Effects of temperature and precipitation on drought trends in Xinjiang, China (postprint)

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Abstract

The characteristics of drought in Xinjiang Uygur Autonomous Region (Xinjiang), China have changed due to changes in the spatiotemporal patterns of temperature and precipitation, however, the effects of temperature and precipitation—the two most important factors influencing drought—have not yet been thoroughly explored in this region. In this study, we first calculated the standard precipitation evapotranspiration index (SPEI) in Xinjiang from 1980 to 2020 based on the monthly precipitation and monthly average temperature. Then the spatiotemporal characteristics of temperature, precipitation, and drought in Xinjiang from 1980 to 2020 were analyzed using the Theil-Sen median trend analysis method and Mann-Kendall test. A series of SPEI-based scenario-setting experiments by combining the observed and detrended climatic factors were utilized to quantify the effects of individual climatic factor (i.e., temperature and precipitation). The results revealed that both temperature and precipitation had experienced increasing trends at most meteorological stations in Xinjiang from 1980 to 2020, especially the spring temperature and winter precipitation. Due to the influence of temperature, trends of intensifying drought have been observed at spring, summer, autumn, and annual scales. In addition, the drought trends in southern Xinjiang were more notable than those in northern Xinjiang. From 1980 to 2020, temperature trends exacerbated drought trends, but precipitation trends alleviated drought trends in Xinjiang. Most meteorological stations in Xinjiang exhibited temperature-dominated drought trend except in winter; in winter, most stations exhibited precipitation-dominated wetting trend. The findings of this study highlight the importance of the impact of temperature on drought in Xinjiang and deepen the understanding of the factors influencing drought.

Full Text

Preamble

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Effects of temperature and precipitation on drought trends in Xinjiang, China

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Abstract: The characteristics of drought in Xinjiang Uygur Autonomous Region (Xinjiang), China have changed due to alterations in the spatiotemporal patterns of temperature and precipitation. However, the effects of these two most important factors influencing drought have not yet been thoroughly explored in this region. In this study, we first calculated the Standardized Precipitation Evapotranspiration Index (SPEI) in Xinjiang from 1980 to 2020 based on monthly precipitation and monthly average temperature. We then analyzed the spatiotemporal characteristics of temperature, precipitation, and drought using the Theil–Sen median trend analysis method and Mann–Kendall test. A series of SPEI-based scenario-setting experiments combining observed and detrended climatic factors were utilized to quantify the effects of individual climatic factors. The results revealed that both temperature and precipitation exhibited increasing trends at most meteorological stations, particularly spring temperature and winter precipitation. Due to temperature influences, intensifying drought trends were observed in spring, summer, autumn, and at annual scales. Additionally, drought trends in southern Xinjiang were more notable than those in northern Xinjiang. From 1980 to 2020, temperature trends exacerbated drought conditions, while precipitation trends alleviated them. Most meteorological stations exhibited temperature-dominated drought trends except in winter, when precipitation-dominated wetting trends prevailed. These findings highlight the importance of temperature impacts on drought in Xinjiang and deepen understanding of drought-influencing factors.

Keywords: standardized precipitation evapotranspiration index (SPEI); climate change; drought characteristics; trend analysis; arid area; temperature trend; contribution analysis

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1 Introduction

Drought is typically caused by precipitation persistently remaining below normal conditions or an imbalance between evapotranspiration and precipitation. Globally, drought characteristics have been altered in the context of climate change, with drought events becoming more frequent and severe. Drought notably impacts agricultural, ecological, and socioeconomic security and stability, and these adverse effects are projected to increase further in the future. Understanding drought characteristics is essential for regional drought disaster management. While precipitation directly influences drought, temperature also affects drought by influencing potential evapotranspiration (PET). In the context of climate change, increased PET due to rising temperatures, coupled with uncertainty relating to extreme precipitation, influences drought dynamics.

A series of drought indices have been proposed for monitoring drought and assessing its impacts. Among these, the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Palmer Drought Severity Index (PDSI) have been widely applied at regional and global scales. Unlike the SPI, the SPEI considers temperature’ s influence on drought. Since drought monitoring is generally based on the difference between precipitation and PET, the SPEI is particularly suitable for drought assessment against the background of global climate change. The SPEI was chosen for this study also because it requires less data than the PDSI and can monitor drought at different time scales. Zhao et al. (2021) used 3-month SPEI in May, August, November, and February to represent drought conditions in spring, summer, autumn, and winter, respectively, and 12-month SPEI in December to represent annual drought conditions.

