Analysis of Interdecadal Variation of the Dominant Mode of Summer Precipitation in Xinjiang and Its Influencing Factors: Postprint

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Abstract

To investigate the formation mechanism of the dominant modes of summer precipitation in Xinjiang and potential external forcing influences, this study employs precipitation data from 89 stations in Xinjiang during 1979–2023 and the sliding EOF method to obtain evolution characteristics of the dominant precipitation modes, and conducts a comparative analysis focusing on the dominant modes and their circulation configurations as well as related sea surface temperature and snow cover changes. The results indicate that the dominant mode of summer precipitation in Xinjiang shifted from a regionally uniform pattern to a western-southern-Xinjiang pattern around 2005. The regionally uniform pattern of above-normal (below-normal) precipitation is closely associated with a strengthened (weakened) Ural blocking high, an active (attenuated) Central Asian low vortex, a stronger (weaker) Bay of Bengal anticyclone, and a positive (negative) phase of the East Asia–Pacific teleconnection pattern (EAP). The anomalous distribution of high-, mid-, and low-latitude systems leads to the enhancement (weakening) of four moisture transport pathways originating from the Arctic Ocean, Northwest Pacific, Bay of Bengal, and Caspian Sea–Aral Sea region. The circulation anomalies are influenced by sea surface temperature (SST) anomalies in the equatorial central-eastern Pacific, the tropical Indian Ocean Basin-Wide (IOBW) SST pattern, and the North Atlantic tripole (NAT) SST pattern. The western-southern-Xinjiang pattern of above-normal (below-normal) precipitation is primarily influenced by an anticyclone–cyclone (cyclone–anticyclone) meridional dipole wave train from the Caspian Sea to Lake Baikal and the intensification (weakening) of the Tashkent low vortex, which shows a significant correlation with the dipole anomaly of above-normal (below-normal) snow cover in the east and below-normal (above-normal) snow cover in the west over Eastern Europe–West Siberia during the preceding winter. Snow cover anomalies in key regions can, through the "snow–soil moisture–atmosphere feedback" process, promote the formation of a zonal dipole wave train from West

Siberia to Lake Baikal and a meridional tripole wave train from Eastern Europe to the Iranian Plateau, thereby modulating the convergence-divergence anomalies of the east–west winds over northern Xinjiang and the intensity changes of the Tashkent low vortex, establishing a physical pathway influencing the precipitation distribution of the western-southern-Xinjiang pattern.

Full Text

Preamble

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Interdecadal Variations and Influencing Factors in the Leading Modes of Summer Precipitation in Xinjiang

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Abstract: To investigate the formation mechanisms and potential external forcing impacts of the dominant summer precipitation patterns in Xinjiang, this study analyzed precipitation data from 89 meteorological stations spanning 1979–2023 using the sliding Empirical Orthogonal Function (EOF) method. The evolutionary characteristics of these patterns were examined through comparative analysis of precipitation modes, atmospheric circulation configurations, and associated variations in sea surface temperature (SST) and snow cover. The results reveal that the primary mode of summer precipitation in Xinjiang underwent a regime shift around 2005, transitioning from a region-wide consistent pattern to a western-southern Xinjiang pattern. Region-wide consistent precipitation anomalies (positive or negative) were closely linked to the strength of Ural blocking highs, activity of the Central Asian vortex, intensity of the Bay of Bengal anticyclone, and the phase of the East Asia–Pacific teleconnection pattern (EAP). The anomalous distribution of circulation systems across high, middle, and low latitudes enhanced (or weakened) four major water vapor transport pathways originating from the Arctic Ocean, Northwest Pacific, Bay of Bengal, and Aral Sea. These circulation anomalies were influenced by SST anomalies in the equatorial central-eastern Pacific, the tropical Indian Ocean Basin-wide mode, and the North Atlantic Triple pattern. Conversely, positive (negative) precipitation anomalies in the western-southern Xinjiang pattern were primarily driven by an anticyclone–cyclone (cyclone–anticyclone) meridional dipole wave train extending from the Caspian Sea to Lake Baikal, together with intensifica-

