Characteristics of Climate Warming and Wetting in Xinjiang at Different Temporal Scales (Postprint)

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Abstract

In the early 21st century, studies proposed that the climate in Northwest China, especially Xinjiang, was undergoing "warm-humidification"; however, clear conclusions regarding the characteristics of this "warm-humidification" in Xinjiang across different time scales are still lacking. Based on observed climatic and hydrological data from the Xinjiang region, combined with recently published new findings, this study conducted a comprehensive review and comparative analysis of the "warm-humidification" characteristics in Xinjiang, China from the historical period to the interdecadal scale, and comprehensively evaluated the evolution characteristics of climate "warm-humidification" in Xinjiang across different time scales. The results indicate: (1) Over the past millennium and century, the climate of Xinjiang has primarily exhibited a warm-dry/cold-wet hydrothermal configuration, with significant interdecadal variability in the recent century. Notably, since the 1980s, Xinjiang has experienced a distinct "warm-humidification" process, though the magnitude of change has not exceeded the variability range of historical periods; (2) Since 1961, the climate in the mid-to-high latitudes of the Northern Hemisphere has generally shown "warm-humidification" characteristics, with Xinjiang and the Siberian region to its north, northern Europe, and other areas all exhibiting significant "warm-humidification" features. Xinjiang connects the high-latitude regions experiencing "warm-humidification" with the Tibetan Plateau region, indicating that climate "warm-humidification" is not unique to Xinjiang; however, the humidification process in Xinjiang's climate possesses distinctiveness among mid-latitude regions; (3) During 1961–2019, the interannual temperature-humidity configuration in Xinjiang's climate was dominated by "warm-wet/warm-dry" patterns, with annual and seasonal conditions in Xinjiang predominantly warm-wet after the 1990s. The rates of warming and humidification have intensified across successive climate normal periods, but show a slowing trend in the current period, indicating that the warming and humidification trends have phased characteristics and exhibit nonlinear increasing

patterns. Although the "warm-humidification" trend in Xinjiang' s climate has been pronounced over the past 30 years, with gradually intensifying warming and strong evaporation demand, the absolute increase in precipitation is not substantial, and the current humidification characteristics cannot alter Xinjiang' s arid climate environment. The research findings provide an important scientific foundation for the assessment of Xinjiang' s climate and "warm-humidification" at different spatial scales.

Full Text

Preamble

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Characteristics of Climate "Warming-Wetting"in Xinjiang at Different Time Scales

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Abstract

Studies since the early 21st century have proposed that Northwest China, particularly Xinjiang, is experiencing climate "warming-wetting," yet clear conclusions regarding the characteristics of this phenomenon across different time scales remain lacking. Based on observed climatic and hydrological data from the Xinjiang region, combined with recently published findings, this study comprehensively reviews and comparatively analyzes the "warming-wetting" characteristics of Xinjiang' s climate from historical to interdecadal time scales, providing a comprehensive assessment of its evolution across multiple temporal scales. The results indicate: (1) Over the past millennium and century, Xinjiang' s climate has primarily exhibited a "warm-dry, cold-wet" configuration, with significant interdecadal variability. Since the 1980s, the region has experienced a notable "warming-wetting" process, though the magnitude of change has not exceeded the variability range of historical periods. (2) Since 1961, the mid-to-high latitudes of the Northern Hemisphere have generally shown "warming-wetting" characteristics, with Xinjiang and the Siberian region to its north, as well as northern Europe, all displaying clear warming-wetting trends. This demonstrates that climate warming-wetting is not unique to Xinjiang, though the humidification process in Xinjiang exhibits distinctiveness within the mid-latitude zone. (3) The interannual temperature-precipitation configuration in Xinjiang during 1961–2019 was dominated by "warm-wet" and "warm-dry" patterns. After the 1990s, annual and seasonal climates in Xinjiang mostly showed warm-wet configurations. The rates of warming and wetting increased across successive climate-state periods but have shown a slowing trend in the current period, indicating that the warming-wetting trend exhibits phased characteristics and a nonlinear increasing pattern. Although the warming-wetting trend has been evident in Xinjiang over the past 30 years, with gradually intensifying warming, the absolute increase in precipitation remains modest. The current humidification characteristics cannot alter Xinjiang' s arid climate environment. These findings provide an important scientific foundation for assessing climate and warming-wetting trends in Xinjiang across different spatio-temporal scales.