Extensive research has examined drought spatiotemporal characteristics, providing references for drought-adaptation policy formulation. Some studies focused on meteorological factors such as precipitation and temperature, finding that dominant influencing factors vary by region. Generally, increased precipitation can relieve drought intensification resulting from temperature increases. Research shows that temperature’ s influence on drying-wetting trends is usually greater than precipitation’ s in the Pearl River Basin and Songnen Plain; however, on the Loess Plateau, precipitation rather than PET remains the dominant factor affecting drought occurrence. At the global scale, increases in drought duration and severity can be attributed primarily to precipitation pattern changes. These studies have deepened understanding of drought-influencing factors and provided references for drought-adaptation strategies.

Xinjiang Uygur Autonomous Region, located in northwestern China, is crucial for the Silk Road Economic Belt and China-Pakistan Economic Corridor. As a region highly susceptible to global climate change, the area affected by drought has expanded over recent decades. Extensive research has examined drought spatiotemporal characteristics in the region, providing important references for exploring drought patterns. However, previous studies focused primarily on drought spatiotemporal patterns. Despite being the two most important factors influencing drought, temperature and precipitation effects have not been thoroughly studied in this region. Xinjiang, a typical arid area, is highly sensitive to climate change, and significant changes in temperature and precipitation have occurred there. Further research is needed to better understand how these factors affect drought characteristics.

In this study, we explored the impacts of temperature and precipitation changes on drought characteristics in Xinjiang. The main objectives are: (1) to analyze variation trends in temperature, precipitation, and drought from 1980 to 2020, and (2) to quantify the influences of temperature and precipitation trends on drought. This study will deepen understanding of temperature and precipitation impacts on drought in Xinjiang, providing a reference for formulating more targeted drought-adaptation strategies.

2.1 Study Area

Xinjiang (34°20 11 -49°10 55 N, 73°29 54 -96°23 03 E) is located in the midlatitude inland region of northwestern China. As shown in Figure 1 [Figure 1: see original paper], the Tianshan Mountains divide Xinjiang into southern and northern Xinjiang. Due to its geographical location and topography, Xinjiang exhibits a typical temperate continental climate, with an annual average temperature of approximately 9.72°C and precipitation concentrated in summer. Annual precipitation in northern Xinjiang generally varies between 150 and 200 mm, whereas in southern Xinjiang it is less than 100 mm. Xinjiang is the core component of arid Central Asia, and drought is the main meteorological disaster in this region, characterized by long durations and severe impacts.

Fig. 1 Location of 56 meteorological stations adopted by this study in Xinjiang. Note: The figure is based on the standard map (No. 新 S(2021)047) of the Xinjiang Uygur Autonomous Region Platform for Common Geospatial Information Services (https://xinjiang.tianditu.gov.cn/main/bzdt.html) marked by the Department of Natural Resources of Xinjiang Uygur Autonomous Region, and the base map has not been modified.

2.2 Data

This study used daily average temperature and daily precipitation data from 56 meteorological stations in Xinjiang (Fig. 1 [Figure 1: see original paper]). The data were downloaded from the National Meteorological Science Data Center (https://data.cma.cn/) and subjected to quality control and homogeneity testing. After quality control, the proportion of missing values for most stations was less than 0.2%. Missing values over periods of only 1-2 days were replaced using data from adjacent dates, and remaining missing values were replaced by multiyear averages from the same period. Monthly temperature and precipitation data were calculated from the daily data.

2.3.1 SPEI Calculation

The SPEI is a drought index based on the water balance between precipitation and PET that considers temperature’ s effects on drought occurrence and development. As such, the SPEI is more suitable for drought monitoring than the SPI against the background of global climate change. Moreover, the SPEI can monitor drought over different time scales and has been widely applied in drought impact assessment. The detailed methodology for SPEI calculation is as follows (Vicente-Serrano et al., 2010):

(1) Calculating PET

This study adopted the Thornthwaite method to calculate PET, which has been widely used due to its simple calculation process and minimal data requirements.

$$PET_i = 16\left(\frac{10T_i}{H}\right)^a \cdot \frac{N}{30} \cdot \frac{u}{12}, \quad (1)$$

where PET_i is the PET in month i (mm); u is the monthly average daily sunshine hours in month i (h); N is the number of days in month i; T_i is the average temperature in month i (°C); and H is the heat index.

$$a = (6.75 \times 10^{-7})H^3 - (7.71 \times 10^{-5})H^2 + (1.79 \times 10^{-2})H + 0.49, \quad (2)$$

(2) Calculating water deficit

$$D_i = P_i - PET_i, \quad (3)$$

where P_i is the precipitation in month i (mm); and D_i is the water deficit in month i (mm).