tion (weakening) of the Tashkent low vortex. This pattern showed significant correlation with a dipole snow cover anomaly over Eastern Europe and Western Siberia during the preceding winter, characterized by more snow in the east and less in the west (or vice versa). Snow cover anomalies in key regions can induce a "snow-soil moisture-atmosphere feedback" process that establishes a zonal dipole wave train from Western Siberia to Lake Baikal and a meridional triple wave train from Eastern Europe to the Iranian Plateau. These wave trains modulate the convergence and divergence of east-west winds over northern Xinjiang and alter the intensity of the Tashkent low vortex, thereby creating a physical pathway that influences the distribution of precipitation in western-southern Xinjiang.

Keywords: summer; dominant precipitation modes; interdecadal variation; atmospheric circulation; Xinjiang

Introduction

Under global climate warming, Northwest China' s arid region, particularly Xinjiang, has exhibited significant warming and humidification trends. Summer represents the primary precipitation season in Xinjiang, with both total precipitation and extreme precipitation events showing increasing trends. Compared with long-term trends, interannual variability contributes more substantially to precipitation variations. Xinjiang's unique mountain-basin desert climate results in pronounced spatiotemporal heterogeneity of precipitation anomalies, which has led to intensifying flash flood disasters and rising damage indices, posing significant threats to local industry, agriculture, and public safety. Therefore, understanding the spatiotemporal characteristics of Xinjiang' s summer precipitation and identifying potential predictive signals are crucial for grasping regional climate change patterns, improving climate prediction accuracy, and implementing effective disaster prevention and mitigation strategies.

Due to Xinjiang' s complex geography, precipitation exhibits large spatial variations, and the causes of precipitation anomalies are extremely complicated. Anomalous atmospheric circulation systems directly cause precipitation anomalies. Previous studies have revealed that the South Asian High' s multi-modal characteristics, the north-south oscillation of the West Asian subtropical westerly jet, the position and intensity of the Central Asian vortex, and phase transitions of atmospheric teleconnections all directly influence precipitation anomalies. In addition to internal atmospheric variability, external forcing factors such as oceans, snow cover, and sea ice can affect precipitation through complex physical processes. For instance, El Niño events during the preceding winter can enhance summer precipitation by modulating the South Asian High and shifting the subtropical westerly jet southward. Similarly, North Atlantic SST anomalies can excite atmospheric vorticity anomalies that influence large-scale circulation over Central Asia, leading to precipitation anomalies. However, most previous research has focused on precipitation anomalies across the entire region or specific sub-regions without clearly distinguishing how different factors influence distinct precipitation spatial patterns. Precipitation spatial distribution is key to seasonal precipitation forecasting, and Empirical Orthogonal Function (EOF) analysis is widely used to identify dominant precipitation modes. While precipitation modes are not temporally stable and may undergo interdecadal changes, most studies on interdecadal shifts in China’ s precipitation patterns have concentrated on eastern monsoon regions, leaving research on dominant mode evolution in Northwest China’ s arid areas relatively scarce.

This study addresses these gaps by employing sliding EOF analysis on Xinjiang summer precipitation data from 1979-2023 to characterize the evolution of dominant precipitation modes. We analyze circulation anomalies and key system configurations associated with different modes and investigate related external forcing signals to improve summer precipitation prediction capabilities in Xinjiang.

Data and Methods

This study focuses on interannual variability of summer (June–August) precipitation in Xinjiang. Precipitation data consist of monthly records from 89 meteorological stations across Xinjiang for the period 1979–2023. Atmospheric circulation data, including wind fields, geopotential height, and specific humidity, were obtained from the NCEP/DOE Reanalysis II dataset at 2.5°$×2.5°horizontalresolution.SSTdataweresourcedfromtheHadleyCentre′smonthlyglobalseasurfacetem resolution in this study. The climatological baseline period is defined as 1991-2020.

