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Climate Transition from Warm-Dry to Warm-Wet in Eastern Northwest China

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Abstract: During the second half of the 20th century, eastern Northwest China experienced a warming and drying climate change. To determine whether this trend has continued or changed during the present century, this study systematically analyzes the characteristics of warming and dry–wet changes in eastern Northwest China based on the latest observational data and World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 6 (CMIP6) collection data. The results show that eastern Northwest China has warmed continuously during the past 60 years with a sudden temperature change occurring in the late 1990s. However, the temperature in the 2000s decreased slowly, and that in the 2010s showed a warming trend. The amount of precipitation began to increase in the late 1990s, which indicates a contemporary climate transition from warm-dry to warm-wet in eastern Northwest China. The contribution of precipitation to humidity is significantly more than that of temperature. Long-term and interannual variations dominate the temperature change, with the contribution of the former much stronger than that of the latter. However, interannual variation dominates the precipitation change. The warming accelerates from period to period, and the temperature spatial consistently increased during the three most recent climatic periods. The precipitation decreased from 1961–1990 to 1981–2010, whereas its spatial consistency increased from 1981–2010 to 1991–2019. The significant warming and humidification which began in the late 1990s and is expected to continue until the end of the 21st century in the medium emission scenario. However, the current sub-humid climate will not easily be changed. The warming could cause a climate transition from warm temperate to subtropical by 2040. The dry-to-wet climate transition in eastern Northwest China could be related to a synergistic enhancement of the East Asian summer monsoon and the westerly circulation. This research provides a scientific decision-making basis for implementing western development strategies, ecological protection, and high-quality development of the Yellow River Basin Area as well as that for ecological construction planning and water resource management of eastern Northwest China.

Keywords: eastern Northwest China; warming; dry–wet; transition

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1. Introduction

The eastern region of Northwest China, located on the Qinghai–Tibet Plateau slope, has a complex topography and diverse landforms. This area is also located at the northern edge of summer monsoon activity and experiences the most sensitive and prominent summer monsoon effects. The obvious characteristics of the summer monsoon edge line and its large swing range result in annual climate differences based on the strength of the summer monsoon and are prominent in the typical summer monsoon impact transition area [1]. The sensitive climate and fragile ecological environment of this region are crucial in the global environmental system [2]. As the confluence area of the Yellow River Basin's upper reaches, this region has a climate that affects the ecological construction and high-quality development of the Yellow River Basin area. Therefore, climate change in this region has long been a vital issue that has been studied extensively by researchers and the Chinese government [3,4].

Many studies suggest that an aridification trend has occurred in the 20th century in the eastern region of Northwest China under the background of global warming, particularly since the 1970s [5,6]; some researchers [7,8] have found that warming is a critical factor in this trend. The increasing temperature has enhanced the intensity and scope of aridification by 4% to 7%. Therefore, a warming and drying trend in this region has been identified by many scholars, as manifested by a recent, rapid glacier recession, significant vegetation deterioration, increased disappearance of wetlands, and other changes in the natural environment during the same period [9]. However, recent studies [10–12] have reported that precipitation in Northwest China has shown an increasing trend from 2001 to 2016 yet a long-term decreasing trend from 1951 to 2001. This phenomenon forms the basis of our theory such that the North China climate changed from dry to wet in 2001.

In fact, more than 10 years ago, Shi et al. [13,14] proposed a hypothesis of warm-dry to warm-wet transition in Northwest China. They found that although the western region of Northwest China has undergone such a transition, eastern Northwest China is still showing a warming and drying trend, which could change in the future. Although their view was of high concern to the community, the observation data coupled with the small increase in precipitation within a short period does not indicate a climate transition trend [15]. Moreover, the water balance between the increased evapotranspiration caused by the increases in temperature and precipitation indicates that not all locations are wet; instead, many locations are still showing a drying trend [2]. Therefore, a lack of academic consensus remains on whether the climate has transitioned to warm and humid in Northwest China [16]. However, the international perspective of the interaction land–atmosphere is such that the global arid region will be drier and the wetter region will be wetter under global warming [17]. Moreover, historical data show that the global arid zones have become increasingly dryer during the past 100 years [18]; the arid areas have continued to expand [19,20]; and major drought events are occurring with greater frequency in arid areas [21]. This opposite trend in Northwest China's arid regions from those in other locations worldwide remains poorly understood.

In addition, although increased global warming has long been the consensus of the international community, more research attention has been paid to its hiatus in recent years [22–24]. Many Chinese scholars [25–28] have offered profound discussions on this topic. Such research suggests that several regions in China have also experienced the phenomenon of warming mitigation since the end of the 1990s under the background of a global warming hiatus. However, it has not been established whether this transformation from dry to wet is attributed to the increases in temperature and precipitation in eastern Northwest China since the beginning of this century. Moreover, abundant observation data have been collected during the nearly 20 years since Shi et al. proposed the dry–wet transition. Therefore, it is necessary to comprehensively and objectively understand the evolution of precipitation and temperature in the eastern part of Northwest China and to further explore the climate transformation.

The present study uses extended comprehensive observational data to systematically analyze the temporal and spatial evolution of precipitation and temperature in eastern Northwest China and to study its climate transition. In addition, the future temperature and humidity changes are examined, and the leading causes of such dry-to-wet changes are discussed. Furthermore, a scientific guarantee is provided for implementing western development strategies and the ecological construction and high-quality development of the Yellow River Basin area. The results of this study provide a decision-making basis for the formulation of ecological construction planning, water resource management policies, and socio-economic development goals in this region.

2. Materials and Methods

2.1. Study Area

The eastern region of Northwest China includes Shaanxi, Ningxia, and part of Gansu east of the Yellow River (Figure 1) and is located in the East Asian summer monsoon zone [29]. With an average annual rainfall of 400–800 mm, the precipitation in this area is scarce, and the climate is dry. The diurnal and annual temperature ranges are very large, and the average annual temperature is 2–16 °C. This area also includes the Qinling Mountains, Gannan Plateau, Loess Plateau, Guanzhong Plain, and Hanshui Valley, all of which have complex terrain and fragile ecological environments (Figure 1a) of mid-temperate, warm–temperate, and subtropical zones (Figure 1b) from the northwest to the southeast [30]. Although the climate in this area also changes from semi-arid to dry–wet to wet (Figure 1c) from the northwest to southeast [31], it is generally temperate and semi-humid.