(3) Calculating the cumulative water deficit at different time scales

The calculated values of D_i were aggregated at different time scales. The difference in water deficit for a given month i of year j depends on the selected time scale k. For instance, the accumulated difference for a specific month in year j using a 12-month time scale is calculated as follows:

$$X_{i,j}^{k} = \sum_{l=1}^{k} D_{j-1,l} + \sum_{l=1}^{i} D_{j,l}, \quad (4)$$

where $X_{i,j}^{k}$ is the cumulative water deficit in month i of year j at the selected timescale k (mm); $D_{j-1,l}$ is the value of precipitation minus PET in month l of year $j-1$ (mm); and $D_{j,l}$ is the value of precipitation minus PET in month l of year j (mm).

(4) Fitting the probability distribution of the cumulative water deficit to obtain the SPEI

We used a log-logistic probability density function to calculate the probability density of the cumulative water deficit.

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2}, \quad (5)$$

where $f(x)$ is the probability density function of cumulative water deficit; x is the cumulative water deficit (mm); and α, β, and γ are the scale, shape, and location parameters, respectively. These parameters are calculated as follows:

$$\alpha = \frac{w_0 - 2w_1}{\Gamma(1+1/\beta)\Gamma(1-1/\beta)}, \quad (6)$$

$$\beta = \frac{2w_1 - w_0}{3w_2 - w_0} - \frac{\ln 2}{\ln 3}, \quad (7)$$

$$\gamma = w_0 - \alpha\Gamma(1+1/\beta)\Gamma(1-1/\beta), \quad (8)$$

where Γ is a gamma function; and w_0, w_1, and w_2 are the probability-weighted moments calculated by the method of Sheng and Hashino (2007). The probability-weighted moments are calculated by Equation 9:

$$w_r = \frac{1}{n}\sum_{m=1}^{n}(1-F_m)^r x_m, \quad r = 0,1,2, \quad (9)$$

where w_r is the rth probability-weighted moment; n is the sample size; and x_m is the vector of the mth observation arranged in descending order.

Thus, the probability distribution function of the log-logistic distribution can be expressed as follows:

$$F(x) = \left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-1}, \quad (10)$$

where $F(x)$ is the probability distribution function of cumulative water deficit.

Then, the probability distribution function $F(x)$ of the cumulative water deficit of each month is normalized by Equation 11. If $Y \leq 0.5$:

$$W = -c_0 + c_{1Y} + c_{2Y}^2, \quad (11)$$

$$Y = \sqrt{-2\ln(F(x))}, \quad (12)$$

If $Y > 0.5$:

$$W = c_0 + c_{1Y} + c_{2Y}^2, \quad (13)$$

$$Y = \sqrt{-2\ln(1 - F(x))}, \quad (14)$$

where W is the standardized normal variable that reflects the cumulative probability of water deficit; and c_0, c_1, c_2, d_1, d_2, and d_3 are constants used in the polynomial approximation to accurately convert cumulative probabilities to values on the standard normal distribution ($c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$). Table 1 shows drought classifications based on SPEI values.

Table 1 Drought classification based on the value of standardized precipitation evapotranspiration index (SPEI)

Value	Classification
SPEI < -2.00	Extreme drought
-2.00 ≤ SPEI < -1.50	Severe drought
-1.50 ≤ SPEI < -1.00	Moderate drought
-1.00 ≤ SPEI < -0.50	Slight drought
-0.50 ≤ SPEI ≤ 0.50	Normal
SPEI > 0.50	Wet

2.3.2 Trend Analysis Method

We used the Theil–Sen median method to calculate linear trends in precipitation, temperature, and SPEI, and tested significance via the Mann–Kendall method. Both are nonparametric methods unaffected by outliers and widely used in long-time-series trend analysis research.

The calculation processes are as follows:

$$\text{Sen's slope} = \text{median}\left(\frac{X_b - X_a}{b - a}\right), \quad a < b, \quad (15)$$

$$S = \sum_{k=1}^{q-1} \sum_{j=k+1}^{q} \text{sgn}(X_j - X_k), \quad (16)$$

$$\text{Var}(S) = \frac{q(q-1)(2q+5)}{18}, \quad (17)$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases}, \quad (18)$$

where Sen' s slope is the change trend of the indicator; X_a is the observed value in year a; X_b is the observed value in year b; q is the length of the time series; S is the test statistic; Z is the standardized test statistic; and $\text{Var}(S)$ is the variance of S. A Sen' s slope > 0 indicates the indicator increased during the study period, while < 0 indicates a decrease. In this study, the Sen' s slope value was multiplied by ten to represent the change in temperature, precipitation, or SPEI per decade. If $|Z| > Z_{(1-\alpha/2)}$, the trend is significant at $\alpha = 0.05$ (or 0.01) level.