All data were detrended and subjected to a 9-year high-pass filter to isolate interannual variability before analysis. To reveal the evolution of dominant precipitation modes, we applied sliding EOF analysis by dividing the original time series into shorter overlapping windows and performing EOF decomposition on each window’s precipitation field. This method has proven effective in capturing the evolutionary characteristics of dominant modes. To identify the timing of mode transitions, we first determined the shift point through sliding EOF analysis, then applied conventional EOF analysis to obtain the dominant modes and their temporal coefficients for different periods. Regression and composite analyses were subsequently used to diagnose corresponding atmospheric circulation and external forcing anomalies.

Interdecadal Adjustment of Xinjiang Summer Precipitation Modes

EOF decomposition of Xinjiang summer precipitation from 1979–2023 reveals that the dominant mode underwent an interdecadal shift around 2005. Before 2005, the first EOF mode exhibited a region-wide consistent pattern, while after 2005 it displayed an out-of-phase relationship between western-southern Xinjiang and most other regions (hereafter referred to as the western-southern Xinjiang pattern). The North test confirmed that the first mode in each period represents an independent mode, explaining 29–46% of the variance. Based on these characteristics, we define 1979–2005 as the region-wide consistent period and 2006–2023 as the western-southern Xinjiang period.

To verify the reliability of the sliding EOF results, we performed conventional EOF decomposition for the two periods separately. During 1979–2005, the first mode showed a typical region-wide consistent pattern [Figure 2a: see original paper], with large loading values mainly distributed in western southern Xinjiang, the Ili River Valley, and the Tianshan Mountains, explaining 29.3% of the variance. The second mode exhibited a non-typical western-southern Xinjiang pattern opposite to most other regions, explaining 17.8% of the variance. The third mode showed a north–south opposite pattern between northern and western Xinjiang versus other regions, explaining 10.7% of the variance. During 2006–2023, the first mode displayed a western-southern Xinjiang pattern opposite to other regions, explaining 46.2% of the variance [Figure 2d: see original paper]. The second mode showed a non-typical region-wide consistent pattern with reduced importance, explaining 14.3% of the variance. The third mode exhibited an east–west opposite pattern between eastern Xinjiang and other regions, explaining only 8.9% of the variance. These results demonstrate that the first mode variance contribution far exceeds other modes in each period, confirming that sliding EOF effectively captures the primary spatial distribution characteristics of Xinjiang summer precipitation interannual variability.

Circulation Characteristics Associated with Precipitation Mode Transitions

High-, mid-, and low-latitude circulation systems, subtropical westerly jet oscillations, and water vapor transport all intimately relate to Xinjiang precipitation. When region-wide precipitation is consistently above normal [FIGURE:3a–c], the West Asian subtropical westerly jet strengthens and shifts southward across West and East Asia. The anomalous jet position shows strong southward shifts over the Iranian Plateau–western Tibetan Plateau and the North China Plain–Japanese islands. The jet's meridional position strongly correlates with Xinjiang summer precipitation, with a southward shift favoring increased precipitation across Xinjiang. The jet' s north and south sides exhibit a "+ − +" zonal wind anomaly pattern, enhancing positive vorticity and forming trough regions, while weakened mid-high latitude westerlies favor blocking formation and maintenance.

Ural blocking highs are strong, with their southern flank extending south of 60°N. The northeasterly winds ahead of the ridge guide cold air southward into Xinjiang. Meanwhile, the Central Asian vortex is active, spanning from the Caspian Sea to western Xinjiang, with southerly winds on its southern flank guiding warm air northward. The convergence of cold and warm air enhances precipitation, while upstream vortex anomalies also transport positive vorticity eastward, promoting cyclonic development and vertical ascent in the lower troposphere. Notably, an anomalous anticyclone over the Bay of Bengal merges with the Central Asian vortex, enhancing eastward moisture transport. The western Pacific subtropical high shifts significantly westward, and a "anticyclone-cyclone-anticyclone" meridional circulation anomaly extends from the western Pacific to the Okhotsk Sea, forming a positive EAP teleconnection phase. This configuration guides Northwest Pacific moisture inland along a cyclone over East Asia, increasing atmospheric water content and precipitation over Xinjiang.

