Postprint: Response of Vegetation Change to Meteorological Drought in the Tianshan Mountains, Xinjiang

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Abstract

Against the backdrop of global climate change, investigating the impacts of drought on vegetation is of great significance for ecological conservation and sustainable development. Utilizing data from the Meteorological Drought Composite Index (MCI) and Normalized Difference Vegetation Index (NDVI) spanning 2001–2023, this study explores the spatiotemporal dynamic characteristics of vegetation in the Tianshan Mountains region during the growing season (April–October) and reveals its response mechanisms to meteorological drought stress. The results indicate that: (1) Vegetation NDVI in the Tianshan Mountains region shows an overall slow increasing trend, but a declining tendency has emerged since 2019. (2) The MCI exhibits fluctuating variations with an overall slow decreasing trend, particularly after 2020, when drought conditions in the Xinjiang Tianshan Mountains region have significantly intensified, especially during summer when drought severity becomes particularly pronounced and the MCI declines sharply. (3) A moderately positive correlation exists between MCI and NDVI, demonstrating that meteorological drought exerts a significant influence on vegetation growth. Vegetation coverage displays pronounced seasonal and spatial heterogeneity, while drought severity demonstrates an overall pattern of being milder in the western region, intensified in the central region, and most severe in the eastern region. (4) The response of vegetation changes to meteorological drought varies across different regions, with the impact of meteorological drought on vegetation coverage being most pronounced in Wuqia County in the southwestern region. These research findings provide a scientific basis for understanding climate change in the Tianshan Mountains region, ecological responses to meteorological drought, and the formulation of drought mitigation strategies.

Full Text

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Abstract

In the context of global climate change, investigating the impacts of drought on vegetation is of great significance for ecological protection and sustainable development. Using meteorological drought composite index (MCI) and normalized difference vegetation index (NDVI) data from 2001 to 2023, this study examines the spatiotemporal dynamics of vegetation during the growing season (April–October) in the Tianshan Mountains and reveals its response mechanisms to meteorological drought stress. The results show that: (1) NDVI in the Tianshan Mountains exhibited an overall slow increasing trend, but a declining tendency emerged after 2019. (2) MCI values fluctuated but generally showed a slow decreasing trend, with drought conditions in Xinjiang' s Tianshan Mountains intensifying significantly after 2020, particularly during summer when MCI dropped sharply. (3) A moderate positive correlation between NDVI and MCI demonstrated that meteorological drought exerts significant influence on vegetation growth. Vegetation coverage displayed pronounced seasonal and spatial heterogeneity, while drought severity followed a gradient of being milder in the west, intensifying in the central region, and most severe in the east. (4) The response of vegetation changes to meteorological drought varied across different regions, with the most significant impact observed in Wuqia County in the southwestern area. These findings provide a scientific basis for understanding climate change in the Tianshan Mountains, assessing ecological responses to meteorological drought, and formulating drought mitigation strategies.

Keywords: vegetation change; meteorological drought; response analysis; Tianshan Mountains

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1 Introduction

Global warming has increased climate system variability, leading to more frequent and widespread drought events. Extreme drought events are projected to become more frequent and severe, posing challenges to regional water resource allocation and triggering cascading disasters that can cause severe damage to terrestrial ecosystems [1]. Vegetation plays an irreplaceable role in maintaining climate stability, and its dynamic changes serve as important indicators for evaluating ecological conditions [2]. Vegetation can respond to meteorological drought, and when facing insufficient water and nutrient supply, its growth becomes constrained, leading to reduced vegetation coverage [3] and even triggering vegetation ecosystem disasters. Due to the multi-dimensional complexity of drought formation mechanisms and their significant interactions with external environments, numerous research gaps remain regarding the physiological and ecological mechanisms of vegetation response to drought. The response characteristics of vegetation to drought stress and its feedback mechanisms have become important scientific questions in global drought ecology research [4].

