Analysis of Climate Change Characteristics in the Pan-Central Asian Arid Region (Postprint)

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Abstract

Using the latest 0.5°× 0.5° gridded monthly mean dataset from the Climatic Research Unit (CRU) for the period 1949-2018, this study discusses the characteristics of climate change in the Pan-Central Asian arid region over the past 70 years, primarily from the perspectives of EOF decomposition and wavelet analysis. The results indicate that: (1) Over the past 70 years, precipitation in the Pan-Central Asian arid region has shown an increasing trend at a rate of 1.393mm・(10a)-1, with summer precipitation exhibiting a decreasing trend while the other three seasons show increasing trends, among which winter is the most pronounced [0.834 mm・(10a)-1], and simultaneously, winter also shows the greatest warming magnitude [0.360 ℃・(10a)-1]; (2) EOF analysis of the precipitation anomaly field reveals that: precipitation change trends in the Pan-Central Asian arid region exhibit overall consistency (the first precipitation mode), a southwest-northeast opposite-phase variation characteristic (the second precipitation mode), and a west-to-east "-+-"alternating distribution pattern (the third precipitation mode); all three modes exhibit significant quasi-3 a cycles, the first mode also exhibits 5~7 a and quasi-12 a cycles, and the third mode exhibits a quasi-7 a variation cycle; (3) EOF analysis of the temperature anomaly field indicates that: temperature anomaly variations exhibit overall consistency (the first temperature mode) and an east-west opposite-phase variation characteristic (the second temperature mode); the first mode has significant quasi-2 a, 8~10 a cycles, while the second mode has distinct 2~4 a, quasi-5 a cycles. The traditionally defined warm season does not exhibit relatively obvious warming and increased precipitation, whereas the cold season instead shows greater warming magnitude and more pronounced precipitation increase. Central Kazakhstan, Turkmenistan, and most of Mongolia show obvious drying trends, while both sides of eastern and western Kazakhstan, northern Xinjiang of China, and parts of the Pamir Plateau exhibit significant wetting trends, and most of northwestern China overall shows a weak wetting trend. With the weakening of the Asian summer monsoon, the precipitation increment in the cold season is higher than that in the warm season, which seems to indicate that the influence of the Asian winter monsoon on precipitation in the Pan-Central Asian arid region is increasing. The results of this study aim to deepen the understanding of climate change characteristics in the Pan-Central Asian arid region and provide a scientific basis for further disaster prevention and mitigation, rational response to climate change, and adherence to sustainable development strategies.

Full Text

Analysis of Climate Change Characteristics in the Pan-Central-Asia Arid Region

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Abstract

Based on the monthly 0.5°$×0.5°gridpointdatasetfromtheClimaticResearchUnit,thisstudyexaminestheclim
Central−Asiaaridregionoverthepast70yearsusingempiricalorthogonalfunction(EOF)andwaveletanalyses.T
(1)Precipitationincreasedatarateof1.393mm·(10a)^{-1},withsummerprecipitationdecreasingwhiletheotherthreeseasonsi
1}];(2)Temperaturealsoincreasedmostinwinter[0.360℃ · (10a)^{-1}$]; (3) EOF analysis reveals three precipitation modes: overall consistency (first mode), southwest-northeast reverse patterns (second mode), and west-east alternating distribution (third mode), with quasi 5-7 year periods in the first mode and quasi 7-year periods in the third mode; (4) Temperature anomalies show overall consistency (first mode) and east-west reverse patterns (second mode), with quasi 8-10 year periods in the first mode and 2-4 year periods in the second mode. The warm season did not show pronounced warming and wetting, while the cold season exhibited greater warming and precipitation increases. Central Kazakhstan, Turkmenistan, and most of Mongolia show drying trends, while the east and west sides of Kazakhstan, northern Xinjiang, and parts of the Pamir Plateau show significant wetting trends, with most of Northwest China showing weak wetting. With weakening Asian summer monsoon, cold season precipitation increments exceed warm season increments, suggesting increasing influence of the Asian winter monsoon on precipitation. These results deepen understanding of climate change characteristics in the Pan-Central-Asia arid region and provide scientific support for disaster

prevention, climate adaptation, and sustainable development.

Keywords: Pan-Central-Asia arid area; EOF decomposition; wavelet analysis; changing trend

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1 Introduction

Arid regions exhibit complex and variable climate, dense population, and fragile ecosystems, making climate change a key research focus and challenge. Drought is among the most complex and least understood natural disasters, accounting for over 85% of economic losses from meteorological disasters, with drought alone contributing 50% of these losses. The mid-latitude regions of Asia host the highest-latitude arid zone globally, comprising the Central Asian arid zone (including most of the five Central Asian countries) and the China-Mongolia arid zone (including most of northwestern China and central Mongolia). Located deep within continents far from oceans, these regions feature plateau, mountain, and desert terrain, primarily influenced by westerly and monsoon circulations. Due to similar arid climate formation mechanisms, we collectively term these the Pan-Central-Asia arid region, also known as Central Asia arid region or Central-East Asia arid region.

