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Postprint: New Insights into Climate Transition in Northwestern China

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Date: 2022-06-07T00:00:00+00:00

Abstract

In recent years, climate change in Northwest China has attracted widespread attention from various sectors of society. Shi Yafeng proposed in 2002 that the climate in Northwest China might transition from warm-dry to warm-wet, and since then, scholarly attention to the "warming and wetting" phenomenon in Northwest China has gradually increased, yielding new insights into the timing, scope, and magnitude of climate transition over the past two decades. Based on this, monthly temperature and precipitation data from 1960–2019 were employed to conduct a reanalysis of climate change characteristics in Northwest China. The results indicate that: (1) From 1960–2019, both mean temperature and precipitation in Northwest China exhibited increasing trends, with a significant warming trend and a less pronounced wetting trend. (2) After 1997, temperature and precipitation increased rapidly, particularly in the eastern region of Northwest China, where the rate of precipitation increase exceeded that of the western region during the same period. The study further suggests that since 1997, the climate in Northwest China has indeed exhibited a trend toward warm-wet transition, with the transition occurring earlier than anticipated by previous research. (3) The scope of climate transition has also changed compared to earlier studies: the Longdong region of Gansu shifted from a non-transition zone to a significant transition zone; the eastern and western regions of Qinghai transitioned from mild transition zones to significant transition zones; while the central and western sections of the Qilian Mountains changed from significant transition zones to mild transition zones.

Full Text

Preamble

New Insights into Climate Transition in Northwest China

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Abstract: In recent years, climate change in Northwest China has attracted widespread attention from all sectors of society. In 2002, Shi Yafeng proposed that the climate in Northwest China might be transitioning from warm-dry to warm-wet conditions, prompting increased scholarly attention to the "warming and wetting" phenomenon in the region. New insights have emerged regarding the timing, extent, and magnitude of this climate transition since the beginning of the 21st century. Based on this context, this study reanalyzed climate change characteristics in Northwest China using monthly temperature and precipitation data from 1960 to 2019. The results show that: (1) Both average temperature and precipitation in Northwest China exhibited upward trends from 1960 to 2019, with a significant warming trend and a weaker wetting trend. (2) After 1997, temperature and precipitation increased rapidly, particularly in eastern Northwest China, where the precipitation increase rate exceeded that of the western region during the same period. The study preliminarily concludes that Northwest China has indeed shown a warm-wet transition trend since 1997, with the transition occurring earlier than previously anticipated. (3) The spatial extent of the climate transition has also changed compared with earlier research: the Longdong region of Gansu Province has shifted from a non-transition zone to a significant transition zone; eastern and western Qinghai Province have changed from mild transition zones to significant transition zones; while the central-western Qilian Mountains region has shifted from a significant transition zone to a mild transition zone.

Keywords: Northwest China; climate change; warm-wet transition; spatial-temporal pattern; standardized precipitation index (SPI)

Introduction

The term "climate transition" originally referred to the shift in mid-Pleistocene climate cycles from being dominated by 40 ka cycles to 100 ka cycles [?], or to significant spatial changes in climate types, such as transitions from semi-arid to semi-humid climate zones [?]. In the early 21st century, Shi Yafeng et al. [?] proposed the scientific inference that Northwest China's climate might transition from warm-dry to warm-wet during the 21st century, and divided the region into three categories based on transition criteria: significant transition zones, mild transition zones, and non-transition zones, demonstrating that climate change exhibits regional and typological differences, with precipitation changes being the most significant indicator. Against the backdrop of global warming, Northwest China has experienced rising temperatures, increased total precipitation, greater river and lake water volumes, and rising groundwater levels, with clear "warming and wetting"signals [?, ?]. Previous research has shown that long-term dry-wet variation trends in northern China follow a "wetter in the west, drier in the east"pattern [?, ?]. Specifically, western Northwest China shows a significant wetting trend, while the eastern region exhibits a drying trend closely related to continuous precipitation reduction, with sustained temperature rise being an important factor intensifying and expanding the drying trend [?]. Subsequently, Zhang Qiang et al. [?] found that while Northwest China experienced significant temperature increases from 1961 to 2009, precipitation changes showed marked spatial heterogeneity, with an overall warm-drying trend and localized warm-wetting phenomena. Zhao Chuancheng et al. [?] discovered that precipitation in eastern Northwest China underwent a turning point from decrease to increase in the early 21st century, with greater increases after 2000. However, Yao Junqiang et al. [?] found that in the arid region of Northwest China, 45.0% of stations showed precipitation increases from the mid-to-late 1980s, forming wetting centers in the Tianshan and Qilian Mountains, but 95.9% of stations exhibited decreasing precipitation from the 1990s onward, with the eastern region showing particularly pronounced reductions due to weakening monsoon intensity. These divergent findings raise important questions: What new changes have actually occurred in temperature and precipitation in Northwest China? Has the climate undergone a dry-wet transition in recent decades, particularly the past 20 years? And has the transitional region itself changed? These issues warrant in-depth investigation.

