Analysis of Spatial and Seasonal Variations in Climate Warming and Wetting in Northwest China (Postprint)

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Abstract

Further investigation into the warm-wet trend in Northwest China contributes to a deeper understanding of the response of arid and semi-arid regions in the mid-to-high latitudes of the Northern Hemisphere to global climate warming, which represents an important scientific question. Based on temperature and precipitation data from 127 stations in Northwest China from 1961 to 2021, combined with statistical methods such as linear trend analysis, Kriging interpolation, and non-parametric Mann-Kendall test, the analysis reveals: (1) Over the past 60 years, Northwest China as a whole has exhibited a significant warm-wet trend. The regional warming trend is relatively consistent at 0.32 ℃·(10a)-1, whereas the wetting shows pronounced regional imbalance, with the western part of Northwest China experiencing earlier, more stable, and more significant wetting than the eastern part. The wetting in the west is mainly distributed in northwestern Xinjiang, while wetting in the east is primarily observed in Qinghai Province; (2) The interdecadal variability of warming and wetting demonstrates prominent imbalance. Abrupt changes in temperature and precipitation in Northwest China occurred in 1993 and 2010, respectively. After the abrupt changes, the climate tendency rates of warming and wetting increased by 0.08 ℃·(10a)-1 and 37.60 mm·(10a)-1 compared with those before the shifts, respectively. The warm-wet trend became more pronounced after the abrupt changes, characterized primarily by eastward expansion of the warm-wet pattern; (3) Analysis of seasonal imbalance in the warm-wet trend further indicates that, across Northwest China over the past 60 years, winter warming has been the most significant, followed by spring warming. However, after the abrupt changes, both the eastern and western regions show the most significant warming occurring in spring. Winter precipitation increased significantly in western Northwest China, while spring and summer precipitation increased

markedly in eastern Northwest China. The research findings can provide a theoretical basis for formulating climate change response strategies in Northwest China.

Full Text

Introduction

Climate change not only affects human living environments but also influences global economic and social progress. The world is currently experiencing the sixth period of global warming. The IPCC Sixth Assessment Report indicates that compared with pre-industrial levels, global mean surface temperature increased by 0.84–1.10 °C during 2011–2020, with land warming (1.59 °C) significantly exceeding ocean warming (0.99 °C) [-1]. Under the background of global warming, China's surface temperature increased at a rate of $0.26\,°\mathrm{C} \cdot (10\mathrm{a})^{-1}$ from 1951–2020, significantly higher than the global average, while Northwest China warmed even more dramatically at $0.34\,°\mathrm{C} \cdot (10\mathrm{a})^{-1}$ [ ]. This climate change, characterized by global warming, has triggered numerous extreme temperature events worldwide, such as forest fires, and such disaster risks will continue to increase with ongoing warming [ ]. Concurrently, extreme climate events have become more pronounced in Northwest China [ ].

In the context of significant warming, Shi Yafeng et al. [ ] proposed that Northwest China, particularly the Tianshan Mountains region in Xinjiang, exhibited a strong signal of climate transition from warm-dry to warm-wet conditions around 1987, a finding validated by numerous subsequent studies [ ]. These studies revealed that the annual mean temperature, extreme minimum temperature, and extreme maximum temperature in Northwest China increased at rates of $0.42\,°\mathrm{C} \cdot (10\mathrm{a})^{-1}$, $0.58\,°\mathrm{C} \cdot (10\mathrm{a})^{-1}$, and $0.39\,°\mathrm{C} \cdot (10\mathrm{a})^{-1}$, respectively, with accelerated warming since 1987. Meanwhile, precipitation increased at a rate of $4.87\,\mathrm{mm} \cdot (10\mathrm{a})^{-1}$, most notably in the eastern Hexi Corridor region [ ]. This trend was also reflected in atmospheric precipitable water, river runoff, and lake levels [ ]. Recent observational analyses have further revealed a "seesaw" phenomenon in moisture trends between eastern and western Northwest China, with the west becoming wetter and the east drier [ ], although this wetting trend began expanding eastward in the 21st century, with eastern Northwest China also showing signs of warming and humidification [ ]. Although model simulations suggest that warming and humidification in Northwest China will persist [ ], historical studies indicate that the warming and humidification trend in Xinjiang began to slow in the early 21st century [ ], and the overall arid and semi-arid climate pattern of Northwest China remains unchanged [ ].