Previous research falls into two categories: (1) separate analyses of Central Asia or China-Mongolia regions, which has limitations since arid climate zones are not formed by small-scale changes alone; and (2) treating the region as a whole, such as studies using EOF analysis of temperature changes over the past 100 years, reporting regional average warming rates of 0.18-0.21 ℃ · (10a)$^{-1}$—significantly higher than global rates. However, most EOF analyses of precipitation use original meteorological fields rather than anomaly fields.

As the highest-latitude arid region globally, its climate change characteristics differ fundamentally from other arid zones and significantly impact Asian and global climate. Under global climate change, have temperature and precipitation in the Pan-Central-Asia arid region exhibited new changes? Are there spatial differences and connections within the region? These questions lack systematic research. This study uses the latest high-resolution global monthly grid dataset (CRU TS v.4.03, 0.5°$×$0.5° resolution) from January 1949 to December 2018. Developed by the University of East Anglia, this dataset integrates several well-known databases, provides complete uninterrupted climate data with strict temporal homogeneity testing, and directly interpolates observations to eliminate proxy data uncertainties. Widely used in IPCC assessment reports, numerous studies confirm good agreement between this grid data and observations in China and Central Asia, making it suitable for decadal climate research.

This paper analyzes precipitation and temperature anomaly fields to investigate changes over the past 70 years (1949-2018) in the Pan-Central-Asia arid region.

Using EOF decomposition and wavelet analysis, we examine main modes and their periodic variations to deepen understanding of climate change characteristics and provide scientific support for disaster prevention, climate adaptation, sustainable development, and the Belt and Road Initiative.

1.1 Study Area Overview

The study focuses on the mid-latitude arid region of Asia (35.25°-50.75°N, 50.75°-110.25°E), including the five Central Asian countries, Mongolia, and most of northwestern China and Inner Mongolia. The climate is generally dry, with most areas receiving less than 400 mm annual precipitation (below 50 mm in deserts). Terrain is higher in the east (Pamir Plateau, Mongolian Plateau, Tianshan Mountains, Taklamakan Desert) and lower in the west (Kazakh Hills, Turan Plain).

1.2 Data Sources

Data are from the Climatic Research Unit (CRU) TS v.4.03 dataset developed by the University of East Anglia, UK, widely adopted in climate research.

1.3 Methods

1.3.1 Drought Index Calculation

The Aridity Index (AI), widely used in arid climate research, classifies regions as hyper-arid (AI<0.05), arid (0.05≤AI<0.2), semi-arid (0.2≤AI<0.5), and dry sub-humid (0.5≤AI<0.65). AI is calculated as $AI = P/PET$, where P is annual precipitation and PET is potential evapotranspiration computed using the Penman-Monteith equation.

1.3.2 EOF Analysis

Empirical Orthogonal Function (EOF) analysis decomposes time-varying variable fields into time-independent spatial functions and time-dependent functions, using the first few principal components to reflect main features. We use North's significance test method to verify whether EOF components represent meaningful signals. To accurately capture recent changes, we first compute precipitation and temperature anomaly fields before EOF decomposition.

1.3.3 Wavelet Analysis

Wavelet analysis describes local characteristics in time (space) and frequency (scale) domains, overcoming Fourier transform limitations. Its advantage lies in local signal analysis, identifying hidden structural characteristics that other methods cannot detect.

1.3.4 Trend Test

The Mann-Kendall trend test is a non-parametric statistical method requiring no specific probability distribution, suitable for non-normal sequences with extreme values. Recommended by the World Meteorological Organization, it is widely used in meteorological and hydrological trend analysis.

2 Results

2.1 Characteristics of Temperature and Precipitation Changes

Figure 2 shows interannual variations of regional average precipitation anomalies. With intensifying global warming, both global and Pan-Central-Asia arid regions show significant increasing precipitation trends. Global precipitation peaked in the mid-1950s and early 1970s, remained negative from the mid-1970s to late 1970s, and has been consistently positive since the late 1970s. In contrast, precipitation anomalies in the Pan-Central-Asia arid region show no clear pattern, with alternating positive and negative anomalies superimposed on an overall increasing trend, reflecting the complexity of climate change in arid regions.

Temperature anomaly changes show strong consistency across the region (Figure 2c, d), with a clear transition in the late 1970s from predominantly negative anomalies before to positive anomalies thereafter.