Drought significantly affects plant growth, and many researchers have focused on this scientific issue, yielding valuable insights. For instance, Pi Guining et al. [5] analyzed the spatiotemporal variations of vegetation growth status and meteorological drought in Guizhou Province over the past 20 years, finding that vegetation growth showed varying degrees of positive correlation with meteorological drought at different time scales, with the strongest responses in southwestern and northern Guizhou. Xu Zehua [6] used the Standardized Precipitation Evapotranspiration Index (SPEI) to analyze the impacts of annual, seasonal, and monthly drought on Net Primary Productivity (NPP) and NDVI in Shandong Province, revealing significant positive correlations between NPP/NDVI and SPEI, with the strongest correlation in grasslands and the weakest in water bodies. In northwestern China, Wei Yanqiang et al. [7] analyzed the relationship between vegetation growth and climate across the Qinghai-Tibet Plateau, Heihe River Basin, Weihe River Basin, Xinjiang, and the entire northwestern region. Existing research has primarily focused on correlations between vegetation dynamics and climate factors in northwestern China, particularly emphasizing interactions between vegetation changes and single climate elements and their time-lag effects. However, systematic studies on vegetation responses to meteorological drought in mountainous ecosystems of Xinjiang remain limited.

Under global warming, analyzing precipitation and temperature changes alone is insufficient to reflect the actual dry/wet conditions of a region, particularly in arid areas where precipitation is far less than evaporation. The Meteorological Drought Composite Index (MCI), which comprehensively considers multiple meteorological factors, has been widely applied in drought monitoring and assessment. Chen Jianing et al. [8] evaluated MCI and analyzed its applicability across different regions, demonstrating its good applicability and accuracy in drought monitoring. Wu Xiulan et al. [9] analyzed the spatiotemporal characteristics of drought in Xinjiang using MCI, revealing significant regional differences in drought distribution across the region. Luo Xiaoling et al. [10] studied drought characteristics in the Hexi Corridor and their response to El Niño events, further validating the effectiveness of MCI in drought monitoring. Xu Dan et al. [11] analyzed the spatiotemporal distribution and disaster variation characteristics of drought in Guizhou Province using MCI as the drought indicator. Given that previous studies have shown good correlation between MCI and NDVI at different time scales, this paper selects the Tianshan Mountains as the study area and the April–October growing season as the research period to analyze the spatiotemporal evolution characteristics of vegetation and drought, and to clarify the response patterns and spatial heterogeneity of vegetation changes to drought, thereby providing a scientific basis for understanding climate change, ecological responses to meteorological drought, and mitigating drought impacts on ecosystems in the Tianshan Mountains.

1.1 Study Area Overview

The study area encompasses the Chinese section of the Tianshan Mountains, extending from the China-Kyrgyzstan border in the west to the Xingxingxia Gobi east of Hami City in the east, with a total length of approximately 1,700 km and an average width of 250–350 km. The mountain ridge line has an average elevation of 4,000 m. As the geographical boundary between northern and southern Xinjiang, the Tianshan Mountains' unique topography, climatic conditions, and soil types collectively form diverse ecosystems [12]. The study area is dominated by forests and grasslands, which serve not only as a germplasm resource bank for high-quality forage but also play a crucial ecological role in regulating regional water cycles and increasing precipitation through transpiration. For high-altitude regions like the Tianshan Mountains, extreme drought may accelerate glacier melting, affect watershed hydrological cycles, and consequently influence vegetation growth and distribution [13].

1.2 Data Sources and Processing

Meteorological data were obtained from the Xinjiang Climate Center, including quality-controlled daily observations of temperature, precipitation, sunshine duration, wind speed, and humidity from 47 national meteorological stations in the Tianshan Mountains of Xinjiang from 2001 to 2023, used to calculate MCI. Seasonal division standards in this study: the vegetation growing season is April–October, with spring (April–May), summer (June–August), and autumn (September–October).

Remote sensing data were derived from the MOD13Q1 dataset of the NASA Land Processes Distributed Active Archive Center (https://ladsweb.modaps.eosdis.nasa.gov), with a temporal span of 2001-2023, spatial resolution of 250 m, and temporal resolution of 16 days. Monthly maximum value composites were generated, and seasonal and annual values for the vegetation growing season were calculated. Land use/cover data at 25 m × 25 m resolution were obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Platform (http://www.resdc.cn/Default.aspx).

1.3 Methods

1.3.1 MCI Calculation Method The Meteorological Drought Composite Index (MCI) comprehensively considers precipitation (based on weighted average precipitation) and evapotranspiration (based on relative humidity), while integrating quarter-scale (30 days) and half-year scale (150 days) precipitation deficit effects through weighted calculations of recent 60-day, 90-day, and 150-day periods. This index typically reflects drought conditions more accurately than single meteorological indicators (e.g., precipitation alone). Previous studies have demonstrated that MCI drought classification standards have good applicability in Xinjiang (excluding perennial drought areas) [14]. Therefore, this study uses MCI to analyze drought severity and its impacts on vegetation.