The contribution of climate change to overall warming and humidification has also attracted attention. Research indicates that summer and autumn precipitation primarily contributes to the wetting trend [ ], while the latest studies show that winter precipitation contributed most significantly to warming and humidification in Northwest China during 1961–2018 [ ]. However, few studies have examined seasonal contributions to warming and humidification phenomena.

In summary, numerous studies demonstrate that arid and semi-arid regions in the mid- to high latitudes of the Northern Hemisphere respond more strongly to global warming than other climate zones, with prominent regional imbalances. This has enhanced scientific understanding of warming and humidification in Northwest China. However, current research lacks the most intuitive and up-to-date quantitative description of this regional imbalance, which manifests not only in interdecadal issues of primary concern but also in seasonal-scale attention. To address this gap, this study collected and compiled temperature and precipitation data from 127 stations in Northwest China from 1961–2021. By analyzing the regional imbalance and multi-scale temporal characteristics of warming and humidification, with particular focus on seasonal-scale adjustments and changes, this research provides a theoretical basis for investigating the causes of warming and humidification in Northwest China and aims to deepen understanding of climate change patterns and mechanisms in the region.

1.1 Study Area

Northwest China comprises Xinjiang, Qinghai, Gansu, Ningxia, and Shaanxi provinces. The terrain is dominated by plateaus, basins, and mountains. Xinjiang features alternating mountain ranges and basins, while the eastern region consists primarily of the Loess Plateau, Hetao Plain, and Ningxia Plain. Located deep inland and far from the ocean, the high plateaus and mountainous terrain block the transport of moist air, resulting in scarce precipitation that decreases from east to west. The spatial distribution of underlying surfaces varies significantly, transitioning from Gobi desert and desert steppe in the west to Gobi desert and Loess Plateau in the east. Due to the extensive longitudinal range, climate change exhibits large spatial variations in Northwest China. To ensure objective and reasonable research, following the classification method of Miao Qilong [ ], Northwest China is divided into western and eastern regions, with western Northwest China comprising Xinjiang and eastern Northwest China comprising Shaanxi, Gansu, Ningxia, and Qinghai (hereinafter referred to as the west and east).

1.2 Observation Data

Data were obtained from the National Meteorological Information Center, comprising daily temperature and precipitation records from 127 surface meteorological stations in Northwest China. Since most basic and reference meteorological stations in China have relocated, and observation instruments and standards changed before 1961, data after 1961 show better consistency [ ]. Therefore, the study period was selected as 1961–2021. Raw data underwent quality control: months with missing daily data were marked as missing, stations with more than 3 missing months were excluded, and remaining missing data were interpolated temporally. The final dataset included 127 stations. Seasons were defined as spring (March–May), summer (June–August), autumn (September–November), and winter (December–February) based on Northwest China's climate characteristics.

1.3 Research Methods

Linear trend analysis [ ] was used to calculate climate tendency rates for temperature and precipitation. Kriging interpolation [ ] was employed for spatial analysis. Based on a predefined covariance model, Kriging provides unbiased, optimal estimates of regionalized variables, compensating for limitations of linear trend methods in analyzing spatial differences in meteorological elements. The non-parametric Mann-Kendall test [ ] was used to assess trend significance and interdecadal shifts, offering the advantage of not requiring specific data distributions or being affected by outliers, making it suitable for temperature and precipitation variables. Specific implementation followed Zhang Shenglin et al. [ ]. Additionally, the Mann-Kendall test was used to detect decadal shifts in temperature and precipitation, analyzing differences in climate variability before and after these shifts.