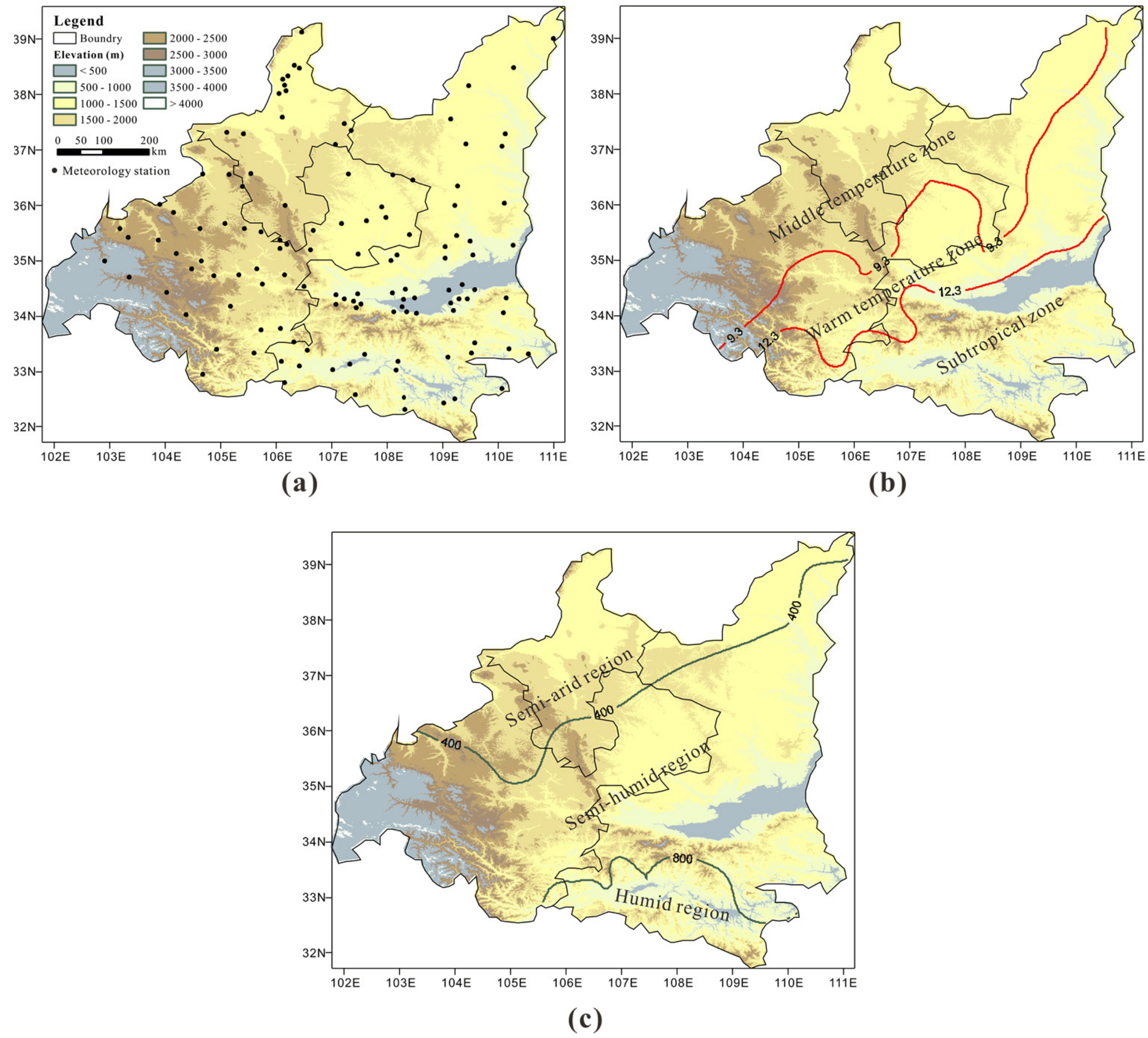

Figure 1. Overview of the study area: (**a**) digital elevation model and representative stations; (**b**) temperature zone division; (**c**) precipitation zone division.

2.2. Data

Meteorological observation, circulation, and forecast data were analyzed in this study. The meteorological data of 124 stations in eastern Northwest China were obtained by the National Meteorological Information Center of China Meteorological Administration (Figure 1a), including average temperature, maximum temperature, minimum daily temperature, precipitation, wind speed, relative humidity, and sunshine hours from 1961 to 2019.

To ensure the representativeness of the observation data and to maintain consistency in the research time series, homogenization correction and quality control were performed on the site data [32,33]. The circulation data were obtained from the reanalyzed altitude and wind fields from 1961 to 2019 jointly produced by the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR).

The projected data adopt the multi-model ensemble data from 2015 to 2099 [34,35] under the medium-emission scenario climate models Shared Socio-Economic Pathway 2 and Representative Concentration Pathway 4.5 (SSP2–RCP4.5) of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP6). The ensemble grid data (https://esgf-node.llnl.gov/projects/cmip6/, accessed on 11 October2020) were interpolated to 124 meteorological stations using two linear interpolation methods. The observed and estimated data from 2015 to 2019 showed good agreement (Figure 2), although the estimated temperature (precipitation) data were lower (higher) than the observed data. Therefore, we established a linear relationship between the observed and estimated monthly precipitation and temperature from 2015 to 2019 and used the results to correct the forecast temperature and precipitation from 2020 to 2099. Thus, the revised forecast data had relatively good continuity with the observational data of 1961 to 2019.