According to the national standard *Classification of Meteorological Drought* (GB/T20481-2017), MCI is calculated as follows:

$$MCI = K_a \times (a \times SPIW_{60} + b \times SPIW_{90} + c \times SPI_{150} + d \times MI_{30})$$

where $SPIW_{60}$ and $SPIW_{90}$ are standardized weighted precipitation indices for 60-day and 90-day periods, SPI_{150} is the 150-day standardized precipitation index, MI_{30} is the 30-day moisture index, and a, b, c, d are weight coefficients (0.3, 0.25, 0.3, and 0.15, respectively, for Xinjiang). Detailed algorithms for each component are provided in the literature [15]. The MCI classification standard is shown in Table 1.

Table 1 Drought classification standard of MCI

MCI Range	Drought Level
MCI > -0.5	No drought
-1.0 < MCI ≤ -0.5	Mild drought
-1.5 < MCI ≤ -1.0	Moderate drought
-2.0 < MCI ≤ -1.5	Severe drought
MCI ≤ -2.0	Extreme drought

Note: MCI = Meteorological Drought Composite Index. The same below.

1.3.2 NDVI Maximum Value Composite Method NDVI is a commonly used remote sensing index for assessing vegetation conditions, with values typically ranging from -1 to 1, where higher values indicate denser vegetation cover and lower values indicate sparse or absent vegetation.

The maximum value composite method extracts vegetation growth status by comparing NDVI maxima across different time periods to obtain information on vegetation coverage and growth conditions. By selecting the maximum NDVI value for each pixel across multiple time periods, a new composite image is generated. This composite image enables further spatial analysis and applications such as vegetation coverage analysis and vegetation growth change monitoring. This study employed monthly maximum value composites to generate NDVI maps, which were then averaged to obtain seasonal and annual values.

1.3.3 Correlation Analysis Between MCI and NDVI Correlation analysis is a statistical method used to evaluate relationships between two or more variables. This study used the commonly applied Pearson correlation method to reflect the degree and direction of correlation between drought monitoring indicators (MCI) and vegetation change indicators (NDVI).

The Pearson correlation coefficient is calculated as:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where r_{xy} is the correlation coefficient between variables x and y; x_i and y_i are the i-th sample values of variables x and y; $\bar{x}$ and $\bar{y}$ are the mean values of the samples; and n is the total number of samples. The correlation coefficient r ranges from -1 to 1. When $r > 0$, variables are positively correlated; when $r < 0$, they are negatively correlated; and $|r| = 1$ indicates perfect linear correlation.

1.3.4 Other Research Methods Trend analysis of meteorological indices employed univariate linear regression for trend estimation. The least squares method was used to fit observational data and solve for regression coefficients a and b, where slope a represents the interannual trend of climatic elements, with its sign (positive or negative) indicating the rate of increase or decrease.

2 Results

2.1 Spatiotemporal Variation Characteristics of Vegetation in the Tianshan Mountains, Xinjiang The interannual variation time series of NDVI in the Tianshan Mountains from 2001 to 2023 shows fluctuating changes with an overall slow increasing trend at a rate of $0.001 \cdot a^{-1}$ (Fig. 2). Notably, since 2019, this increasing trend has shown a subtle reversal, indicating a declining tendency and suggesting a deviation in vegetation growth conditions in recent years. The multi-year average NDVI value for the study area during the growing season is 0.42, with a maximum of 0.48 occurring in 2013 and a minimum of 0.35 in 2008.

[Figure 2: see original paper]

Based on multi-year averages, this study examined the spatial distribution characteristics of annual and seasonal (spring, summer, autumn) NDVI in the study area. To more intuitively assess vegetation coverage, the following classification standard was adopted: NDVI > 0.5 indicates high vegetation coverage, representing dense vegetation; 0.3–0.5 indicates moderate vegetation coverage, showing good but not dense vegetation growth; 0.1–0.3 indicates low vegetation coverage, reflecting sparse vegetation; and NDVI < 0.1 represents no vegetation coverage, typically corresponding to non-vegetated surfaces such as bare soil, water bodies, or ice/snow [16].

