

Historical temperature variability in a representative high-latitude region in the monsoon-continental climate transition zone in China

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Research Article

Keywords: dendroclimatology, climate reconstruction, climate change, high-latitude region

Posted Date: August 22nd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1753009/v2>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Stochastic Environmental Research and Risk Assessment on February 6th, 2023. See the published version at <https://doi.org/10.1007/s00477-023-02387-3>.

Abstract

Global warming has exacerbated the instability of the climate and has led to the frequent occurrence of extreme cold and warm events. In this study, we constructed a standardized tree-ring width chronology of Korean spruce (*Picea koraiensis* Nakai) growing in a representative high-latitude region in the monsoon-continental climate transition zone in China from 1845 to 2016 and used it to analyse the response of the radial growth of Korean spruce to climatic factors such as temperature and precipitation. The results show that the annual mean temperature was the dominant climatic factor affecting the growth of Korean spruce. Hence, we reconstructed the annual mean temperature series of this region spanning the past 172 years. The analysis results show that the study area experienced five warm periods and five cold periods in the past 172 years. Cold years were dominant before 1960s, while temperature continuously rose and changed drastically in the early 21st century. The reconstructed annual mean temperature series has variability cycles of 3 a, 7 a, 10–12 a, 15–22 a, and 30–40 a. The results of this reconstruction enrich the tree-ring database in the representative regions of the monsoon-continental climate transition zone in China and provide a reference for systematically understanding the climate change patterns in the representative regions of the transition zone.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report pointed out that Global warming would reach 1.5°C in the near-term, which would bring many risks to ecosystem and human. (Hennessy et al. 2022) and that extreme climate events occurred frequently around the world (Sieck et al. 2021). Therefore, it is imperative to understand the long-term variability pattern of temperature. Asia is the most prominent monsoon region in the world (Li et al. 2013). The overlap of a temperate continental climate and temperate monsoon climate (two major climate types) formed a special transition zone sensitive to hydrological climate change in China under the profound impact of climate change. Understanding climate change in this transition zone over a long historical period is of great significance.

After Douglass, the father of dendrochronology, proposed dendroclimatology in the first half of the 20th century (Fritts 1972), tree-ring data have been widely used worldwide for the reconstruction of historical climatic factor data, including precipitation, temperature, runoff, and drought. The reconstructed mean maximum summer temperatures in the Andes Mountains in southern South America over the past 5682 years showed that since the 1960s, a warming trend has appeared in southern South America (Lara et al. 2020). The reconstructed tree-ring chronology of whitebark pine (*Pinus albicaulis* Engelm.) and Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) growing in the western part of the United States revealed the spatiotemporal variability characteristics of the paleoclimate over the past millennium in this area (Rochner et al. 2021). Szymański and Wilczyński (2021) predicted that although global warming is still continuing, the temperature will decline rapidly in Europe in the future based on the reconstructed tree-ring width chronology of European larch (*Larix decidua* Mill.). Leonelli et al. (2017) reconstructed the continuous late summer temperature in the Mediterranean region of Italy over a long historical period for the first time using the tree-ring data of conifers and broad-leaved trees and found that the years with

extremely low summer temperatures were related to large-scale volcanic eruptions and global climate. Rydval et al. (2017) reconstructed the summer temperature in the Cairngorm Mountains from 1200 to 2010. They recognized the temperature in the 1690s as the coldest decade on record and found that the temperature dropped significantly 1 year after volcanic eruption. Song et al. (2021) reconstructed the winter temperature from 1300 to 2000 using a dataset of 260 tree rings in eastern Asia and concluded that since the 14th century, East Asia has been showing a long-term warming trend under the influences of winter sunshine in the midlatitude region of the Northern Hemisphere and global human activities.

