Interdecadal Variations of the Leading Mode of Summer Precipitation Anomalies in Arid Northwest China and Its Associated Circulation: Postprint

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Abstract

Based on daily precipitation data from 102 meteorological stations and ERA5 monthly mean atmospheric reanalysis data for June–August 1961–2022 in the arid region of Northwest China, and using statistical methods such as empirical orthogonal function decomposition and univariate linear regression, we analyzed the interdecadal variations of the leading modes of summer precipitation anomalies and their associated circulation in the arid region of Northwest China. The results show that: (1) Summer precipitation in the arid region of Northwest China has experienced significant interdecadal variation characteristics, which can be divided into two periods: a dry period (1961–1986) and a wet period (1987–2022). During the wet period, the increase in precipitation over the Tarim Basin was contributed by both increased precipitation days and increased precipitation intensity, with the increase in precipitation days being particularly significant (exceeding 2 days). In other regions, enhanced precipitation intensity played the dominant role. (2) During the dry period, the leading modes of summer precipitation anomalies in the arid region of Northwest China were, in order, the northern Xinjiang pattern, Tarim Basin pattern, and Hexi-Alashan pattern. During the wet period, the leading modes of summer precipitation anomalies changed to the northern Xinjiang pattern, Hexi-Alashan pattern, and western Tarim Basin pattern. (3) Under different interdecadal backgrounds, the circulation associated with the same precipitation anomaly mode showed significant differences, mainly manifested in the shift of the subtropical westerly jet position, the configuration of Central Asian cyclones and Mongolian anticyclones (cyclones), and changes in the source regions and pathways of moisture transport.

Full Text

Preamble

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Interdecadal Changes and Associated Circulations in the Dominant Modes of Summer Rainfall Anomaly in the Arid Region of Northwest China

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Abstract

Based on daily rainfall data in summer at 102 meteorological stations in the arid region of northwest China and monthly ERA5 atmospheric circulation reanalysis data for 1961-2022, the interdecadal changes in the dominant modes of summer rainfall anomaly in the arid region of northwest China and the associated circulations of these modes are investigated. The results show that: (1) The summer rainfall in the arid region of northwest China exhibits obvious interdecadal variation, which can be divided into two periods: the dry period (1961–1986) and the wet period (1987–2022). During the wet period, the increase in rainfall in the Tarim Basin is attributed to an increase in the number of rainfall days and the rainfall intensity, especially the increase in the number of rainfall days, which is more than 2 d, whereas it is attributed to an increase in rainfall intensity in the rest of the region. (2) The dominant modes of summer rainfall in the arid region of northwest China during the dry period are the northern Xinjiang type, the Tarim Basin type, and the Hexi-Alagxa type, whereas during the wet period, the dominant modes of summer rainfall are the northern Xinjiang type, the Hexi-Alagxa type and the western Tarim Basin type. (3) There are obvious differences in the circulations of the same rainfall type over different interdecadal periods, and such differences in circulations are mainly reflected in the movement of the subtropical westerly jet, the structures of the Central Asian cyclone and the Mongolian anticyclone (cyclone), and changes in the source and path of water vapor transport.

Keywords

Summer rainfall anomaly; Interdecadal change; Dominant modes; Associated circulations; Arid region of northwest China

Against the backdrop of global warming, atmospheric water vapor content has increased and the hydrological cycle has accelerated, but the response of terrestrial precipitation shows significant regional differences [1]. The arid region of northwest China constitutes an important component of the arid regions of central Asia, with an extremely fragile ecological and environmental system, making it one of the regions most significantly affected by global climate change [2]. Since the mid-to-late 1980s, the climate of northwest China has transitioned from warm-dry to warm-wet, with both the area and intensity of wetting increasing since the early 21st century, and annual precipitation at most meteorological stations showing a significant increasing trend [3-5]. Although the increase in precipitation in the arid region of northwest China is significantly smaller than that in the monsoon region, it holds important ecological and environmental significance.