According to this classification, spatial distribution analysis of NDVI during the growing season reveals that high vegetation coverage areas are mainly concentrated in the eastern and southern parts of the Ili River Valley and along the northern Tianshan Mountains, accounting for approximately 37.9% of the study area. Moderate vegetation coverage areas are widely distributed across most of the Ili River Valley, the northern mountainous areas of Bayingolin Mongol Autonomous Prefecture, and parts of the northern Tianshan region, comprising 21.2% of the area. Low vegetation coverage areas occupy a larger proportion of about 41.7%, mainly distributed in the eastern and southwestern parts of the Tianshan Mountains. Non-vegetated areas account for 16.4% of the study area, primarily distributed along mountain ridges.

Seasonal variations are pronounced. In spring, NDVI ranges from -0.10 to 0.88, with moderate and low vegetation coverage areas dominating. Summer shows the highest vegetation vigor, with NDVI ranging from -0.16 to 0.81. High vegetation coverage areas increase significantly to 66.5% of the total area, while non-vegetated areas decrease to 14.6%. In autumn, NDVI ranges from -0.10 to 0.88, but high vegetation coverage areas drop sharply to only 13.65% of the study area. Low vegetation coverage becomes dominant at 50.6%, and moderate coverage remains relatively stable at approximately 21.2%. The combined proportion of low and moderate vegetation coverage reaches 71.8%, characterizing autumn vegetation conditions (Fig. 3).

[Figure 3: see original paper]

2.2 Variation Characteristics of Meteorological Drought Events at Different Time Scales The interannual variation of MCI during the growing season in the Tianshan Mountains shows fluctuating changes with an overall slow decreasing trend at a rate of $-0.006 \cdot a^{-1}$, indicating a slight intensification of meteorological drought (Fig. 4). This trend became more pronounced after 2010, with drought conditions significantly worsening after 2020. The most severe drought year occurred in 2022, while 2003 was the relatively wettest year with the highest MCI value.

[Figure 4: see original paper]

Seasonal MCI variations show that spring values are generally higher, indicating relatively fewer drought events. However, after 2020, drought conditions in the Tianshan Mountains intensified noticeably, particularly in summer when MCI values dropped sharply, representing the most severe drought season. Autumn drought remained serious after 2020 (Fig. 5).

[Figure 5: see original paper]

2.3 Spatial Variation of Meteorological Drought at Different Time Scales Analysis of annual MCI spatial distribution during the growing season from 2001 to 2023 reveals significant regional variations. The southwestern mountainous areas show relatively mild drought conditions. The central Tianshan region experiences relatively severe drought, particularly in areas near the northern parts. The eastern Tianshan region shows significantly higher drought severity than the western and central areas, with the most severe conditions in the easternmost parts. Overall, drought severity in Xinjiang' s Tianshan Mountains follows a pattern of being milder in the west, intensifying in the center, and most severe in the east (Fig. 6).

[Figure 6: see original paper]

Seasonally, spring shows severe drought across most of the southwestern mountainous areas, while central mountain drought transitions from severe to mild, particularly in the east-central region. Summer exhibits relatively mild drought in the southwest, gradually intensifying toward the central region, especially in north-central mountainous areas. Eastern mountain areas, particularly near the eastern edges and northern regions, suffer the most severe drought conditions. Autumn shows mild drought in the southwest (the relatively wettest area), moderate drought in central regions, and severe drought across most eastern areas, especially in northern eastern regions where MCI values are lowest (Fig. 6).

2.4 Response of Vegetation to Meteorological Drought in the Tianshan Mountains The scatter plot constructed from MCI and NDVI values in the Tianshan Mountains shows a linear positive correlation with a correlation coefficient of 0.3685, indicating a moderate positive relationship (Fig. 7). As the drought index increases, NDVI also shows an upward trend. Although the correlation is not particularly strong, MCI as an indicator of drought severity clearly influences NDVI, demonstrating that drought conditions indeed affect vegetation growth status in this region.