Dendrochronological research in China was started in the 1980s when the first dendrochronology data bank in China was established in Urumqi, Xinjiang (Li et al. 2000), which laid the foundation for dendrochronological research in China. At present, research on tree rings in China is mainly concentrated in the cold and arid regions of middle and high latitudes. For example, climate changes over the past 400 years in Xinjiang were reconstructed using tree-ring width data (Peng et al. 2020; Wang et al. 2021), and the results showed that since the 1980s, the climate in central Asia has been showing a trend of increasing temperature and humidity and that temperature variability in this area has been closely related to volcanic eruption. The temperature variability in the Tibetan Plateau in Central Asia from 1340 to 2007 was reconstructed based a tree-ring network of spruce and other tree species, and the reconstructed series captured unusual warming since the 1930s and indicated that 1990–2009 was the warmest period in the past six centuries (Huang et al. 2019; Keyimu et al. 2020; Yin et al. 2021). The reconstructed past temperature variability in the Daxing'an Mountains showed that the periodic and interdecadal temperature variability had significant spatial correlations with the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) (Jiang et al. 2021; Jiang et al. 2020). Sun et al. (2021) reconstructed the first tree-ring width chronology of *Platycladus orientalis* (L.) franco in the world, and the reconstructed temperature series recorded a low temperature period in the 17th and 18th centuries and a warming period in the late 20th century.

In the context of global warming, climate change has become a focus of social concern. The monsoon-continental climate transition zone in China, which obliquely runs through northeastern China to northwestern China, is an area sensitive to climate change. However, the hydrological and climatic instrumental data of the transition zone were mostly measured within the past 100 years, which greatly hinders our understanding of historical climate change in this area. The Daxing'an Mountains are in a high-latitude cold and arid area and constitute a representative region in the monsoon-continental climate transition zone in China. Climate change has a significant limiting effect on the radial growth of trees. In this study, Chifeng City, Inner Mongolia, was selected as the study area; the northern part of this city is located in the southern Daxing'an Mountains. Chifeng City is in the transition zone from a cold, arid, and semiarid climate to a humid and semihumid monsoon climate (Xie et al. 2020). Trees in this area contain rich climatic information that reflects that this area is sensitive to climatic and hydrological factors. Tree-ring data of Korean spruce (*Picea koraiensis* Nakai) have been used to reconstruct the precipitation series in the study area over the past 160 years (Liu et al. 2003). However, research on the historical temperature variability in this area is still lacking. In view of this, we reconstructed the annual mean temperature variability of the past 172 years in a representative high-latitude region in the transition zone by

constructing a tree-ring width chronology of Korean spruce, a dominant tree species in the study area, based on the analysis of the response of tree growth to climatic factors. The results of this study reproduce the climate change in this region during the period without meteorological records and provide a reference for future research on climatic factors.

2 Materials And Methods

2.1 Overview of the study area

The samples were collected at the Baiyinaobao National Nature Reserve of Hexigten Banner, Chifeng City (Fig. 1), which is located in a semiarid (forest-steppe) monsoon climate in the continental cold temperate zone and is a representative region of the changes in hydrological climate and ecological environment in Inner Mongolia. The reserve is located in northeastern China at the intersection of the North China and the Daxing'an Mountains, on the southeastern edge of the Mongolian Plateau, and on the grassland in the northeastern part of the Hunshandake Sandy Land. The Gonggeer River and the Aobao River are the main rivers in this region. This area has canopy closure of approximately 0.6–0.8 and an altitude between 1300 and 1500 m. The annual precipitation in the study area is approximately 300–350 mm, mostly in June–August, a period with high temperature. The annual evaporation is approximately 1526 mm, which is 4.3 times the precipitation, and droughts of different severity occur throughout the year (Liu et al. 2003), especially in spring and summer.

2.2 Hydrological and climatic data

In this study, the annual and monthly runoff data from 1972 to 2016 at the Xilinhote Hydrological Station (Fig. 2a), which is the closest to the sampling site, were collected from the hydrological yearbook of the local hydrological survey bureau. The meteorological data from 1951 to 2016 of the Linxi Meteorological Station (Fig. 2b) were collected from the National Meteorological Information Centre of China, including the annual and monthly data of the mean temperature, the mean minimum temperature, the mean maximum temperature, and the precipitation.