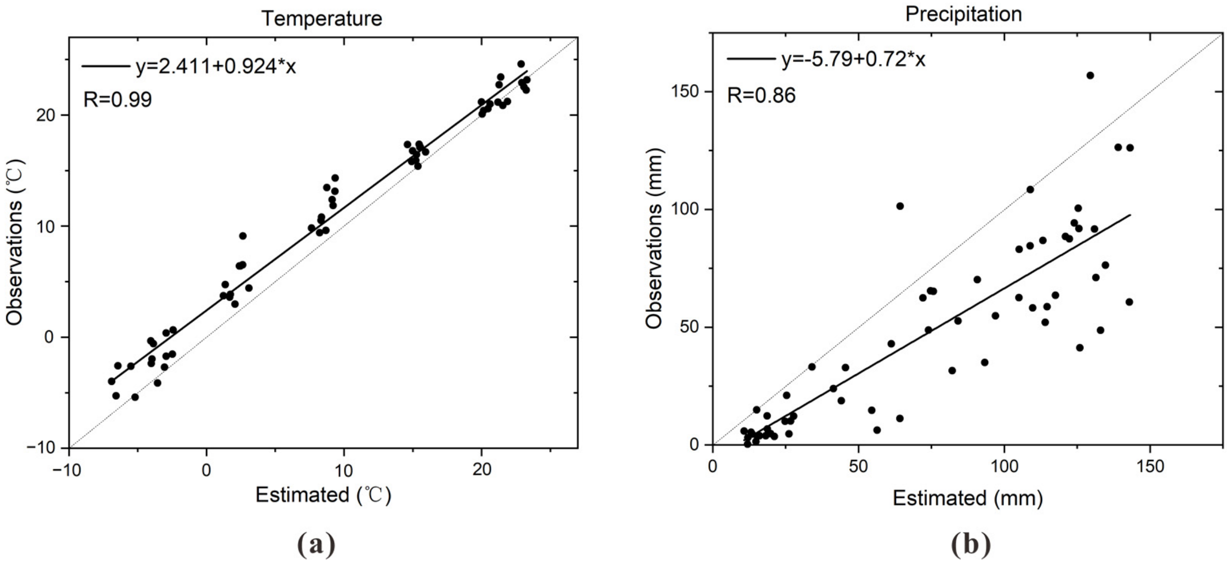

Figure 2. Observed versus estimated monthly (**a**) temperature and (**b**) precipitation from 2015 to 2019.

The linear fitting formulas for temperature and precipitation are

$$T = 2.65 + 0.90 \times ty, \quad (1)$$

$$P = -5.97 + 0.72 \times py, \quad (2)$$

where T and P are the corrected temperature and precipitation, respectively; and ty and py are the estimated temperature and precipitation, respectively.

2.3. Method

The dryness index (I_{AI}) was applied the following index defined by Zhang et al. [36]

$$I_{AI} = \frac{E_{TO} - P_{RE}}{E_{TO}} \quad (3)$$

where E_{TO} is the potential evapotranspiration calculated using the Penman–Monteith model [37], and P_{RE} is the precipitation. In this relationship, a larger aridity index relates to a drier climate.

Although many indices are currently used to express East Asian summer monsoon activity [38], those of Zhang et al. [39], Li and Zeng [40], and Zhao and Zhou [41] show different perspectives, and no strong correlation exists among them. In the present study, the East Asian summer monsoon index established by Wang and Fan [42] was used

$$MI = U_{850}\ [5°\text{-}15°\ N, 90°\text{-}130°\ E] - U_{850}\ [22.5°\text{-}32.5°\ N, 110°\text{-}140°\ E], \quad (4)$$

where MI is the index of the East Asian summer monsoon, and U is the average zonal wind at 850 hPa (m s^{-1}). The index MI uses the difference of regional average zonal wind at 850 hPa between (5°–15° N, 90°–130° E) and (22.5°–32.5° N, 110°–140° E) to express the intensity of East Asian summer monsoon. Hence, this index is a good indicator of climate anomalies in the eastern part of Northwest China [43].

The Westerly Index, also known as the Rossby Index, can be expressed in many ways [44,45]. In the present study, the regional Westerly Index given by [46] was used

$$I = \frac{1}{17}\left[\sum_{\lambda=1}^{17} H(\lambda, 35°\ N) - \sum_{\lambda=1}^{17} H(\lambda, 50°\ N)\right] \quad (5)$$

where WI is the regional westerly index; H is the 500 hPa height field (gpm) averaged along the 35° N and 50° N latitudes, respectively; and λ is the longitude taken along the latitude at an interval of 2.5°. This index uses the difference in zonal average 500 hPa height field between 35° N and 50° N in the longitude range of 70°–110° E to characterize the strength of the westerly circulation.

The ensemble empirical mode decomposition (EEMD) method averages the measured values of multiple decompositions and adds appropriate white noise to the original data to simulate multiple observations. The results are then averaged after multiple calculations. This model shows improvement over the empirical mode decomposition method (EMD), which is suitable for processing nonstationary data series and decomposing the fluctuations and trends of various scales in the signal to obtain the intrinsic mode function (IMF) component, i.e., a data series with different characteristic time scales. The EMD method can be used to decompose complex signal functions into finite sums of intrinsic mode functions. Although the EMD method has obvious advantages in signal analysis, it also has defects such as edge effects and scale mixing.

New noise-assisted data analysis adopted in the EEMD method can solve the scale-mixing problem of the EMD method. The widely used EEMD method [47–49] is characterized by introducing Gaussian white noise and averaging the data set; this effectively avoids the scale-mixing problem and makes the obtained IMF components physically unique. The most important feature is that each IMF component needs to comply with two prerequisites: (1) the number of local extreme points and that of zero-crossing points during the entire perspective of the analysis period must be equal or at most different by one and (2) the envelope average determined by the local extrema must be zero.

3. Temporal and Spatial Characteristics of Temperature and Precipitation

3.1. Temporal Evolution of Temperature and Precipitation

The regional average temperature and precipitation variations in eastern Northwest China from 1961 to 2019 are plotted in Figure 3a,b, respectively. Overall, the warming characteristics in this region are the same as those reported throughout the country. In particular, the temperature has increased at a rate of 0.27 °C/10 years since the early 1960s, with the main temperature increase beginning in the 1980s, and the mutation of the average occurring in the late 1990s (figure not shown). However, the temperatures of the 2000s decreased slowly during the warming process, which might be a response to global warming stagnation [22–24], and another warming trend occurred during the 2010s. Precipitation decreases of 26.2 mm/10 years before 1997 and 32.9 mm/10 years after 1997 were noted. Eastern Northwest China showed significant warming and drying before 1997, and significant warming and humidification afterward, which implies a transition from warm-dry to warm-wet around 1997.