2. Spatiotemporal Characteristics of Annual Mean Temperature and Precipitation

Northwest China has a temperate arid climate with large interannual fluctuations in temperature and precipitation. The 60-year average temperature was 8.31 °C (standard deviation: 1.26 °C), ranging from 5.72 °C to 11.02 °C. Average annual precipitation was 296 mm (standard deviation: 142.39 mm), ranging from 218 mm to 532.55 mm. Temperature anomalies rose rapidly after 1993, with an overall climate tendency rate of $0.32\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$ (significant at the 0.01 level). Temperature anomalies were primarily negative before 1993 and all positive after 1993, reaching 1.26 °C in 2021. Annual precipitation anomalies showed a slow upward trend from 1961–2010, followed by a rapid increase, with an overall climate tendency rate of $24.05\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$ (significant at the 0.01 level). The post-2010 rate reached $37.60\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$, indicating accelerated precipitation increases in recent years.

Mann-Kendall test results revealed a significant shift in annual mean temperature around 1993 (Fig. [Figure 3: see original paper]a). The post-shift warming rate was $0.24\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$, $0.08\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$ higher than the pre-shift rate of $0.16\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$ (both significant at the 0.01 level), consistent with Zhang et al. [ ]. Annual precipitation shifted around 2010 (Fig. [Figure 3: see original paper]b), exceeding the 0.05 significance level after the shift. The post-shift precipitation tendency rate was $39.84\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$, significantly higher than the pre-shift rate of $2.24\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$.

Due to large latitudinal spans, temperature and precipitation differ substantially between western and eastern Northwest China. Western and eastern regions had average temperatures of 7.92 °C and 7.67 °C, respectively (maximum: 8.99 °C and 8.81 °C; minimum: 6.60 °C and 6.19 °C; standard deviations: 1.05 °C and

1.26 °C). Average annual precipitation was 295.95 mm in the west and 532.55 mm in the east (maximum: 396.37 mm and 532.55 mm; minimum: 99.84 mm and 218 mm; standard deviations: 142.39 mm and 160.00 mm). Overall, the east was colder and wetter than the west, with more intense interannual fluctuations in both temperature and precipitation.

Comparative analysis revealed that western temperature and precipitation anomalies showed steady upward trends from the mid-1980s, with climate tendency rates of $0.32\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$ and $7.78\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$, respectively (both significant at the 0.01 level). Eastern temperature and precipitation anomalies showed climate tendency rates of $0.32\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$ and $26.79\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$ (significant at the 0.01 level). Both western and eastern regions warmed at similar rates, but western humidification was more stable and significant. Western and eastern temperature shifts occurred in 1994 and 1993, respectively, with post-shift warming rates of $0.21\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$ and $0.20\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$, slightly higher than pre-shift rates. Western precipitation showed significant continuous increase after the mid-1980s, shifting around 1985 with a post-shift rate of $9.38\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$, much higher than the pre-shift rate of $4.38\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$. Eastern precipitation showed substantial interdecadal fluctuations, with continuous increase beginning in the mid-1990s, peaking in the 2010s, and shifting around 2010. The post-shift rate was $43.47\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$, significantly higher than the pre-shift rate of $3.88\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$. Overall, western warming began earlier and was more stable than eastern warming, and western humidification started approximately 10 years earlier than eastern humidification, demonstrating that significant warming and humidification occurred earlier in western Northwest China.