2.3 Tree-ring sampling and chronology establishment

Korean spruce (*Picea koraiensis* Nakai) is an evergreen tree species of genus *Picea* in the family Pinaceae, with a height of more than 30 m and a diameter at breast height of 60–80 cm. Korean spruce has high shade- and cold-tolerance and high adaptivity to various site conditions, it distributed throughout the study area except for marshes and arid sunny slopes and ridges. It is listed as an endangered species in the International Union for Conservation of Nature (IUCN) (Thomas and Farjon 2013) and is a rare and precious tree species.

Tree-ring samples of Korean spruce were collected from the Baiyinaobao Nature Reserve in August 2017 in strict accordance with the sampling requirements of the International Tree-ring Data Bank (Stokes and

Smiley 1968). Trees not damaged by natural disasters (such as forest fires and pests) during growth were sampled at sites with little human disturbance, shallow solum depths, large slopes, and low canopy closure. After the sampling sites were selected, the names, latitudes, and longitudes of the sampling sites, as well as the growth status, ecological environmental conditions, species, location, and date of collection of the trees, were recorded. A Trephor tool was selected as the tree-ring sampling tool because it limits damage to trees and features convenient and fast operation in order to protect the ecological environment and to not affect the normal growth of trees. Two tree core samples were drilled along the directions vertical and parallel to the slope at the breast height (1.3 m) of the tree using the Trephor tool, and one extra sample was collected for particularly old trees. The tree core samples were placed in a PVC pipe with predrilled ventilation holes to prevent the core samples from breaking and rotting during transportation. A total of 80 core samples were collected from 37 trees.

After the collected samples were naturally dried in a cool and ventilated place, they were polished step by step using dry sanding paper with different meshes from coarse to fine until the sample surface was smooth and flat and the boundaries between the annual rings were clearly identifiable. After the polished sample cores were scanned by a high-definition scanner, the tree-ring widths were measured using a tree-ring analysis system (WinDENDRO™). To ensure the accuracy of dating and measurement, the cross-dating and measurement results were tested using the COFECHA program (McBride 1983) to examine whether the sample cores had missing rings, false rings, dating errors, or other problems. The ineligible sample cores were excluded to improve data quality and reliability. The problematic tree-ring cores were retested, and the individual series with poor correlation with the main series and too many singularities were excluded. Ultimately, 76 Korean spruce cores were used for chronology construction.

To reduce the loss of low-frequency signals, the most conservative negative exponential function method in the ARSTAN program (Cook 1986) was used to remove the interference caused by intrinsic genetic factors of the trees and the growth trend. Then, the double-weighted average method (Cook et al. 1994) was used to establish three types of tree-ring width chronology, namely, the standardized chronology, the residual chronology, and the autoregressive chronology (Li 1989), based on the detrended series (Fig. 3).

The subsample signal strength (SSS) was used to determine the minimum number of replicas of a reliable chronology (Wigley et al. 1984). To ensure the reliability of the reconstructed series and preserve the maximum length, the confidence interval of the chronology was defined as $SSS > 0.85$. The basic characteristics of the radial growth of trees and the environmental information contained in the tree-ring chronology can be reflected from the statistical characteristics of the chronology (Fritts 1972). The mean sensitivity (MS), signal-to-noise ratio (SNR), and overall representativeness of the samples were used to evaluate the quality of each chronology. The statistical characteristic parameters of each chronology are shown in Table 1.