Based on these questions, this study analyzed monthly average temperature and precipitation data from 1960 to 2019 in Northwest China to examine their temporal and spatial patterns, further investigate climate transition characteristics, and reveal additional facts about the shift toward warm-wet conditions, providing references for climate change adaptation and disaster prevention in Northwest China.

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1 Study Area, Data, and Methods

1.1 Study Area Overview

Northwest China is located between 31°35 -49°15 N and 73°25 -110°55 E, encompassing all of Xinjiang, Gansu, Qinghai, Ningxia, and Shaanxi provinces, as well as western Inner Mongolia (Fig. [Figure 1: see original paper]). The land area accounts for approximately 31.7% of China' s total territory. The region is deep inland, far from the ocean, surrounded by high mountains that block moist maritime airflows, making it China' s most arid area. Additionally, the region has harsh natural conditions, fragile ecosystems, and a typical continental climate.

1.2 Data Sources and Processing

Monthly average temperature and precipitation data used in this study were obtained from the China Meteorological Data Sharing Service System (http://data.cma.cn). Data preprocessing involved discarding stations with severe data gaps, conducting homogeneity checks, and performing temporal and spatial consistency verification. Based on these checks, necessary interpolation and correction were applied. After processing, complete temperature and precipitation data from 1960 to 2019 were selected from 223 meteorological stations. Previous research indicates spatial differences in climate change characteristics between eastern and western Northwest China, generally using 100°E as the boundary [?, ?]. Seasonal divisions are: March–May as spring, June–August as summer, September–November as autumn, and December–February as winter.

1.3 Research Methods

(1) Meteorological Data Homogeneity Testing

Long-term meteorological observations are affected by instrument replacement, station relocation, observation protocol adjustments, and subjective operator factors, leading to skewed data, missing values, outliers, and overall data inhomogeneity. Therefore, homogenization is necessary. This study used the RHtest method to test and correct meteorological data sequences in Northwest China. Developed by the Climate Research Division of Environment Canada, this method detects breakpoints in meteorological data series based on a two-phase linear regression model [?, ?], with its feasibility and rationality widely validated [?, ?].

(2) Moving Average Method

To describe long-term temperature and precipitation trends, a linear regression model was established to characterize linear trends, with 11-year moving averages used to display variation patterns [?].

(3) Cumulative Anomaly Method

Cumulative anomaly curves intuitively reveal variation trends, allowing identification of long-term evolution patterns and approximate timing of abrupt changes [?].

(4) Climate Tendency Rate

The climate tendency rate describes trends and magnitudes of climate elements, using 10 times the linear regression coefficient (℃ $\cdot$ $(10a)^{-1}$ or mm $\cdot$ $(10a)^{-1}$) as the tendency rate [?].