While most global land arid regions have become drier, the climate of the arid region of northwest China has shown a wetting trend, accompanied by a significant increase in summer rainfall, whose causes have received widespread attention [6-8]. The weakening of the East Asian summer monsoon favors the westward extension of the North Pacific subtropical high and the formation of a Mongolian anticyclone, enhancing the transport of water vapor from the tropical Indian Ocean and Pacific to the arid region of northwest China, which represents one of the main reasons for the increase in summer rainfall in this region over the past two decades [9]. The weakening of the South Asian summer monsoon leads to cooling in the middle and upper troposphere over Central Asia, favoring the formation of Central Asian cyclones and the northward transport of water vapor from the tropical Indian Ocean, corresponding to increased summer rainfall in western northwest China [10]. When the Central Asian subtropical westerly jet shifts southward, it corresponds to increased summer rainfall anomalies in western northwest China, while a northward shift in the East Asian subtropical westerly jet position leads to increased summer rainfall anomalies in eastern northwest China [11]. The intensification and westward shift of the Pacific teleconnection wave train is an important cause of the interdecadal increase in summer rainfall in Xinjiang [12]. The North Atlantic Multidecadal Oscillation transitioning from a negative to a positive phase excites an anomalous Mongolian anticyclonic circulation, and the weakening of the East Asian summer monsoon favors the interdecadal increase in precipitation in the arid region of northwest China [13].

Over the past century, precipitation in southern China has undergone multiple changes in its dominant modes, with a shift from less to more around the 1970s [14]. Sea surface temperatures in the tropical central-eastern Pacific and increased snow cover on the Tibetan Plateau have contributed to the interdecadal shift of the positive phase center of the dominant mode of summer precipitation in eastern China from north to south [15]. Summer precipitation in the arid region of northwest China has also experienced significant interdecadal variation [16-17]. Therefore, do the dominant modes of summer rainfall anomaly in the arid region of northwest China also change under different interdecadal

backgrounds? Have the associated atmospheric circulations and water vapor transport also changed? To address these questions, this study uses summer precipitation series from 1961-2022, employing empirical orthogonal function (EOF) decomposition and univariate linear regression methods to investigate the interdecadal variation characteristics of the dominant modes of summer rainfall anomaly in the arid region of northwest China, reveal the key influencing circulations of each rainfall anomaly mode under different interdecadal backgrounds, and enhance understanding of the mechanisms of climate anomalies in this region.

2.1 Interdecadal Variation Characteristics of Summer Precipitation

Summer precipitation in the arid region of northwest China exhibits significant interdecadal variation characteristics (Fig. 2). The summer precipitation series from 1961-2022 shows that precipitation was generally below normal before 1986 and above normal after 1987. Based on this, the study period is divided into two phases: a dry period (1961-1986) and a wet period (1987-2022). The difference distribution of precipitation between the wet and dry periods (Fig. 3) reveals that, except for a few stations in eastern Xinjiang and the Hexi Corridor, summer precipitation increased at most stations, particularly significantly in the Tianshan Mountains, Ili River Valley, and western Tarim Basin, where the increase exceeded 15 mm in the Tianshan Mountains and Ili River Valley and over 10 mm in the western Tarim Basin. The difference distribution of precipitation days between the wet and dry periods (Fig. 4) shows that precipitation days decreased in eastern Xinjiang and the Alagxa region, while they increased overall in northern Xinjiang and the Tarim Basin, especially significantly in the central-western Tarim Basin with an increase of more than 2 days. The difference distribution of precipitation intensity between the wet and dry periods (Fig. 5) indicates that summer precipitation intensity strengthened overall in the arid region of northwest China, particularly in the Hexi-Alagxa region, Tianshan Mountains, and central-western Tarim Basin. These results demonstrate that summer precipitation in the arid region of northwest China has undergone a significant interdecadal increase, with distinct regional differences in the contributions of precipitation days and intensity to this increase.

