

Spatiotemporal variations and driving mechanisms of flash droughts during 1981-2020 in the Qilian Mountains, China postprint

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Abstract

Flash drought is characterized by a period of rapid drought intensification with impacts on agriculture, water resources, ecosystems, and human environment. In the Qilian Mountains, northwestern China, flash droughts are becoming more frequently due to the global climate warming. However, the spatiotemporal variations and their driving factors of flash droughts are not clear in this region. In this study, the European Centre for Medium-range Weather Forecasts (ECMWF) Reanalysis v5-Land (ERA5-Land) dataset was utilized to identify two types of flash drought events (heatwave-induced and water scarcity-induced flash drought events) that occurred in the growing season (April-September) during 1981-2020 in this area. The results showed that the frequency of heatwave-induced flash droughts has decreased since 2010, while the frequency of water scarcity-induced flash droughts has declined markedly. Spatially, heatwave-induced flash droughts were predominantly concentrated in the western Qilian Mountains, whereas water scarcity-induced flash droughts were primarily concentrated in the central and eastern Qilian Mountains. A significantly increasing temporal trend in both types of flash droughts in the eastern Qilian Mountains was found. Meanwhile, there was a decreasing temporal trend of heatwave-induced flash droughts in the southwestern part of the region. Additionally, the influence of two major atmospheric modes, i.e., the El Niño Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO), on these two types of flash droughts was explored by the Superposed Epoch Analysis. The ENSO mainly influences flash droughts in the central and eastern parts of the Qilian Mountains by altering the strength of the East Asian monsoon, while the NAO mainly affects flash droughts in the entire parts of the Qilian Mountains by inducing anomalous westerlies activity. Our findings have important implications for predicting the evolution of flash drought events in the Qilian Mountains region under continued climate warming.

Full Text

Preamble

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Spatiotemporal Variations and Driving Mechanisms of Flash Droughts in the Qilian Mountains, China, During 1981–2020

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Abstract: Flash drought is characterized by a period of rapid drought intensification with impacts on agriculture, water resources, ecosystems, and the human environment. In the Qilian Mountains of northwestern China, flash droughts are becoming more frequent due to global climate warming. However, the spatiotemporal variations and driving factors of flash droughts remain unclear in this region. In this study, the European Centre for Medium-range Weather Forecasts (ECMWF) Reanalysis v5-Land (ERA5-Land) dataset was utilized to identify two types of flash drought events (heatwave-induced and water scarcity-induced) that occurred during the growing season (April–September) from 1981–2020. The results showed that the frequency of heatwave-induced flash droughts has decreased since 2010, while the frequency of water scarcity-induced flash droughts has declined markedly. Spatially, heatwave-induced flash droughts were predominantly concentrated in the western Qilian Mountains, whereas water scarcity-induced flash droughts were primarily concentrated in the central and eastern Qilian Mountains. A significantly increasing temporal trend in both types of flash droughts was found in the eastern Qilian Mountains, while a decreasing temporal trend of heatwave-induced flash droughts occurred in the southwestern part of the region. Additionally, the influence of two major atmospheric modes—the El Niño–Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO)—on these two types of flash droughts was explored using Superposed Epoch Analysis. The ENSO mainly influences flash droughts in the central and eastern parts of the Qilian Mountains by altering the strength of the East Asian monsoon, while the NAO mainly affects flash droughts across the entire Qilian Mountains by inducing anomalous westerly activity. Our findings have important implications for predicting the evolution of flash drought events in the Qilian Mountains region under continued climate warming.

Keywords: heatwave-induced flash drought; water scarcity-induced flash drought; El Niño-Southern Oscillation (ENSO); North Atlantic Oscillation (NAO); Superposed Epoch Analysis (SEA); wavelet coherence

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1 Introduction

Drought is a climatological phenomenon characterized by a prolonged period of anomalously low precipitation, persisting over varying temporal scales (days, months, or years) and resulting in hydrological deficits and reduced water availability in affected regions (Otkin et al., 2013). Such hydrological deficits impact local soil environments and aquatic systems, subsequently adversely affecting agriculture, economic activity, and human livelihoods (Sheffield et al., 2012). Drought classifications include hydrological drought, agricultural drought, meteorological drought, and socioeconomic drought (Mishra and Singh, 2010). The impacts of drought can be extensive and severe; many regions worldwide, such as Sub-Saharan Africa and Australia, frequently experience long-term droughts lasting several years or even decades (Zhang et al., 2021b; Ayugi et al., 2022). Meanwhile, areas such as California in the United States, parts of Europe, and northern China often face seasonal and short-term drought events (Spinoni et al., 2018).