(5) Standardized Precipitation Index (SPI)

SPI is sensitive to drought changes, computationally simple, applicable across multiple time scales and spatial comparisons, and convenient for data acquisition, making it one of the most widely used meteorological drought indices. Its calculation principle follows McKee et al. [?], with calculation programs provided by the National Drought Mitigation Center at the University of Nebraska-Lincoln (https://drought.unl.edu/droughtmonitoring/SPI/SPIProgram.aspx). Drought classification criteria [?] were also obtained from this website (Table). This study calculated SPI3 and SPI12 values to represent seasonal and interannual drought variations, respectively. Different time-scale SPI values characterize drought conditions differently; SPI12 considers precipitation surpluses/deficits over the preceding 12 months, with gradually emerging periodic characteristics that reflect long-term drought-flood variations. Drought intensity describes drought severity, generally represented directly by SPI values at individual stations during specific periods.

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2 Results and Analysis

2.1 Temporal Variation Characteristics

2.1.1 Annual Average Variation Characteristics Based on the temperature and precipitation variation curves for Northwest China from 1960 to 2019 (Fig. [Figure 2: see original paper]), the region' s warming characteristics align with previous research results [?, ?]. The average temperature showed a fluctuating upward trend (P < 0.01), with a climate tendency rate of 0.34 ℃ $\cdot$ $(10a)^{-1}$. The average temperature was 6.73 ℃ before the 1980s and 7.97 ℃ after the 1990s. A step-change occurred in the late 1980s, particularly after the 1990s when average temperature increased significantly. Precipitation before 1987 decreased at a rate of 3.99 mm $\cdot$ $(10a)^{-1}$, while after 1987 it increased rapidly at 3.55 mm $\cdot$ $(10a)^{-1}$. Northwest China exhibited obvious warming and drying before 1987, followed by pronounced warming and wetting. Around 1997 represents the turning point from warm-dry to warm-wet conditions (Fig. [Figure 2: see original paper]).

Single temperature or precipitation factors cannot fully describe dry-wet conditions, so SPI12 was selected to characterize meteorological drought. The variation trend (Fig. [Figure 2: see original paper]) shows that precipitation and SPI12 curves follow consistent patterns near the horizontal axis, with an increasing but non-significant trend, indicating slightly alleviated drought conditions. SPI12 shows an increasing trend, suggesting that precipitation increases are insufficient to compensate for potential evapotranspiration increases caused by rising temperatures, potentially making the climate even drier. This indicates that dry-wet conditions in Northwest China are primarily influenced by precipitation. Similar characteristics appear in other indices; for example, analysis using the drought index (potential evaporation to precipitation ratio) shows significant decreases in Northwest China' s arid regions from 1960 to 2010 [?, ?].

However, the step-change point for average temperature coincides with the timing of the dry-wet climate transition, suggesting this transformation is primarily related to temperature and precipitation changes. Most of Northwest China has arid and semi-arid climates with relatively low precipitation. Before 1997, precipitation dominated, with rising temperatures accompanied by decreasing precipitation, leading to warmer and drier conditions. After 1997, due to sustained warming, temperature became more dominant, with precipitation increases accompanying temperature rises, gradually creating warmer and wetter conditions. However, given Northwest China' s large east-west span and significant regional climate differences, discussion by decade and region is necessary.

2.1.2 Seasonal Variation Characteristics Seasonal temperature anomalies all show increasing trends (Fig. [Figure 3: see original paper]), with the largest increase in winter [0.42 ℃ $\cdot$ $(10a)^{-1}$], followed by spring [0.38 ℃ $\cdot$ $(10a)^{-1}$], autumn [0.29 ℃ $\cdot$ $(10a)^{-1}$], and smallest in summer [0.24 ℃ $\cdot$ $(10a)^{-1}$] ($P < 0.01$). Winter contributes most to annual average temperature increases. Since the 1990s, seasonal average temperatures have increased significantly, consistent with annual average temperature trends.

Seasonal precipitation anomaly variations (Fig. [Figure 4: see original paper]) show the largest increase in summer [1.73 mm $\cdot$ $(10a)^{-1}$, $P < 0.01$], with summer precipitation accounting for 58.2% of annual precipitation. Spring and autumn increases are relatively small [0.88 mm $\cdot$ $(10a)^{-1}$ and 0.13 mm $\cdot$ $(10a)^{-1}$, respectively], while winter shows the second-largest increase [1.18 mm $\cdot$ $(10a)^{-1}$]. After the 1990s, seasonal precipitation mostly increased, particularly since the 2000s with significant increases in precipitation anomalies.

