

Topographic modulation of drought propagation establishes low-elevation hotspots and mid-elevation climatic refugia in Southern Africa

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ABSTRACT

Drought dynamics across Southern Africa remain poorly understood, particularly regarding the topographic mechanisms that influence their spatial development and ecological consequences. Yet, the mechanisms by which local topography modulates drought propagation across elevation gradients, a key control on regional vulnerability, remain uncertain. We precisely quantify this critical mechanism. This study integrates high-resolution climate data (1950–2022) with future Standardized Precipitation Evapotranspiration Index (SPEI) projections to quantify three key aspects: 1) multi-year drought regimes, 2) topographic controls on drought propagation mechanisms, and 3) identification of hotspots of hydroclimatic vulnerability across various topographical complexities. We found the most severe long-term aridification occurs at higher elevations (2000–2500 m), where SPEI24 trends are strongest ($r = 0.6$). In contrast, mid-elevation zones (1000–1500 m) displayed a persistent hydroclimatic buffer, exhibiting the slowest drought propagation rates and a decadal-scale shift toward shorter drought timescales, a pattern projected to intensify, with low-elevation zones accelerating toward more persistent drought conditions. This buffering effect, driven by orographic precipitation and reduced evaporative demand, creates distinct climatic refugia. Regionally, we identified a significant post-2000 expansion in the dominance of short-term droughts (SPEI01, SPEI03), with the fastest drought propagation in low-elevation and regional hotspots (e.g., Angola and Namibia). Our results demonstrated that drought development is fundamentally controlled by the interaction of timescale and topography. We, therefore, conclude that effective early warning systems must be spatially and temporally tailored by prioritizing rapid-onset agricultural alerts for lowlands while monitoring long-term hydrological deficits in high-elevation areas to mitigate ecological and societal consequences across Southern Africa.

1. Introduction

The savannas and drylands of Southern Africa, which are home to iconic biodiversity and a rich tapestry of cultures, maintain a fragile hydro-climatic balance (Midgley and Thuiller, 2011; Osborne et al., 2018). In recent decades, this equilibrium has been increasingly destabilized by intensifying climate extremes, particularly multi-year droughts and heat waves that have come to characterize the new normal (IPCC, 2023). Recurrent water scarcity poses a threat not only to prominent megafauna and unique flora such as the succulents of the Karoo (Hilton-Taylor, 1996), but also to the livelihoods of millions who depend on rain-fed agriculture and pastoralism (Okolie et al., 2023).

Consequently, the social-ecological resilience of the region is fundamentally contingent on the implementation of innovative water risk management strategies (Nyahunda, 2024). This resilience must evolve from incremental adjustments to more fundamental, transformational adaptation to address systemic aridification.

The pronounced longitudinal and topographically induced latitudinal variability in aridity significantly influences distinct drought propagation timescales across the climatic gradients of Southern Africa region (Rouault et al., 2024). However, regional climate and hydrological models remain limited, often masking complex local interactions that are critical for effective planning. Observational analyses of 20th-century African climate trends have documented significant

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continental warming, regional precipitation declines, and desert expansion, while also concluding that modeling such regional hydroclimatic change remains a persistent challenge (Thomas and Nigam, 2018). This vulnerability was vividly illustrated in the early 2020s when a multi-year El Niño event triggered one of the most severe anthropogenic water crises recorded (UNCCD, 2025; van Mourik et al., 2025). The event resulted in the catastrophic failure of rain-fed agriculture and water reservoirs, illustrating droughts with new, non-stationary features that deviate from historical variability (Pascale et al., 2020; Tladi et al., 2022). These emerging features primarily encompass altered temporal patterns (Pascale et al., 2020), increased spatial coherence (Gong et al., 2024), and thermodynamically driven signal amplification (Chivangulula et al., 2023).

To effectively capture the non-stationary behavior of drought, the Standardized Precipitation-Evapotranspiration Index (SPEI) serves as a comprehensive tool for monitoring drought conditions (Vicente-Serrano et al., 2010). It integrates both water supply, represented by precipitation, and atmospheric water demand, indicated by potential evapotranspiration. This integration provides a more detailed assessment of water balance than indices that rely solely on precipitation, such as the Standardized Precipitation Index (SPI) (Vergni et al., 2021; Vicente-Serrano et al., 2020). This is particularly critical in regions experiencing rapid warming, where intensifying heat waves exacerbate hydrological deficits by accelerating soil moisture depletion and increasing ecological stress (Bhardwaj et al., 2025; Liu et al., 2025). The multi-scalar nature of SPEI effectively captures the temporal propagation of droughts, from their meteorological onset to their agricultural and hydrological consequences (Li et al., 2020). Although other factors, such as groundwater systems, play a role in influencing drought progression, the consideration of evapotranspiration is essential (Li et al., 2022). The long-term effects of these impacts result in enduring ecological and hydrological degradation, highlighting the urgent necessity to understand the mechanisms of drought propagation. The complex topography of Southern Africa drives elevation-dependent climatic responses, with projected ecological shifts including upslope species migration and range contraction across these gradients due to climate and land-use change.

Recent advances have applied complex network theory to understand drought synchronization and propagation, yet a dedicated framework for applying these advances to agricultural drought specifically remains an active area of development (Wen et al., 2025; Xu et al., 2024). This research work delivers a critical advancement in understanding hydroclimatic change across Southern Africa through multi-scale drought characterization spanning from 1950 to 2022. We demonstrate previously undocumented elevation-dependent drought propagation patterns that redefine climate resilience frameworks for complex landscapes. Our identification of specific drought hotspots and the temporal reorganization of seasonal aridity provides a mechanistic framework for predicting climate impacts across tropical regions worldwide.

This study establishes a novel methodological standard for drought characterization and 30-year multi-timescale SPEI projection. It delivers urgently needed insights for climate adaptation policy and conservation planning in at-risk ecosystems. By moving beyond generalized models, we reveal fine-scale topographic controls and future drought trajectories. This approach addresses critical knowledge gaps and helps to avert maladaptation, where poorly designed interventions can reinforce vulnerability, by enabling precisely targeted strategies.

This study addresses three critical objectives: First, we investigate how variations in topography regulate the propagation of drought across different elevation gradients. We specifically examine mechanisms that contribute to the vulnerability of lowland areas versus the buffering effects observed at mid-elevations and project how these relationships will evolve over the next 30 years. Second, we examine how characteristic timescales associated with drought intensification vary spatially across the climatic gradients of the region and how these timescales

evolve from meteorological to hydrological timescales. Third, we consider how identifying dominant drought timescales and spatial hotspots informed by future projections can enhance the precision of early-warning systems and guide targeted adaptation strategies. Through these objectives, we establish a novel framework for understanding the interactions between climate, topography, and drought. Our work combines historical analysis and forward-looking projections to provide actionable insights for building resilience in this climate-sensitive region.

2. Materials and methods

2.1. Study area

This study focuses on Southern Africa, a domain encompassing Angola, Botswana, Eswatini, Lesotho, Namibia, South Africa, and Zimbabwe (Fig. 1a). The delineation is based on shared environmental and hydrological characteristics, excluding northern territories dominated by the Zambezi River Basin and East African Rift System lakes. The region is predominantly situated on the South African Plateau, ranging from hyper-arid coastal and inland deserts to more humid high-elevation areas, resulting in significant disparities in water availability, leaving most countries in the study area vulnerable to various forms of water scarcity (Matchaya et al., 2019). A unimodal summer rainfall pattern (October–March) prevails, with a winter rainfall zone in the southwestern Cape (Moise and Hudson, 2008). The region's hydroclimatic heterogeneity, shown by a precipitation gradient from <100 mm to >1500 mm and strong temperature variations (Fig. 1b, c), combined with a heavy reliance on rain-fed agriculture, renders it critically vulnerable to drought dynamics. Such heterogeneity supports a mosaic of unique biomes, from the hyper-arid Namib to the water-dependent Cape Floristic Region (Grobler and Cowling, 2021).

2.2. Data acquisition and processing

The integrated methodological framework for this study is presented in Fig. S1. This study utilized a multi-source data framework, with data acquisition conducted in Google Earth Engine (GEE) to enhance computational efficiency. The primary drought variable analyzed was the SPEI sourced from the Global SPEI database (SPEIbase v.2.10, <http://spei.csic.es/>) at a spatial resolution of 0.5° for the period from 1950 to 2022 (Beguería et al., 2024). We analyzed six distinct timescales to effectively capture drought phenomena across meteorological (SPEI01 and SPEI03), agricultural (SPEI06 and SPEI09), and hydrological (SPEI12 and SPEI24) domains (Vicente-Serrano et al., 2010). The contextual datasets comprised elevation data from the Shuttle Radar Topography Mission (SRTMGL1_003), MAP data from the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS Daily, v.2.0), and MAT data from ERA5-Land (ERA5-L). To ensure spatial consistency for subsequent analysis, all source datasets (including the 0.5° SPEI data) were resampled to a common 1-km spatial resolution grid using bilinear interpolation (Jones, 1999). The method produces smoothly transitioning values across space, as opposed to maintaining constant values within an area, making it suitable for spatially continuous variables such as the climate data used in this study.