With ongoing climate change, the frequency and intensity of extreme weather phenomena are increasing globally (Diffenbaugh et al., 2017; Shenoy et al., 2022). Rising temperatures directly enhance atmospheric evaporation rates, accelerating terrestrial water loss and exacerbating existing drought conditions (Zhao et al., 2024). Global warming also alters precipitation patterns, leading to decreased rainfall and uneven distribution across regions, further intensifying drought occurrence and development (Dai et al., 2018). Additionally, the complexity of the global climate system may result in some regions simultaneously experiencing droughts alongside other extreme events such as heatwaves, heavy rainfall, or floods (Hoover et al., 2022). When multiple extreme events co-occur in space and time, their cumulative impacts can be markedly amplified, greatly

surpassing the effects of any individual event (Zscheischler et al., 2018; Raymond et al., 2020).

Climate change can profoundly affect the spatiotemporal distribution of droughts, potentially transforming single drought events into multifaceted composite events. This transformation creates compound extreme droughts characterized by unpredictability, complex causative mechanisms, and potential destructiveness, making them a focal point of current research. The term “flash drought” is now commonly used to denote sudden, volatile drought events (Svoboda et al., 2002), which can lead to widespread and devastating ecological and socioeconomic impacts (Gazol and Camarero, 2022; Tabari and Willems, 2023).

Current flash drought research spans various spatiotemporal scales. Neelam and Hain (2024) analyzed flash drought characteristics at the global watershed scale during 1980–2019, emphasizing spatiotemporal dynamics across diverse watersheds, particularly focusing on initiation, duration, and spatial coverage. Shi et al. (2024) examined flash drought events across China’s climatic sub-regions, highlighting interactions between flash droughts and heatwaves and demonstrating how such interconnectivity amplifies the frequency, severity, and persistence of extreme phenomena, underscoring hazards to ecosystems and socioeconomic systems. Řehoř et al. (2024) conducted a detailed analysis of flash drought events in central Europe during 1961–2021, adopting rigorous criteria and investigating major atmospheric circulation drivers. Alizadeh et al. (2020) studied the spatiotemporal evolution of flash drought–heatwave compound events in the United States over the past century, emphasizing increasing risks from synergistic effects of multiple extreme phenomena. O and Park (2024) analyzed global ecosystem responses to flash droughts during 2001–2020, emphasizing disruptions to water absorption, photosynthesis, and evapotranspiration. Yao et al. (2022) analyzed effects on vegetation photosynthesis and the carbon cycle, highlighting declines in gross primary productivity that disturb ecological equilibrium and compromise stability. However, research identifying and characterizing two distinct flash drought types—heatwave-induced and water scarcity-induced—remains limited, especially in western China.

Numerous scholars have systematically investigated flash drought formation mechanisms and impacts, particularly regarding two atmospheric circulation modes: the El Niño–Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO). Existing research indicates that atmospheric oscillations during their peak winter phase, especially ENSO and NAO, typically impact regional droughts in the following summer (Ogi et al., 2003; Chen and Jin, 2020; Xing et al., 2024). Vicente-Serrano et al. (2017) conducted a multiscale analysis of compound drought events in Ecuador, exploring ENSO’s influence on flash drought spatiotemporal variability and finding marked impacts of El Niño and La Niña phases on regional drought severity across timescales. Park et al. (2020) identified a positive correlation between ENSO and East African climate, where El Niño enhances precipitation and reduces drought events, whereas La Niña in-

duces drier conditions that intensify drought severity. Similarly, López-Moreno and Vicente-Serrano (2008) found that positive NAO phases generally induce drought in southern Europe and enhance precipitation in northern Europe, while negative phases increase rainfall in southern Europe and create drier conditions in northern Europe.

China's diverse geography and climate contribute to pronounced regional heterogeneity in flash drought events. Current research indicates that northwestern, southwestern, and northeastern China, as well as the Yellow River Basin, are flash drought hotspots, with northwestern and northeastern events exhibiting greater intensity and persistence (Fu and Wang, 2022; Gong et al., 2022). Temporally, flash drought peaks predominantly occur from late spring to summer, while a secondary peak emerges in September–October in northwestern regions (Hu et al., 2024; Xue et al., 2024). The Qilian Mountains, serving as an ecological corridor between the Loess Plateau and Tibetan Plateau and housing major river headwaters, host a climate-sensitive ecosystem vulnerable to drought-induced disturbances under warming conditions (Nogués-Bravo et al., 2007; Zhang et al., 2021a; Bai et al., 2023). Most previous studies, such as Wang et al. (2021) and Zhou et al. (2024), have focused on all of China or the Tibetan Plateau, while investigations of atmospheric circulation influences remain lacking. Consequently, research gaps persist regarding localized flash drought dynamics and compound events in the Qilian Mountains.