Drought intensity (SPI3 anomaly) seasonal variations (Fig. [Figure 5: see original paper]) show that spring, summer, and winter drought intensity anomalies show increasing trends, with drought intensity weakening. Spring had 7 drought events (frequency 11.7%), summer had 6 events (10.0%), and winter had 8 events (13.3%). Autumn anomalies show a slight increasing trend with 7 drought events (11.7%). Overall, seasonal drought variation in Northwest China shows severe autumn droughts and weakening winter droughts.

2.2 Spatial Variation Characteristics

2.2.1 Annual Average Spatial Distribution Spatial distributions of annual average temperature, precipitation, and SPI12 tendency rates in Northwest China from 1960 to 2019 (Fig. [Figure 6: see original paper]) show that temperature tendency rates are mostly positive (Fig. [Figure 6: see original paper]a), with significant warming zones mainly in the western study area and weaker, more uniform warming in the east. Xinjiang' s northern region shows significant warming, with the Altay area increasing by 0.6–0.7 ℃ $\cdot$ $(10a)^{-1}$, followed by areas south of the Qaidam Basin and the Turpan Basin, while areas south of the Tianshan Mountains show the smallest increase [<0.1 ℃ $\cdot$ $(10a)^{-1}$]. Eastern Northwest China shows relatively uniform warming, with more obvious increases in northern areas; southern areas show weaker warming trends [<0.1 ℃ $\cdot$ $(10a)^{-1}$], particularly near Qinghai Lake and the Qinling Mountains.

Precipitation tendency rates show a southeast-to-northwest increasing trend (Fig. [Figure 6: see original paper]b), with significant increases in the western study area [1.18-23.02 mm$\cdot$(10a)$^{-1}$], particularly in northern Xinjiang and eastern/western Qinghai. The eastern region overall shows decreasing precipitation trends [-0.23 to -33.78 mm$\cdot$(10a)$^{-1}$], with significant decreases in areas east of the Yellow River in Gansu and south of the Qinling Mountains in Shaanxi. Stations showing decreasing trends are mostly concentrated on the southeast side of the 400 mm isohyet.

SPI12 tendency rates show spatial distributions similar to precipitation (Fig. [Figure 6: see original paper]c), with decreasing trends in the southeast including most of southeastern Gansu and Shaanxi, and significant increasing trends in the western study area. Similar spatial patterns appear in other indices; for example, Palmer Drought Index calculations show increasing drought area trends in eastern Northwest China and decreasing trends in the west [**?**]. Chen Yaning et al. [**?**] found that wetting areas in Northwest China are mainly concentrated in Xinjiang, while the monsoon marginal zone in eastern Hexi Corridor shows drying trends.

2.2.2 Variation Characteristics in Different Periods To analyze spatial distribution features in different periods, the study period was divided into three climatic periods: 1960-1986 (Period I), 1987-1999 (Period II), and 2000-2019 (Period III), to describe spatial distribution characteristics of temperature and precipitation tendency rates.

In all three periods, temperature increased at 97.5%, 98.4%, and 86.1% of stations, respectively, with warming intensity gradually increasing. Period III shows weaker warming than Period II, but Period II has the highest proportion of stations with warming trends (96.7%). Overall, temperature shows an upward trend, with the most warming stations in Period II. Comparing eastern and western Northwest China across periods reveals that the western region has larger increase rates, with warming rates slowing after 2000, while the eastern region, despite smaller increase rates, shows sustained increases after 1990 (Fig. [Figure 7: see original paper]).

Spatial distributions of precipitation tendency rates in the three periods (Fig. [Figure 8: see original paper]) show that Periods I and II had decreasing precipitation trends at 58.2% and 49.2% of stations, respectively, with only localized small-scale increases. Period III shows a significant shift to increasing trends at 59.8% of stations, particularly meaningful for precipitation increases in Period III. The increase in Period II was relatively weak, while Period III shows a significant increasing trend, with 88.5% of stations showing precipitation increases. Thus, Periods I and II showed warming and drying trends (temperature increase with precipitation decrease), while Period III shows warming and wetting trends (weakened temperature increase with sustained precipitation increase).