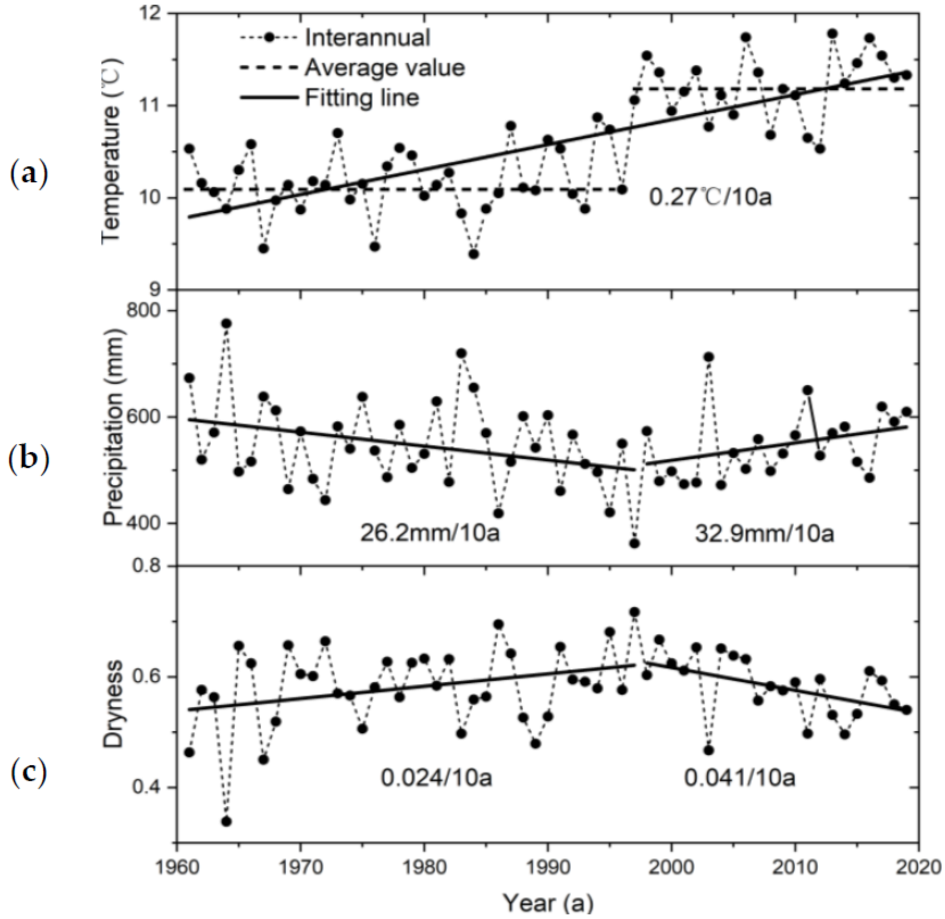

Figure 3. Variation curve of (**a**) temperature, (**b**) precipitation, and (**c**) aridity index from 1961 to 2019.

Precipitation increases enhance humid climates, and temperature increases often cause dry climates by accelerating potential evaporation. An aridity index change curve was plotted in Figure 3c to clarify the dry–wet changes under the combined effects of precipitation and temperature. The fitting curve of precipitation and dryness was symmetrical near the horizontal axis. The dry-to-wet climate transition occurring around 1997 indicates that the climate change in eastern Northwest China was dominated by precipitation, which might be related to the impact of the temperate climate zone.

However, the sudden change in mean temperature is consistent with the sudden dry-to-wet transition. Thus, we speculate that the transition is related to the dominant effects of precipitation and temperature. Precipitation can cool the atmosphere through the land surface evaporation process, and the increased cloud cover decreases the solar radiation; of these, the latter has a more notable effect. Temperature affects atmospheric saturated water vapor pressure and large-scale circulation through atmospheric thermal processes and influences the local water cycle through land surface processes to significantly affect precipitation. Eastern Northwest China has a semi-humid climate with relatively high precipitation. Before 1997, the leading role of precipitation was prominent, causing an opposite relationship between temperature and precipitation. Temperature increase accompanied the precipitation decrease, producing warm and dry conditions. After 1997, the temperature increased owing to the continuous heating in the previous period, making the temperature more dominant. The precipitation increase accompanied the increased temperature, creating warm and humid conditions.

3.2. Multiple Time Scales of Temperature and Precipitation

The evolution curves of temperature and precipitation indicate both prominent interannual and interdecadal variations. The widely used EEMD method [48,50] was applied to clarify the multiple time scales of the regional average temperature and precipitation. We decomposed the precipitation and temperature sequence on multiple time scales and extracted different periodic oscillation components/IMF and long-term trend signals, recorded as IMF1, IMF2, IMF3, IMF4, and ST. These IMF values refer to interannual to multi-decadal scales. These components further explain the multiple time-scale characteristics of temperature and precipitation occurring in eastern Northwest China since 1961.

Long-term variation dominated the temperature change (Table 1), with a contribution rate of 45.8%. The interannual variation was also notable, with a contribution of 28.0%. The quasi-decadal (9.1 years)-scale contribution rate was 13.1%, whereas that at the multi-decadal scale was only 13.1%. The contribution of the IMF4, at 39.3 years, was slightly larger than that of the IMF3, at 19.7 years. For precipitation (Table 2), the interannual scale contribution rate reached 89.5%, of which the contribution rates of the IMF1, at 3.0 years, and IMF2, at 5.9 years, were 62.7% and 26.8%, respectively. The contribution of the long-term trend was only 3.0%; the decadal and multi-decadal scales were also not prominent, with a total contribution rate of only 7.5%.

Table 1. Contribution and period of temperature components after EEMD.

	IMF1	**IMF2**	**IMF3**	**IMF4**	**Trend**
Period (years)	3.3	9.1	19.7	39.3	/
Contribution (%)	28.0	13.1	4.4	8.7	45.8

Table 2. Contribution and period of precipitation components after EEMD.