During this period, four water vapor pathways affect Xinjiang [Figure 3c: see original paper]: (1) from the Arctic Ocean via West Siberia, (2) from the Northwest Pacific via Central Siberia, (3) from the Caspian Sea via Central Asia, and (4) from the Bay of Bengal via the Indian Peninsula. These pathways converge over and west of Xinjiang, with moisture entering the region through the Central Asian vortex's westerly flow. The mutual supplementation of moisture from the Arctic Ocean, Northwest Pacific, Bay of Bengal, and Aral Sea constitutes a crucial factor for widespread precipitation increases.

When precipitation exhibits a western-southern Xinjiang surplus with deficits elsewhere [FIGURE:3d-f], the West Asian westerly jet shifts northward and strengthens, a pattern unfavorable for widespread Xinjiang precipitation. Zonal wind anomalies west and east of 60°E show a "− + −" meridional dipole pattern, creating negative vorticity west of 60°E and positive vorticity east of it. In the mid-lower troposphere, anomalous anticyclones and cyclones align along the subtropical jet [Figure 3e: see original paper]. The Caspian Sea anticyclone extends northeast-southwest, with its northeasterly anomalies pushing from northwestern Xinjiang to south of the Balkhash Lake, while a Lake Baikal cyclone extends northwest-southeast, with its northwesterly anomalies moving southward across northeastern Xinjiang. These northeasterly and northwesterly winds diverge over northern Xinjiang, suppressing convective development and precipitation.

A broad negative height anomaly exists over the Iranian Plateau-Tashkurgan region, forming a significant positive vorticity center near Tashkurgan [Figure 3f: see original paper]. This Tashkent low vortex extends eastward, controlling western-southern Xinjiang. The vortex' s southwesterly flow guides moisture from west of Xinjiang into western-southern Xinjiang. The Caspian Sea, Aral Sea, and Balkhash Lake serve as important moisture sources. The Caspian anticyclone transports moisture northward to West Siberia, where it turns southward, passes the Balkhash Lake to replenish moisture, and continues southward. The Tashkent low vortex then redirects this southward moisture flux westward into western-southern Xinjiang. Thus, the combined action of the Caspian anticyclone and Tashkent low vortex establishes a westward moisture pathway from the Caspian-Aral Sea-Balkhash Lake region, providing favorable moisture conditions for western-southern Xinjiang precipitation.

In summary, region-wide consistent precipitation anomalies correlate with a southward-shifted West Asian jet, strong Ural blocking, active Central Asian vortex, strong Bay of Bengal anticyclone, and positive EAP phase. The western-southern Xinjiang pattern relates more closely to dipole circulation anomalies along the westerly jet and mid-lower tropospheric Tashkent low vortex activity.

External Forcing of Xinjiang Summer Precipitation Modes

Forcing of the Region-Wide Consistent Pattern

Besides internal atmospheric variability, external forcings like SST and snow cover serve as important predictability sources for climate anomalies. Region-wide consistent precipitation correlates with equatorial central-eastern Pacific SST anomalies from the preceding winter through early spring, resembling an El Niño decay year [Figure 5: see original paper]. The tropical Indian Ocean exhibits basin-wide warming from the preceding winter to summer, with the warming center gradually shifting eastward—a pattern consistent with El Niño decay years. This Indian Ocean capacitor effect is crucial for sustaining the ENSO influence into summer. The persistent Indian Ocean warming excites eastward-propagating Kelvin waves that suppress convection over the tropical Northwest Pacific, strengthening the western Pacific subtropical high and inducing a positive EAP phase that facilitates moisture transport. Additionally, it triggers a Matsuno-Gill atmospheric response over the Indian Ocean, strengthening and shifting the South Asian High southward, which modulates the subtropical westerly jet and deepens the Central Asian vortex, favoring moisture convergence over Xinjiang.