Spatial distribution of annual mean temperature tendency rates (Fig. [Figure 6: see original paper]a) showed warming across all of Northwest China, with the most significant warming ($>0.5\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$) concentrated in northeastern Xinjiang and Qinghai. The Hami (Yizhou) station recorded the highest warming rate at $0.81\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$. Central and western Xinjiang and Shaanxi showed relatively lower warming rates. Analysis of isotherm shifts revealed that the area enclosed by the 7 °C isotherm expanded significantly after the 1993 shift, with the 8 °C isotherm moving northward, indicating faster warming in warm centers. In the eastern region affected by the Qinghai-Tibet Plateau, Qinghai represented a cold center, with both 5 °C and 6 °C isotherms shifting northward, demonstrating expansion of warm centers and contraction of cold centers under climate warming.

Spatial distribution of annual precipitation tendency rates (Fig. [Figure 6: see original paper]b) showed the most significant increases ($>10\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$) in central Qinghai and northwestern Xinjiang. The Wuqia station in Xinjiang had the maximum rate at $25.40\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$, followed by Golmud in Qinghai at $22.21\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$. Southeastern Xinjiang and northwestern Gansu showed weak increasing trends, while western Shaanxi and southern Gansu showed slight decreases. Analysis of isohyet shifts revealed that a dry center existed in western

Xinjiang, with the 70 mm isohyet area shrinking significantly after the 2010 shift. The 400 mm isohyet moved northward, particularly in Qinghai where precipitation increased significantly. Overall, warming and humidification differed between western and eastern Northwest China, with humidification concentrated in northwestern Xinjiang and Qinghai.

3. Seasonal Characteristics of Temperature and Precipitation

3.1 Temporal Evolution Characteristics of Temperature and Precipitation in Each Season

Different seasons contribute differently to climate warming and humidification. Seasonal temperature trends all showed significant increases, with climate tendency rates of 0.34 °C · $(10a)^{-1}$, 0.28 °C · $(10a)^{-1}$, 0.29 °C · $(10a)^{-1}$, and 0.40 °C · $(10a)^{-1}$ for spring, summer, autumn, and winter, respectively (all significant at the 0.01 level), with winter showing the highest rate. Moving average results revealed similar interdecadal fluctuations for spring and summer temperatures, with relatively small fluctuations between 1961–1990 and rapid increases thereafter. Interdecadal fluctuations were less pronounced for autumn and winter. Shifts occurred in 1993, 2005, 1999, and 1987 for spring, summer, autumn, and winter, respectively, with winter shifting earliest and spring latest. Pre- and post-shift climate tendency rates were 0.16 vs. 0.26 °C · $(10a)^{-1}$ for spring, 0.09 vs. 0.41 °C · $(10a)^{-1}$ for summer, 0.20 vs. 0.49 °C · $(10a)^{-1}$ for autumn, and 0.10 vs. 0.47 °C · $(10a)^{-1}$ for winter. Post-shift warming was more pronounced, with spring showing the most significant increase. Thus, seasonal contributions to regional warming from largest to smallest were: winter, autumn, spring, and summer before the shift, but changed to spring (most significant), winter, summer, and autumn after the shift.

Seasonal precipitation also showed increasing trends, with climate tendency rates of 1.56 mm · $(10a)^{-1}$, 3.48 mm · $(10a)^{-1}$, 0.77 mm · $(10a)^{-1}$, and 1.05 mm · $(10a)^{-1}$ for spring, summer, autumn, and winter, respectively, with only summer significant at the 0.05 level. Moving average results showed large interdecadal fluctuations for autumn and winter precipitation and smaller fluctuations for spring and summer. Shifts occurred in 2010, 1999, and 1986 for spring, summer, and winter, respectively, with winter shifting earliest and spring latest. Because the spring shift occurred less than a decade ago (2010), the post-shift period cannot effectively represent interdecadal trends. Therefore, pre- and post-shift rates were calculated for summer and winter: summer rates were 5.21 vs. 2.85 mm · $(10a)^{-1}$, and winter rates were 1.02 vs. 5.15 mm · $(10a)^{-1}$. Post-shift precipitation increases weakened but remained positive. Overall, summer precipitation contributed most to regional humidification, followed by winter.