Urgent systematic investigation is required to elucidate drought typologies, driving mechanisms, and atmospheric teleconnections (e.g., ENSO and NAO) in this region. Such efforts are critical for improving early-warning systems, mitigating socioeconomic risks, and developing climate-adaptive conservation strategies. This study aims to identify flash drought events in the Qilian Mountains from 1980 to 2020, analyze their spatiotemporal variations, and explore relationships with ENSO and NAO. Our findings will contribute to better understanding of regional occurrence patterns and help prevent ecological and environmental issues related to flash droughts under future warming scenarios.

2.1 Study Area

The Qilian Mountains (36°43'–39°42' N, 94°24'–103°46' E) are situated in northwestern China, spanning the northeastern part of Qinghai Province and the western border of Gansu Province, and extending approximately 800 km. Positioned deep inland and far from the ocean, this region belongs to the inland arid and semi-arid climate zone, characterized by a typical continental climate with low annual precipitation that occurs predominantly in summer (Lan et al., 2003; Bai et al., 2023). The region features complex topography with high mountains, deep valleys, and basins. In the central and western Qilian Mountains, elevations are relatively high, generally ranging from 3500 to over 6000 m, while the eastern part has lower elevations below 3000 m. This topography

adds to the complexity and severity of regional climate and hydrological conditions. Geographically, the Qilian Mountains lie on the northeastern margin of the Tibetan Plateau, at the confluence of the mid-latitude westerlies and East Asian monsoon belt (Fig. 1 [Figure 1: see original paper]) (Huang et al., 2023; Li and Peng, 2023). Moist air brought by the westerlies rises over windward slopes, causing precipitation, while leeward slopes remain relatively dry. However, the influence of the East Asian summer monsoon on the Qilian Mountains is limited because moist air masses reaching the eastern part gradually weaken with increased elevation.

2.2 Data

This study utilized the European Centre for Medium-range Weather Forecasts (ECMWF) Reanalysis v5-Land (ERA5-Land) dataset (<https://cds.climate.copernicus.eu>). The ERA5-Land dataset provides detailed surface-variable changes over several decades at higher resolution than ERA5. Produced by rerunning the land component of the ECMWF ERA5 climate reanalysis, it has a temporal resolution of 1 h and spatial resolution of 9 km on a condensed Gaussian grid (TCO1279). Data from the Climate Data Store (CDS) is re-gridded to a standard $0.1^\circ \times 0.1^\circ$ latitude-longitude grid. This dataset has been used previously by numerous scholars, yielding robust research outcomes that demonstrate its reliability. For example, Zou et al. (2022) analyzed its performance for air temperature in southeastern China's coastal urban agglomeration; Zha et al. (2023) used it to examine flash drought characteristics in the Pearl River Basin; and Wei et al. (2023) employed it to analyze temperature variations in the Qilian Mountains. Herein, we utilized three ERA5-Land climatic variables: skin temperature, evaporation from bare soil, and volumetric soil moisture. Volumetric soil moisture was assessed across four vertical layers: 0–7, 7–28, 28–100, and 100–289 cm. Given that most vegetation roots are concentrated within the top 100 cm of soil (Jackson et al., 1997), volumetric soil moisture in this depth range directly impacts plant water uptake and growth. This upper soil layer generally exhibits short-term but significant effects on vegetation, and shallow soil moisture changes are more sensitive to short-term precipitation and evaporation variations, allowing timelier assessment of drought onset and development (Seneviratne et al., 2010). Therefore, we focused on volumetric soil moisture data from the top three layers (0–7, 7–28, and 28–100 cm), ensuring reliable data acquisition. Temperature and precipitation data were obtained from the National Climate Center (<https://data.cma.cn>). Temperature and precipitation data for 1981–2017 were used, excluding 2018–2020 due to incomplete station coverage.

The ENSO index was obtained from the National Oceanic and Atmospheric Administration (NOAA; <https://psl.noaa.gov/data/climateindices/list>), while NAO index data were obtained from the National Centers for Environmental Information (NCEI; <https://www.ncei.noaa.gov/access/monitoring/nao>).