2.3 Climate Transition Analysis

2.3.1 Timing of Climate Transition The above analysis shows that Northwest China' s annual average temperature increase rate reached 0.34 ℃·$(10a)^{-1}$ from 1960 to 2019, with a step-change around 1997. Since the 1960s, Northwest China has experienced continuous warming, with an abrupt change in the late 1990s. Around 1997, both temperature and precipitation in Northwest China increased rapidly, consistent with annual average temperature trends, aligning with Dong Siyan et al.' s [?] conclusion that precipitation increases with rising temperatures, indicating certain correlations between temperature and precipitation changes. Continuous temperature rise and multi-year precipitation increases have led to increased runoff and glacier melt, further altering water-heat balance, causing vegetation improvement [?], lake area expansion [?], and desert area reduction [?] in some areas. Media reports indicate that over the past 20 years, Northwest China' s climate has significantly warmed with increased precipitation, causing increased river runoff, rising groundwater levels, and even flooding in previously dry areas. Shi Yafeng et al. [?] suggested that if such climate change facts appear continuously over a period (e.g., 20 years), it can be called a transition to warm-wet conditions. Based on continuous temperature rise and multi-year precipitation increases, Northwest China' s climate has gradually transitioned to warm-wet conditions, with obvious transition evidence after 1997.

2.3.2 Regional Climate Transition To systematically analyze spatial variations of annual average temperature and precipitation in Northwest China across different periods, especially after 1997, spatial distributions of differences between the 1997-2019 average and the 1960–1996 average were analyzed (Fig. [Figure 10: see original paper]). After 1997, all stations showed temperature increases, with larger increases on both sides of the Tianshan Mountains, in central-eastern Qinghai, central Inner Mongolia, and the Longdong region of Gansu (Fig. [Figure 10: see original paper]a). Precipitation differences show positive values in most areas (Fig. [Figure 10: see original paper]b), with larger increases in southwestern Xinjiang, south of the Tianshan Mountains, central and eastern Qinghai, southern Shaanxi, and Longdong region of Gansu. Some areas east of the Yellow River in Gansu and parts of Ningxia show negative precipitation values, while other areas show increases. After 1997, all stations experienced varying degrees of temperature increase, with 72.0% of stations increasing by 0–30 mm in precipitation and 24.0% increasing by more than 30 mm; 24.0% of stations experienced varying degrees of precipitation decrease. The large spatial differences in climate change across the study area result in varying degrees of transition.

Based on the magnitude of temperature and precipitation changes, climate transition regions were classified: areas with significant increases in both temperature and precipitation (increment reaching 0.3 ℃ and 30 mm) were designated as significant transition zones; areas with slight increases (0.1–0.3 ℃ and 0–

30 mm) as mild transition zones; and areas with no increase or decreases as non-transition zones. The analysis reveals that northern Xinjiang, the Tianshan Mountains and adjacent areas, western Tarim Basin, eastern and southern Qinghai, southeastern Qaidam Basin, Longdong region of Gansu, and central Inner Mongolia are significant climate transition zones with notable annual temperature and precipitation changes. Eastern Xinjiang, parts of southern Tarim Basin, central-western Qilian Mountains, northwestern Qinghai, and eastern Shaanxi show slight temperature and precipitation increases, classified as mild transition zones. Additionally, areas east of the Yellow River in Gansu (except Longdong) and western Ningxia show large temperature increases but decreasing precipitation, classified as non-transition zones.

Compared with Shi Yafeng et al.' s [?] classification of climate transition zones in Northwest China, the Longdong region of Gansu, southern Qinghai, most of Shaanxi, and central Inner Mongolia have changed from non-transition zones to significant transition zones; eastern and western Qinghai have shifted from mild to significant transition zones; while the central-western Qilian Mountains region has changed from a significant transition zone to a mild transition zone.