The MS is one of the important indicators for judging the quality of a chronology. The smaller the MS of the chronology is, the weaker the limiting effect of climatic factors, and the lower the climatic information

content. Series with $MS > 0.2$ are generally considered suitable for study (Fritts 1972). Table 1 shows that the MS values of the three chronologies all exceed 0.2, indicating the good quality of the chronologies. The autocorrelation coefficient reflects the continuous impact of climatic conditions on tree growth. A chronology with a smaller autocorrelation coefficient has a higher quality. The autocorrelation coefficients of the three chronologies are between 0.160 and 0.192, which indicates that the climatic conditions of the previous year had little effect on the tree-ring growth of Korean spruce. The SNR is a statistic used to measure the amount of environmental information contained in the sample. A high SNR indicates that a chronology contains abundant climatic information and thus is suitable for dendroclimatological research. Of the three chronologies established, the standardized chronology has the highest SNR, which means that it contains more climatic information than the other two chronologies. The express population signal (EPS) is used to evaluate the representativeness of the chronology compared with the true chronology. The larger the EPS value is, the better the sample representativeness. Generally, when the EPS exceeds 0.85, the established chronology is reliable. All three chronologies meet this criterion, indicating that the constructed chronologies are suitable for dendroclimatological research. The statistical characteristic values, such as the SNR and EPS, of the standardized chronology are higher than those of the other two chronologies and contain more high-frequency information and rich low-frequency information. In addition, the standardized chronology has the longest effective length and can reflect climate change on multiple scales. These results indicate that the standardized chronology is suitable for dendroclimatological analysis. Hence, the standardized chronology was selected for analysis.

Table 1
Statistical indicators of Korean spruce standardized chronology

Statistical indicators	STD	RES	ARS
Average value	1.000	1.000	1.004
Median	1.004	0.998	1.008
Skewness	0.066	-0.329	0.043
Kurtosis	0.910	3.298	1.017
Mean sensitivity	0.245	0.253	0.233
Standard deviation	0.147	0.115	0.145
The first-order autocorrelation coefficient	0.535	0.138	0.544
The average correlation coefficient between each sequence and the main sequence	0.301	0.223	0.297
Mean correlation coefficient between trees	0.192	0.160	0.191
SNR(Signal to Noise Ratio)	18.493	14.912	18.425
Overall representativeness of samples	0.949	0.937	0.949
First year of subsample with signal strength > 0.85	1845	1851	1845

2.4 Data analysis methods

(1) The correlation between chronology and annual (monthly) temperature and precipitation data was analysed using the Pearson correlation method (Blasing et al. 1984).

(2) The temperature equation was reconstructed using the unary linear regression model.

(3) The stability and reliability of the reconstructed model were tested using the one-by-one elimination method (Cook et al. 1999).

(4) To make the temperature variability more concise and clearer, the Z-score method was used to standardize the reconstructed historical series. The calculation formula is as follows:

$$Z\text{-score} = \frac{R - MN}{SD}$$

1

where R is the reconstructed temperature, °C; MN is the mean value of the reconstructed series, °C; and SD is the standard deviation, °C.

(5) The coefficient of variation (CV) is used to determine the degree of change in the reconstructed historical temperature series (Ghorbani et al. 2021). The CV was calculated using the following formula:

$$CV = |SD/MN|$$

2

where SD is the standard deviation of the reconstructed historical temperature series, °C; and MN is the mean value, °C.

(6) In the reconstructed historical temperature series, a year with temperature exceeding $\text{Mean} + \sigma$ is defined as a warm year, the period with temperature below $\text{Mean} - \sigma$ is defined as a cold year, and a year with temperature between $\text{Mean} - \sigma$ and $\text{Mean} + \sigma$ is defined as a normal year, where:

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^N (X_i - \mu)^2}$$

3

where σ – standard deviation, °C; x_i – the temperature corresponding to the i th year, °C; μ – mean value, °C; and N – the number of samples,

(7) The periodic variability in the reconstructed historical temperature series was analysed using the Morlet wavelet analysis method (Venugopal and Foufoula-Georgiou 1996), which is defined as:

$$\psi(t) = Ce^{-t^2/2} \cos 5t \quad (4)$$

The Morlet wavelet scaling factor, a , has the following relationship with period T :

$$T = \left[\frac{4\pi}{\omega_0 \sqrt{2 + \omega_0^2}} \right] \times a$$

5

where an empirical value near 6.2 is usually assigned to ω_0 .