2.3. Drought metric calculation and trend analysis

Drought events ($\text{SPEI} \leq -1$) were identified using the run theory (Yevjevich, 1967). Five drought metrics were calculated for the entire period (1950–2022): Drought Duration (Dd), Drought Frequency (Df, Eq. S1), Drought Severity (Ds; Eq. S2), Drought Intensity ($\text{DI} = \text{Ds}/\text{Dd}$; Eq. S3), and Drought Risk ($\text{DR} = \text{Df} \times \text{Ds}$). Trends in annual Ds, DI, and DR were analyzed using the non-parametric Mann-Kendall test (Mann, 1945) with pre-whitening to account for serial autocorrelation (Yue and Wang, 2002). The magnitude of significant trends ($p < 0.05$) was

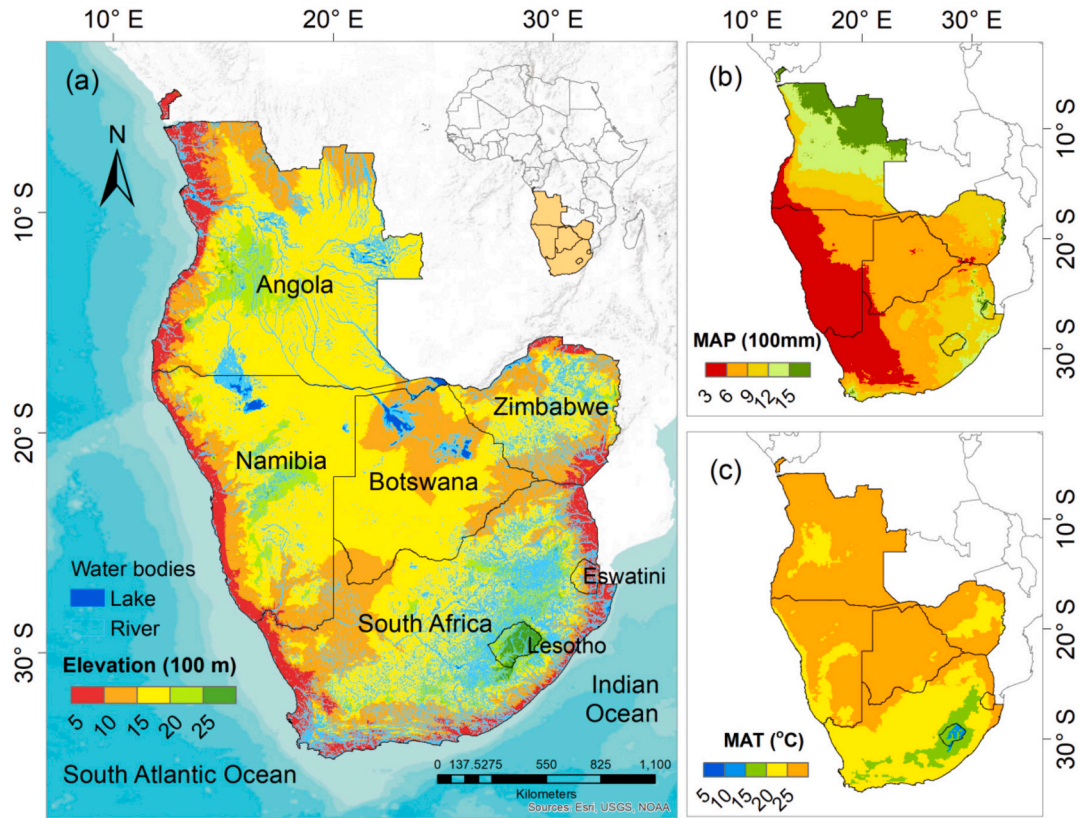


Fig. 1. Study region overview showing (a) topography and major water bodies, (b) mean annual precipitation (MAP), and (c) mean annual temperature (MAT). The region is located between 5°S and 35°S latitude and 10°E and 35°E longitude.

quantified using the Theil-Sen slope estimator (Sen, 1968). The detailed equations for the Mann-Kendall statistic and the Theil-Sen slope are provided in the Supplementary Materials (Eqs. S4-S7).

2.4. Decadal dominant timescale analysis

To detect changes in the characteristic timescales of drought over time and to address their spatial variation across the climatic gradients of the region, we conducted a decadal dominant timescale analysis. For each grid cell and for each decade from the 1950s to the 2010s, we computed the decadal mean SPEI value for all six timescales (SPEI01 to SPEI24). The interdecadal trend slope (β_k) for each timescale k was then calculated using linear regression (Eq. 1):

$$\beta_k = \frac{[\sum(t \times \text{SPEI}_{kt}) - (\sum t \sum \text{SPEI}_{kt})/T]}{[\sum t^2 - (\sum t)^2/T]} \quad (1)$$

where t represents the decade number, and T denotes the total number of decades. The dominant timescale for each pixel was defined as the timescale exhibiting the largest absolute trend slope ($|\beta_k|$), considering only statistically significant trends ($p < 0.05$, derived from the Mann-Kendall test applied to the decadal mean time series). This approach identifies the timescale at which drying or wetting trends are most pronounced, revealing whether short-term meteorological droughts (SPEI01 to SPEI03) or long-term hydrological/ecological droughts (SPEI12 and SPEI24) have been the dominant factors driving recent hydroclimatic changes. The geographic distribution of these dominant timescales was analyzed to identify spatial patterns and their correlation with broad-scale climate gradients. Furthermore, the final spatially explicit dominant drought timescales serve as a key product for the development of precision early-warning systems, as they indicate the most relevant monitoring period for a specific location.

2.5. Drought propagation analysis

The drought propagation rate (PR) was calculated to quantify the transition of drought signals across different SPEI timescales. Following the run theory method used in drought propagation studies (Yevjevich, 1967), corresponding drought events between shorter and longer SPEI timescales (e.g., SPEI01-to-SPEI03) were first identified and matched based on temporal overlap. Potential temporal asynchrony was managed by defining correspondence strictly when the onset of a short-timescale drought (SPEI01) occurred within an ongoing longer-timescale drought (SPEI03). To evaluate sensitivity to the selected moderate drought threshold ($\text{SPEI} \leq -1$), a parallel analysis using a strict threshold ($\text{SPEI} \leq -1.5$) confirmed the robustness of the identified drought propagation patterns. The drought propagation rate for matched events was then defined as the ratio of the Dd at the longer timescale (Dd long) to the duration at the shorter initiating timescale (Dd short) (Eq. 2).

$$\text{PR} = \text{Dd long} / \text{Dd short} \quad (2)$$

A $\text{PR} > 1$ indicates drought amplification, where short-term meteorological droughts develop into disproportionately longer-term hydrological droughts. All statistical analyses were performed in R version 4.4.3 (R Core Team, 2025) using the following key packages: *terra* (Hijmans, 2025) for raster data processing, *sf* (Pebesma and Bivand, 2023) for spatial vector operations, and *trend* (Pohler, 2023) for the Mann-Kendall trend analysis.

2.6. Multi-Timescale SPEI projection and future drought risk analysis

To project future drought evolution, we developed a 30-year (2023–2052) multi-timescale SPEI projection framework. For each grid cell and timescale, a pixel-specific Theil-Sen trend (β_{hist}) from the

historical record (1950–2022) formed the baseline projection (Eq. 3). Future monthly SPEI was modeled as:

$$SPEI_{t+p} = SPEI_t + \beta_{hist}p + \varepsilon_{seas}(t+p) + \omega_{pars} \quad (3)$$

The drought projection model forecasts future SPEI ($SPEI_{t+p}$) by adjusting the observed initial condition ($SPEI_t$) with a scaled historical trend ($\beta_{hist}p$), a deterministic seasonal adjustment term ($\varepsilon_{seas}(t+p)$). To account for persistent, location-specific climatic effects tied to landscape features, a topographic modulation parameter ω_{pars} is a time-invariant, pixel-specific parameter derived as the long-term mean residual component from the detrended, deseasonalized historical SPEI series for each pixel. This term represents a statistically persistent, spatially explicit climatic baseline, capturing the net effect of time-invariant local factors (e.g., topographic position) on the historical moisture balance (Wang et al., 2022).

Uncertainty was propagated by sampling from bootstrapped distributions of the fitted coefficients. The resultant 1000-member ensemble quantifies the projection uncertainty inherent to the extrapolation model's core assumption of trend and pattern stationarity.

Projected changes ($\Delta Metric$) and future trends were analyzed across 500-m elevation zones to quantify topographic modulation. For each zone, the median projected change and interquartile range summarized the central tendency and uncertainty. The Kruskal-Wallis test

determined if $\Delta Metric$ distributions differed significantly across elevations, with the post-hoc Dunn's test (Bonferroni-corrected) identifying specific differences. This pinpoints 'islands of resilience' (zones with minimal projected drying) and 'hotspots of vulnerability' (zones with amplified risk). Integrating this with the decadal dominant timescale and drought propagation analyses links historical dynamics, transitional processes, and future risks for precision adaptation.