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3 Discussion

Northwest China began showing "warming and wetting" phenomena at the beginning of the 21st century, with the "wetting" essentially based on precipitation increases. Western Northwest China shows continuous precipitation increases, and in the early 21st century, eastern Northwest China also experienced precipitation increases, confirming findings by Ma Pengli et al. [?] and Ma Zhuguo et al. [?]. Earlier studies by Shi Yafeng et al. [?] and Tang Maocang et al. [?] supported the conclusion that climate transition is occurring in Northwest China. Combined with this study' s findings, from 1960 to 2019, 76.0% of stations in Northwest China showed temperature increases, and 52.0% showed precipitation increases, with eastern precipitation increase rates even exceeding those in the western region during the same period. These transition facts indicate that Northwest China' s climate, especially in the eastern region, has begun transitioning, with significant transition evidence.

Notably, drought conditions in Northwest China have been partially alleviated. Seasonally, temperature and precipitation changes show certain asymmetry, with obvious winter warming and summer wetting. The degree of summer warming has limited impact on evaporation intensity, but increased precipitation can alleviate drought to some extent and may have positive effects on ecosystems. It should be emphasized that precipitation in Northwest China has increased by about 10 mm $\cdot$ $(10a)^{-1}$, with cumulative increases not exceeding 30 mm. The trend of precipitation increase should not be overstated in terms of its impact on climate state changes; the arid and semi-arid climate pattern in Northwest China has not fundamentally changed, and precipitation increases cannot fundamentally alter the region' s arid climate conditions.

This study' s analysis of drought characteristics in Northwest China is based on precipitation and the SPI index, belonging to the category of meteorological drought. However, the essence of dry-wet conditions is the balance of surface water budgets, which cannot be fully characterized by precipitation and drought indices alone from a surface water budget perspective [?]. Additionally, future predictions of the "warming and wetting" trend in Northwest China remain an important research question, and the impacts of asymmetry between warming and wetting, as well as seasonal asymmetry, require further investigation.

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4 Conclusions

Using temperature and precipitation data from Northwest China from 1960 to 2019, this study analyzed temporal and spatial variation patterns to further investigate climate transition characteristics, reaching the following conclusions:

(1) From 1960 to 2019, the annual average temperature in Northwest China showed a significant upward trend ($P < 0.01$), with a step-change occurring around 1997. Winter showed the greatest increase ($P < 0.01$). The Altay region [0.6–0.7 ℃ · $(10a)^{-1}$] showed the largest increase, while areas near the southern Tianshan Mountains showed the smallest [<0.1 ℃ · $(10a)^{-1}$]. Significant warming and cooling zones mostly appeared in marginal areas, with more pronounced warming trends at higher latitudes.

(2) Annual precipitation in Northwest China from 1960 to 2019 showed an increasing trend, with a step-change occurring in 1997. After 1997, 76.0% of stations experienced precipitation increases, with the largest increase in summer ($P < 0.01$). Spatially, precipitation increased from southeast to northwest, with eastern precipitation increase rates exceeding those in the western region during the same period. The largest increases occurred in northern Xinjiang and eastern/western Qinghai.

(3) SPI12 showed an increasing trend, with significant increases beginning in 1997 and gradually weakening drought intensity. SPI3 reflects decreasing seasonal drought intensity year by year, with more severe autumn droughts possibly related to reduced autumn precipitation, while alleviated winter droughts may be related to faster warming and precipitation increases (second only to summer). Changes in water-heat balance have led to improved winter drought conditions.

(4) Since the 1960s, Northwest China has experienced continuous temperature increases, with an abrupt change in the late 1990s. Around 1997, significant warm-dry and warm-wet trends appeared in western and eastern Northwest China, respectively, indicating that the region' s climate began transitioning from warm-dry to warm-wet conditions in the later period. The Longdong region of Gansu, southern Qinghai, most of Shaanxi, and

central Inner Mongolia have changed from non-transition zones to significant transition zones; eastern and western Qinghai have shifted from mild to significant transition zones; while the central-western Qilian Mountains region has changed from a significant transition zone to a mild transition zone. Northwest China' s climate is undergoing a fundamental transition.

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

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