The region-wide consistent pattern also corresponds to a negative North Atlantic SST Tripole phase [Figure 5: see original paper], with anomalies persisting from the preceding winter through summer. The warm SST center over the tropical North Atlantic is most pronounced. Tropical North Atlantic SST anomalies correlate positively with the EAP index during the preceding winter and play an important role in influencing summer circulation anomalies. Negative NAO anomalies can excite a quasi-barotropic zonal teleconnection wave train across Eurasia, strengthening anticyclonic circulation near the Ural Mountains. Simultaneously, the warm tropical North Atlantic SST anomalies associated with negative NAO positively influence the formation and maintenance of cyclonic circulation over Central Asia. The combined effect of Ural anticyclonic anomalies and Central Asian cyclonic anomalies facilitates southward moisture transport from the Arctic Ocean and enhances upward motion over Xinjiang. In summary, preceding winter–spring SST anomalies, particularly NINO3.4, Indian Ocean Basin-wide, and North Atlantic Tripole patterns, are closely linked to the region-wide consistent precipitation mode, with the Indian Ocean capacitor effect serving as a critical bridge.

Forcing of the Western-Southern Xinjiang Pattern

In contrast to the region-wide pattern, SST forcing has a weaker influence on the western-southern Xinjiang pattern. Only the NINO3.4 index shows correlation with this mode [Figure 4b: see original paper], but significant correlations are confined to the preceding winter–spring, with signals weakening rapidly in late spring and failing to persist into summer. This suggests oceanic forcing is not the primary pathway influencing the western-southern Xinjiang pattern.

Winter–spring Eurasian snow cover serves as an effective cross-seasonal climate predictor through albedo and hydrological effects that force summer climate anomalies. Snow cover anomalies in different regions exert varying impacts on local climate. Significant snow cover anomalies associated with the western-southern Xinjiang pattern are located over Eastern Europe and Western Siberia, exhibiting opposite changes. We defined a snow dipole index (EUSISD) as the difference in snow water equivalent between Eastern Europe (47°–60°N, 40°–50°E) and Western Siberia (50°–60°N, 55°–80°E). The EUSISD index correlates significantly with the temporal coefficient of the western-southern Xinjiang pattern, passing the 99% confidence level.

Winter snow anomalies primarily influence summer climate through hydrological effects. Regression of EUSISD onto monthly shallow soil moisture shows that when the preceding winter exhibits an east-positive/west-negative snow dipole, soil moisture displays an east-wet/west-dry dipole pattern that strengthens from late spring and persists through summer and autumn [Figure 7a: see original paper]. Soil moisture anomalies alter land–atmosphere heat exchange, thermodynamically forcing the atmosphere. Increased soil moisture cools the mid-lower troposphere, reducing atmospheric thickness and lowering geopotential height. The east-wet/west-dry soil moisture pattern corresponds to an east-cool/west-warm temperature anomaly and an east-low/west-high height pattern [Figure 7b: see original paper].