Keywords: dry-wet change; warming-wetting trend; temperature-precipitation configuration; multi-scale pattern; Xinjiang

1 Data Sources

Meteorological Data: Monthly temperature and precipitation data from 1961 to 2019 for the Xinjiang region were selected. These data have undergone quality control and homogenization correction and have been widely used in numerous studies.

Dry-Wet Indices: The dry-wet indices used include the self-calibrating Palmer Drought Severity Index (sc_{PDSI}) and the Aridity Index (AI). The sc_{PDSI} index is the most commonly used proxy for dry-wet conditions, comprehensively considering precipitation, soil moisture, runoff, and potential evapotranspiration. Global sc_{PDSI} data were obtained from https://crudata.uea.ac.uk/cru/data/drought/#global. The AI index is calculated as AI = (PET - PRE)/PET, where PET represents potential evapotranspiration and PRE represents precipitation. Potential evapotranspiration characterizes evaporative demand. The sc_{PDSI} index incorporates temperature effects on evapotranspiration to characterize climatic dry-wet conditions and can be used to represent the degree of regional "warming-wetting." All data were sourced from the Climatic Research Unit (CRU) at the University of East Anglia, with a resolution of 0.5°$×$0.5°. This dataset shows relatively small biases except in polar, oceanic, or plateau regions. Comparative studies between CRU TS v4.04 data and observational records from representative stations in Northwest China have demonstrated strong correlations, confirming the dataset' s reliability for regional climate change trend analysis.

2 Comparison of Dry-Wet Climate Change Trends Between Xinjiang and Other Typical Northern Hemisphere Regions

2.1 Comparison of Temperature and Precipitation Trends

To investigate the spatial extent of climate "warming-wetting" in the Northern Hemisphere, we first examined the spatial distribution of temperature and precipitation trends across the region. Under the background of global warming, the Northern Hemisphere exhibited consistent warming trends during 1961–2019, with more pronounced warming at mid-to-high latitudes above 35°N, where warming trends exceeded 0.3°C · decade^{-1} and passed significance tests at the 0.05 level (Figure 1). This indicates significant warming in the mid-to-high latitude regions of the Northern Hemisphere, including Xinjiang.

Compared with the consistent temperature changes, precipitation variation showed obvious spatial heterogeneity. From 1961–2019, regions with significant precipitation increases were mainly located above 50°N, including northern Europe and Siberia. In contrast, areas south of 35°N, including the Xinjiang arid region, the Tibetan Plateau, and the Aral Sea region, also showed clear increasing precipitation trends. Conversely, regions surrounding the Mediterranean, central Europe, southern Central and West Asia, the Mongolian Plateau, and North China exhibited clear precipitation decreasing trends (Figure 1).