3. Results

3.1. Drought duration and frequency

The analysis revealed a clear scaling pattern where Dd increased with longer SPEI timescales, peaking at 37.3% (327 months) for SPEI24 compared to 29.8% (261 months) for SPEI01 (Fig. S4). Spatially, the longest durations were concentrated in the arid south, exhibiting a distinct northward decline and notable intensification along the hyper-arid coastal zones (Fig. 2). A similar upward trend was observed for Df, which also reached its maximum at SPEI24 (Fig. S2). Geographically, high-frequency drought hotspots were dominant in the central and southern regions, such as Botswana, South Africa, and Zimbabwe, though their spatial extent contracted at the longer SPEI24 scale. Conversely, the western region, encompassing parts of Angola and

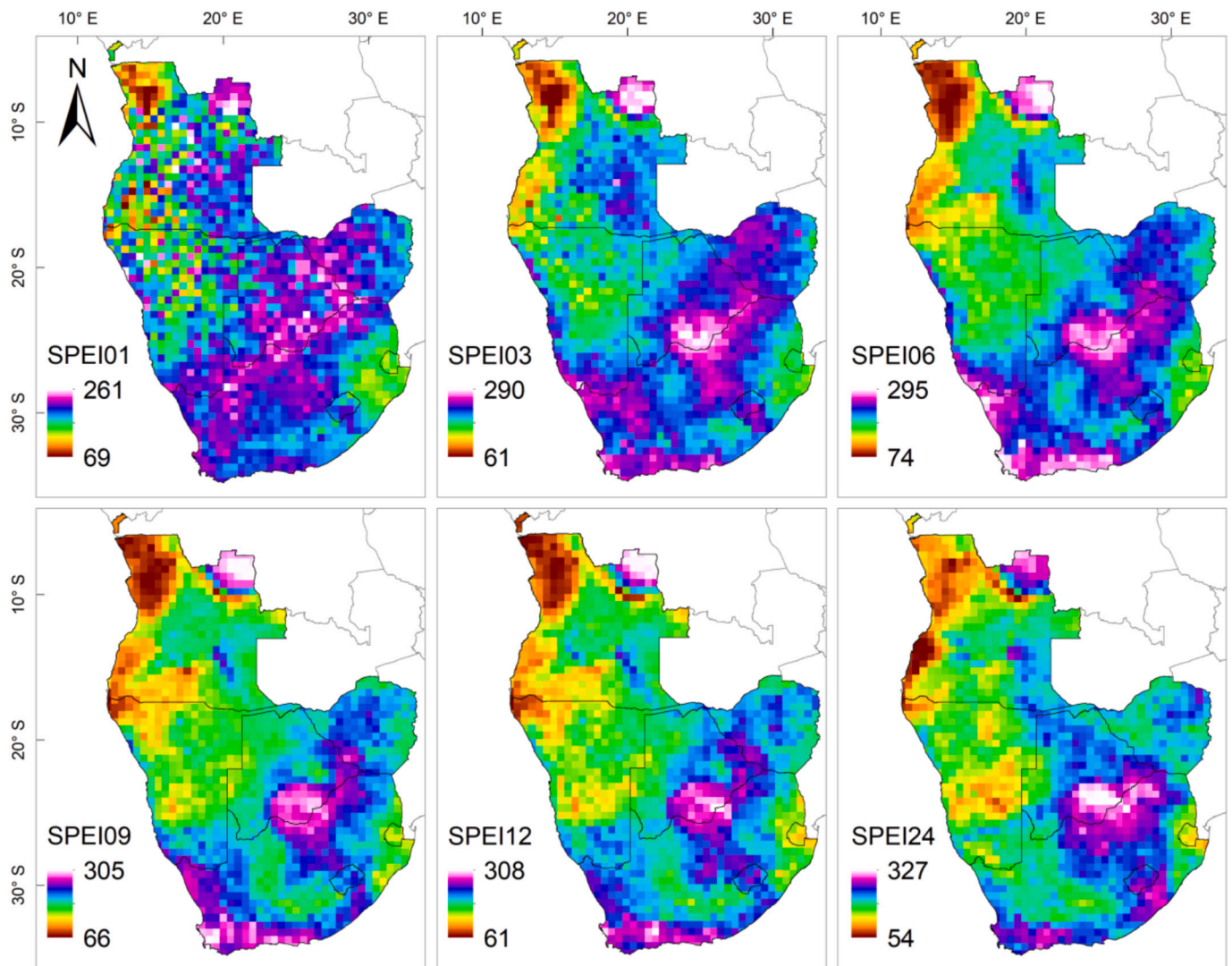


Fig. 2. Spatial pattern of drought duration (days) across Southern Africa (1950–2022). Duration increases from brown/yellow (shorter) to purple/white (longer). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Botswana, was characterized by predominantly low drought frequencies that became more pronounced with extended timescales, indicating a shift toward less frequent but longer-lasting drought events.

3.2. Drought severity and intensity

Drought severity exhibited a pronounced scaling with the SPEI timescale, with maximum values increasing from 3.29 at SPEI01 to 67.54 at SPEI24, reflecting the accumulation of water deficits over longer periods (Fig. S3). Spatially, the most severe conditions were consistently identified in northern, central, and southeastern Angola, along with central Botswana, highlighting these areas as persistent drought hotspots. Complementing this, DI representing the average monthly deficit also showed a significant non-linear increase, intensifying from 1.24 at SPEI01 to 2.31 at SPEI24 (Fig. 3). This intensification was most pronounced in the humid-transitioning east and persistently high in central Angola. In contrast, the arid southern tip showed relative resilience, with little change in intensity as the SPEI timescale increased, suggesting an adaptation to persistent water scarcity.

3.3. Spatial distribution of drought trends

Trend analysis revealed significant drying patterns across Southern

Africa, with their nature and intensity varying by region and timescale. A significant increase in DI ($p < 0.05$) was identified in northern Namibia at short-term scales (SPEI01–SPEI03), while a more pronounced intensification ($p < 0.01$) in Ds was observed across all SPEI timescales and elevation gradients, as indicated by consistently negative Mann-Kendall Tau values (Fig. 5a).

The magnitude of this drying trend strengthened substantially with longer timescales, with Tau values intensifying from approximately -0.15 (SPEI01) to less than -2.0 (SPEI24), a progression mirrored in the increasing rate of change from -0.007 units/year to -0.017 units/year, respectively (Fig. 5b). Spatially, these statistically significant trends became consistent and robust above 500 m (Fig. 4). The relationship between elevation and drought trends was complex and nonlinear, with the strongest correlation ($r = 0.6$) recorded at the highest elevations (2000–2500 m), though this was not consistent across all elevation bands (Fig. 5c).

3.4. Interannual and seasonal drought patterns

The decadal analysis revealed a systematic scaling of drying trends, with longer SPEI timescales over the seven-decade study period. Longer timescales (SPEI06–SPEI24) showed significant drying ($p < 0.05$), indicating intensified agricultural and hydrological droughts (Fig. 6a). A