2.3 Definitions of Flash Drought Events

Methods for defining flash droughts are highly diverse. This study integrated and refined the method proposed by Wang and Yuan (2018) to identify flash drought events based on three hydrological indicators: temperature, evapotranspiration, and soil moisture. We classified flash droughts into two primary categories based on their dominant drivers: heatwave-induced and water scarcity-induced flash drought. This classification method evaluates drought conditions from multiple perspectives, making it effective for identifying droughts under different climatic conditions.

Using the ERA5-Land dataset, we first extracted hourly temperature, evapotranspiration, and soil moisture data during the warm season (April–September) from 1981–2020 across the Qilian Mountains. This season length follows criteria used by most flash drought researchers (Zhang et al., 2024; Ma and Yuan, 2025) and corresponds to the growing season (April–September) in the Northern Hemisphere (Mo and Lettenmaier, 2015). Starting in April, temperatures in the Northern Hemisphere gradually rise, daylight hours increase, and soil temperatures rise accordingly until September, when temperatures decrease, daylight hours shorten, and soil temperatures begin to drop or freeze.

Because soil moisture data were obtained from multiple depth layers, these layers required synthesis for comprehensive analysis. Specifically, following actual plant water uptake conditions, we adopted soil moisture data from the top three layers (0–7, 7–28, and 28–100 cm) of the ERA5-Land dataset. Due to a lack of detailed soil characteristic data, we assigned soil moisture weights according to layer thickness. Soil moisture content between 0 and 1 m was calculated by summing moisture content for each layer and weighting it by thickness (Zhong et al., 2023). Weights assigned to these layers were 0.07, 0.21, and 0.72, respectively, representing relative contributions of each depth to the overall soil moisture profile. By applying weighted averaging, we consolidated soil moisture information from different depths into a single composite indicator for further analysis. Following weighting, we aggregated hourly temperature, evapotranspiration, and soil moisture data into 5-day intervals (Wang and Yuan, 2018). This conversion of high-frequency data to a more manageable temporal scale allows long-term trends and patterns to be captured while enhancing stability and reliability of subsequent trend analysis. Finally, using processed 5-day interval data, we identified and classified flash drought events by assessing their frequency and intensity.

To determine whether an event featured anomalously high temperatures, we used one standard deviation from the mean temperature anomaly as the threshold. To assess unusually dry conditions, we used the 30th percentile of soil moisture data as the threshold, representing the lower end of the soil moisture distribution (Wang et al., 2018). Additionally, we analyzed evapotranspiration

anomaly to classify flash drought events: a positive evapotranspiration anomaly suggests heatwave-induced drought, while a negative anomaly indicates water scarcity as the primary driver. This dual mechanism ensures comprehensive evaluation incorporating both temperature and moisture conditions to accurately characterize drought events.

The two types of flash drought events were identified by the following criteria (Fig. 2 [Figure 2: see original paper]): Type I (heatwave-induced flash drought): $T_{ano} > T_{std}$, $SMq < 30\%$, and $ET_{ano} > 0$; and Type II (water scarcity-induced flash drought): $T_{ano} > T_{std}$, $SMq < 30\%$, and $ET_{ano} < 0$, where T_{ano} is temperature anomaly (K); T_{std} is the standard deviation of temperature anomaly (K); SMq is soil moisture within a specific 5-day period (%); and ET_{ano} is evapotranspiration anomaly (mm/d).

2.4 Theil-Sen Median Trend Analysis and Mann-Kendall (MK) Trend Test

The Theil-Sen median trend analysis, also called the Theil-Sen estimator, is a robust approach for estimating trend line slope in bivariate data. Particularly suited to linear trends, it offers relatively fast computation, especially with modern tools, making it efficient for trend analysis. The calculation formula is as follows (Jiang et al., 2015):

$$\beta = \text{Median} \left(\frac{x_j - x_i}{j - i} \right), \quad \forall i < j$$

where β is the Theil-Sen trend slope, representing the median rate of change in the data sequence; Median is the median function; and x_i and x_j are flash drought identification data at the grid point for years i and j , respectively. If $\beta > 0$, the cumulative number of flash drought days is increasing; if $\beta = 0$, it remains stable; and if $\beta < 0$, it is decreasing.