2.2 Dominant Modes of Summer Precipitation Anomaly Under Different Interdecadal Backgrounds

During the dry period (1961-1986), the cumulative variance contribution of the first three EOF modes of summer precipitation anomaly in the arid region of northwest China exceeds 45% of the total variance, explaining most of the spatiotemporal variation characteristics of summer precipitation anomalies during the dry period. Therefore, these three modes are selected as the dominant modes of summer precipitation anomaly variation in the arid region of northwest China. The first mode reflects the out-of-phase variation between summer

precipitation anomalies in the Tarim Basin and those in northern Xinjiang and the Hexi-Alagxa region (Fig. 6). Combined with the time coefficient series (Fig. 7), the large-value area of precipitation anomaly variation is located mainly in northern Xinjiang, particularly in the Tianshan Mountains, so this mode is named the Northern Xinjiang type. The second mode reflects the out-of-phase variation between precipitation in the Altay region of northern Xinjiang and the Hexi-Alagxa region and that in other regions (Fig. 8). Combined with the time coefficient series (Fig. 9), the large-value area of precipitation anomaly variation is located mainly in the Tarim Basin, so this mode is named the Tarim Basin type. The third mode reflects the out-of-phase variation of precipitation anomalies between northern Xinjiang and the Tarim Basin and Hexi-Alagxa region (Fig. 10), with the large-value area of precipitation anomaly variation located mainly in the Hexi-Alagxa region, so this mode is named the Hexi-Alagxa type. During the dry period, the temporal variation of the Northern Xinjiang type precipitation is dominated by interannual variability, the Tarim Basin type shows both interannual and interdecadal variation characteristics, while the Hexi-Alagxa type is dominated by interdecadal variation, with overall above-normal precipitation in this region after the mid-1990s.

During the wet period (1987-2022), the cumulative variance contribution of the first three EOF modes of summer precipitation anomaly in the arid region of northwest China accounts for approximately 42% of the total variance, a slight decrease compared to the dry period, but still sufficient to explain the main spatiotemporal characteristics of summer precipitation anomaly variation during the wet period. The first mode is very similar to the first mode of the dry period, showing in-phase variation across most regions except the western Tarim Basin (Fig. 11). Combined with the time coefficient series (Fig. 12), the large-value area of precipitation anomaly variation remains in northern Xinjiang, particularly in the Ili River Valley and Tianshan Mountains, so this mode is still named the Northern Xinjiang type. The second mode reflects the out-of-phase variation between precipitation anomalies in the Hexi-Alagxa region and Xinjiang (Fig. 13). Combined with the time coefficient series (Fig. 14), the Hexi-Alagxa region is the large-value area of summer precipitation anomaly variation, so this mode is named the Hexi-Alagxa type. The third mode shows in-phase variation across all regions except the Tianshan Mountains, and combined with the time coefficient series (Fig. 15), the western Tarim Basin belongs to the large-value area of precipitation anomaly variation, so this mode is named the Western Tarim Basin type. During this period, the Northern Xinjiang type precipitation shows obvious interannual and interdecadal variation characteristics, with below-normal precipitation during 1987-2000 and above-normal precipitation during 2001-2022. The Western Tarim Basin type precipitation also shows significant interdecadal variation characteristics (Fig. 15), with below-normal precipitation during 2001-2010 and above-normal precipitation during 2011-2022, consistent with existing research [17].

2.3 Associated Circulations of Dominant Modes Under Different Interdecadal Backgrounds

Summer precipitation in the arid region of northwest China is mainly modulated by westerly circulation, with both the intensity and position changes of the westerly jet exerting important influences on summer precipitation in this region [21-23]. The regression distribution of the time coefficient of the first mode during the dry period with 200 hPa zonal wind (Fig. 16) shows a positive-negative-positive spatial pattern of zonal wind anomalies from low to high latitudes over East and Central Asia. The Northern Xinjiang type precipitation is weakly associated with the Central Asian subtropical westerly jet but closely related to the northward shift of the East Asian subtropical jet position. The regression distribution of the time coefficient of the second mode during the dry period with 200 hPa zonal wind (Fig. 17) reveals a north-south out-of-phase variation in westerly jet anomalies over Central Asia, indicating that a southward-shifted Central Asian subtropical westerly jet favors anomalous increases in summer precipitation in the Tarim Basin [11]. The regression distribution of the time coefficient of the third mode during the dry period with 200 hPa zonal wind (Fig. 18) shows that the jet most closely related to this precipitation mode is located mainly over the Tibetan Plateau; when this jet shifts southward, it corresponds to above-normal summer precipitation in the Hexi-Alagxa region.