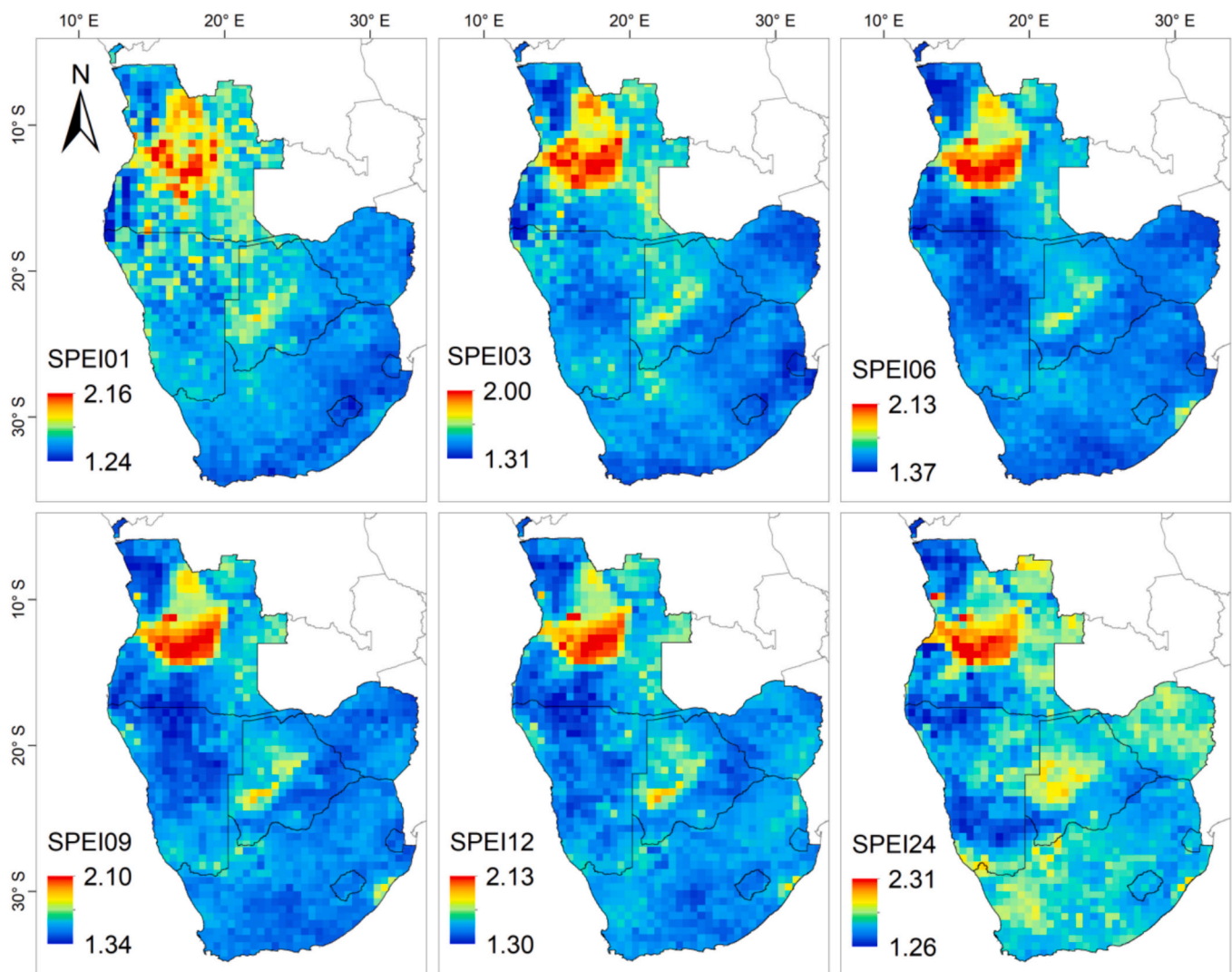


Fig. 3. Spatial pattern of drought intensity across Southern Africa (1950–2022). Intensity increases from blue (low) to red (high). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

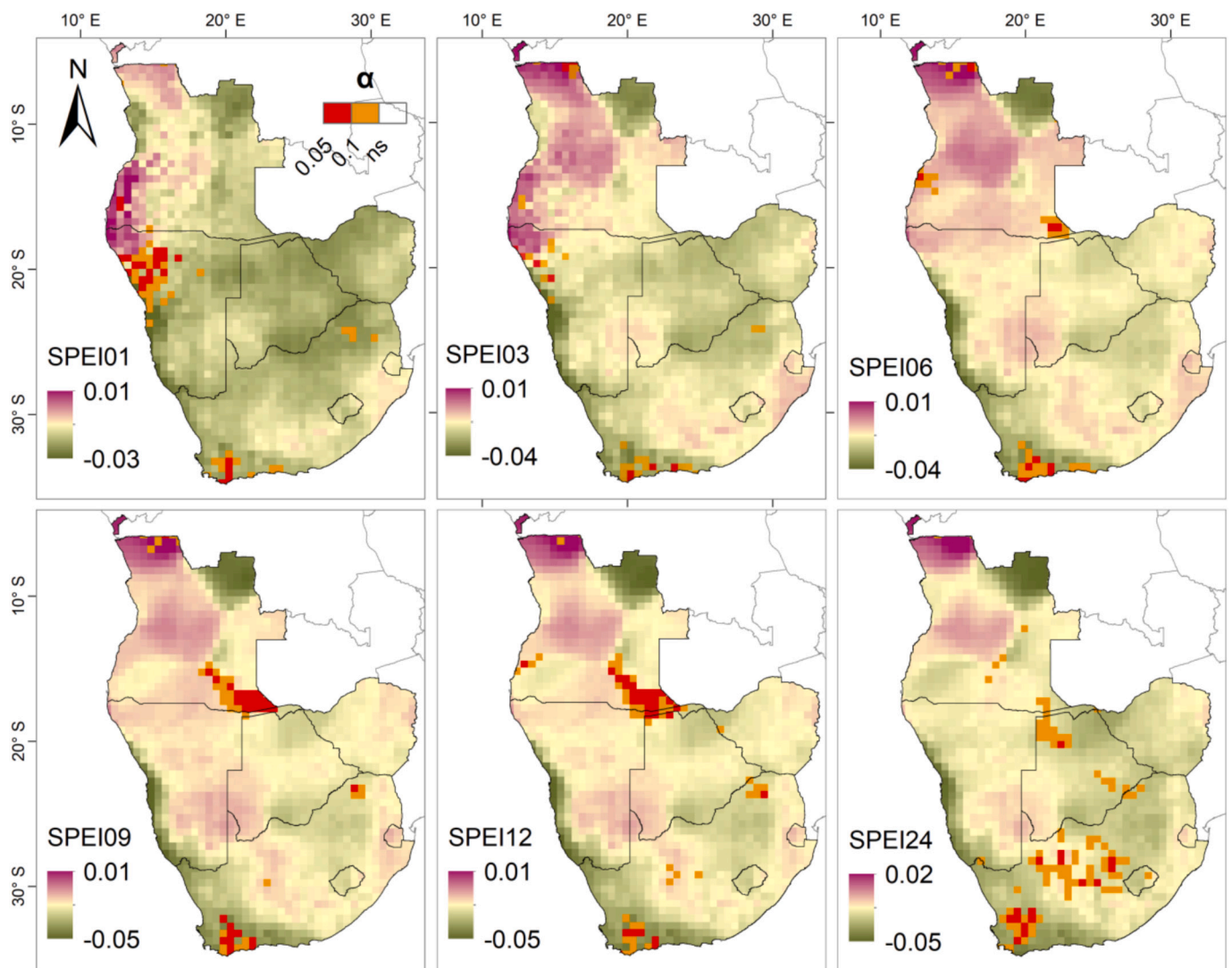


Fig. 4. Trend in drought conditions across Southern Africa (1950–2022). The colour scale indicates trend direction from green (negative) to purple (positive). Significant trends ($p < 0.05$ in red; $p < 0.1$ in orange) are overlaid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

significant shift toward drier conditions was evident at medium- and long-term scales. This was most substantial for hydrological droughts, with SPEI12 (slope = -0.012 , $p = 0.003$) and SPEI24 (slope = -0.017 , $p = 0.001$) showing the strongest trends (Fig. 5b), underscoring the accumulation of water deficits over time. A finer-scale monthly analysis during the core rainy season (October–March) further refined this pattern (Table S1). Significant drought intensification occurred in early summer (Oct $\beta = 0.286$, Nov $\beta = 0.255$, Dec $\beta = 0.225$), posing risks to crop establishment and water recharge. In contrast, the late summer months (January–March) exhibited statistically no significant trends, indicating a critical temporal narrowing of the most pronounced drying signal to the onset of the growing season (Fig. 6b).

3.5. Spatiotemporal drought evolution

Our analysis revealed a fundamental divergence in drought behavior between short-term variability and long-term trends. Shorter timescales (SPEI01 and SPEI03) exhibited high-frequency oscillations, while longer aggregation periods showed more intense and more persistent drought-wet cycles (Fig. S5a). Spatially, a consistent longitudinal pattern of drought intensification was identified within the 25–30°S latitude belts. A significant temporal shift was observed post-1990, characterized by

improving conditions at latitudes below 15°S that sharply contrasted with the persistent aridification at higher latitudes (Fig. S5b).

3.6. Drought propagation dynamics

Drought propagation analysis revealed consistent amplification across Southern Africa ($PR > 1$), with events lengthening from meteorological to hydrological timescales. Amplification was strongest for long pathways (e.g., SPEI12–24) at high-elevation areas (2000–2500 m), where PR exceeded 14% (Fig. 7a, Table S4). Spatial analysis identified major drought hotspots in Zimbabwe, Lesotho, and eastern South Africa (Fig. 7b). Drought propagation was critically modulated by topography, with slower propagation rates at mid-elevations (1000–1500 m) showing a significant buffering zone ($p < 0.01$, Fig. 7c, Table S4). The sole exception was attenuation ($PR = 0.53$) for the SPEI01–03 pathway at the highest elevations.