Spatial distribution of seasonal temperature tendency rates (Fig. [Figure 9: see original paper]) showed significant warming across all seasons (shaded areas, significant at the 0.01 level), with clear spatial heterogeneity. The most significant spring warming (>0.5 °C · (10a)$^{-1}$) occurred in northeastern Xinjiang, with 23 stations exceeding this rate, the highest at Hami (Yizhou) station (0.86 °C · (10a)$^{-1}$). Summer warming was less intense than spring but still concentrated in eastern Xinjiang, with 14 stations exceeding 0.5 °C · (10a)$^{-1}$, again highest at Yizhou station (0.75 °C · (10a)$^{-1}$). Autumn warming patterns resembled summer, with 13 stations exceeding 0.5 °C · (10a)$^{-1}$. Winter warming was most intense, with significant warming areas in northern Xinjiang and central Qinghai, where 23 stations exceeded 0.5 °C · (10a)$^{-1}$, including 16 in Xinjiang and 7 in Qinghai, with the maximum at Yizhou station (0.89 °C · (10a)$^{-1}$). These results indicate that significant regional warming occurred across Northwest China, most prominently in winter and concentrated in northeastern Xinjiang and Qinghai.

Spatial distribution of seasonal precipitation tendency rates (Fig. [Figure 10: see original paper]) showed increasing precipitation across most of Northwest China in all seasons, but significant increases (shaded areas) were relatively limited and spatially heterogeneous. The most significant spring increases (>5 mm · (10a)$^{-1}$) occurred in southern Qinghai, with 9 stations exceeding this rate, maximum at Dari station (9.56 mm · (10a)$^{-1}$). Summer increases were larger in magnitude and area, with significant areas in central-eastern Qinghai, western Xinjiang, and Shaanxi, where 25 stations exceeded 5 mm · (10a)$^{-1}$, including 13 in Qinghai, 9 in Xinjiang, and 3 in Shaanxi, with maximum at Shiquan station (22.21 mm · (10a)$^{-1}$). No significant autumn increases were found across the region. Winter increases were significant in northern Xinjiang, where 15 stations exceeded 5 mm · (10a)$^{-1}$, maximum at Yining station (7.11 mm · (10a)$^{-1}$). These results indicate that regional humidification was primarily contributed by summer and spring precipitation increases in Qinghai and winter precipitation increases in northern Xinjiang.

3.2 Temporal Evolution of Seasonal Temperature and Precipitation in Western and Eastern Regions

In addition to large east-west differences in long-term seasonal trends, interdecadal variations also showed clear regional disparities. Seasonal temperature anomalies in western Northwest China (Fig. [Figure 11: see original paper]) showed climate tendency rates of 0.38 °C · (10a)$^{-1}$, 0.23 °C · (10a)$^{-1}$, 0.28 °C · (10a)$^{-1}$, and 0.39 °C · (10a)$^{-1}$ for spring, summer, autumn, and winter, respectively (all significant at the 0.01 level). Moving average results revealed similar interdecadal fluctuations for spring and summer temperatures, with slight cooling before the mid-1980s followed by continuous warming. Autumn temperatures increased significantly before the early 1990s then cooled noticeably. Winter temperatures increased significantly before the early 1970s then declined slightly. Shift years were 2010, 1999, 1999, and 1987 for spring, summer, autumn, and winter, respectively. Pre- and post-shift rates were 0.16 vs. 0.41 °C · (10a)$^{-1}$ for spring, 0.09 vs. 0.11 °C · (10a)$^{-1}$ for summer, 0.20 vs. 0.28 °C · (10a)$^{-1}$ for autumn, and -0.01 vs. 0.20 °C · (10a)$^{-1}$ for winter. Interdecadal warming rates were not obvious for summer and winter but were clear for autumn, with spring showing particularly significant post-shift warming. Compared with pre-shift periods, post-shift warming rates were greater for summer, autumn, and especially spring. Based on interdecadal fluctuations, recent warming can be attributed primarily to spring, consistent with the finding that spring warming became most significant across Northwest China after the shift.