The MK trend test is a non-parametric method for assessing time series trends. It does not require normally distributed measurements and is robust to missing values and outliers, making it suitable for detecting significant trends (Li et al., 2021). The test statistic S is calculated as follows (Hamed and Ramachandra Rao, 1998; Güçlü, 2020):

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

where S represents MK statistics reflecting consistency of increasing and decreasing trends; n is the number of observations; and $\text{sgn}(x_j - x_i)$ is the sign function defined as:

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases}$$

The variance is given by (Hamed and Ramachandra Rao, 1998; Güçlü, 2020):

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

This approach works well for long-term time series because combining MK trend test with Theil-Sen median trend analysis provides unmatched benefits over conventional univariate linear regression (Adib et al., 2024). Under standard normal distribution, at 90%, 95%, and 99% confidence levels, the trend passes significance testing when the absolute value of W is greater than 1.65, 1.96, and 2.58, respectively (Hamed and Ramachandra Rao, 1998).

2.5 Composite Analyses for Responses to Anomalous ENSO and NAO Years

We first identified extreme anomalous years of ENSO and NAO indices during 1981-2020 (López-Moreno and Vicente-Serrano, 2008; Vicente-Serrano et al., 2017; Dogar and Sato, 2018). We averaged ENSO and NAO indices for December, January, and February to determine winter season values. Next, we detrended the time series to eliminate long-term trend influences and applied Z-score normalization to standardize the data. The Z-score measures data point distance from the mean in standard deviations. Based on these normalized time series, we selected event years: those with Z-score > 1 were selected as positive event years, while Z-score < -1 indicated negative event years (Fig. 3 [Figure 3: see original paper]; Table 1).

Superposed Epoch Analysis (SEA) is widely used to explore impacts of multiple events (Liang et al., 2019; Shi et al., 2021). We performed SEA on flash drought events in the Qilian Mountains corresponding to identified anomalous ENSO and NAO years. During SEA, data from each positive and negative phase year were aligned with event onset. To ensure robustness and statistical significance, we conducted a t-test to determine whether observed variability was significantly linked to ENSO or NAO events rather than random fluctuations. Ultimately, SEA results allow comprehensive discussion of different mechanisms by which positive and negative ENSO and NAO phases influence flash drought events in the Qilian Mountains, illuminating potential roles of these climate modes in triggering or mitigating flash droughts across the region.

2.6 Wavelet Coherence

Wavelet coherence is an analytical method utilizing wavelet transforms to identify localized correlations between two time series, particularly suitable for non-stationary signals (Lee et al., 2016). We detect dependencies by calculating coherence in both time and frequency domains, providing insights into correlation degree at specific frequencies or scales and how relationships evolve over time. Key features include time-frequency localization, allowing localized correlations to be uncovered in certain periods and at specific frequencies, and multiscale analysis, enabling simultaneous examination of dependencies ranging from short-term fluctuations to long-term trends.

2.7 Integrated Vapor Transport (IVT)

IVT quantitatively characterizes atmospheric water vapor flux intensity and direction by combining wind speed and specific humidity. We performed vertical integration of atmospheric moisture flux throughout the entire atmospheric column to construct composite moisture transport fields under climatological mean states and different ENSO phases. Subsequently, we analyzed spatial differences between composite moisture transport fields during different ENSO phases and the climatological mean state. By incorporating atmospheric circulation patterns, we further explored modulation effects of different ENSO phases on moisture transport in the study region. IVT is calculated as follows (Lavers and Villarini, 2013):

$$\text{IVT} = \frac{1}{g} \int_{p_{\text{surface}}}^{p_{\text{top}}} q \cdot \sqrt{u^2 + v^2} dp$$

where g is standard gravitational acceleration; q is specific humidity defined as water vapor mass to moist air mass ratio (kg/kg); u and v are zonal and meridional wind velocity components (m/s); and p is atmospheric pressure (Pa), integrated vertically from the surface (p_{surface}) to the top of the atmosphere (p_{top}).

3.1 Temporal Variation of Flash Droughts

Heatwave-induced flash droughts in the Qilian Mountains during 1981–2020 exhibited marked interannual and decadal fluctuations (Fig. 4 [Figure 4: see original paper]). A 10-year low-pass filter of annual heatwave-induced flash drought frequency showed higher frequencies during the late 1990s and early 2010s, while the early 2000s and other intervals contained fewer occurrences. There was no statistically significant correlation between heatwave-induced flash drought frequency and warm-season (April–September) mean temperature changes ($r =$

0.230, $P = 0.180$), suggesting these droughts were not solely temperature-driven; other climatic factors (e.g., precipitation and wind speed) may be important. However, short-term temperature increases could exacerbate droughts during specific periods, particularly the late 1990s and early 2010s when heatwave-induced flash droughts occurred more frequently.