3.7. Dominant SPEI timescale trends across Southern Africa

A significant change in the characteristics of drought over the decades was found by the spatiotemporal analysis of the dominating SPEI timescales. The dominance of shorter drought timescales (SPEI01,

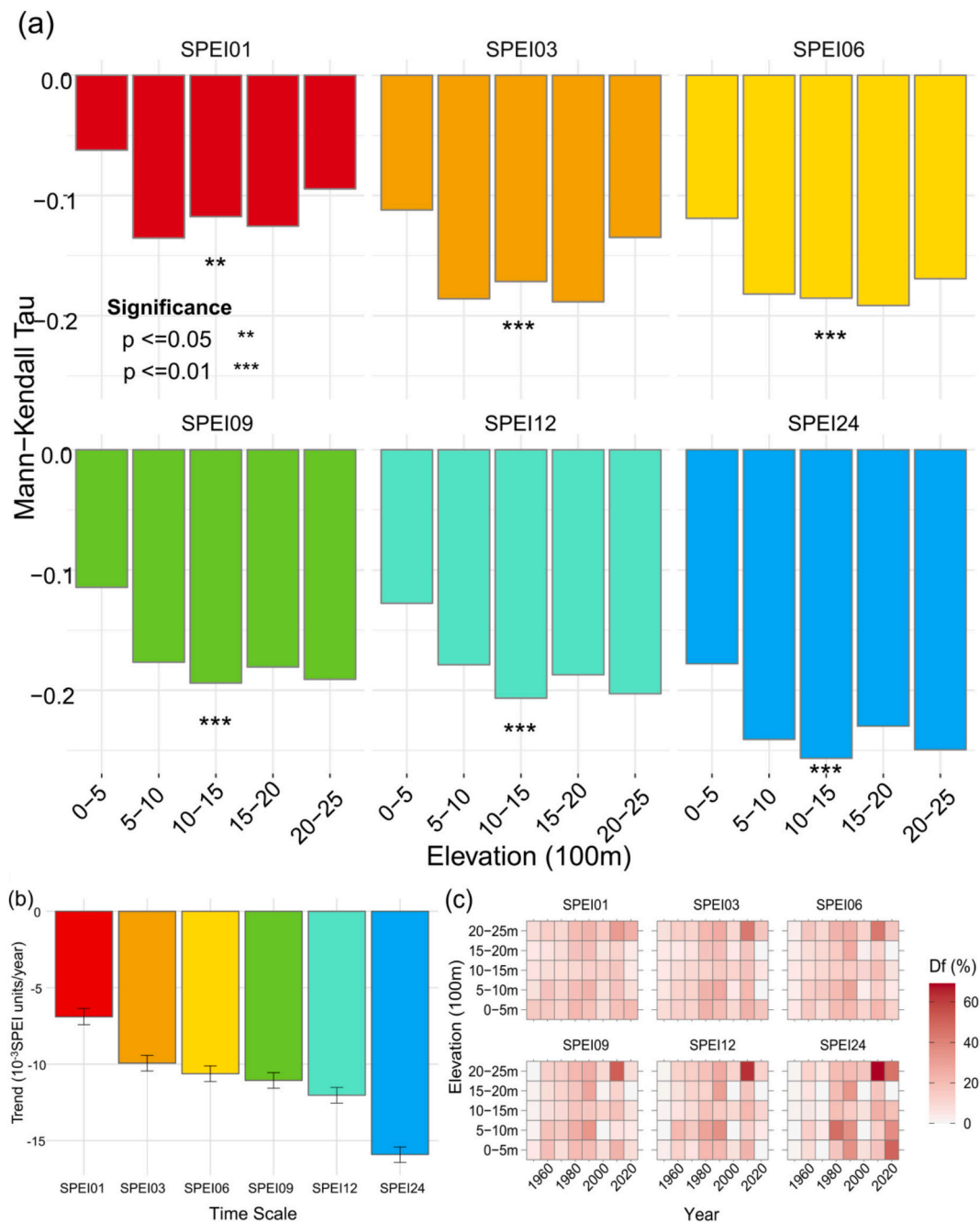


Fig. 5. Drought trend analysis (1950–2022): (a) Mann-Kendall Tau values for wetting/drying trends across elevation zones, (b) Significant SPEI trends (units/year) by timescale ($p < 0.05$), and (c) Heat map of SPEI frequency anomalies across elevation gradients. Asterisks denote significant trends ($p < 0.05$).

SPEI03) was explained significantly across the study area, particularly in the northern and eastern regions during the 2000s (Relative Contribution, RC = 0.8), followed by the 2010s (RC = 0.6) (Fig. 8a).

This shift was most pronounced in the west and south (Angola, Namibia), indicating a growing influence of short-term meteorological deficits. Concurrently, an elevation-dependent stratification was evident. At lower elevations (0–500 m), the dominance of shorter timescales (SPEI01, SPEI03) increased significantly by the 2010s. In contrast, SPEI24 emerged as the persistently dominant timescale at higher elevations, achieving nearly complete dominance above 2000 m by the 2010s (Fig. 8b). This signifies a substantial and divergent shift in hydrological patterns, with low-elevations experiencing more transient droughts while high-elevations are increasingly defined by long-term hydrological aridification.

3.8. Amplification and buffering of drought in future decades

Low-elevations (<1000 m) exhibited moderate drying (−0.08%/month) with only 17% of pixels showing significant drying trends ($p < 0.05$). In contrast, mid-elevations (1000–2000 m) showed slightly stronger mean drying (−0.09%/month) but greater variability, with 33% of pixels experiencing significant drying (Fig. 9b, Table S5–S7). Unexpectedly, high-elevation (>2000 m) displayed the most pronounced drying (−0.10%/month), with 67% of pixels showing significant trends (Fig. 9a).

The trend distributions confirmed topographic influences: low-elevation trends were 1.5-fold more variable (SD = 0.03) than mid-elevation trends (SD = 0.02), and trend magnitude increased systematically with elevation across all SPEI timescales (linear regression $p <$

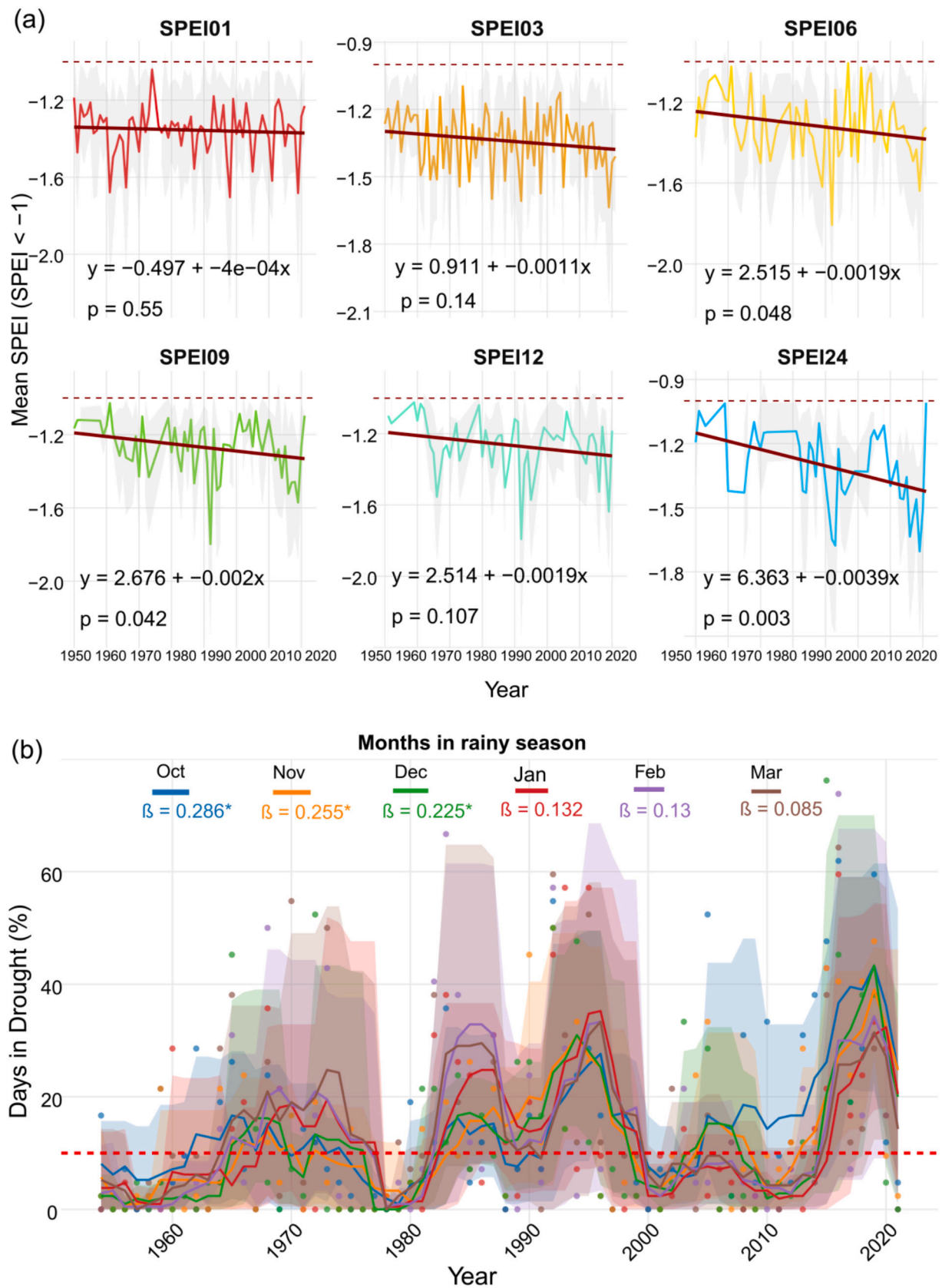


Fig. 6. Drought variability in Southern Africa (1950–2022). (a) Interannual variability of drought conditions (SPEI < -1). (b) Percentage of rainy season days (Oct–Mar) in drought across different SPEI timescales (SPEI01–SPEI24).