Table 1 presents linear trends of annual and seasonal precipitation and temperature. Globally, precipitation increases are largest in winter [0.703 mm · $(10a)^{-1}$], followed by autumn [0.759 mm · $(10a)^{-1}$] and spring [0.248 mm · $(10a)^{-1}$], while summer shows a decreasing trend (not statistically significant). In the Pan-Central-Asia arid region, winter precipitation increase is also largest [0.834 mm · $(10a)^{-1}$], followed by autumn [0.360 mm · $(10a)^{-1}$] and spring [0.169 mm · $(10a)^{-1}$], with summer showing a decreasing trend.

For temperature, global warming is highest in spring [0.248 ℃ · $(10a)^{-1}$], while the Pan-Central-Asia arid region shows maximum warming in winter [0.360 ℃ · $(10a)^{-1}$]. Both annual and seasonal warming trends in the Pan-Central-Asia arid region exceed global trends.

Spatial analysis reveals varying rates of change across the region (Figure 3). Most of Northwest China, northern and central Tajikistan, eastern Kyrgyzstan, and areas between the Caspian and Aral Seas show increasing precipitation, with maximum values in western Tajikistan [15.716 mm · $(10a)^{-1}$]. Decreasing precipitation occurs mainly in western Mongolia [minimum -8.745 mm · $(10a)^{-1}$]. The Aridity Index (AI) shows high consistency with precipitation changes.

Significant wetting trends appear on the east and west sides of Kazakhstan, northern Xinjiang in China, and parts of the Pamir Plateau, while central Kazakhstan, Turkmenistan, and most of Mongolia show obvious drying trends. Most of Northwest China exhibits a weak wetting trend overall.

The analysis shows that warming in the Pan-Central-Asia arid region exceeds global warming in all seasons, particularly in winter and spring, with summer warming being the slowest. This confirms that warming in global arid and semi-arid regions mainly occurs in cold seasons. Despite the "global warming hiatus" since 2000, precipitation increase in this inland region far from oceans has not slowed but has shown a jump-like surge, though this hasn' t changed the overall arid conditions.

2.2 EOF Analysis of Precipitation and Temperature

To investigate spatiotemporal variation characteristics, we performed EOF decomposition on the 1949-2018 precipitation anomaly field. The first eight eigenvalues and variance contributions are shown in Table 3. The first three modes pass the North significance test, with cumulative variance contribution reaching 47.332%. From the fourth mode onward, variance contributions decrease gradually, with the first eight modes explaining 86.830% of total variance, thus we select the first three modes for analysis.

The first precipitation mode (Figure 4) shows overall consistency across the Pan-Central-Asia arid region, with an anomaly center near Kyrgyzstan indicating more intense precipitation changes there. The time coefficient shows significant interannual variability, with wet and dry years alternating. The most anomalous years were 1969 and 2017.

The second mode exhibits a southwest-northeast reverse pattern: when precipitation is above normal in northwestern Mongolia and the western Loess Plateau of China, it is below normal in northern Iran, and vice versa. The time coefficient shows that northern Iran had above-normal precipitation before 1975, below-normal from 1975-1995, and above-normal again from 1995 onward. Northwestern Mongolia and western Loess Plateau show opposite patterns, with the most significant reverse changes occurring in 1998.

The third mode shows an alternating "wet-dry-wet" distribution from west to east, with Iran, northern Mongolia, and western Loess Plateau sharing the same precipitation changes, opposite to those in the Kazakh Hills and western Altai Mountains. The most significant "wet-dry-wet" years were 1969 and 1983.

For temperature anomalies (Figure 5, Table 4), the first mode shows overall consistency with a gradient decreasing from northwest to southeast, suggesting common influencing factors. The variance contribution (77.660%) is much higher than the second mode, representing the most common spatial distribution pattern. Notably, the Hexi Corridor and northeastern slopes of the Tibetan Plateau show more moderate temperature changes, consistent with Section 2.1.

The second temperature mode (variance contribution 9.170%) shows east-west reverse changes between Central Asia and the China-Mongolia region, with anomaly centers in northwestern Mongolia and northwestern Kazakhstan. This pattern was most significant in 1998.

2.3 Wavelet Spectrum Analysis of Principal Components

To reveal periodic variations, we performed wavelet analysis on time series of the first three precipitation anomaly modes and first two temperature anomaly modes.

For precipitation anomalies (Figure 6), the first mode shows significant quasi 5-7 year periods throughout 1949-2018, passing the Gaussian white noise significance test. The second mode exhibits significant quasi 2-4 year periods, most prominent during 1960-1980 but not significant after 1980. The third mode shows significant quasi 7-year periods, most evident during 1960-1980 but not passing the test after 1980.

For temperature anomalies (Figure 7), the first mode shows significant quasi 8-10 year periods from the 1960s to 1990s, with quasi 2-year periods also significant but weaker. The second mode exhibits obvious 2-4 year cycles, strongest during 1960-1980 and passing the test, while quasi 5-year cycles are evident during 1970-1980 but not significant after 1980.