Seasonal precipitation anomalies in western Northwest China (Fig. [Figure 12: see original paper]) showed climate tendency rates of 3.21 mm·(10a)$^{-1}$, 1.73 mm·(10a)$^{-1}$, 1.07 mm·(10a)$^{-1}$, and 1.44 mm·(10a)$^{-1}$ for spring, summer, autumn, and winter, respectively (all significant at the 0.01 level). Moving average results showed that spring, summer, and winter precipitation decreased slowly before the early 1990s then increased, with summer showing more significant fluctuating increases than spring and winter. Autumn interdecadal fluctuations were not obvious. Shift years were 2010, 1999, and 1986 for spring, summer, and winter, respectively. Pre- and post-shift rates were 1.43 vs. 0.55 mm·(10a)$^{-1}$ for spring, 1.51 vs. 3.20 mm·(10a)$^{-1}$ for summer, -0.70 vs. 2.18 mm·(10a)$^{-1}$ for autumn, and 1.41 vs. 1.48 mm·(10a)$^{-1}$ for winter. Summer precipitation contributed most to humidification, followed by autumn, winter, and spring. Comparing post-shift contributions between western and entire Northwest China reveals that summer precipitation increases weakened in the west while remaining strongest across the entire region, indicating that western contributions to regional humidification after the shift came mainly from spring, autumn, and winter, with smaller summer contributions.

Seasonal temperature anomalies in eastern Northwest China (Fig. [Figure 13: see original paper]) showed climate tendency rates of 0.42 °C·(10a)$^{-1}$, 0.26 °C·(10a)$^{-1}$, 0.30 °C·(10a)$^{-1}$, and 0.41 °C·(10a)$^{-1}$ for spring, summer, autumn, and winter, respectively (all significant at the 0.01 level), with long-term warming rates very similar to those in the west. Moving average results showed that spring and summer temperatures cooled slowly before the early 1990s then warmed rapidly, similar to the west. Autumn and winter interdecadal variations were not obvious. Shift years were 2010, 1999, and 1993 for spring, summer, and winter, respectively; no shift occurred in autumn. Because the spring shift occurred less than a decade ago (2010), pre- and post-shift rates were calculated for summer and winter: summer rates were 0.15 vs. 0.33 °C·(10a)$^{-1}$, and winter rates were 0.09 vs. 0.22 °C·(10a)$^{-1}$. Overall, eastern warming was most significant in spring and winter, consistent with the west and entire region. Post-shift warming trends were more significant for all seasons except winter. Notably, like the west, spring warming became most significant after the shift in the east, but with higher overall rates. Based on interdecadal fluctuations, recent eastern warming can be attributed primarily to spring, followed by winter, with smaller contributions from summer and autumn. Compared with the west, post-shift spring and winter warming was weaker in the east (by 0.16 °C·(10a)$^{-1}$).

Seasonal precipitation anomalies in eastern Northwest China (Fig. [Figure 14: see original paper]) showed climate tendency rates of 0.72 mm·(10a)$^{-1}$, 3.65 mm·

$(10a)^{-1}$, 0.17 mm · $(10a)^{-1}$, and 0.70 mm · $(10a)^{-1}$ for spring, summer, autumn, and winter, respectively, with summer increases most significant. Moving average results showed that spring, summer, and winter precipitation decreased slowly before the early 1990s then increased, with summer showing more significant fluctuating increases. Autumn interdecadal fluctuations were not obvious. Shift years were 2010, 1999, and 1993 for spring, summer, and winter, respectively; no autumn shift occurred. Pre- and post-shift rates were 3.47 vs. 1.84 mm · $(10a)^{-1}$ for summer and 0.27 vs. -0.45 mm · $(10a)^{-1}$ for winter. The long-term trend showed summer increases most significant, followed by spring and winter with similar rates, and minimal autumn increases. This seasonal pattern was consistent with the west and entire region. The shift sequence matched that of the entire region, and interdecadal fluctuations were similar to those across Northwest China, indicating that eastern Northwest China had greater influence on regional interdecadal variations than the west.