For more detailed analysis of the heterogeneity in climate warming-wetting, we selected regions at the same latitude or longitude as Xinjiang (35°–50°N, 75°–95°E) for comparative analysis. These included the Siberian region to Xinjiang's north (55°–65°N, 55°–85°E), the Mediterranean region to the west (35°–50°N, 10°W–15°E), and North China to the east (35°–50°N, 105°–125°E). Analysis revealed that Xinjiang's precipitation increased significantly during 1961–2019, with a trend rate of 4.6 mm · decade^{-1} ($P < 0.01$). The Siberian region to its north also showed significant precipitation increases, with a trend rate of 10.4 mm · decade^{-1} ($P < 0.01$). The adjacent Tibetan Plateau at the same longitude also exhibited clear wetting, reflecting a large-scale and consistent humidification process extending from the southern margin of the Tibetan Plateau northward to the Arctic region. However, along the same latitude belt in the east-west direction, despite the common influence of the westerly circulation, precipitation changes showed clear regional differences. Both the Mediterranean region and North China showed non-significant decreasing precipitation trends, with rates of -4.6 mm · decade^{-1}, failing to pass significance tests (Figure 2). This demonstrates that in the mid-latitudes of the Northern Hemisphere, precipitation changes in the westerly-influenced Xinjiang region differ significantly from those in the East Asian monsoon and Mediterranean climate zones, reflecting the uniqueness of Xinjiang's humidification process.

2.2 Comparison of Dry-Wet Climate Trends

The above analysis examined the spatial characteristics of "warming-wetting" from the perspective of temperature-precipitation configuration. However, regional dry-wet changes are controlled by the water balance status, which is influenced not only by temperature and precipitation but also by soil moisture, surface runoff, and potential evapotranspiration. The sc_{PDSI} index comprehensively incorporates water cycle factors such as water evapotranspiration, runoff, and soil moisture exchange, as well as the effects of previous precipitation and water supply on subsequent periods, making it a robust proxy for dry-wet conditions.

From the perspective of sc_{PDSI}-revealed dry-wet changes, the spatial heterogeneity of dry-wet climate change in the Northern Hemisphere becomes even more apparent (Figure 3). The sc_{PDSI} index shows that the Northern Hemisphere is generally dominated by drying trends, with humidification only occurring in northern Europe, the Aral Sea region, Xinjiang and the Tibetan Plateau, and eastern Siberia. Xinjiang represents one of the most significant humidification regions in the Northern Hemisphere. The AI index reflects a similar spatial pattern of dry-wet changes (Figure 3), but differs in that it shows the Northern Hemisphere is generally drying, with humidification only in northern Europe, the Aral Sea region, Xinjiang and the Tibetan Plateau, and eastern Siberia. Notably, the sc_{PDSI} index reveals humidification regions at higher latitudes compared to the temperature-precipitation configuration.

The sc_{PDSI} index also reflects significant drying characteristics in high-latitude regions, possibly related to Arctic amplification, where increased evaporative demand due to warming is not offset by increased precipitation. In typical regional comparisons, Xinjiang shows the most significant humidification trend in the Northern Hemisphere, with a sc_{PDSI} trend of $0.31 \cdot \text{decade}^{-1}$ ($P < 0.01$), while western Siberia shows $0.20 \cdot \text{decade}^{-1}$ ($P < 0.01$). In contrast, drying rates are larger and more significant, such as in the Mediterranean region ($-0.58 \cdot \text{decade}^{-1}$, $P < 0.01$) and North China ($-0.34 \cdot \text{decade}^{-1}$, $P < 0.01$). Notably, the drying rate in significantly drying regions is nearly double that in significantly wetting regions, reflecting that under global warming, the trend and risk of warming-drying in the Northern Hemisphere are gradually intensifying, while humidification only occurs in specific unique regions and higher latitudes.

3 Characteristics of Xinjiang's Climate "Warming-Wetting" at Different Time Scales

3.1 Characteristics of Xinjiang' s Climate "Warming-Wetting" Over the Past Millennium

Based on typical lake sediment records, Xinjiang' s climate over the past millennium has primarily exhibited a "warm-dry, cold-wet" temperature-precipitation configuration. Sediment records from Jili Lake in northern Xinjiang show that over the past 2,500 years, the climate displayed a "warm-dry, cold-wet" configuration, with the Medieval Warm Period (800–1200 AD) showing a "warm-dry" pattern. Tiewaike Lake sediment records indicate that over the past 900 years, the climate also showed a "warm-dry, cold-wet" pattern. Bosten Lake records reveal that over the past millennium, climate on centennial scales was dominated by "warm-dry, cold-wet" configurations, with the Little Ice Age (1400–1900 AD) showing a distinct "cold-wet" climate that was more humid compared to the "warm-dry" climate under recent warming. Therefore, millennium-scale sediment records consistently reflect Xinjiang's "warm-dry, cold-wet" climate configuration, without showing any clear "warm-wet" climate stage.