(8) The MK test (Sun et al. 2019) was used to determine the years with abrupt temperature changes.

3 Results And Discussion

3.1 Response of tree growth to hydrological and climatic factors

The tree-ring width of a tree is generally constrained by the genetic characteristics of the tree and the external environment (Fritts 1972). The genetic characteristics of an individual tree are relatively stable, and the growth trend of the tree-ring data is removed, so the growth environment of the tree is the main factor affecting its radial growth. To further understand the relationship between the growth of Korean spruce trees and hydrological and climatic factors, the correlation between the standardized chronology of Korean spruce and the annual, seasonal, and monthly data of hydrological and climatic factors in the study area was studied using SPSS software (Fig. 4).

The figure shows that the standardized chronology of Korean spruce is negatively correlated with the annual, seasonal, and monthly data of the mean temperature, the mean minimum temperature, and the mean maximum temperature and that its correlation with the annual mean temperature is extremely significant. The chronology has a positive correlation with runoff in all periods except for winter and December and a primarily positive correlation with precipitation, which is not significant overall.

In arid and semiarid regions, temperature is a relatively climatic factor that tree growth is sensitive to. The correlation between the standardized chronology of Korean spruce and the annual mean temperature is the highest, with a correlation coefficient of -0.557 ($p < 0.001$), which passes the significance test at the 99.99% confidence level, followed by the correlation between the standardized chronology and the annual mean minimum temperature ($r = -0.507$). In terms of seasons, the correlations between the standardized chronology and the three types of temperatures in spring and summer are higher than those in the other two seasons, with the weakest correlation in winter. In spring, the trees are in the early growing season. Since the precipitation is low in spring (Fig. 2), temperature is the most important factor affecting the

growth of Korean spruce. The temperature rise causes drought stress to inhibit the radial growth of trees. The study area has a temperate continental monsoon climate. The precipitation is mostly concentrated in July and August. Although the precipitation increases in summer, the temperature also reaches the annual peak in summer. If the increased precipitation is not sufficient to complement the evaporation of soil water caused by high temperature, narrow tree rings are formed due to water shortage. In winter, trees become dormant, so the effect of temperature on trees is weakened. The temperature in May and June has a stronger limiting effect on the growth of the trees than that in other months, and the correlations between the three types of temperatures and the chronology all pass the significance test at the 99% confidence level. During May and June, the precipitation in the study area is relatively low, and the high temperature limits the growth of the tree cambium cells, which results in narrow tree rings. In August, the correlation between the three types of temperatures and the growth of trees in the study area is relatively poor because the effect of temperature on tree growth is not significant due to the high precipitation and runoff and the joint effect of a variety of climatic factors on Korean spruce in August.

The correlation between the standardized chronology and the runoff in spring is the highest ($0.543(p < 0.001)$), followed that in summer, and the weakest and negative correlation is observed in winter. In spring, the trees are in the early growing period, and the increase in runoff can provide a sufficient water source for tree growth. In summer, the trees are in the vigorous growth period, and runoff promotes the growth of the trees. In winter, the temperature is extremely low in the study area, so excessive moisture causes frost damage to the dormant Korean spruce trees, and soil freezing is not conducive to tree root respiration. The correlation between runoff and chronology from March to June is better than that in other months and passes the significance test at the 99% confidence level. The correlation between the chronology and runoff in December is negative but not significant.

Except for the annual precipitation, the correlations between the precipitation and the chronology of Korean spruce on other time scales are weak and do not pass the significance test. This may be because the precipitation in the semiarid study area is relatively low and mainly concentrated in summer, while the summer temperature in the study area is extremely high, which results in much higher evaporation than precipitation and consequently a limited effect from precipitation on trees and low dependence of tree growth on precipitation.

In summary, air temperature and runoff play an important role in the growth of Korean spruce. Appropriate temperature and high runoff are more conducive to the growth of trees. The seasonal differences in runoff in the study area make tree growth more sensitive to temperature. Hence, temperature is the main limiting factor for the radial growth of Korean spruce.