The regression distribution of the time coefficient of the first mode during the wet period with 200 hPa zonal wind (Fig. 19) shows changes in the position of the jet over Central Asia; when the Central Asian subtropical westerly jet shifts southward, it favors the occurrence of summer precipitation in this region [11]. The regression distribution of the time coefficient of the second mode during the wet period with 200 hPa zonal wind (Fig. 20) indicates that both the Central Asian and East Asian subtropical westerly jets shift northward, favoring increased summer precipitation anomalies in eastern northwest China (the Hexi-Alagxa region) [24]. The regression distribution of the time coefficient of the third mode during the wet period with 200 hPa zonal wind (Fig. 21) reveals an out-of-phase variation between the Central Asian subtropical westerly jet and the East Asian subtropical westerly jet, with the Central Asian subtropical westerly jet shifting southward while the East Asian subtropical westerly jet shifts northward. Compared with Fig. 11, the relationship between summer precipitation in the Tarim Basin and the westerly jet weakens during this period, consistent with existing research [25].

500 hPa anomalous cyclones (troughs) and anticyclones (ridges) are among the important circulation systems affecting summer precipitation in the arid region of northwest China [26-27]. The regression distribution of the time coefficient of the first mode during the dry period with 500 hPa horizontal wind (Fig. 22) shows a cyclone-anticyclone-cyclone spatial pattern from low to high latitudes over East Asia, with cyclonic shear over northern Xinjiang under the control of a low-pressure trough, thus favoring the occurrence of summer precipitation.

The regression distribution of the time coefficient of the second mode during the dry period with 500 hPa horizontal wind (Fig. 23) reveals that Central Asia is controlled by an anomalous cyclone, with anomalous southerly winds prevailing over the Tarim Basin, representing the key circulation causing anomalous increases in summer precipitation in this region [8,34,45]. The regression distribution of the time coefficient of the third mode during the dry period with 500 hPa horizontal wind (Fig. 24) shows that the Mongolian Plateau is controlled by an anomalous anticyclone, whose southern part causes anomalous easterly winds to prevail over the region, strengthening vertical wind shear and forming dynamic conditions favorable for precipitation.

The regression distribution of the time coefficient of the first mode during the wet period with 500 hPa horizontal wind (Fig. 25) reveals the formation of an East Asia-Pacific teleconnection wave train of anticyclone-cyclone-anticyclone from low to high latitudes over East Asia, causing anomalous easterly winds to prevail over northern Xinjiang, while Central Asia is simultaneously controlled by an anomalous cyclone, both providing favorable dynamic conditions for summer precipitation in northern Xinjiang. The regression distribution of the time coefficient of the second mode during the wet period with 500 hPa horizontal wind (Fig. 26) shows that the Mongolian Plateau and northern China are controlled by anomalous cyclones and anticyclones, respectively, transporting water vapor from high-latitude regions and China' s coastal areas to eastern northwest China (the Hexi-Alagxa region), providing favorable moisture conditions for precipitation occurrence. The regression distribution of the time coefficient of the third mode during the wet period with 500 hPa horizontal wind (Fig. 27) indicates that low latitudes over eastern China are controlled by an anomalous anticyclone, enhancing the transport of tropical oceanic water vapor to the East Asian monsoon region, and the anomalous anticyclone over the Mongolian Plateau further transports this monsoon-region water vapor westward, providing favorable moisture conditions for summer precipitation in the Hexi-Alagxa region.

The atmospheric column water vapor content in the arid region of northwest China is only one-third of that in North China at the same latitude, making external water vapor transport one of the important conditions for precipitation occurrence in this region. External water vapor is mainly contributed by westerly transport, but tropical oceanic water vapor also plays an important role [21,25-26,42]. Tropical oceanic water vapor cannot directly affect the arid region of northwest China, but through a relay transport process, water vapor from the tropical Indian Ocean and western North Pacific can be transported to the region [19,24].