3.2 Characteristics of Xinjiang's Climate "Warming-Wetting" Over the Past Century

Tree-ring records can effectively reflect regional climate changes over the past century. Available tree-ring records in Xinjiang are mainly distributed in the Tianshan Mountains in central Xinjiang and the Altai Mountains in the north, including reconstructed sequences of annual temperature and precipitation, though most sequences are less than 500 years long.

In the Altai Mountains, climate changes over the past 300 years differ from those in the Tianshan region. Analysis of three precipitation reconstruction sequences reveals good consistency in dry-wet changes, with stable precipitation from 1700–1850, persistent drought from 1850–1920, and a decreasing precipitation trend since the late 1980s. Comprehensive analysis of multiple temperature, precipitation, and dry-wet reconstruction sequences shows that the Altai region's interdecadal climate over the past 300 years was dominated by "warm-dry" and "cold-wet" configurations, accounting for 35.7% and 28.6% respectively, while "cold-dry" and "warm-wet" configurations were comparable, each accounting for 17.9%. Since 1980, the Altai climate has been characterized by warm-wet conditions.

In the Tianshan Mountains, numerous precipitation and dry-wet reconstruction sequences show large variations in trends but share consistent dry-wet stages. Reconstructed precipitation in the central and western Tianshan indicates that over the past 300 years, precipitation experienced three dry stages and two wet stages, with the 20th century being the driest period, while the 1980s marked the beginning of a rapid humidification process. Based on extensive precipitation reconstruction sequences, the Tianshan region has shown consistent humidification since the 1980s, though the magnitude has not exceeded the range of historical humidification variability. A 550-year reconstruction from central Tianshan reveals distinct regional dry-wet stages, with predominantly wet conditions from 1470–1650, followed by a long-term persistent dry period, and interdecadal fluctuations dominating the past century, with notably wet conditions since the 1980s.

Zheng et al.' s reconstruction of dry-wet conditions in northern Xinjiang over the past 300 years shows interdecadal-scale fluctuations as the main pattern, with the 1980s marking a transition to wet conditions. Comprehensive analysis indicates that over the past century, Xinjiang' s dry-wet changes have been dominated by interdecadal-scale fluctuations, maintaining a "warm-dry, cold-wet" temperature-precipitation configuration, particularly evident in the past 300 years. However, since the 1980s, most regions have experienced consistent humidification, though the amplitude remains within historical variability ranges.

3.3 Modern Climate "Warming-Wetting" Characteristics in Xinjiang

3.3.1 Temperature-Precipitation Configuration Changes in Modern Xinjiang Climate To clarify the temperature-precipitation configuration relationship in Xinjiang' s modern climate, we examined 9-year moving averages of temperature anomalies, precipitation anomaly percentages, and sc_{PDSI} index changes from 1961–2019. Temperature and precipitation in Xinjiang show roughly consistent patterns across different time scales, experiencing alternating warm/cold and wet/dry periods. The early 1960s featured low temperatures and less precipitation, while the mid-1980s onward showed clear warming and wetting trends. Notably, wetter periods began in the mid-1980s, earlier than the warming periods. Since the 21st century, warming has slowed or stagnated, while wetting has gradually intensified. The sc_{PDSI} index reveals distinct phased transition characteristics in dry-wet evolution, with a dry period before the mid-1980s followed by a wet period. Within the wet period, humidification also shows phased changes, reflecting the combined influence of temperature, precipitation, and other hydrological fluctuations. Overall, Xinjiang' s climate experienced a transition from "cold-dry" to "warm-wet" configuration around the mid-1980s, with clear warming-wetting characteristics after the 1990s.