3.2 Reconstruction and verification of annual mean temperature

Based on the above analysis, the annual mean temperature data and the standardized chronology of the observation period (1951–2016) at the Xilinhote Meteorological Station were used to reconstruct the

annual mean temperature variability in the study area during the past period without meteorological records. The reconstructed values were compared with the measured values (Fig. 5). The reconstruction equation of the annual mean temperature in the study area is as follows:

$$y_i = -3.074x_i + 7.642$$

$$(r = 0.557, N = 66, R^2_{\text{adj}} = 0.310, F = 28.78, p < 0.001)$$

where y_i is the annual mean temperature in the i th year and x_i is the standardized tree-ring chronology series.

The stability of the equation directly affects the quality of the reconstructed series. The stability, reliability, and accuracy of the reconstruction equation are tested using the one-by-one elimination method used in international tree-ring studies. The tested statistics included the product mean, correlation coefficient, sign test, etc. The reconstruction equation has an error reduction (RE) value of 0.682 and an effective coefficient (CE) of 0.305, which are both positive. This result indicates that the reconstructed annual mean temperature series is accurate and reliable. The correlation coefficient (r) between the reconstructed and measured series is 0.557, and their first-order autocorrelation coefficient passes the significance test at the 99.99% confidence level. Therefore, the correlation between the two is excellent. The high- and low-frequency sign tests both pass the significance test at the 95% confidence level, which indicates that the equation can reflect the changes in high and low frequencies well. All parameters of the equation meet the requirements and pass the reliability test.

Figure 5 shows that the reconstructed and measured series of the annual mean temperature match well and that the overall temperature fluctuation trend remains consistent. However, the reconstructed series and the measured series exhibit some differences in certain years, perhaps because the accuracy of the reconstructed series was affected by a variety of climatic factors that affect the radial growth of trees. In general, all the test parameters of the reconstruction equation pass the significance test. The reconstructed series has high reliability and contains more climatic information. The reconstructed and measured series exhibit the same trend. Hence, the reconstruction equation can be used to reconstruct the annual mean temperature in the study area.

3.3 Variability characteristics of the reconstructed annual mean temperature series

To understand the characteristics of cold and warm cycles in the reconstructed historical climate series, the 11-year moving average method was used to process the standardized reconstructed series. A period with moving average temperature above the mean temperature was defined as a warm period, and a period with moving average temperature below the mean temperature was defined as a cold period.

Since 1845, the study area has experienced five stages of warming-cooling-gradual change-warming-cooling, including five warm periods and five cold periods. The longest cold period started in 1889 and

ended in 1923, lasting for 35 years, and the decadal mean temperature of this period was the lowest. The longest warm period started in 1962 and ended in 1991, lasting for 30 years. The mean annual temperature in the study area was the highest in the period of 1996–2012 (2.186°C), and the temperature variability was the most dramatic in this period (CV = 11.3%).

The reconstructed series of annual mean temperature in the study area showed an overall upwards trend (0.0012°C/10a), with relatively large fluctuations at a relatively high frequency. In the past 172 years, there were two abrupt changes, in 1906 and 1981, and a total of 25 cold years (14.5%) and 18 warm years (10.5%). Most (75%) of the past 172 years were normal years. From 1845 to 1853, the temperature rose at 0.0808°C/10 a and reached the highest temperature (5.38°C) in 1853, which was also the highest temperature in the 19th and 20th centuries. In 1856, the temperature abruptly declined at 0.0494°C/10 a. The temperature stopped declining and started to rise in 1873. During this period (1856–1873), the study area experienced 7 cold years, mainly in the 1970s. In the following 30 years, the temperature fluctuated in the normal range. In 1906, the temperature began to decline at 0.0275°C/10 a, resulting in successive cold years from the 1910s to the 1920s, with the occurrence of the lowest decadal mean temperature and the longest cold period (Fig. 6a). A clustering of cold years also occurred from 1950s to 1960s, and the related cold period lasted for 30 years. In 1981, the temperature in the study area abruptly rose at 0.1129°C/10 a. A large number of warm years occurred from the early 2000s to the 2010s, accounting for 61% of all warm years, and the decadal mean temperature in this period reached the historical high of the recent two centuries (Fig. 6b). After 2008, a warming hiatus started, and the temperature decreased linearly at -0.1878°C/10 a. In 2016, the temperature in the study area reached the criterion for cold years.