	IMF1	**IMF2**	**IMF3**	**IMF4**	**Trend**
Period (years)	3.0	5.9	10.7	29.5	/
Contribution (%)	62.7	26.8	2.6	4.9	3.0

The multiple time-scale variations shown in Figure 4 indicate that the continuous warming since 1961 is attributed to long-term increases in temperature and precipitation. The significant increase in precipitation after 1997 was caused by the increase in the trend item and IMF4.

Multiple time scale analysis showed that temperature in eastern Northwest China was dominated mainly by long-term variation during the past half-century. The quasi-three-year interannual variation was also notable, whereas the interdecadal and multi-decadal scales were negligible. The significant warming of the past 60 years resulted from a significant long-term increase. The precipitation changes were mainly on the interannual scale; those on the decadal-scale were not obvious. The quasi-30 year scale variation superimposed the long-term increase result of the precipitation increase since 1997.

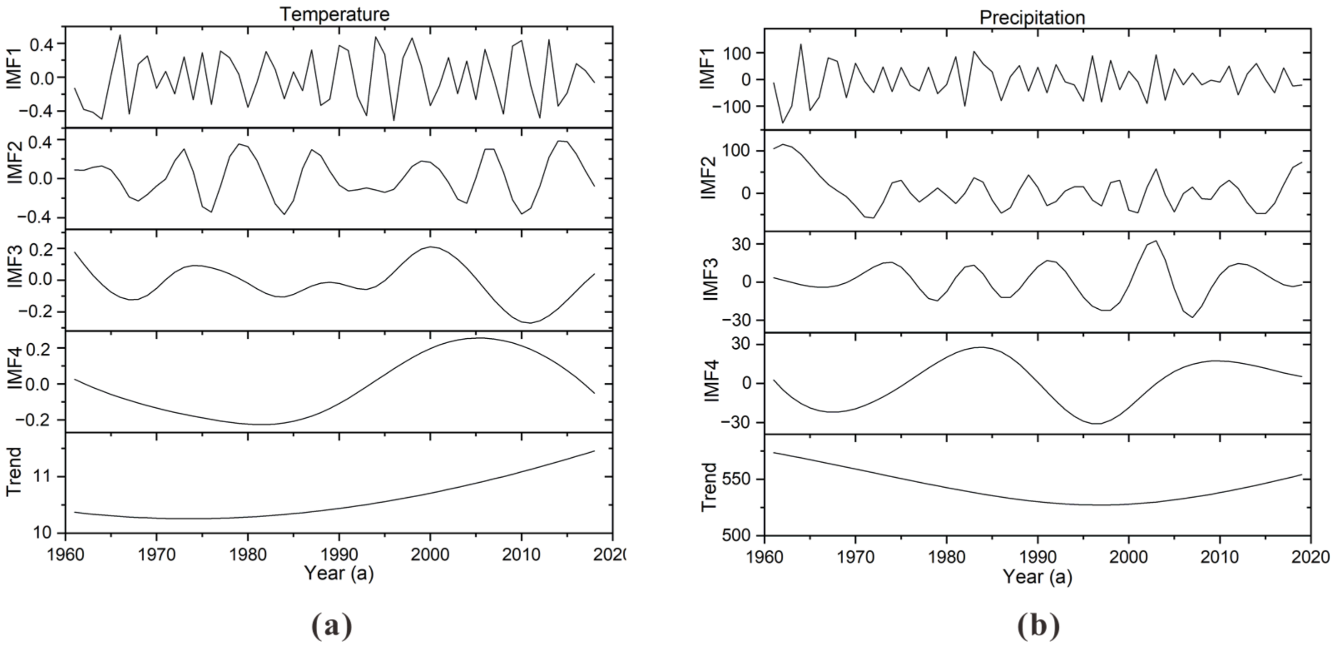

Figure 4. Decomposition of (**a**) temperature and (**b**) precipitation variation derived from EEMD.

4. Dynamics of Warming and Dry–Wet Transition

Under the overall trend, regional climate change will inevitably have specific spatial differences; the same applies to eastern Northwest China. To further understand the dynamics of warming and dry–wet transition in eastern Northwest China, we analyzed the spatial distribution evolution of the linear temperature and precipitation tendency rates.

4.1. Dynamic Spatial Variation in Temperature Increase

The spatial distribution of the annual average temperature change rate during the four climatic periods of 1961–1990, 1971–2000, 1981–2010, and 1991–2019 were plotted to compare the spatial characteristics of warming (Figure 5). During 1961 and 1990, the temperature increased in the north and decreased in the south at a small range. The temperature increased consistently in the entire region during the other three periods. In the range of −0.5–0 °C/10 years, the linear tendency rate of the temperature during the four periods was 52.4%, 0.0%, 0.0%, and 0.0%, respectively; that in the range of 0–0.5 °C/10 years was 46.8%, 87.9%, 50.0%, and 80.7%, respectively; and that in the range of 0.5 °C/10 years was 0.8%, 12.1%, 50.0%, and 19.3%, respectively.

The normal probability distribution of the linear temperature tendency rate of the four climatic periods (Figure 6) was concentrated at −0.01 °C/10 years, 0.29 °C/10 years, 0.52 °C/10 years, and 0.35 °C/10 years, respectively. The warming strength during 1991–2019 was weaker than that during 1981–2010, whereas the warming strength increased during the other three climatic periods. During the last period, the warming strength was weaker than that in 1981–2010, which might be a response to the slowing of global warming. Therefore, the warming trend in eastern Northwest China has generally been increasing since 1961.