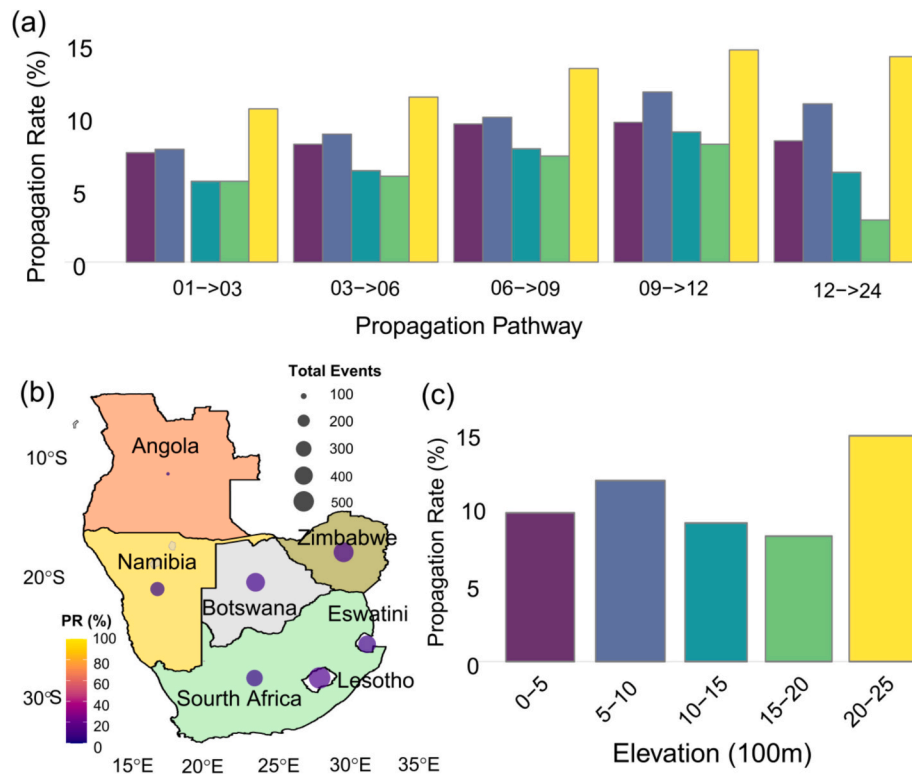


Fig. 7. Drought propagation dynamics in Southern Africa (1950–2022): (a) Scale dependency of drought propagation rate (PR) versus drought duration, (b) Spatial frequency of drought events with hotspots, and (c) Elevation-dependent drought propagation rates.

0.05 for intercepts). While the expected low-mid-elevation divergence was evident in trend variability and spatial patterns, the strongest drying signals emerged at the highest elevations (Table S5).

3.9. A conceptual framework for topographic drought mediation

Our analysis culminated in a novel conceptual framework that explained the topographic partitioning of drought regimes in Southern Africa (Fig. 10). The framework integrated four key components: (1) the formation of stable mid-elevation climatic refugia through orographic buffering (Fig. 10a); (2) the concurrent development of vulnerable drought hotspots in low-elevation and high-elevation areas due to accelerated aridification (Fig. 10b). These contrasting outcomes were mechanistically driven by (3) a differential drought propagation process, where the speed of drought propagation from meteorological to hydrological timescales ranked fastest at high-elevation areas, followed by low-elevation areas, and slowest in climatic refugia, directly governing cumulative Ds (Fig. 10c). Collectively, these processes resulted in (4) the distinct topographic mediation of observed spatial drought patterns and projected future drying trajectories across Southern Africa (Fig. 10d).

4. Discussion

This study examined the characteristics and propagation of drought across Southern African region from 1950 to 2022. Three key patterns emerged from our analysis: (1) the accelerating long-term aridification, particularly reflected in the significant decline of SPEI12 and SPEI24 values; (2) significant topographic modulation, where low-elevations exhibit faster drought PR and higher DS compared to buffered mid-elevations; and (3) the emergence of spatial hotspots with increased Df and Dd, particularly in southeastern regions including Zimbabwe, Lesotho, and eastern South Africa. Building upon these historical patterns, our future projections extend the analysis to 2053, revealing that

these dynamics are not only persistent but also intensifying under continued climate change. These findings underscore the need for targeted adaptation strategies, particularly in water resource management and agriculture in drought-prone zones.

4.1. The topographic mediation of drought regimes

Topography critically regulates drought propagation, with mid-elevations acting as buffered climatic refugia due to orographic effects, while low-elevations face accelerated vulnerability. Specifically, mid-elevations (1000–1500 m) exhibit a unique buffering effect, demonstrated by slower drought PR (Fig. 7c) and distinct temporal trends (Fig. 5a). This climatic stability is consistent with the region's role as a documented evolutionary refuge, as evidenced by its recent formal delineation as the greater mid-elevations Centre of Floristic Endemism, Eastern South Africa, a congruent mid-elevation zone hosting over 220 endemic plant species (Carbutt, 2023). The attribution of mid-elevation buffering to orographically enhanced precipitation and reduced evaporative demand is now explicitly supported by high-resolution regional climate studies conducted in Southern Africa (Chikoore et al., 2024; Conradie et al., 2022) and is corroborated by regional observational evidence showing widespread declines in pan evaporation linked to local land-cover changes (Chapman et al., 2021), confirming the regional validity of these atmospheric drivers. This fine-scale topographic control operates within a continent-wide context of significant 20th-century warming, regional precipitation declines, and desert expansion, trends which observational analyses conclude are remaining challenges for regional climate models to accurately capture (Thomas and Nigam, 2018).

While these atmospheric drivers are primary, our analysis acknowledges that local subsurface characteristics, particularly soil water retention capacity and vegetation cover, also critically mediate moisture availability and drought signal propagation (Sun et al., 2026). This aligns with a growing global body of research on elevation-dependent

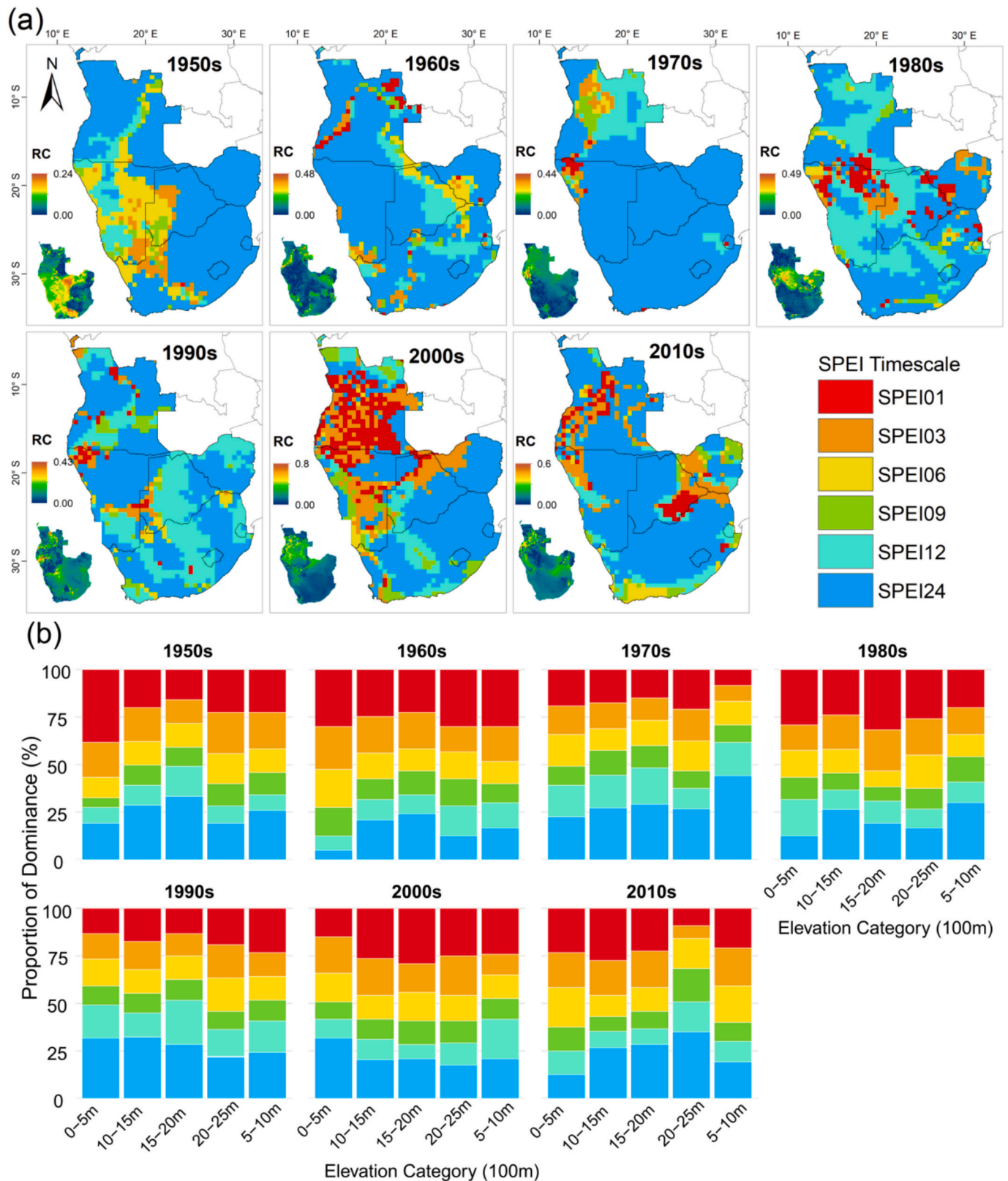


Fig. 8. Dominant SPEI timescales (1950s–2010s) and their relative contributions (RC). (a) Spatio-temporal distribution with decadal RC. (b) Variation across elevation categories.