Water scarcity-induced flash droughts also exhibited significant interannual and decadal fluctuations (Fig. 4b). From 1981 to approximately 2000, water scarcity-induced drought events increased in frequency, but after 2000, frequency began decreasing, particularly evident from 2010 onward. Notably, we identified a significant negative correlation ($r = -0.388$, $P = 0.018$) between water scarcity-induced flash droughts and total precipitation (Fig. 4b and d). Specifically, between 1990 and 2000, the increasing frequency of water scarcity-induced droughts strongly coincided with decreasing warm-season total precipitation. After 2010, as total annual precipitation increased, the frequency anomaly of water scarcity-induced flash drought events gradually decreased.

3.2 Spatial Variation of Flash Droughts

Accumulated episodes of heatwave-induced flash drought exhibited significant spatial variability, characterized by fewer events in the central and eastern parts, more events in the western part, and increased frequency along southern edges (Fig. 5a [Figure 5: see original paper]). Spatial variability of water scarcity-induced flash drought episodes was less pronounced, with a general pattern of more events in the central and eastern parts, fewer in the western part, and higher frequencies around the periphery compared to the central region (Fig. 5b). Theil-Sen median trend analysis and MK trend test indicated that heatwave-induced flash drought events significantly increased in the central and eastern parts, significantly decreased in the western part, and remained stable (increase trends not significant) across other areas during 1981–2020 (Fig. 6a [Figure 6: see original paper]). Temporal trend analysis revealed that water scarcity-induced flash drought events significantly increased in the eastern part during the study period, with most other areas showing no significant increase (Fig. 6b).

3.3 Responses of Flash Droughts to Anomalous ENSO and NAO Events

We selected anomalous ENSO and NAO years for composite analysis. At the 95% confidence level, composite mean values of water scarcity-induced flash droughts during ENSO positive phases and NAO positive phases, along with heatwave-induced flash droughts during ENSO negative phases, were significantly anomalous (Table 2). Subsequently, we conducted composite analysis of

flash drought event time series for anomalous years and tested their anomalies.

Wavelet coherence analyses indicated significant correlations between temporal variability of flash droughts in the Qilian Mountains and ENSO and NAO changes at interannual timescales (Fig. 7 [Figure 7: see original paper]). Phase dynamics between ENSO and NAO indices and the two flash drought types were observed across different interannual cycle lengths. Specifically, ENSO exhibited a significant in-phase relationship with both flash drought types at interannual timescales (1.0–4.0 years) during 1990–2010, aligning with coherence peaks during ENSO positive and negative phase years including 1983, 1987, 1991, 1992, and 1998, suggesting ENSO activity in these years may have directly influenced corresponding periods of heatwave-induced and water scarcity-induced drought events.

NAO impacts exhibited more complex phase relationships. During 1981–2020, NAO showed an out-of-phase relationship with both flash drought types at 2.0–6.0 year timescales, but an anti-phase relationship at 4.0–6.0 year timescales. Moreover, a significant in-phase relationship occurred between water scarcity-induced droughts and NAO at 6.0–8.0 year cyclicity. These phase differences indicated that NAO positive and negative phase years—including 1985, 1987, 1993, 1994, 1996, 2009, 2010, 2014, 2015, and 2018—may have influenced spatiotemporal distributions of flash drought events in this region.

Anomalous ENSO events, through complex oceanic and atmospheric interactions, may profoundly affect temperature and precipitation within the Qilian Mountains (Fig. 8 [Figure 8: see original paper]). El Niño phases typically bring warm, moist climates, while La Niña phases may lead to drier, cooler conditions. During El Niño episodes, heatwave-induced flash droughts commonly occurred along the western and southern fringes where significant heatwave effects were observed, with 70.50% of grid cells passing the 0.05 significance test (Fig. 8a). In contrast, fewer water scarcity-induced flash droughts were observed during this phase, especially in the central and eastern parts, with 57.42% of grid cells meeting the same significance criterion (Fig. 8c). During La Niña episodes, both heatwave-induced and water scarcity-induced flash drought events showed limited, spatially dispersed distributions, with 40.16% and 44.08% of grid cells, respectively, passing the 0.05 significance test (Fig. 8b and d).

Variations in ENSO phases typically lead to anomalous sea surface temperature fluctuations in the tropical Pacific, enhanced convection, and increased cyclone activity, which alter atmospheric circulation patterns. These changes affect Walker Circulation intensity, resulting in shifts in the Asian monsoon system that subsequently influence moisture transport to the Qilian Mountains. During El Niño events, circulation changes induced by anomalous sea surface temperature increases in the central and eastern tropical Pacific weaken the Walker Circulation, further enhancing Asian monsoon systems—especially the East Asian monsoon—allowing warm, moist airflows from the South China Sea and Indian Ocean to be transported to the Qilian Mountains (Fig. 9a [Figure 9: see original paper]), thereby alleviating growing-season drought conditions.