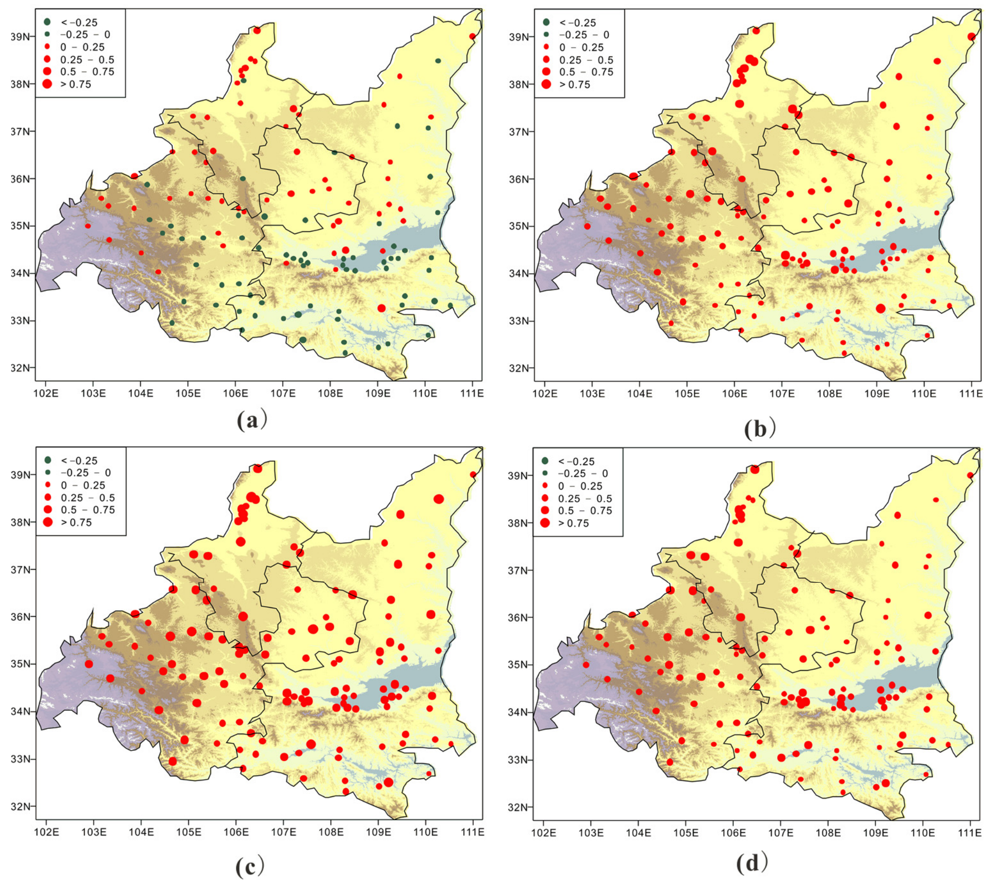

Figure 5. Spatial distribution of temperature change rate in different periods (unit: °C/10 years): (**a**) 1961–1990; (**b**) 1971–2000; (**c**) 1981–2010; (**d**) 1991–2019.

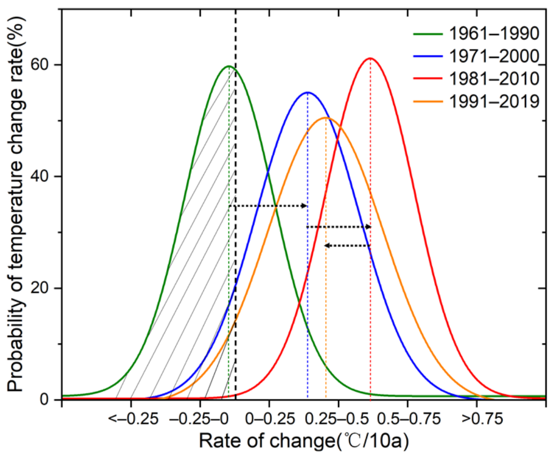

Figure 6. Probability distribution of annual temperature change rate in different periods.

4.2. Dynamic Spatial Variation of the Dry–Wet Transition

The precipitation change rates of the spatial distribution in different climatic periods were plotted to analyze the spatial dynamic variation in the dry–wet transition (Figure 7). The precipitation during the first three periods showed a decreasing trend with a local increase in small areas. From 1991 to 2019, the precipitation in eastern Northwest China showed a consistent increasing trend.

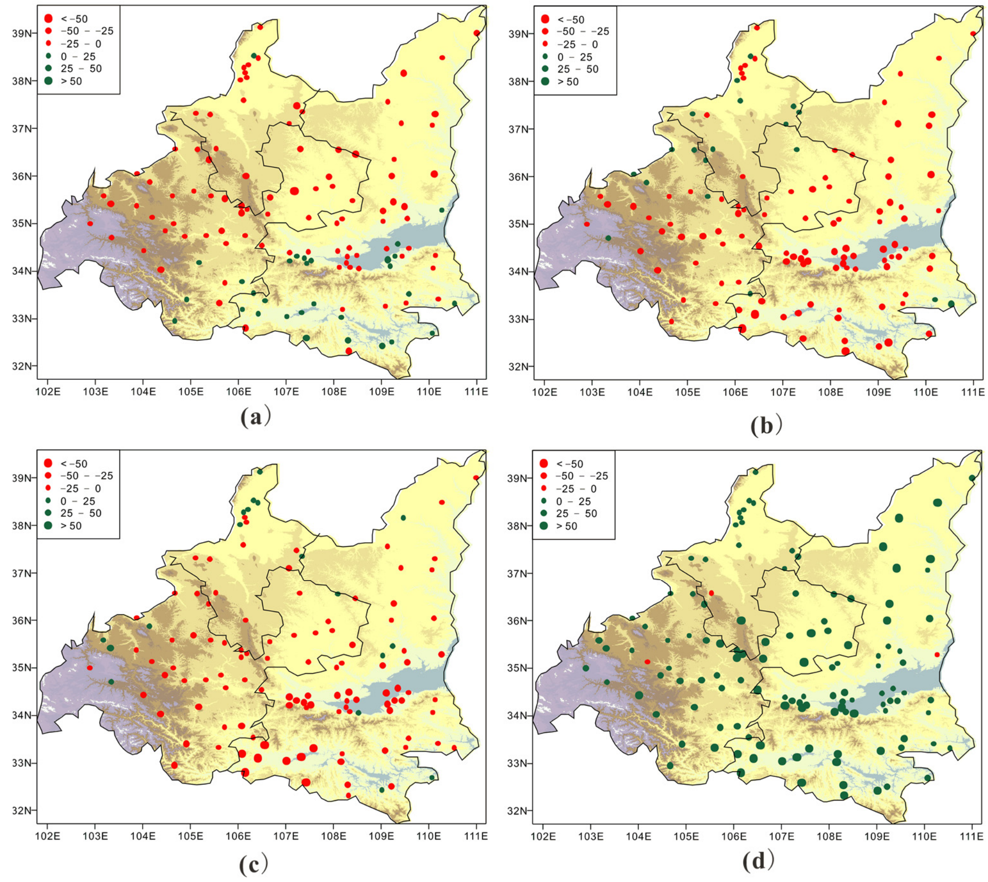

Figure 7. Annual precipitation change rate in different time periods (unit: mm/10 years): (**a**) 1961–1990; (**b**) 1971–2000; (**c**) 1981–2010; (**d**) 1991–2019.