The regression distribution of the time coefficient of the first mode during the dry period with water vapor flux (Fig. 28) shows that northern Xinjiang is controlled by anomalous cyclonic shear, with anomalous northwesterly winds transporting water vapor from high latitudes southward. Research indicates that the Arctic Ocean and high-latitude Asian regions are among the main moisture sources for

summer precipitation in the arid region of northwest China [43]. The regression distribution of the time coefficient of the second mode during the dry period with water vapor flux (Fig. 29) reveals that when summer precipitation in the Tarim Basin is above normal, the Indian Peninsula is controlled by an anomalous anticyclone, enhancing the northward transport of water vapor from the Arabian Sea, while Central Asia is controlled by anomalous cyclonic circulation that further transports water vapor to the Tarim Basin, representing a typical relay transport process [8,34,45]. The regression distribution of the time coefficient of the third mode during the dry period with water vapor flux (Fig. 30) shows that the Mongolian Plateau is controlled by an anomalous anticyclone that transports warm and moist air from the East Asian monsoon region to eastern northwest China (the Hexi-Alagxa region), providing favorable moisture conditions for precipitation occurrence.

The regression distribution of the time coefficient of the first mode during the wet period with water vapor flux (Fig. 31) indicates that northwestern India is controlled by an anomalous anticyclone and Central Asia by an anomalous cyclone, which together transport water vapor from the Arabian Sea to northern Xinjiang through a relay process [19]. The regression distribution of the time coefficient of the second mode during the wet period with water vapor flux (Fig. 32) shows that northern China and the Mongolian Plateau are controlled by anomalous anticyclones and cyclones, respectively, transporting water vapor from China' s coastal areas and high-latitude regions to eastern northwest China (the Hexi-Alagxa region), providing favorable moisture conditions for precipitation. The regression distribution of the time coefficient of the third mode during the wet period with water vapor flux (Fig. 33) reveals that through the relay circulation of the Central Asian anomalous cyclone and the anomalous anticyclone over the Mongolian Plateau, water vapor from the Arabian Sea and western North Pacific can be transported to the western Tarim Basin, causing anomalous increases in summer precipitation in this region.

3 Discussion

Previous studies have classified precipitation in the arid region of northwest China using different methods, revealing the temporal and spatial interannual variation characteristics of different precipitation patterns [34,46]. Interdecadal changes in precipitation have an important influence on the spatial dominant modes of precipitation anomalies. For example, over the past 100 years, precipitation in southern China has undergone multiple changes in its dominant modes, with an interdecadal shift from less to more around the 1970s [14]. The spatial dominant modes of precipitation anomalies during the flood season in eastern northwest China have also changed significantly under different interdecadal backgrounds [35]. Therefore, do the dominant modes of summer rainfall anomaly in the arid region of northwest China also change under different interdecadal backgrounds? This study shows that the dominant modes of summer rainfall anomaly in the arid region of northwest China during the dry period are

the Northern Xinjiang type, Tarim Basin type, and Hexi-Alagxa type, whereas during the wet period they are the Northern Xinjiang type, Hexi-Alagxa type, and Western Tarim Basin type. Both the order and spatial characteristics of these precipitation anomaly modes changed significantly under different interdecadal backgrounds, which is valuable for understanding the spatial features of precipitation anomalies under varying interdecadal contexts.

Atmospheric circulation and water vapor transport conditions are direct causes of precipitation anomalies. Although previous studies have examined the relationship between atmospheric circulation factors and regional summer precipitation anomalies in the arid region of northwest China [21-23,47], analyses under different interdecadal backgrounds remain limited. This study confirms that the dominant modes of summer rainfall anomaly in the arid region of northwest China changed significantly across different periods, but have the associated atmospheric circulation and water vapor transport conditions also changed? During the dry period, Northern Xinjiang type precipitation was mainly closely related to the position of the East Asian subtropical jet, whereas during the wet period, the relationship shifted to the position of the Central Asian subtropical westerly jet, and water vapor transport changed from westerly circulation during the dry period to monsoon circulation from the tropical Arabian Sea during the wet period. The relationship between Tarim Basin type precipitation and the Central Asian subtropical westerly jet weakened significantly during the wet period compared to the dry period, but water vapor transport from the western North Pacific increased, closely related to changes in East Asian monsoon intensity [17]. The controlling circulation for the Hexi-Alagxa type shifted from an anomalous anticyclonic circulation during the dry period to an anomalous cyclonic circulation during the wet period, consequently causing fundamental changes in water vapor transport pathways. Previous research has indicated that the synergistic variation of westerly and monsoon circulations is the fundamental cause of summer precipitation anomalies in the arid region of northwest China [48]. Based on these conclusions, summer precipitation anomalies in western northwest China (Xinjiang) are closely related to westerly circulation during the dry period, but the connection with monsoon circulation strengthens during the wet period. These findings have important scientific significance for understanding the causes of interdecadal transitions in the dominant modes of summer rainfall anomaly in the arid region of northwest China.