Concurrently, precipitation brings evaporative cooling that mitigates drought likelihood in the eastern and central parts. However, moist airflows from the East Asian monsoon weaken markedly when reaching the western part, where insufficient rainfall fails to alleviate high temperatures, leading to frequent occurrence of both flash drought types.

In contrast, during La Niña events, anomalously low sea surface temperatures in the central and eastern tropical Pacific strengthen the western branch of the Walker Circulation, weakening the East Asian monsoon and hindering transport of warm, moist air masses to the Qilian Mountains (Fig. 9b), meaning both flash drought types are generally infrequent. Simultaneously, owing to higher altitudes in the southern region, cold, dry airflows extending eastwards from northern areas contribute to a reduction in heatwave-induced flash drought events, particularly in northern and western parts.

Changes in westerlies induced by different NAO phases profoundly impact heat and moisture transport in the Qilian Mountains (Fig. 10 [Figure 10: see original paper]). During positive NAO phases, heatwave-induced and water scarcity-induced flash droughts occurred extensively throughout the region. Except for a few eastern areas, most of the region experienced high frequency and intensity of such drought events, with approximately 92.23% and 77.64% of grid cells passing the 0.05 significance test for heatwave-induced and water scarcity-induced flash droughts, respectively (Fig. 10a and c). Negative NAO phases had less impact on flash droughts in the Qilian Mountains. Apart from the central area, heatwave-induced flash drought occurrence was less frequent across the region, and water scarcity-induced flash droughts were more frequent in the east than the west, with only 32.38% and 28.93% of grid cells passing the 0.05 significance test, respectively (Fig. 10b and d).

Variations in NAO phases are associated with abnormal westerly changes in mid-latitudes of the Northern Hemisphere. During positive NAO phases, westerlies intensify and anticyclonic circulation strengthens, resulting in descending air flows. This abnormal subsidence reduces convective activity, weakening precipitation and cloud formation processes, which increases surface solar radiation and ground heating, potentially increasing probabilities of both flash drought types across the Qilian Mountains. During negative NAO phases, the high-pressure system over the North Atlantic weakens, correspondingly weakening westerlies. The weakened westerly flow allows cold air from the Arctic and Siberia to move southward more easily into inland Europe and Asia, including the Qilian Mountains. This southward-moving cold air remains cool when reaching the Qilian Mountains during summer, leading to local temperature reductions and relatively cool conditions that decrease heatwave-induced flash drought occurrence in the northern part. However, due to high topography, the cold air cannot continue moving southward, limiting its influence on central and southern parts. Furthermore, interaction of southward-moving cold air with westerly flows favors precipitation, increasing rainfall likelihood in lower-altitude northwestern areas. Overall, however, due to lack of moisture input, most parts of the Qilian

Mountains experience reduced precipitation, meaning water scarcity-induced flash drought events are more likely to occur.

4 Discussion

This study investigated spatiotemporal variations of heatwave-induced and water scarcity-induced flash droughts in the Qilian Mountains and explored their relationships with ENSO and NAO. We found that temporal variations of these two flash drought types exhibit some correlation with overall temperature and precipitation trends in the Qilian Mountains. Heatwave-induced flash droughts may be closely linked to regional-scale temperature changes and recent global warming trends (Cui et al., 2022). Higher temperatures increase evaporation rates and reduce soil moisture, leading to more frequent drought occurrence. Observed negative anomalies in annual heatwave-induced flash drought frequency between 2000 and 2010 appear related to “warming hiatuses” observed in the Qilian Mountains and many other global areas (Kosaka and Xie, 2013). The general reduction in water scarcity-induced flash drought occurrence also corresponds to overall precipitation increases in recent decades (Tian et al., 2014; Wang et al., 2018; Bai et al., 2023), which may have helped alleviate long-standing drought issues and altered regional water resource spatiotemporal distribution.