The possibility range of the precipitation linear tendency rates at less than −50 mm/10 years for the four climatic periods was 0.8%, 3.2%, 6.5%, and 0.0%, respectively; that in the range of −50–0 mm/10 years was 75.0%, 81.4%, 79.0%, and 2.4%, respectively; that in the range of 0–50 mm/10 years was 24.2%, 15.3%, 14.5%, and 67.0%, respectively; and that at more than 50 mm/10 years was 0.0%, 0.0%, 0.0%, and 30.6%, respectively.

The precipitation linear tendency rates of the four periods showed concentrations of −8.8 mm/10 years, −19.7 mm/10 years, −20.1. mm/10 years, and 37.1 mm/10 years, respectively (Figure 8). The periods of 1961–1990, 1971–2000, and 1981–2010 showed a drying trend. That from 1961–1990 to 1971–2000 was significant, whereas that from 1971–2000 to 1981–2010 was relatively weak. The transition showed significant wetting from 1981–2010 to 1991–2019. It can be inferred that the dry-to-wet transition around 1997 resulted in the wetting trend of the last period.

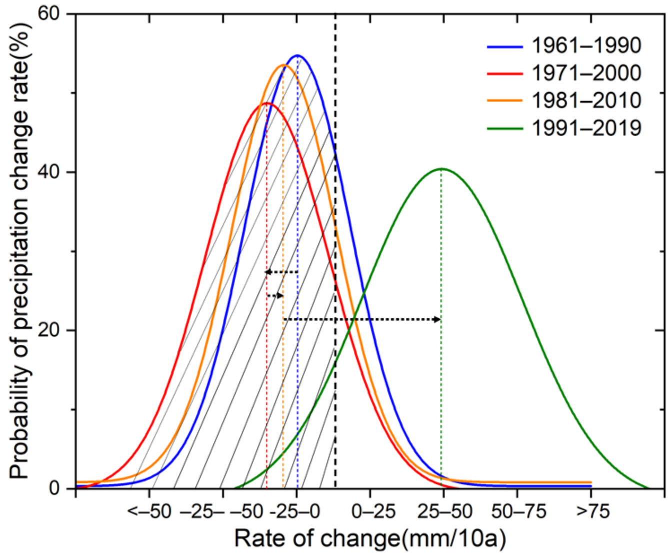

Figure 8. Probability distribution of annual precipitation change rate in different periods.

5. Discussion

The previous analysis showed that eastern Northwest China has been warming continuously since 1961 and has also became wetter since the late 1990s. Will this warming and humidification continue in the future? If it continues, what are its extent and duration? Will it change the current climate pattern?

Based on the past 59 years of observation, the multi-model ensemble has predicted the inter-annual variation of the average temperature and precipitation for the next 80 years under the CMIP6 medium-emission scenario (Figure 9). The temperature increased 0.27 °C/10 years during the past 59 years and will continue to rise at almost the same rate during the next 80 years, at 0.28 °C/10 years. The continuous warming since 1961 has not changed the overall warm-temperate climate, according to the temperature zone division of Ma et al. [30], with regional average temperatures ranging between 9.3 °C and 12.3 °C. However, it is expected that the temperature will reach 12.3 °C in 2040, which would cause the climate in eastern Northwest China to transition from warm temperate to subtropical.

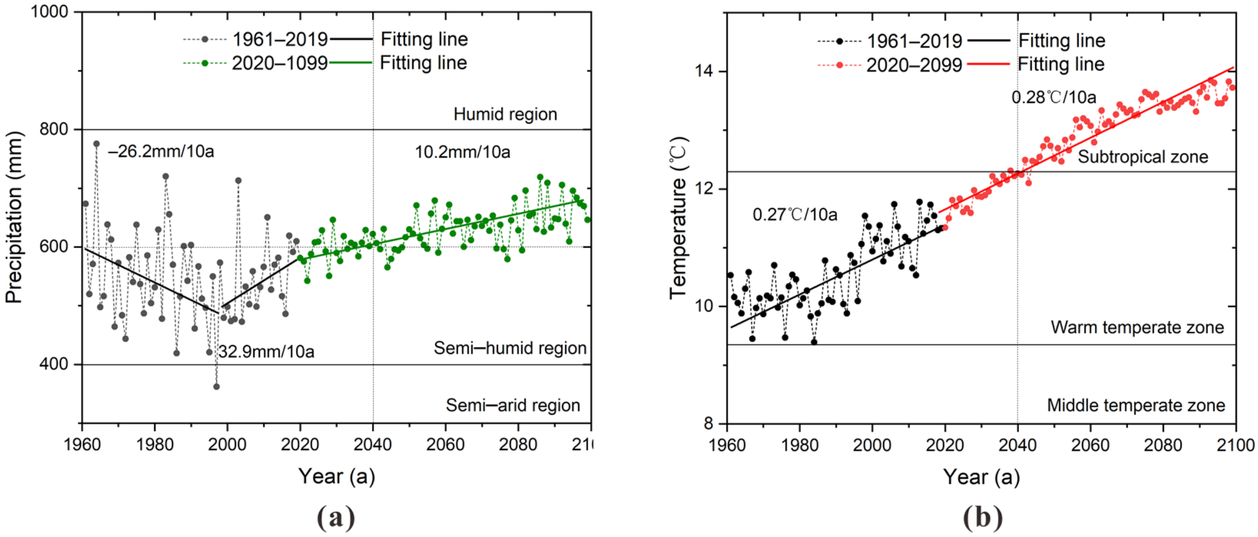

Figure 9. Observed and predicted temperature (**a**) and precipitation (**b**) values.