2.3.3 Determining the Contributions of Temperature and Precipitation

To determine the contributions of temperature and precipitation trends to drought trends, we employed a linear-detrending method to remove trends in temperature and precipitation. This approach has been widely applied for detrending meteorological data. The SPEI was subsequently calculated under three distinct scenarios (Table 2):

- **Scenario 1 (Obs)**: SPEI calculated based on observed temperature and precipitation ($SPEI_{Obs}$)
- **Scenario 2 (DtOp)**: SPEI calculated based on detrended temperature and observed precipitation ($SPEI_{DtOp}$)
- **Scenario 3 (OtDp)**: SPEI calculated based on observed temperature and detrended precipitation ($SPEI_{OtDp}$)

Table 2 Scenario setting

Scenario	Description
Obs	SPEI calculated on the basis of observed temperature and observed precipitation
DtOp	SPEI calculated on the basis of detrended temperature and observed precipitation
OtDp	SPEI calculated on the basis of observed temperature and detrended precipitation

Note: Obs, observed temperature and precipitation; DtOp, detrended temperature and observed precipitation; OtDp, observed temperature and detrended precipitation.

After calculating SPEI under different scenarios, we determined the contributions of temperature and precipitation trends to drought trends using Equations 19 and 20:

$$Cr_{tas} = \frac{Slope_{SPEI_{DtOp}} - Slope_{SPEI_{Obs}}}{Slope_{SPEI_{Obs}}} \times 100\%, \quad (19)$$

$$Cr_{pre} = \frac{Slope_{SPEI_{OtDp}} - Slope_{SPEI_{Obs}}}{Slope_{SPEI_{Obs}}} \times 100\%, \quad (20)$$

where Cr_{tas} and Cr_{pre} are the contributions of temperature and precipitation trends to drought trends, respectively; and $Slope_{SPEI_{Obs}}$, $Slope_{SPEI_{DtOp}}$, and $Slope_{SPEI_{OtDp}}$ are the linear trends in $SPEI_{Obs}$, $SPEI_{DtOp}$, and $SPEI_{OtDp}$, respectively. A negative SPEI trend indicates drought intensification, while a positive trend indicates wetting. When Cr_{tas} or Cr_{pre} is negative, the corresponding factor intensifies drought trends (negative contribution). When positive, it leads to wetting trends (positive contribution). The larger the absolute value, the greater the contribution.

To explore dominant factors influencing drought trends, we classified the 56 meteorological stations into four types by comparing absolute values of Cr_{tas} and Cr_{pre}: ( ) temperature-dominated drought trend; ( ) temperature-dominated wetting trend; ( ) precipitation-dominated drought trend; and ( ) precipitation-dominated wetting trend. The classification criteria are shown in Table 3 .

Table 3 Division rule for the dominant factors of drought and wetting trends

Dominant type	Abbreviation	Cr_{tas}	Cr_{pre}	Absolute value comparison
Temperature-dominated drought	T_{drought}	Negative	Positive	$\lvert Cr_{tas}\rvert > \lvert Cr_{pre}\rvert$
Temperature-dominated wetting	T_{wet}	Positive	Negative	$\lvert Cr_{tas}\rvert > \lvert Cr_{pre}\rvert$
Precipitation-dominated drought	P_{drought}	Negative	Negative	$\lvert Cr_{tas}\rvert < \lvert Cr_{pre}\rvert$
Precipitation-dominated wetting	P_{wet}	Positive	Positive	$\lvert Cr_{tas}\rvert < \lvert Cr_{pre}\rvert$

Note: Cr_{tas}*, contribution of temperature trend to drought trend;* Cr_{pre}*, contribution of precipitation trend to drought trend.*

3.1 Trends in Temperature and Precipitation

From 1980 to 2020, Xinjiang' s temperature exhibited statistically significant increases at interannual and seasonal scales, except in winter (Fig. 2 [Figure 2: see original paper]). Spring temperature trends were greater than in other seasons, with upward trends exceeding 0.50°C/10a at most stations (Fig. 2a). In winter, temperature trends at most stations did not exceed 0.20°C/10a and were nonsignificant; some stations in northern Xinjiang even showed nonsignificant decreasing trends (Fig. 2d). Summer temperatures increased significantly at most stations, with slightly greater increases in northern Xinjiang (Fig. 2b). In autumn, southern Xinjiang stations showed significant temperature increases, while northern Xinjiang stations mostly showed nonsignificant increases below 0.30°C/10a (Fig. 2c). At the annual scale, most stations showed significant temperature increases greater than 0.30°C/10a (Fig. 2e).