Although this study reveals the characteristics of circulations associated with the dominant modes of summer rainfall anomaly in the arid region of northwest China under different interdecadal backgrounds, it does not analyze the causes of changes in atmospheric circulation and water vapor transport conditions across these backgrounds. For example, during the wet period, the relationship between Western Tarim Basin type precipitation and the Central Asian subtropical westerly jet weakens. The eastward shift of the Central Asian subtropical westerly jet position is an important factor causing this weakened relationship between the jet and summer precipitation in the eastern Tarim Basin [25], but why the Central Asian subtropical westerly jet position shifts

eastward requires further research.

4 Conclusion

Based on daily precipitation data from 102 meteorological stations in the arid region of northwest China and ERA5 reanalysis data from 1961-2022, this study employs empirical orthogonal function decomposition and univariate linear regression methods to analyze the interdecadal changes in the dominant modes of summer rainfall anomaly and their associated circulations in the arid region of northwest China. The main conclusions are as follows:

(1) Summer precipitation in the arid region of northwest China exhibits obvious interdecadal variation characteristics, which can be divided into two periods: a dry period (1961-1986) and a wet period (1987-2022). Compared with the dry period, summer precipitation increased overall in the arid region of northwest China during the wet period, influenced by changes in both precipitation days and intensity. The interdecadal increase in summer precipitation in the western Tarim Basin is contributed by both increased precipitation days and enhanced precipitation intensity, particularly the increase in precipitation days (by more than 2 days), while precipitation intensity enhancement plays the major role in other regions.

(2) The first three EOF modes are selected as the dominant spatial modes of summer precipitation anomaly in the arid region of northwest China during both the dry and wet periods. The dominant modes during the dry period are, in order, the Northern Xinjiang type, Tarim Basin type, and Hexi-Alagxa type, whereas during the wet period they are the Northern Xinjiang type, Hexi-Alagxa type, and Western Tarim Basin type. Under different interdecadal backgrounds, the first precipitation mode is consistently the Northern Xinjiang type, representing the most important characteristic of summer precipitation in the arid region of northwest China. The second and third modes switch positions between the dry and wet periods, indicating the changing relative importance of these two modes across different periods.

(3) During the dry period, Northern Xinjiang type summer precipitation is mainly controlled by anomalous cyclonic circulation shear, with moisture primarily originating from high-latitude Asian regions. During the wet period, this precipitation type is influenced by the southward shift of the Central Asian subtropical westerly jet position and anomalous cyclones over Central Asia, with water vapor from the Arabian Sea reaching northern Xinjiang through relay transport. During the dry period, Hexi-Alagxa type summer precipitation is influenced by an anticyclone over the Mongolian Plateau that transports warm and moist air from the East Asian monsoon region to eastern northwest China. During the wet period, this precipitation type is affected by the combined influence of the northward shift of the East Asian subtropical westerly jet, anomalous cyclones

over the Mongolian Plateau, and anomalous anticyclones over northern China, which strengthen vertical wind shear and simultaneously facilitate the westward transport of monsoon-region water vapor. During the dry period, Tarim Basin type summer precipitation is influenced by the combined effects of a southward-shifted Central Asian subtropical westerly jet and anomalous cyclones over Central Asia, with water vapor from the Arabian Sea reaching the Tarim Basin through relay transport. During the wet period, Western Tarim Basin type summer precipitation is mainly affected by anomalous cyclones over Central Asia and anomalous anticyclones over the Mongolian Plateau, which together enhance the transport of water vapor from the Arabian Sea and western North Pacific to the western Tarim Basin.

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