As shown by the time-frequency distribution diagram of Morlet wavelets (Fig. 6c) and the wavelet variance diagram (Fig. 6d), the reconstructed mean temperature series of the study area show distinct cycles of 3 a, 7 a, 10–12 a, 15–22 a, and 30–40 a. The maximum peak in the wavelet variance diagram corresponds to a cycle of approximately 15–22 a, indicating that the periodic oscillation on the scale of 15–22 a is the strongest, followed by the extreme value of the wavelet variance on the scale of 30–40 a. Large-scale fluctuations in climatic cycles have a regional impact, which indirectly affects the growth conditions of trees. The cycles of 3 a and 7 a in the study area basically coincide with the ENSO cycles. ENSO is one of the major drivers of interannual climate change, which shortens the duration of summer and reduces the precipitation. The cycle of 10–12 a basically coincides with the short cycle (11 a) of sunspots (Guttu et al. 2021). Solar radiation affects the vertical temperature of the Earth, causing changes in temperature, so the activity of sunspots affects the growth of trees. The cycle of 15–22 a might be related to the Atlantic Multidecadal Oscillation (AMO). If the PDO is associated with the positive phase of the AMO, the monsoon would be affected. Since the study area is in the monsoon-continental climate transition zone, the cycle of 15–22 a plays a vital role in tree growth.

3.4 Comparison with historical events and other reconstructed results

To verify the accuracy of the reconstructed series, we compared the reconstructed temperature series with the historical meteorological disasters recorded in the *Dictionary of Meteorological Disasters in China—Inner Mongolia Volume* (Shen 2008) and found severe natural disasters corresponding to the cold years and warm years in the reconstructed temperature series. The start year of the chronology coincided with the 25th year of Daoguang of the Qing Dynasty, when high temperature led to locust disasters. In the 5th year of Tongzhi, the extreme high temperature led to different degrees of drought in the study area, and people had to eat bark and wild vegetables due to the frequent famines. From the 3rd to 5th year of Xianfeng, people had to borrow seeds from government-owned barns for resowing, as crops died due to drought in many places, and the imperial government relieved the famine by allocating government-owned grains to the public and exempted the farmers from farm rent. Severe drought in the spring and summer of the 4th year of Guangxu (1878) greatly reduced the grain yields, which, on top of the poor harvest in the previous fall, resulted in inadequate grain storage. According to modern drought records, the severe drought in Chifeng in 1968 made crops small and weak, negatively affecting agricultural harvests. In 1983, a periodical drought occurred in Chifeng in early summer. Persistent drought occurred in the study area in 1950–1953, 1960–1963, 1970–1975, 1980–1982, and 1986–1989, which precisely coincided with the warm period in the reconstructed series, indicating that the reconstructed warm period is reliable. In the 1st year of Xuantong (1909), the study area suffered continuous severe drought and snow disasters in winter. In the 3rd year of Xuantong, the people became helpless victims of the heavy snowfall events in winter and spring. In 1913–1918, the snow disasters in the study area caused severe great livestock casualties and a fuel shortage. In 1934, snow began in October at Xilingol League, and the accumulated snow did not melt until March of the following year. From 1952 to 1958, snow disasters occurred in both winter and spring in the study area, with the lowest temperature reaching -42°C , causing the loss of tens of thousands of livestock and road blockages. Natural disasters, including snow disasters, cold waves, and chilling damage, were found in the records of the study area corresponding to the cold years in the reconstructed series, which provided strong support for the accuracy of the reconstruction results.