The EUSISD index regression onto summer 500 hPa streamfunction anomalies reveals a cyclone-anticyclone dipole pattern over Eastern Europe–Western Siberia, with two wave energy propagation pathways [Figure 8a: see original paper]. Eastward-propagating wave energy disperses from West Siberia to Lake Baikal, forming a northwest–southeast oriented cyclone that generates a negative–positive zonal wave train. Southward-propagating wave energy disperses from Eastern Europe through the Caspian Sea to the Iranian Plateau, forming a "negative–positive–negative" meridional wave train. The Caspian anticyclone strengthens significantly and connects with the West Siberian anticyclone, forming a northeast–southwest oriented anticyclonic anomaly. The northeasterly anomalies from this anticyclone' s northeastern flank and the northwesterly anomalies from the Lake Baikal cyclone' s northwestern flank diverge over northern Xinjiang [Figure 8b: see original paper]. Meanwhile, the southern end of the meridional wave train affects the Iranian Plateau–southern Xinjiang region, enhancing positive vorticity anomalies. The enhanced positive vorticity center is located along the Iranian Plateau-western-southern Xinjiang line, resembling the Tashkent low vortex [Figure 3f: see original paper]. These analyses demonstrate that preceding winter snow cover is an effective factor influencing the western-southern Xinjiang precipitation pattern.

Conclusions and Discussion

Xinjiang summer precipitation exhibits significant interannual variability, with both region-wide consistent and western-southern Xinjiang patterns representing dominant modes that underwent clear interdecadal adjustment around 2005. Using 89-station precipitation data and sliding EOF analysis, this study characterized the mode transition and compared circulation configurations and external forcing factors. The main conclusions are:

1) The dominant summer precipitation mode in Xinjiang shifted interdecadally around 2005. During 1979–2005, the region-wide consistent pattern prevailed, while during 2006–2023, the western-southern Xinjiang pattern dominated, characterized by out-of-phase precipitation variations between western-southern Xinjiang and other regions.

2) The region-wide consistent mode is influenced by circulation systems across all latitudes. When precipitation is uniformly above (below) normal, the West Asian jet shifts southward (northward), Ural blocking strengthens (weakens), the Central Asian vortex intensifies (attenuates), the Bay of Bengal anticyclone strengthens (weakens), and the EAP pattern exhibits positive (negative) phase anomalies. These anomalous systems enhance (weaken) four moisture pathways from the Arctic Ocean, Northwest Pacific, Bay of Bengal, and Aral Sea.

3) The western-southern Xinjiang pattern is primarily influenced by dipole circulation anomalies along the westerly jet and the Tashkent low vortex in the mid-lower troposphere. An anticyclonic anomaly over the Caspian–West Siberia region and a cyclonic anomaly over Northeast Asia create divergence of easterly and westerly winds over northern Xinjiang, suppressing convection. The upstream anticyclone and Tashkent low vortex jointly guide moisture from the Caspian–Aral Sea and Balkhash Lake into western-southern Xinjiang, favoring above-normal precipitation in this pattern.

4) SST represents an important climate prediction source. The region-wide consistent mode correlates with preceding winter–spring NINO3.4, Indian Ocean Basin-wide, and North Atlantic Tripole SST anomalies that persist into summer, with the Indian Ocean capacitor effect serving as a critical bridge. In contrast, the western-southern Xinjiang pattern is more strongly influenced by the preceding winter’ s Eastern Europe–Western Siberia snow dipole. An east-positive/west-negative snow anomaly leads to east-wet/west-dry soil moisture in summer, thermodynamically forcing atmospheric circulation. This generates eastward and southward propagating wave energy, forming a zonal dipole wave train from West Siberia to Lake Baikal and a meridional triple wave train from Eastern Europe to the Iranian Plateau. The wave trains modulate wind divergence over northern Xinjiang and enhance the Tashkent low vortex, establishing a physical pathway for the western-southern Xinjiang pattern.

This study focused on the temporal evolution of summer precipitation modes, contrasting circulation differences between modes and exploring predictive signals from SST and snow cover. Previous research indicates that Arctic sea ice can also influence summer precipitation through Eurasian teleconnection wave trains and may synergistically affect Northwest China precipitation together with SST. Such synergistic effects also exist among snow cover, oceans, and internal climate variability. Whether other factors like sea ice and Tibetan Plateau thermal anomalies contribute to different precipitation modes, and whether synergistic multi-factor influences exist, requires further investigation to deepen scientific understanding of local precipitation anomaly formation mechanisms.

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