4. Discussion

The finding that warming and humidification in Northwest China expanded eastward around 2010 is consistent with previous research [ ]. The temperature shift in western Northwest China (1994) aligns with results from Zhang et al. [ ], consistent with this study. The precipitation shift in western Northwest China (1985) differs from some previous studies by approximately 5–10 years [ ], likely due to differences in data period length and station numbers. The precipitation shift in eastern Northwest China (2010) also differs from some studies [ ], again attributable to data differences. Analysis of spatial distributions of isotherms and isohyets before and after shifts revealed no substantial changes in climate patterns, further confirming that the overall arid and semi-arid climate background of Northwest China will not change [ ], primarily because although precipitation has increased, the absolute amounts remain small, while warming increases evaporative demand, preventing the climate from becoming substantially wetter [ ].

The causes of warming and humidification in Northwest China are complex. Research indicates that anthropogenic CO_2 emissions are the primary cause of warming [ ], while causes of humidification are more complicated, involving moisture cycling [ ], decadal-scale atmospheric water vapor transport anomalies [ ], and interactions between monsoon and westerly circulation [ ]. This study only examined temporal variation characteristics of temperature and precipitation; further investigation of atmospheric circulation adjustments is needed to understand the specific causes of eastward humidification expansion and rapid spring warming. Additionally, the shift in primary contributing seasons for humidification from winter to spring requires further attention.

5. Conclusions

Using observational data from 127 stations and statistical analysis methods, this study examined temperature and precipitation as key indicators of climate warming and humidification in Northwest China from 1961–2021, focusing on regional imbalance and multi-scale temporal characteristics, particularly seasonal adjustments. The main conclusions are:

(1) Northwest China experienced significant warming and humidification over the past 60 years. The regional warming trend was relatively consistent at $0.32\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$, while precipitation increased at 6.00–$7.00\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$. A temperature shift occurred around 1993, and a precipitation shift occurred in 2010. After the shifts, warming and humidification rates increased by $0.08\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$ and $37.60\,\mathrm{mm}\cdot(10\mathrm{a})^{-1}$, respectively. Warming and humidification became more prominent after the shifts, with eastward expansion being the main characteristic. Since the 21st century, significant warming and humidification have expanded from Xinjiang to eastern Northwest China (Gansu, Qinghai, Ningxia, Shaanxi).

(2) Seasonal imbalances were evident. Warming was most significant in winter in northwestern Xinjiang, followed by summer. Humidification was dominated by summer precipitation increases across the region, with winter precipitation increases in northern Xinjiang and spring/summer precipitation increases in eastern Northwest China also contributing significantly. Notably, the primary warming season shifted from winter (before the shift) to spring (after the shift), with a more significant rate of $0.47\,°\mathrm{C}\cdot(10\mathrm{a})^{-1}$. While the increasing trend of summer precipitation weakened after the shift, it remained the main contributor to regional humidification, followed by winter.

(3) East-west differences were pronounced. Western warming and humidification occurred earlier and more stably than in the east. Eastern continuous warming began in the mid-1990s, about 10 years later than the western mid-1980s onset, with shifts in 1993 (east) and 1994 (west). Eastern precipitation increases began in the mid-1990s, nearly 10 years later than the western mid-1980s onset, with shifts in 2010 (east) and 1985 (west). Spatially, western warming and humidification concentrated in northwestern Xinjiang, while eastern warming and humidification concentrated in Qinghai. Seasonally, winter warming was most significant in northwestern Xinjiang, while summer warming was most significant in eastern Xinjiang. Humidification was dominated by spring and summer precipitation increases in Qinghai and winter precipitation increases in northern Xinjiang.

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