Generally, natural temperature and precipitation variations exhibit certain configuration relationships over longer time scales, with warm periods typically corresponding to wet periods and cold periods to dry periods. Under anthropogenic warming, these relationships become more complex at shorter scales. Analysis of annual temperature and precipitation anomalies in Xinjiang from 1961–2019 shows that interannual configurations are dominated by warm-wet and warm-dry patterns, accounting for 36.2% and 33.1% respectively, while cold-wet and cold-dry configurations are less frequent, indicating good consistency between temperature and precipitation changes. Seasonal configurations differ significantly: summer and autumn patterns are consistent with annual scales, dominated by warm-wet and warm-dry configurations; spring shows more uniform distribution, with warm-wet, warm-dry, and cold-wet configurations each around 25%; winter is dominated by warm-wet configurations (38.5%). Using the 1990s as a boundary, annual and seasonal climates have mostly shown warm-wet configurations, particularly pronounced in summer and winter.

3.3.2 Dynamic Characteristics of Warming-Wetting Trends in Xinjiang Figure 7 shows the annual variation curves of temperature and precipitation in Xinjiang. From 1961-2019, temperature showed a significant upward trend, with a linear warming rate of 0.30°C · decade^{-1} ($P < 0.01$). Precipitation also showed a clear increasing trend, with a linear increase rate of 9.6 mm · decade^{-1} ($P < 0.05$). Humidification was relatively slow before the mid-1980s but increased significantly afterward. However, since the 21st century, temperature has shown high-level 震荡 variation, with the warming trend appearing to slow, consistent with the global warming hiatus phenomenon.

From a precipitation perspective, the 30-year climate-state average precipitation increased from 149 mm (1961-1990) to 178.6 mm (1990-2019), an increase of 29.6 mm. The linear humidification rate increased from 7.6 mm · decade^{-1} (1961-1990) to 15.6 mm · decade^{-1} (1990-2019), but decreased to 7.6 mm · decade^{-1} in the 1991-2020 period. The sc_{PDSI} index shows that the humidification rate rebounded to 0.31 · decade^{-1} in the 1991-2020 period, reflecting the nonlinear increasing characteristics of the humidification trend.

To further understand the dynamic characteristics of warming-wetting trends, we analyzed the characteristics across 30-year climate-state periods. Figure 8 shows the distribution proportions of temperature and precipitation linear trend rates across different climate-state periods. Both temperature and precipitation averages show continuous warming-wetting development, though the warming trend decreased in the 1991-2020 period compared to previous periods. The sc_{PDSI} index also decreased in the 1991-2020 period, showing a trend toward drying, with a linear trend rate of -0.11 · decade^{-1}. This reflects a new characteristic of slowing current humidification trends, indicating that warming-wetting trends have phased characteristics and do not show continuous linear increases.

3.3.3 Spatial Patterns of Warming-Wetting Trends in Xinjiang To further reveal the spatial extent and pattern changes of warming-wetting trends in Xinjiang, we analyzed the spatial distribution characteristics of temperature and precipitation linear trend rates across different climate-state periods. Overall, Xinjiang shows regionally consistent warming characteristics. During 1961-1990, temperature trend rates were mainly 0-0.30°C · decade^{-1}, covering 71.9% of stations; during 1971-2000 and 1981-2010, the 0.30-0.60°C · decade^{-1} range covered 49.4% and 69.7% respectively; during 1991-2020, the 0.30-0.60°C · decade^{-1} range covered 59.6%, indicating gradually intensifying warming trends and extents.