[Figure 7: see original paper]

At the pixel scale, correlation coefficients between MCI and NDVI during the growing season range from -0.85 to 0.95, showing high spatial heterogeneity (Fig. 8). Extremely significant positive correlation areas and significant positive correlation areas account for 22.64% and 13.65% of the study area, respectively. These regions demonstrate synergistic enhancement effects, particularly in the Ili River Valley in the west, northern mountainous areas of Hami City in the east, and mountainous areas of Kizilsu Kirghiz Autonomous Prefecture in the southwest, where meteorological drought and vegetation growth show high synchrony. Non-significant positive correlation areas are most extensive, covering 34.38%

of the study area and concentrated in central regions, indicating positive associations that do not reach statistical significance. Negative correlation areas are relatively small, including non-significant negative correlation (27.61%), significant negative correlation (1.68%), and extremely significant negative correlation (0.04%), primarily distributed in central Tianshan areas, revealing inhibitory or reverse regulatory effects of drought on vegetation growth under specific environmental conditions (Fig. 8).

[Figure 8: see original paper]

2.5 Response of Vegetation to Meteorological Drought in Typical Regions of the Tianshan Mountains, Xinjiang To further investigate regional differences in vegetation response to meteorological drought, typical stations were selected from western (Xinyuan County), central (Xiaoquzi), eastern (Barkol County), and southwestern (Wuqia County) Tianshan regions to analyze variation characteristics and correlations.

Overall, MCI values in Xinyuan and Xiaoquzi decreased at rates of $-0.03 \cdot a^{-1}$ and $-0.01 \cdot a^{-1}$, respectively, reflecting intensifying drought trends in western and central regions, particularly in the central area. In contrast, MCI in Barkol and Wuqia increased slightly at rates of $0.004 \cdot a^{-1}$ and $0.001 \cdot a^{-1}$, indicating slight drought alleviation in eastern and southwestern regions, though Barkol showed intensifying drought in recent years. NDVI trends also varied regionally: Xinyuan and Xiaoquzi increased slightly at $0.004 \cdot a^{-1}$ and $0.001 \cdot a^{-1}$, showing slow vegetation improvement; Wuqia increased more significantly at $0.013 \cdot a^{-1}$, demonstrating the most substantial vegetation improvement in the southwest; while Barkol decreased slightly at $-0.0002 \cdot a^{-1}$, indicating gradually decreasing vegetation coverage in the east (Fig. 9).

[Figure 9: see original paper]

Interannual variations of NDVI and MCI in the four regions show certain positive correlations, with correlation coefficients varying by region: Wuqia ($r = 0.3094$), Barkol ($r = 0.1049$), Xiaoquzi ($r = 0.1892$), and Xinyuan ($r = 0.3685$) (Fig. 10). Results indicate that vegetation growth and meteorological drought severity are generally positively correlated across the study area—more severe drought corresponds to lower vegetation coverage, and vice versa. However, correlation strength varies regionally. While Xinyuan (west), Xiaoquzi (central), and Barkol (east) show weak to moderate positive correlations, Wuqia in the southwest demonstrates a more significant positive correlation, indicating that meteorological drought has the most pronounced impact on vegetation coverage in this region.

[Figure 10: see original paper]

3 Conclusions

This study reveals the following key findings:

(1) NDVI in the Tianshan Mountains showed a slow increasing trend from 2001 to 2023, indicating overall improving vegetation conditions. However, this trend reversed subtly after 2019, with NDVI declining and showing a deviation in vegetation growth trajectory in recent years. Spatially, vegetation coverage exhibits significant seasonal and spatial heterogeneity, with moderate-to-low coverage dominating in spring, highest coverage in summer, and a shift toward low and moderate coverage areas in autumn.

(2) Meteorological drought severity in the Tianshan Mountains showed fluctuating changes with a slow intensifying trend, particularly after 2020 when drought conditions worsened significantly. Summer experiences the most severe drought conditions. Spatially, drought severity follows a pattern of being milder in the west, more severe in the center, and most severe in the east, particularly in north-central and eastern regions where vegetation growth is most constrained.

(3) A moderate positive correlation between MCI and NDVI indicates that meteorological drought significantly affects vegetation growth. Although not extremely strong, this correlation shows that drought conditions clearly influence vegetation abundance and coverage. Spatially, correlations vary significantly across regions, with Wuqia County in the southwest showing the most significant positive correlation, where meteorological drought has the most pronounced impact on vegetation coverage.

(4) Different regions of the Tianshan Mountains show distinct characteristics in vegetation and drought changes. Western and central regions exhibit intensifying drought trends, with slow vegetation improvement; eastern and southwestern regions show slight drought alleviation, but vegetation coverage is decreasing in the east while improving significantly in the southwest. These differences reflect complex ecological relationships across regions.

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Note: Figure translations are in progress. See original paper for figures.