A slight precipitation increase was observed at most stations from 1980 to 2020 (Fig. 3 [Figure 3: see original paper]). In spring, precipitation slightly increased at most northern Xinjiang stations but showed nonsignificant decreasing trends at most southern Xinjiang stations (Fig. 3a). In summer, most stations in both regions showed nonsignificant increases, except some in northern Xinjiang and eastern southern Xinjiang (Fig. 3b). In autumn, precipitation showed nonsignificant increasing trends at most stations, though some in northeastern southern Xinjiang showed significant downward trends (Fig. 3c). In winter, significant precipitation increases occurred at most northern Xinjiang stations, while southern Xinjiang stations showed nonsignificant increases (Fig. 3d). At the annual scale, most stations showed nonsignificant increasing trends, with slightly greater increases in northern Xinjiang (Fig. 3e).

Fig. 2 Spatial distribution of temperature trends in Xinjiang at seasonal (a–d) and annual (e) scales from 1980 to 2020.

Fig. 3 Spatial distribution of precipitation trends in Xinjiang at seasonal (a–d) and annual (e) scales from 1980 to 2020.

Figure 4 [Figure 4: see original paper] shows temperature and precipitation trends from 1980 to 2020. At the annual scale, temperature increased by about 0.32°C/10a, with similar trends in northern and southern Xinjiang (Fig. 4m, n, o). Seasonally, spring temperature showed the greatest increasing trend, while winter showed the smallest (Fig. 4a, d, g, j). Temperature increases in northern Xinjiang exceeded those in southern Xinjiang in spring and summer, but were smaller in autumn and winter (Fig. 4b, c, e, f, h, i, k, l).

Precipitation increased by 8.58 mm/10a at the annual scale, with slightly greater increases in northern Xinjiang (Fig. 4m, n, o). Winter precipitation increased significantly, by approximately 2.17 mm/10a in Xinjiang overall and 3.42 mm/10a in northern Xinjiang (Fig. 4j, k). Precipitation increases in northern Xinjiang were greater than in southern Xinjiang in all seasons except summer (Fig. 4b, c, e, f, h, i, k, l).

3.2 Drought Trends in Xinjiang

From 1980 to 2020, annual-scale drought conditions intensified, with SPEI changing by approximately -0.21/10a (Table 4). Drought trends differed between southern and northern Xinjiang; intensified drought trends in northern Xinjiang were nonsignificant, while those in southern Xinjiang were significant. Drought intensified in spring, summer, and autumn throughout Xinjiang, with SPEI trends of -0.26/10a, -0.20/10a, and -0.07/10a, respectively (Table 4). In spring and autumn, drought increases in southern Xinjiang were more obvious than in northern Xinjiang. In contrast, drought conditions eased in winter across all areas, with positive SPEI trends of 0.32/10a, 0.30/10a, and 0.15/10a for the whole study area, northern Xinjiang, and southern Xinjiang, respectively, though the southern Xinjiang trend was nonsignificant.

Station-level drought trends varied across Xinjiang. In spring, southern Xinjiang stations mainly exhibited significant drought trends, while northern Xinjiang stations showed nonsignificant trends (Fig. 5a [Figure 5: see original paper]). In summer, most stations showed significant drought trends, though some in northwestern southern Xinjiang showed nonsignificant wetting trends (Fig. 5b). In autumn, most southern Xinjiang stations showed significant drought trends, while northern Xinjiang stations mainly showed nonsignificant trends, with some in southwestern northern Xinjiang showing nonsignificant wetting trends (Fig. 5c). In winter, most northern Xinjiang stations showed significant wetting trends, while most southern Xinjiang stations showed nonsignificant wetting trends (Fig. 5d). At the annual scale, southern Xinjiang stations mostly exhibited significant drought trends, while most northern Xinjiang stations showed nonsignificant drought trends (Fig. 5e).

Table 4 Drought trends in Xinjiang at seasonal and annual scales from 1980 to 2020

Region	Spring	Summer	Autumn	Winter	Full year
Xinjiang	-0.26*	-0.20	-0.07	0.32*	-0.21
Northern Xinjiang	-0.13	-0.04	-0.03	0.30*	-0.14
Southern Xinjiang	-0.38*	-0.32*	-0.20*	0.15	-0.30*

Note: Positive value indicates an increasing trend, while negative value indicates a decreasing trend. , significance at P<0.05 level.*

Fig. 5 Spatial distribution of drought trends in Xinjiang at seasonal (a–d) and annual (e) scales from 1980 to 2020.