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3 Discussion

Studies show the Asian monsoon has weakened overall in recent centuries, with East Asian summer monsoon retreat causing drying trends in the summer monsoon transition zone of the Pan-Central-Asia arid region. Meanwhile, the South Asian summer monsoon, crucial for water vapor transport, first strengthened then weakened, supporting our finding that summer precipitation variability is significantly smaller than in other seasons.

Research indicates cold seasons are the most significant warming period in arid regions, which this study confirms. Additionally, precipitation increments in cold seasons are more pronounced than in warm seasons, suggesting that as the summer monsoon weakens, the Asian winter monsoon (determined by Siberian High strength and position) is exerting increasing influence on precipitation in the Pan-Central-Asia arid region.

The Pan-Central-Asia arid region is long-term controlled by westerly circulation, while plateau monsoon circulation and Asian monsoon advance/retreat are crucial for water vapor transport. The Tibetan Plateau' s thermal effect excites large-scale Rossby wave disturbances that directly affect regional weather and climate. Interactions among westerly circulation, Asian monsoon, and plateau monsoon circulation remain unclear and should be a future research priority.

Precipitation response to global warming is complex and variable. Since the 1980s, while global temperature growth accelerated, precipitation increase in the Pan-Central-Asia arid region intensified with larger fluctuations, responding well to global warming trends. However, since 2000, despite the recognized “global warming hiatus,” precipitation in this inland region far from oceans has not slowed but has shown a jump-like surge, though this hasn' t changed overall arid conditions. The reasons for this different response warrant further study.

EOF analysis reveals spatial patterns such as the southwest-northeast reverse pattern of precipitation and east-west reverse pattern of temperature, demonstrating different regional responses to global climate change within the arid region. This will be a key focus for future research.

Many studies show oceans are important forcing sources for global arid region wet-dry changes, with oscillation signals like the Interdecadal Pacific Oscillation (IPO) and North Atlantic Oscillation (NAO) affecting temperature and precipitation through atmospheric circulation anomalies. However, the Pan-Central-Asia arid region also includes complex terrain with mountains, plateaus, deserts, and water bodies (Mediterranean, Black Sea, Caspian Sea, Aral Sea, Balkhash Lake, etc.) whose evaporation changes affect water cycles, along with human impacts on carbon cycles and dust aerosols from major deserts. The relative contributions and interactions of these factors, and how they create regional differences in precipitation and temperature responses, require future research through enhanced monitoring and numerical simulation.

4 Conclusions

1) Over the past 70 years, precipitation in the Pan-Central-Asia arid region increased at 1.393 mm$\cdot$(10a)$^{-1}$, greater than the global rate of 1.225 mm$\cdot$(10a)$^{-1}$. Summer precipitation decreased while the other three seasons increased, with spring showing the smallest increase [0.169 mm$\cdot$(10a)$^{-1}$] and winter the largest [0.834 mm$\cdot$(10a)$^{-1}$]. Temperature increased at 0.360 ℃$\cdot$(10a)$^{-1}$ in winter, with both annual and seasonal warming trends exceeding global trends. The traditional warm season did not show pronounced warming and wetting, while the cold season exhibited greater warming and precipitation increases. Central Kazakhstan, Turkmenistan, and most of Mongolia show drying trends, while the east and west sides of Kazakhstan, northern Xinjiang, and parts of the Pamir Plateau show significant wetting trends, with most of Northwest China showing weak wetting overall.
2) Precipitation anomaly EOF decomposition yields three modes: (i) overall consistency (first mode, 28.548% variance) with quasi 5-7 year periods; (ii) southwest-northeast reverse pattern (second mode, 10.896% variance) with quasi 2-4 year periods; and (iii) west-east alternating distribution (third mode, 7.888% variance) with quasi 7-year periods. More intense precipitation changes near Kyrgyzstan may be a key factor causing different regional climate responses.
3) Temperature anomaly EOF decomposition yields two significant modes: (i) overall consistency (first mode, 77.660% variance) with quasi 8-10 year periods, showing more moderate changes in the Hexi Corridor and Tibetan Plateau slopes; and (ii) east-west reverse pattern (second mode, 9.170% variance) with 2-4 year periods, reflecting opposite changes between Central Asia and the China-Mongolia region.

4) With weakening Asian summer monsoon, cold season precipitation increments exceed warm season increments, suggesting increasing influence of the Asian winter monsoon on precipitation. Complex interactions among westerly circulation, Asian monsoon, and plateau monsoon, along with terrain, water bodies, dust aerosols, and human activities, create regional differences in climate responses that require further monitoring and numerical simulation research.

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