afghanistan

## CONCLUSION

This study meticulously examined the primary drivers of drought severity in Afghanistan between 1975 and 2014. By employing a robust methodology, including the selection of a representative subset of eight extreme climate indices (ECIs) through rigorous Variance Inflation Factor (VIF) analysis (Table 1), we have provided critical insights into the region's hydroclimatic response to climate change.

Our principal finding is that temperature-related extreme climate indices exhibit consistent and statistically significant upward trends across Afghanistan (Figure S3). This escalating thermal stress is strongly and negatively correlated with the Standardized Precipitation Evapotranspiration Index (SPEI) values, indicating a direct link to increased drought severity. Specifically, we observed strong negative correlation coefficients ranging from approximately -0.5 to -0.65 between SPEI and key temperature indices such as TN90P, TX90P, TXN, and TXX (Figure 3), highlighting their dominant influence. The SPEI itself shows a statistically significant decreasing trend ( $P < 0.05$ ) across both elevation zones (Figure 3a and 3b), particularly pronounced in the southwestern desert regions (Figure S2), signifying a shift from predominantly drought-free conditions pre-1999 to moderate drought post-1999. In contrast, precipitation-related ECIs displayed no significant long-term variation (Figure S4) and exhibited only weak and inconsistent correlations with SPEI (Figure 3), confirming their lesser role in the observed drought intensification. This leads to the unequivocal conclusion that the increasing aridity in Afghanistan is predominantly driven by rising temperatures and their impact on evapotranspiration, rather than significant alterations in precipitation patterns.

These results are largely consistent with the broader scientific understanding articulated by the Intergovernmental Panel on Climate Change (IPCC, 2007, 2021) regarding the exacerbation of extreme events under global warming. Our findings align with regional studies that acknowledge Afghanistan's high vulnerability to climate extremes (Aliyar et al., 2022; Qutbudin et al., 2019) and corroborate the reliability of ERA5 reanalysis data for such assessments in the region (Hayat, 2022; Sediqi et al., 2019). The systematic approach to ECI selection addresses a recognized methodological gap in earlier research concerning comprehensive frameworks for identifying representative indices in Afghanistan (Baig et al., 2020; Noori & Singh, 2021). While previous studies have indicated a general increase in aridity, our research provides robust empirical and statistical evidence explicitly attributing this intensification to temperature extremes.

Theoretically, this study refines our understanding of hydroclimatic responses in complex, data-scarce environments by demonstrating the critical role of temperature extremes in drought propagation (Lacetera, 2019). Practically, the implications are profound for Afghanistan, where over 80% of the population relies on agriculture (Chen et al., 2023; Jahish et al., 2021). The identified temperature-driven intensification of drought necessitates an urgent re-evaluation of water resource management, agricultural planning, and disaster preparedness strategies. Policies must prioritize adaptation measures that account for rising temperatures and increased evapotranspiration, moving beyond solely precipitation-centric approaches to safeguard livelihoods and food security.

Despite its robust methodology, this research has certain limitations. The reliance on reanalysis datasets, though necessary due to the sparsity of in-situ records, inherently carries potential uncertainties. Additionally, the study period (1975–2014) provides a valuable historical context but does not encompass the most recent decade of climatic shifts. The broad categorization of elevation zones, while informative, simplifies Afghanistan's highly heterogeneous topography and its associated microclimates.

Future research should build upon these findings by extending the analysis to include more recent climate data and by incorporating finer spatial resolution analyses, potentially through advanced regional climate models. Investigating the influence of other climatic teleconnections on Afghanistan's drought patterns and conducting detailed socio-economic impact assessments of these temperature-driven droughts are crucial next steps for developing effective and equitable adaptation strategies against climate change in the region.

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## AUTHORS CONTRIBUTION

The corresponding author of this manuscript is Abdul Sami Kohistani, and the other contribution is mentioned below with their responsibility.

**Abdul Sami KOHISTANI:** Conceptualize, Design of Methodology, Validation of formal analysis, Investigation, Resources, Writing-original draft, Writing-review and editing.

**Hasibullah Jahish:** Formal analysis, Investigation, Resources, Writing-original draft, Writing-review and editing, responding to the reviewer comments.

**Zabihullah Rasoli:** Formal analysis, Investigation, Resources, Writing-original draft, Writing-review and editing.

**Mohammad Akram Faizy:** Formal analysis, Investigation, Resources, Writing-original draft, Writing-review and editing.

## CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

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