3.3 Effects of Temperature and Precipitation Trends on Drought Trends

We calculated trends in $SPEI_{Obs}$, $SPEI_{DtOp}$, and $SPEI_{OtDp}$ to analyze temperature and precipitation impacts on drought trends. Compared with $SPEI_{Obs}$, $SPEI_{DtOp}$ demonstrated wetting trends at different seasonal and annual scales across the whole study area, northern Xinjiang, and southern Xinjiang, with significant wetting trends in winter (Table 5). This indicated that increasing temperature trends intensified drought conditions. Conversely, $SPEI_{OtDp}$ showed intensified drought trends in spring, summer, autumn, and at annual scales, and weakened wetting trends in winter, indicating that precipitation trends mitigated drought trends (Table 5).

Figure 6 [Figure 6: see original paper] shows SPEI trends at the 56 meteorological stations under three scenarios. Compared with the Obs scenario (Fig. 6a, d, g, j, m), most stations exhibited wetting trends under the DtOp scenario (Fig. 6b, e, h, k, n), indicating that temperature trends intensified drought at individual stations. When temperature trends were removed and precipitation trends retained, most northern Xinjiang stations showed wetting trends, and approximately half of southern Xinjiang stations showed wetting trends in spring (Fig. 6b). In summer, most eastern Xinjiang stations showed nonsignificant drought trends, while western stations mainly showed wetting trends (Fig. 6e). At autumn and annual scales, most stations exhibited nonsignificant wetting trends (Fig. 6h, n). In winter, southwestern southern Xinjiang stations changed from nonsignificant drought trends to nonsignificant wetting trends (Fig. 6j, k).

Compared with the Obs scenario, most stations exhibited more severe drought trends under the OtDp scenario (Fig. 6c, f, i, l, o), indicating that precipitation trends mitigated drought trends. When precipitation trends were removed and temperature trends retained, the number of stations with significant drought trends in northern Xinjiang increased, and drought trends at each station in southern Xinjiang were exacerbated in spring (Fig. 6c). This phenomenon was also observed in summer (Fig. 6f) and at the annual scale (Fig. 6o). In autumn, more northern Xinjiang stations exhibited drought trends (Fig. 6i). In winter, most northern Xinjiang stations changed from significant wetting trends to nonsignificant wetting trends, while the number of southern Xinjiang stations exhibiting nonsignificant drought trends increased (Fig. 6k, l).

Table 5 Drought trends in Xinjiang at seasonal and annual scales from 1980 to 2020 under different scenarios

Scenario	Region	Spring	Summer	Autumn	Winter	Full year
Obs	Xinjiang	-0.26*	-0.20	-0.07	0.32*	-0.21
	Northern Xinjiang	-0.13	-0.04	-0.03	0.30*	-0.14
	Southern Xinjiang	-0.38*	-0.32*	-0.20*	0.15	-0.30*
DtOp	Xinjiang	-0.19	-0.17	-0.06	0.39*	-0.14
	Northern Xinjiang	-0.03	-0.06	0.00	0.43*	-0.03
	Southern Xinjiang	-0.39*	-0.30*	-0.17	0.25	-0.28*
OtDp	Xinjiang	-0.30*	-0.26	-0.20	0.32*	-0.25
	Northern Xinjiang	-0.19	-0.20	-0.17	0.30*	-0.20
	Southern Xinjiang	-0.43*	-0.39*	-0.39*	0.15	-0.43*

Note: Positive value indicates an increasing trend, while negative value indicates a decreasing trend. , significance at $P<0.05$ level.*

Fig. 6 Spatial distribution of drought trends in Xinjiang from 1980 to 2020 under the Obs (a, d, g, j, m), DtOp (b, e, h, k, n), and OtDp (c, f, i, l, o) scenarios.

3.4 Contributions of Temperature and Precipitation Trends to Drought Trends

Figure 7 [Figure 7: see original paper] shows the contributions of temperature and precipitation trends to drought trends. Generally, temperature trends at most stations negatively contributed to drought trends, exacerbating drought conditions (Fig. 7a, d, g, j, m). From 1980 to 2020, temperature contributions at most stations were less than -0.10/10a except in winter and in northern Xinjiang in autumn. Temperature contributions varied between -0.10/10a and 0.00/10a at most stations in winter (Fig. 7j) and in northern Xinjiang in autumn (Fig. 7g).