climate responses, including work in the Andes (Caro et al., 2024) and the Tibetan Plateau (Liu et al., 2024). Our quantification of reduced PRs provides a critical mechanistic validation, linking orographic processes to drought lifecycles (Table S4). The key regional specificity of our

findings lies in the primary driver: the interaction of the Great Escarpment with persistent southeasterly trade winds, which enhances orographic precipitation at mid-elevations (Koseki and Demissie, 2018). This mechanism differs from systems where buffering is driven by

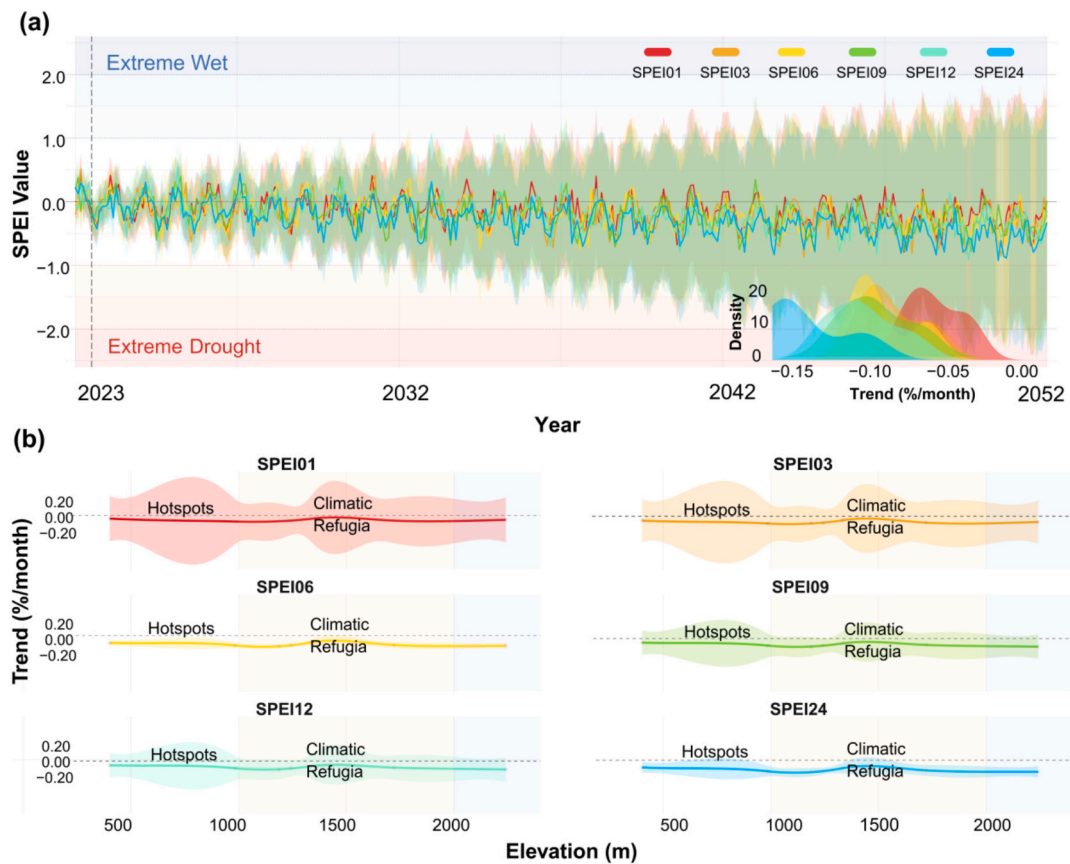


Fig. 9. Future drought projection and topographic risk analysis for Southern Africa (2023–2052). (a) Projected multi-timescale SPEI trajectories, indicating longer accumulation periods. (b) Synthesis of projected elevation-dependent SPEI changes (Δ Metric), identifying topographic hotspots and climatic refugia.

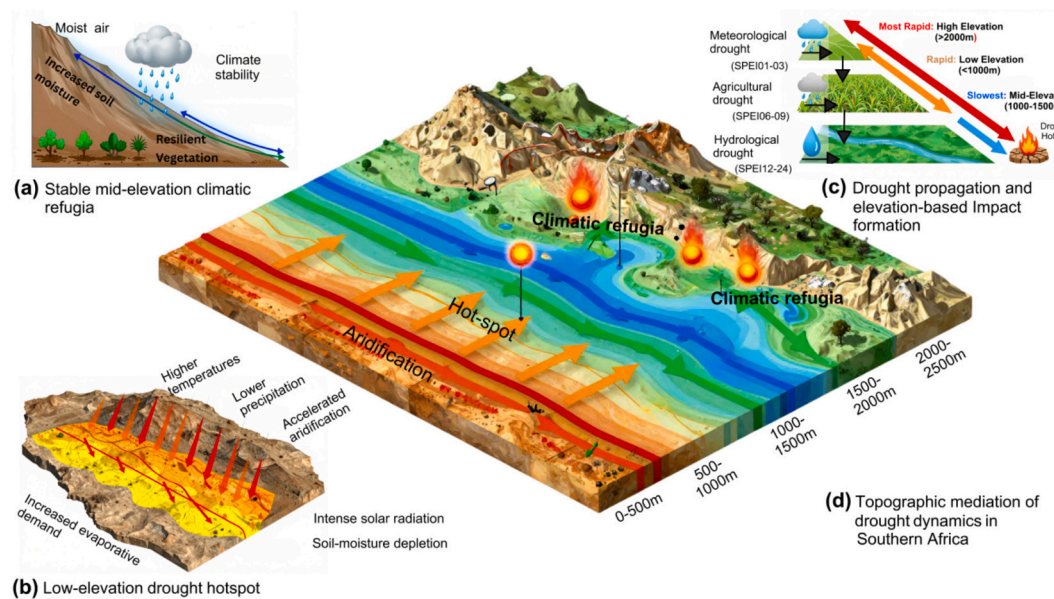


Fig. 10. Integrated conceptual framework of topographically mediated drought dynamics in Southern Africa. The schematic illustrates: (a) the formation of Stable mid-elevation Climatic Refugia via orographic buffering; (b) the development of vulnerable drought hotspots in low- and high-elevations due to accelerated aridification; (c) the drought propagation mechanism, where drought propagation speed governs impact severity; and (d) the resulting Topographic Mediation of spatial drought patterns and future drying trajectories.

continental-scale feedbacks (e.g., the Tibetan Plateau) (Son et al., 2020) or contrasts with Mediterranean regions where dominant summer high-pressure systems lead to mid-elevation drying (Giorgi and Lionello,

2008).

Future projections solidify this finding, confirming the persistence of mid-elevation buffering under climate change, establishing them as

stable climatic refugia with minimal trend shifts ($-0.02\%/month$, $p > 0.1$). In contrast, low-elevations (300–1000 m) are projected to experience accelerated aridification ($-0.15\%/month$, $p < 0.01$), with 78% of pixels showing significant drying and a transition to near-permanent drought conditions by the 2040s. The increased climatic risk in low-lying agricultural and population centers affirms a widespread global trend, consistent with topographic studies from East Africa (Gebreegziabher et al., 2024) to Central Asia (Syldon et al., 2024).

The reduced drought PR at mid-elevations is attributed to a buffering effect from enhanced orographic precipitation and lower evaporative demand. This contrasts with studies in Mediterranean regions where mid-elevations warm faster, accelerating drought risk (Urdiales-Flores et al., 2023). The discrepancy underscores that elevation-dependent responses are not globally uniform but are shaped by regional circulation and land-surface feedbacks. Projection analysis reveals a 1.5-fold greater variability in low-elevation drying trends compared to mid-elevations (Table S6), highlighting amplified uncertainty and vulnerability in low-elevation socio-ecological systems. Consequently, our findings challenge homogeneous approaches in regional climate models and advocate for integrating these non-linear, elevation-specific responses into vulnerability assessments and adaptation strategies.

4.2. Future drought projections and intensifying elevation-dependent risks

Future projections confirm and intensify this elevation-dependent divergence, with high-elevation zones showing unexpected, strong drying trends that redefine long-term hydrological risks. The projections show a clear topographic signature, with all elevation bands trending drier but with varying magnitude and spatial consistency. Low-elevations exhibit the most coherent and accelerated aridification ($-0.15\%/month$, $p < 0.01$), characterized by a strongly negative and widely dispersed trend distribution ($SD = 0.03$), which indicates high spatial heterogeneity in drying intensity. This aligns with their historical role as propagation hotspots and suggests acceleration, consistent with global patterns of low-elevation vulnerability observed in East Africa and Central Asia (Fig. 8a, Table S5).