The precipitation decreased 87 mm at 26.2 mm/10 years during 1961–1997 but increased about 76 mm at 32.9 mm/10 years from 1997 to 2019. The current total precipitation is less than that of the 1960s. A precipitation increase of 10.2 mm/10 years is expected during the next 80 years, although the growth rate will be significantly slower than that currently noted. The regional average precipitation will reach 600 mm around 2040 but will not exceed 800 mm by the end of this century. The humidification lasting from the late 1990s to 2100, according to the climate zone division of Huang et al. [31], would not change the overall semi-humid climate. Therefore, under the medium-emission scenario, eastern Northwest China would continue to show warming and humidification trends during the next 80 years, and the warming rate would be the same as the current rate. The warming will cause a climate transition from warm temperate to subtropical. The humidification degree will be weaker than the current rate, which will not change the current sub-humid climate.

No clear or convincing scientific conclusions have been drawn to explain the precipitation changes in eastern Northwest China. However, one indication is that this climate is affected mainly by the East Asian summer monsoon, and the influence of westerly circulation is prominent [51]. Therefore, it is necessary to consider the westerly circulation movement and the East Asian summer monsoon when analyzing the climate transition from warm-dry to warm-wet in eastern Northwest China.

The decadal changes in the Westerly Index, East Asian Summer Monsoon Index, and Northwestern East Precipitation Index (standardized precipitation) since the 1960s are plotted in Figure 10. These three indices showed consistent interdecadal changes from the 1970s to the 2010s. Increases were noted from the 1970s to 1980s followed by decreases from 1980s to 1990s and increases from 1990s to 2010s. That is, the transition from dry to wet in eastern Northwest China in the late 1990s might be related to the interdecadal synergistic enhancement of the westerly circulation and the East Asian monsoon circulation. The enhanced west wind circulation and the East Asian monsoon circulation can transport more water vapor from the Atlantic and Pacific oceans, respectively, to provide sufficient water vapor conditions for increasing the precipitation in the eastern part of Northwest China.

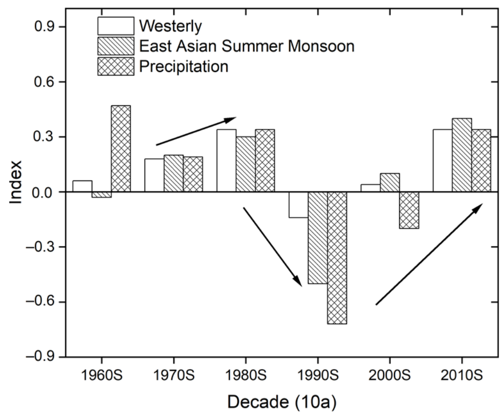

Figure 10. Interdecadal changes of westerly wind, east asian summer monsoon, and precipitation indices.

6. Conclusions

The temperature in eastern Northwest China has continued to increase since the early 1960s, with a sudden change in average temperature occurring in the late 1990s. A gradual decrease in temperature occurred in the 2000s, which might be a response to global warming stagnation, followed by a warming trend in the 2010s. Significant warm-dry and warm-wet trends occurred in eastern Northwest China before and after 1997, respectively, which indicates a transition from warm-dry to warm-wet during the late 1990s. The humidity change in eastern Northwest China since 1961 was caused mainly by precipitation, whereas the contribution of temperature to humidity was relatively low. This might be related to the temperate climate of the study area.

The sudden temperature increase is consistent with the change in humidity, which was very likely caused by the differences from the dominant effect of precipitation and temperature interaction. Precipitation can cool the atmosphere through evaporation of the land surface process, and the increased cloud cover decreases the solar radiation, which has a more prominent effect on the temperature. The temperature affects atmospheric saturated water vapor pressure and large-scale circulation through atmospheric thermal processes and the local water cycle through land surface processes, which significantly affects the precipitation.

Eastern Northwest China has a semi-humid climate with relatively high precipitation. Before 1997, the leading role of precipitation was prominent, causing an opposite relationship between temperature and precipitation. Thus, a temperature increase accompanied a precipitation decrease, resulting in warm and dry conditions. After 1997, the temperature was more prominent due to continuous temperature increases, which caused consistent changes in temperature and precipitation. Thus, the increase in precipitation was accompanied by an increase in temperature, resulting in more warm and humid conditions.

During the past half-century, the long-term change dominated the temperature variation. The quasi-three-year interannual scale variation was also notable, whereas the interdecadal- and multi-decadal-scale changes were relatively weak. The significant warming in the past half-century relates to the significant long-term temperature increase. However, the interannual-scale change controlled mainly the precipitation; the decadal change was relatively weak. The superimposed effect of long-term variation and the quasi-30-year scale change caused the precipitation to increase since 1997.

Consistent spatial temperature increases were noted in the three climatic periods from 1971 to 2000. The warming lasted for three periods from 1961–1990 to 1981–2010 but weakened during the last climatic period, which might be a response to the slowed global warming. In general, the warming trend in Northwest China has been accelerating since 1961.

The climate became drier period-by-period from 1961–1990 to 1981–2010. However, the humidity in 1991–2019 was higher than that in 1981–2010. Spatially constant humidification occurred in the area from 1991 to 2019. The dry-to-wet transition around 1997 caused the wetting trend in the last period.

Eastern Northwest China has shown significant warming and humidification trends since the late 1990s, which are expected to last until the end of the 21st century under the medium-emission scenario. Under this scenario, however, the humidification will not change the overall semi-humid climate in the study area, although warming might cause a climate transition from warm temperate to subtropical around 2040.

Among the factors affecting the precipitation in eastern Northwest China, it is worth noting that the westerly and East Asian summer wind circulations have been relatively consistent with the interdecadal precipitation changes since the 1970s. It can be inferred that the dry-to-wet transition in the late 1990s is related to the synergistic enhancement of the East Asian summer monsoon and westerly circulation.

This study analyzed the warm-dry to warm-wet transition in eastern Northwest China but did not statistically analyze the cause of the precipitation changes. Further research from different approaches and as well as numerical simulation experiments are necessary to fully understand this phenomenon. Moreover, because the global climate model projection data have considerable uncertainty, various downscaling methods need to be applied to simulate and predict the climate of the region.

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