Temperature affected drought trends differently in southern and northern Xinjiang. At spring, autumn, and annual scales, temperature contributions in southern Xinjiang were less than -0.30/10a, while contributions in northern Xinjiang mostly varied between -0.30/10a and -0.10/10a (Fig. 7c, i, o), indicating that temperature intensified drought more strongly in southern Xinjiang. In summer, negative temperature contributions were similar in both regions (approximately -0.31/10a) (Fig. 7f), while winter contributions were relatively small, ranging from -0.10/10a to 0.00/10a (Fig. 7l).

Precipitation trends generally contributed positively to drought trends at most stations, alleviating drought conditions (Fig. 7b, e, h, k, n). In spring, precipitation contributions in northern Xinjiang ranged from 0.00/10a to 0.10/10a, alleviating spring drought trends, while contributions in southern Xinjiang varied between -0.10/10a and 0.00/10a, tending to exacerbate spring drought trends (Fig. 7b). In summer and autumn, positive precipitation contributions in southern Xinjiang were greater than in northern Xinjiang (Fig. 7f, i). Summer precipitation contributions in western southern Xinjiang ranged from 0.00/10a to 0.20/10a, while those in eastern southern Xinjiang ranged from -0.10/10a to 0.00/10a (Fig. 7e). In autumn, positive contributions ranged from 0.00/10a to 0.20/10a at most stations, except some in southeastern northern Xinjiang and northeastern southern Xinjiang (Fig. 7h). In winter and at the annual scale, positive precipitation contributions in northern Xinjiang were greater than in southern Xinjiang (Fig. 7k, l). Winter precipitation contributions in northern Xinjiang ranged from 0.10/10a to 0.30/10a, while those in southern Xinjiang mostly ranged from 0.00/10a to 0.10/10a (Fig. 7k). At the annual scale, positive contributions ranged from 0.00/10a to 0.20/10a at most stations, with negative contributions in eastern southern Xinjiang (Fig. 7n).

By comparing temperature and precipitation contributions, we classified meteorological stations into four categories (Fig. 8 [Figure 8: see original paper]). Most stations exhibited temperature-dominated drought trends in spring, with few showing precipitation-dominated wetting trends (Fig. 8a). At summer, autumn, and annual scales, only some stations in northwestern southern Xinjiang and western northern Xinjiang demonstrated precipitation-dominated wetting trends, while others showed temperature-dominated drought trends (Fig. 8b, c, e). In contrast, most stations demonstrated precipitation-dominated wetting trends in winter, with only a few in southwestern southern Xinjiang showing temperature-dominated drought or wetting trends (Fig. 8d).

Fig. 7 Contribution of temperature and precipitation trends to drought trends at seasonal (a, b, c, d, e, f, h, i, j, k, and l) and annual (m, n, and o) scales in Xinjiang from 1980 to 2020.

Fig. 8 Spatial distribution of dominant factors influencing drought and wetting trends in Xinjiang at seasonal (a–d) and annual (e) scales from 1980 to 2020.

4 Discussion

Xinjiang is particularly sensitive to climate change, and previous studies have explored drought spatiotemporal characteristics in this region. Although these studies used different indices (SPEI, PDSI, SPI), all found intensified drought trends in spring, summer, autumn, and at annual scales, and wetting trends in winter, consistent with our findings. Some studies also examined drought periodic characteristics. For example, Zhang et al. (2021) identified that the first main cycle of SPEI in northern Xinjiang is 11 years at spring, autumn, and winter scales, 28 years in summer, and 25–26 years at the annual scale. Zhang et al. (2023) found the first main cycle of the arid index in Xinjiang is 21 years. These studies provided valuable insights into drought cycles and spatiotemporal patterns. Nonetheless, few studies have examined drought-influencing factors in this region, particularly temperature and precipitation—two critical factors that have altered significantly under global climate change.

Distinct from previous studies, we explored temperature and precipitation trend impacts on drought trends in this region. We found that from 1980 to 2020, temperature trends exacerbated drought trends, while precipitation trends mitigated them. Notably, drought intensification from increasing temperature was greater in southern Xinjiang than in northern Xinjiang. The alleviating effect of precipitation trends on drought was greater in northern Xinjiang at spring, winter, and annual scales, but greater in southern Xinjiang in summer and autumn. By comparing contributions, we classified stations into four categories and found that, aside from a few in the western Tianshan Mountains, most stations had temperature-dominated drought trends at spring, summer, autumn, and annual scales; however, in winter, most stations had precipitation-dominated wetting trends.

These findings highlight the critical role of temperature variations in determining drought dynamics and underscore the need for enhanced focus on temperature influences within drought management strategies.