Conversely, mid-elevation projections demonstrate notable resilience, with trend distributions centered near zero ($-0.02\%/month$, $p > 0.1$) and a significantly narrower spread ($SD = 0.02$). This 1.5-fold lower variability quantifies the buffering capacity of these zones, confirming their role as persistent climatic refugia. This reinforces elevation-dependent buffering mechanisms reported in the Andes (Caro et al., 2024) and the Tibetan Plateau (Liu et al., 2024), while highlighting regional specificity, as it contrasts with accelerated mid-elevation warming in Mediterranean systems.

Unexpectedly, high-elevations (>2000 m) most likely experience the strongest absolute drying ($-0.10\%/month$), with 67% of pixels showing a significant trend. This pronounced high-elevation aridification might be driven by elevation-dependent climate change, where amplified mountain warming (averaging 0.21°C per century faster than low-elevation areas) accelerates evaporative demand (Pepin et al., 2025), coupled with potential shifts in synoptic weather patterns that reduce orographic precipitation efficiency. This suggests nonlinear elevation-dependent responses, where both low and high-elevation areas experience amplified drying through different mechanisms, potentially altered precipitation or evaporative demand linked to large-scale circulation shifts. These findings have critical implications for adaptation. The persistence of mid-elevation climatic refugia offers strategic locations for climate-resilient planning, while accelerated low-elevation aridification necessitates urgent investment in drought-resistant practices.

Furthermore, our multi-timescale analysis shows that longer SPEI timescales (12–24 months) have stronger drying signals across all elevations, indicating a shift toward more persistent hydrological drought. The strongly significant negative slopes observed for extended timescales (SPEI12 and SPEI24), in contrast to the non-significant trends seen in shorter timescales (SPEI01 and SPEI03) (Table S3), illustrate that

short-term atmospheric variability is overlaying a marked, multi-decadal drying trend (Fig. 5b). This projected intensification aligns with and extends the observed historical scale dependency and mirrors global findings where drought signals amplify at longer timescales (Hosseinzadehtalaei et al., 2023; Kourgialas et al., 2015; Ogunrinde et al., 2025; Wang et al., 2026), marking a transition to ecological and hydrological drought types. The profound ecological implication is that accumulated multi-year moisture deficits may exceed ecosystem adaptive capacity. The reduced effectiveness of wet seasons to recharge soil profiles and aquifers leads to a prolonged moisture deficit that extends deeply into the critical zone (Figs. 6b and S4). This challenges conventional drought assessment and underscores the need for management strategies that address cumulative water deficits.

4.3. The spatiotemporal hotspots of drought and propagation pathways

Spatial analysis identifies persistent drought hotspots where large-scale climate drivers and local topography combine to create zones of acute, recurrent vulnerability. Zimbabwe and Lesotho recorded the highest drought burden, experiencing over 500 more events than other regions (Fig. 7b; Table S2). These recurrent droughts were also more severe, lasting longer (37% of months) and with greater DI, solidifying their status as clear aridity hotspots (Figs. 2, 3, S2, and S3). This pattern of spatial clustering aligns with similar findings on drought hotspots in the contiguous United States (Sabut et al., 2025), Mediterranean basins (Akan et al., 2025), Northeast Brazil (Vitório et al., 2025), and Southwest North America (Arregocés et al., 2025), where converging atmospheric patterns lead to systematically increased vulnerability. Our findings contribute by precisely quantifying the multi-dimensional characteristics Df, Dd, and DI that define these hotspots.

We hypothesize that large-scale atmospheric convergence establishes the drought stage, while local topography dictates its rapid onset and intensity (Fig. 7a and c). This combination of large-scale and local forces aligns with processes observed in other global hotspots, such as South America (Geirinhas et al., 2023) and Asia (Fu et al., 2022), illustrating how interactions between tropical Atlantic variability and local conditions lead to recurrent drought. Our study advances this framework by showing how elevation-mediated propagation intensifies drought impacts in low-elevation areas (Fig. 7c), creating particularly severe conditions in topographically vulnerable zones. The rapid progression from meteorological to agricultural/hydrological stress in these hotspots underscores the need for early warning systems that integrate both climate drivers and local amplification mechanisms. Thus, our findings provide a hotspot-based drought management framework applicable to other aridifying regions.

4.4. The temporal evolution and changing seasonality of drought

Drought trends exhibit critical seasonal narrowing, with intensification concentrated at the rainy season's onset, compressing the viable growing period. The robust wetting signals observed during the initial months of the monsoon (October: $\beta = 0.286$; November: $\beta = 0.255$; December: $\beta = 0.225$) stand in stark contrast to the stagnant conditions experienced in the late season (January–March), demonstrating a compression and destabilization of the traditional growth period (Fig. 6b). This shift in intra-seasonal moisture availability concurs with emerging global patterns of monsoon transformation observed in South Asia (Jana et al., 2024) and West Africa (Boateng et al., 2024), where climate change is altering the temporal structure of rainy seasons rather than simply reducing total precipitation. Our study provides critical empirical evidence that similar processes are occurring in Southern Africa, with particularly severe implications for rain-fed agricultural systems that depend on consistent rainfall timing.

Our analysis indicates a significant decoupling between early-season rainfall and soil moisture recharge, a paradox that is increasingly observed in transitional climate zones. Recent studies (Jiang et al., 2021;

Yue et al., 2021) have associated this intra-seasonal redistribution with evolving dynamics of the Indian Ocean Dipole and land-atmosphere feedbacks that preferentially enhance early-season convection while suppressing deeper monsoon establishment. This temporal reshuffling creates a “false start” risk for agriculture, where early rains prompt premature planting before soil moisture is adequate, leading to crop failure during subsequent dry spells. This finding challenges conventional drought assessments focused on seasonal totals and underscores the need for finer-scale temporal analysis to capture these critical mismatches. Our quantification provides a new framework for evaluating climate impacts, highlighting that temporal reorganization, not just magnitude changes, will drive future vulnerability in monsoon regions globally.

4.5. Limitations and future directions

While providing a novel elevation-explicit framework, this study's limitations highlight key avenues for refining drought risk assessment in complex terrains. A key methodological constraint is the spatial resolution of our drought index. The 1 km resolution of the downscaled SPEI data, while an improvement, may still be too coarse to capture fine-scale hydroclimatic gradients in complex topography. While this resolution robustly captures the primary macro-topographic signal (e.g., low-elevation vs. mid-elevation contrasts), it likely smooths local extremes within these zones. Access to consistently measured, high-resolution meteorological data across our study regions was limited. Our reliance on interpolated meteorological data may misrepresent local Ds, particularly in areas with complex terrain.

Furthermore, while our analysis identifies zones of relative hydroclimatic stability, it does not isolate the independent effect of elevation from co-varying factors such as vegetation or soil properties. Although our analysis identifies zones that function as climatic refugia based on stable water balance components, confirming their role as ecological refugia requires direct, long-term data on ecosystem response and resilience. To disentangle these drivers and validate the ecological significance of these climatically buffered zones, future research integrating landscape and ecological datasets is required. Additionally, although we discuss broad climatic drivers like ENSO, the specific attribution of trends to natural variability as opposed to human-induced climate change remains hypothetical without formal modeling. Our focus is also limited to meteorological drought, which means that the actual social-ecological impacts influenced by soils, land use, and water management are not captured. Finally, the historical record may not fully capture the region's long-term natural variability, such as multi-decadal oscillations. Addressing these gaps through downscaling, formal attribution, and the integration of hydrological data presents a clear direction for future research to evolve from merely characterizing climate hazards to assessing comprehensive risk.

5. Conclusion

Southern Africa is currently experiencing a critical climatic transition, as our multi-scale analysis reveals a rapid shift toward more persistent and severe drought conditions. The findings demonstrate a well-defined elevation-dependent pattern of drought propagation, where low-elevation areas exhibit faster intensification and long-term aridification, while mid-elevations (1000–1500 m) act as climatic refugia with buffered drought propagation. Future projections support this topographic divergence, emphasizing the need for an elevation-based framework for targeted climate adaptation, such as early warning systems and climate adaptation strategies. Specifically, our maps of dominant SPEI timescales offer direct guidance: hydrological drought warnings (SPEI24) for high-elevation water catchment areas and agricultural advisories (SPEI03) for low-elevation farming zones. Furthermore, the identified mid-elevation climatic refugia are strategic locations for piloting resilient agricultural practices and for prioritizing

ecological corridors. As Southern Africa emerges as a key indicator for global subtropical hydroclimatic change, our elevation-stratified approach provides a critical tool for mitigating escalating water scarcity and strengthening regional resilience.

CRediT authorship contribution statement

Minyahel Tilahun: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Solomon G. Tesfamichael:** Writing – review & editing, Supervision, Resources, Methodology. **Takehiro Sasaki:** Writing – review & editing, Supervision. **Ayana Angassa:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2026.114807>.

Data availability

This study used the following publicly available datasets: SPEI data (SPEIbase v2.10, <https://spei.csic.es/database.html>), MODIS Terra LST (MOD11A1.061, Doi: <https://doi.org/10.5067/MODIS/MOD11A1.061>), CHIRPS Daily precipitation (<https://www.chc.ucsb.edu/data/chirps>), SRTM elevation data (Doi: <https://doi.org/10.5066/F7PR7TFT>), and the Global Surface Water Dataset (<https://global-surface-water.appspot.com>).

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