The normal distribution of temperature trend rates across major climate-state periods shows that, except for individual stations, rates are concentrated at 0.16°C · decade^{-1} (1961-1990), 0.34°C · decade^{-1} (1971-2000), 0.51°C · decade^{-1} (1981-2010), and 0.42°C · decade^{-1} (1991-2020). The gradually increasing peak values reflect intensifying warming, though the 1991-2020 period shows weaker intensity than 1981-2010, consistent with the global warming hiatus.

The spatial pattern of humidification trends is more complex. Across climate-state periods, precipitation decrease covered 16.9%, 11.2%, and 19.1% of regions respectively, while increase covered 83.1%, 88.8%, and 80.9%. The 0–10 mm·decade^{-1} range accounted for 41.6%, 34.8%, and 32.6%, while the 10–20 mm·decade^{-1} range accounted for 39.3%, 29.2%, and 32.6%. Although regional humidification is evident, the rate and cumulative increase are very limited.

The probability distribution of humidification rates shows stable peak values around 8-10 mm·decade^{-1}, but the distribution range indicates fluctuating humidification extent, smallest in 1981–2010 and expanding in 1991–2020. Precipitation trend spatial distribution shows persistent humidification in northwestern Xinjiang, the Tianshan Mountains, and western Tarim Basin, while southeastern Xinjiang and the southern Tianshan slopes show phased humidification slowdown or drying trends.

4 Discussion and Conclusion

Based on observed climatic and hydrological data from Xinjiang and recent published findings, this study comprehensively reviewed and comparatively analyzed the characteristics of "warming-wetting"trends in Xinjiang from historical to interdecadal time scales, addressing its status across different temporal scales. The findings reveal that over the past millennium and century, Xinjiang' s climate has primarily exhibited a "warm-dry, cold-wet" temperature-precipitation configuration, with significant interdecadal variability. Since the 1980s, the region has experienced an obvious warming-wetting process, though the amplitude has not exceeded historical variability ranges.

From a Northern Hemisphere perspective, since 1961, mid-to-high latitude regions have generally shown warming-wetting characteristics, with Xinjiang, high-latitude areas to its north, and northern Europe all displaying clear warming-wetting trends. This phenomenon is not unique to Xinjiang, though the humidification process in Xinjiang shows uniqueness within the mid-latitude zone. The spatial extent of Northern Hemisphere warming-wetting roughly forms a "T" shape, with Xinjiang connecting the warming-wetting high-latitude regions and the Tibetan Plateau. Xinjiang' s dry-wet changes under westerly influence differ significantly from those in East Asian monsoon and Mediterranean climate zones, reflecting the distinctive nature of Xinjiang' s humidification process.

From a Xinjiang regional perspective, since 1961, the region has shown consistent warming-wetting trends, with a warming rate of 0.30°C·decade^{-1} ($P < 0.01$) and a wetting rate of 9.6 mm·decade^{-1} ($P < 0.05$). Across 30-year climate-state periods, temperature, precipitation, and sc_{PDSI} index averages show continuous warm-wet development, with temperature rates mainly distributed at 0.30-0.60°C·decade^{-1} and wetting rates concentrated at 0–10 mm·decade^{-1}. Warming-wetting rates increased across successive climate-state periods but have slowed in the current period, indicating phased characteristics and nonlinear increasing patterns. Although the warming-wetting trend has been evident in Xinjiang over the past 30 years, with intensifying warming, the absolute precipitation increase remains modest. The current humidification cannot change Xinjiang' s arid climate environment.

Xinjiang's climate warming-wetting has widespread impacts on extreme weather events, vegetation ecology, water resources, agriculture, and pastoralism, with these impacts gradually intensifying with continued warming. Future projections indicate continued precipitation increases in most Xinjiang regions, though warming remains strong and evaporation vigorous. Considering greenhouse gas emission scenarios and socioeconomic development pathways under the "dual carbon" goals, future climate change trends in Xinjiang remain highly uncertain. Whether the warming-wetting trend will continue to expand or shift toward warming-drying cannot yet be determined.

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