Aside from winter, temperature trends were the primary driver of observed drought trends. Against the background of global climate change, significant warming occurred at spring, summer, autumn, and annual scales, while precipitation increases were not significant (Table 6). This may explain temperature dominance in driving drought trends at these scales. A significant wetting trend occurred in winter, corresponding to significant precipitation increases and non-significant temperature increases, with similar phenomena in both southern and northern Xinjiang.

Table 6 Temperature and precipitation trends in Xinjiang from 1980 to 2020

Region	Spring	Summer	Autumn	Winter	Annual
Temperature trend (°C/10a)					
Xinjiang	0.63**	0.31**	0.29*	0.38**	0.34**

Region	Spring	Summer	Autumn	Winter	Annual
Northern Xinjiang	0.67**	0.32**	0.25**	0.32**	0.33**
Southern Xinjiang	0.58**	0.30**	0.34**	0.39**	0.32**
Precipitation trend (mm/10a)					
Xinjiang	2.17*	0.58**	0.39**	7.81*	8.58*
Northern Xinjiang	3.42*	0.33**	0.33**	1.82*	7.81*
Southern Xinjiang	0.58	0.25**	0.33**	0.58	1.82

Note: Positive value indicates an increasing trend, while negative value indicates a decreasing trend. , significance at $P<0.05$ level; **, significance at $P<0.01$ level.*

Atmospheric circulation anomalies are closely related to regional climate changes. Significant warming and precipitation increases have occurred in Xinjiang from 1980 to 2020. Yao et al. (2022a) found that atmospheric circulation at mid-high latitudes of the Northern Hemisphere significantly impacts Xinjiang' s climate. Changes in the Asian polar vortex area and intensity are closely related to temperature variation. Yao et al. (2014) and Zhou et al. (2023) indicated that since 1980, decreases in the Asian polar vortex area and intensity may explain Xinjiang' s warming trend. Xinjiang lies in a westerly-dominated climate zone where precipitation is influenced by mid-latitude atmospheric circulation and Atlantic Multidecadal Oscillation-associated latitudinal wave propagation. Studies indicate that westerly circulation changes greatly influence Xinjiang precipitation. Northern Xinjiang and the western Tianshan Mountains are significantly affected by westerlies, leading to greater precipitation, which may explain why precipitation increases were generally greater in northern Xinjiang. Mountain ranges and plateaus influence moisture transport, affecting drought characteristics. Overall, we found intensifying drought trends from 1980 to 2020, more severe in southern Xinjiang. Southern Xinjiang is surrounded by mountains on three sides; tectonic uplift of the Pamirs, Tianshan Mountains, and Kunlun Mountains, along with their mechanical diversion of westerly winds, has contributed to more severe drought conditions than in northern Xinjiang.

This study has limitations and uncertainties. First, we used the Thornthwaite method to calculate PET and determine SPEI, which may cause overestimation of drought trends. Second, the uneven distribution of meteorological stations may increase uncertainties. Third, the Thornthwaite method only considered precipitation and average temperature, while other factors such as wind speed, humidity, and solar radiation also influence drought trends. Future studies should analyze these factors' impacts.

5 Conclusions

This study systematically analyzed temperature, precipitation, and drought trends in Xinjiang from 1980 to 2020, and quantified temperature and precipitation trend influences using scenario-simulation methods. Both temperature and precipitation exhibited increasing trends. In spring and summer, temperature increases in northern Xinjiang exceeded those in southern Xinjiang; conversely, in autumn and winter, warming in northern Xinjiang was less than in southern Xinjiang. Precipitation increases were greater in northern Xinjiang than southern Xinjiang across all seasons except summer. Drought intensification trends were observed in spring, summer, autumn, and at annual scales; notably, northern Xinjiang trends were nonsignificant while southern Xinjiang trends were significant. Conversely, wetting trends occurred in winter, with significant trends in northern Xinjiang and nonsignificant trends in southern Xinjiang.

Temperature negatively contributed to drought trends at most stations, indicating that increasing temperature exacerbated drought. The adverse effects of increasing temperature were less pronounced in northern Xinjiang than in southern Xinjiang. Precipitation mainly contributed positively to drought, indicating it alleviated drought trends. The alleviating effects were slightly greater in northern Xinjiang. Generally, most stations were classified as having temperature-dominated drought trends at spring, summer, autumn, and annual scales; however, in winter, most stations had precipitation-dominated wetting trends.

This study deepens understanding of temperature and precipitation influences on drought in Xinjiang and highlights temperature' s critical role in determining drought dynamics, providing a reference for formulating more targeted drought-adaptation strategies.

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