Spatial distributions of both flash drought types in the Qilian Mountains exhibit significant heterogeneity due to complex driving factors including regional climate change, topography, and socioeconomic conditions. The western Qilian Mountains tend to exhibit higher mean annual temperatures (particularly during boreal spring and summer) and historically reduced summer precipitation compared to central and eastern parts (Wang et al., 2022). This pronounced east-west climatic gradient is driven by interaction between the East Asian summer monsoon and complex topography. Orographic lifting of moist air masses along eastern slopes enhances adiabatic cooling, resulting in substantial orographic precipitation, while western slopes experience a pronounced rain-shadow effect leading to aridification and elevated temperatures. This inherent aridity, coupled with amplified temperature extremes under global warming, exacerbates heatwave-induced flash drought frequency and intensity in the western Qilian Mountains. Additionally, spatial differences in water storage exist among eastern, central, and western parts. Although precipitation is more abundant in the east, water storage is relatively low due to strong evapotranspiration, large agricultural and domestic water demands, and intense urban and rural groundwater exploitation (Bai et al., 2023); hence, this area is more prone to water scarcity-induced flash drought events. This finding is consistent with previous research finding that droughts triggered by soil moisture deficits were frequent and intense in the eastern and central Qilian Mountains (Yin et al., 2023).

Wavelet coherence analysis revealed that temporal variability of flash drought events in the Qilian Mountains exhibits strong periodic interactions with ENSO

and NAO variations on interannual timescales. Interaction timescales are consistent with previous findings in other Chinese regions. For example, Xing et al. (2019) found a 24- to 40-month resonance period in Guizhou Province, while Zhou et al. (2021) observed 2.60- to 4.93-year cycles in the Yellow River Basin. However, interaction cycles between flash drought events and NAO reported herein deviate slightly from previous research. Xing et al. (2019) demonstrated that the drought index in Guizhou Province significantly interacted with NAO at 2.0-3.0 year timescales, while Lu et al. (2022) found that the drought index in Henan Province exhibited resonance cycles with NAO at 0.5-2.0 year timescales.

Although the Qilian Mountains are located within the Eurasian continent, far from the Pacific and Atlantic oceans, ENSO and NAO effects on flash droughts remain significant (Wang et al., 2014; Zhou et al., 2021; Cui et al., 2022; Zhang et al., 2022). Compared with negative phases, ENSO and NAO positive phases have more significant impacts on both flash drought types in the Qilian Mountains. The NAO impact is more complex than ENSO, potentially inducing more pronounced spatial distribution differences between the two flash drought types, as indicated by Ren et al. (2024).

Mechanisms influencing flash drought distribution in the Qilian Mountains may be intricate, involving multiple factor interactions. Hence, notable limitations exist and some findings warrant cautious interpretation. The primary limitation is failure to comprehensively consider all potential limiting factors. For example, we have not fully accounted for regulatory effects of persistent snow cover and permafrost. The flash drought definition involved relatively simplified treatment of soil moisture data, neglecting spatial distribution characteristics of persistent snow cover and permafrost in the Qilian Mountains and their regulatory effects on soil moisture dynamics. As one of the most prominent permafrost regions on the Tibetan Plateau, the permafrost and snow cover system in the Qilian Mountains markedly influences regional climate regulation, hydrological cycles, ecological processes, and human activities (Yang et al., 2010; Wu et al., 2013). Investigating soil moisture characteristics under permafrost and persistent snow cover influence would contribute to more precise and scientifically robust flash drought definitions. Moreover, anthropogenic influences, particularly urbanization, may markedly contribute to increased extreme temperature event frequency, thereby promoting compound drought events (Tuholske et al., 2021). An integrated approach considering these factors is imperative for improving understanding of such extreme drought events.

5 Conclusions

Using ERA5-Land reanalysis data, we examined two types of flash drought events (heatwave-induced and water scarcity-induced) in the Qilian Mountains region during 1981-2020. Both types exhibited significant interannual oscillations with a common decadal pattern. These variations were consistent to

some extent with observed recent temperature and precipitation variability trends across the Qilian Mountains during 1981–2020. Heatwave-induced flash droughts mainly occur in the western Qilian Mountains, while water scarcity-induced flash droughts are more common in the central and eastern parts. Both drought types have significantly increased in the eastern region during 1981–2020. However, in the western part, heatwave-induced flash droughts have decreased while water scarcity-induced flash drought frequency has remained consistent. Finally, our results suggest that spatial distributions of flash droughts in this region are significantly associated with anomalous ENSO and NAO events. Compared with negative phases, positive phases of ENSO and NAO have stronger impacts on flash drought occurrences in the Qilian Mountains. Moreover, NAO influence is more extensive and complex than ENSO. These findings deepen mechanistic understanding of drought dynamics in the Qilian Mountains and provide scientific references for characterizing regional responses to climate change.

Conflict of 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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