To further verify the reliability of the reconstruction results, the common time periods of the reconstructed historical annual mean temperature series and other reconstructed results in the monsoon-continental climate transition zone in China were comparatively analysed. Figure 7a shows the temperature variability from 1853 to 2012 recorded by tree rings in a paddock (denoted as WC) in China (Wang et al. 2019). The WC borders the study area and has a moderate-temperate continental monsoon plateau mountain climate. Figure 7b shows the results of tree-ring reconstruction of the mean temperature in June and July from 1880 to 2014 in a region in the northern part of the Daxing'an Mountains (denoted as DXA) (Jiang et al. 2020). Figure 7c shows the annual mean temperature of the study area from 1845 to 2016 reconstructed based on the tree-ring width chronology of Korean spruce in a representative area of the transition zone (denoted as GDD). The figure shows that the reconstruction results of the GDD exhibit warming and cooling trends similar to those of the other two regions (the WC and the DXA) and that the three regions experienced the same warm periods (1980–1988, 1996–2002, 2007–2011) and cold periods (1892–1903 and 1931–1947). The GDD had longest cold and warm periods with most intense

temperature fluctuations of the three regions ($CV_{WC} = 2.8\%$, $CV_{DXA} = 5.1\%$, $CV_{GDD} = 8.7\%$). The WC had more frequent alterations between warm and cold periods than the other two regions. The temperature in each region showed relatively synchronous cooling and warming trends. The temperature in the GDD showed a decreasing trend from 1853 to 1872 and from 1885 to 1893, and the cooling duration of the WC (33 years) was longer than that in the GDD (23 years). The temperature in the three regions rose continuously from 1935 to 1940 and from 1958 to 1967, which indicated the transition from a cold period to a warm period. During the period from 1968 to 1975, the temperature declined continuously, and the temperature drop was more rapid in the WC than in the other two regions. The temperature began to rise from 1976 and abruptly dropped in 1985, which indicated the transition from the warm period to the cold period in the GDD, but the temperature fluctuations in the DXA were small. In the 20 years after 1992, the temperature in the GDD increased significantly, and the temperature rose at $0.0325^{\circ}\text{C}/10\text{ a}$, $0.0819^{\circ}\text{C}/10\text{ a}$, and $0.1167^{\circ}\text{C}/10\text{ a}$ in the WC, the northern part of the DXA, and the GDD, respectively. The temperature rise of GDD was faster than that of the other two regions.

4 Conclusion

(1) All the statistical characteristic parameters of the tree-ring chronology of Korean spruce are in line with the standard, the standardized tree-ring width chronology contains more climatic information, and the reconstruction equation is accurate and reliable. The chronology has the highest correlation with the annual mean temperature in the study area, which is main factor affecting tree growth.

(2) The reconstructed mean annual temperature series in the study area generally shows an increasing trend, including five warm periods and five cold periods, with a total of 24 cold years and 18 warm years. Before the 1960s, cold years were dominant. Warm years appeared sporadically in the 19th century. In the early 21st century, the temperature continued to rise with dramatic changes. In 2008, the warming hiatus started. The year 2016 was a cold year.

(3) The reconstructed annual mean temperature series has distinct cycles of 3 a, 7 a, 10–12 a, 15–22 a, and 30–40 a. PDO and AMO are the main drivers of climate change in the study area.

Declarations

Funding information: This research was supported by the National Natural Science Foundation

of China [grant numbers 52069019, 51869016 and 51669016] and the Inner Mongolia Autonomous Region “Grassland Talents” project.

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

Author Contributions: All authors contributed to the study conception and design. **Yingnan Wei** carried out the Conceptualization, Data curation, Formal analysis and Writing - original draft. **Bolin Sun** and **Jing Zhang** helped in the Investigation and Software. **Long Ma** provided guidance in the Funding acquisition,

Investigation, Methodology and Writing - review and editing. **Quanpu Jing** and **Jianjun Xing** helped in Resources, Sample collection and Visualization.

Data Availability: Data are available with the corresponding author.

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Figures

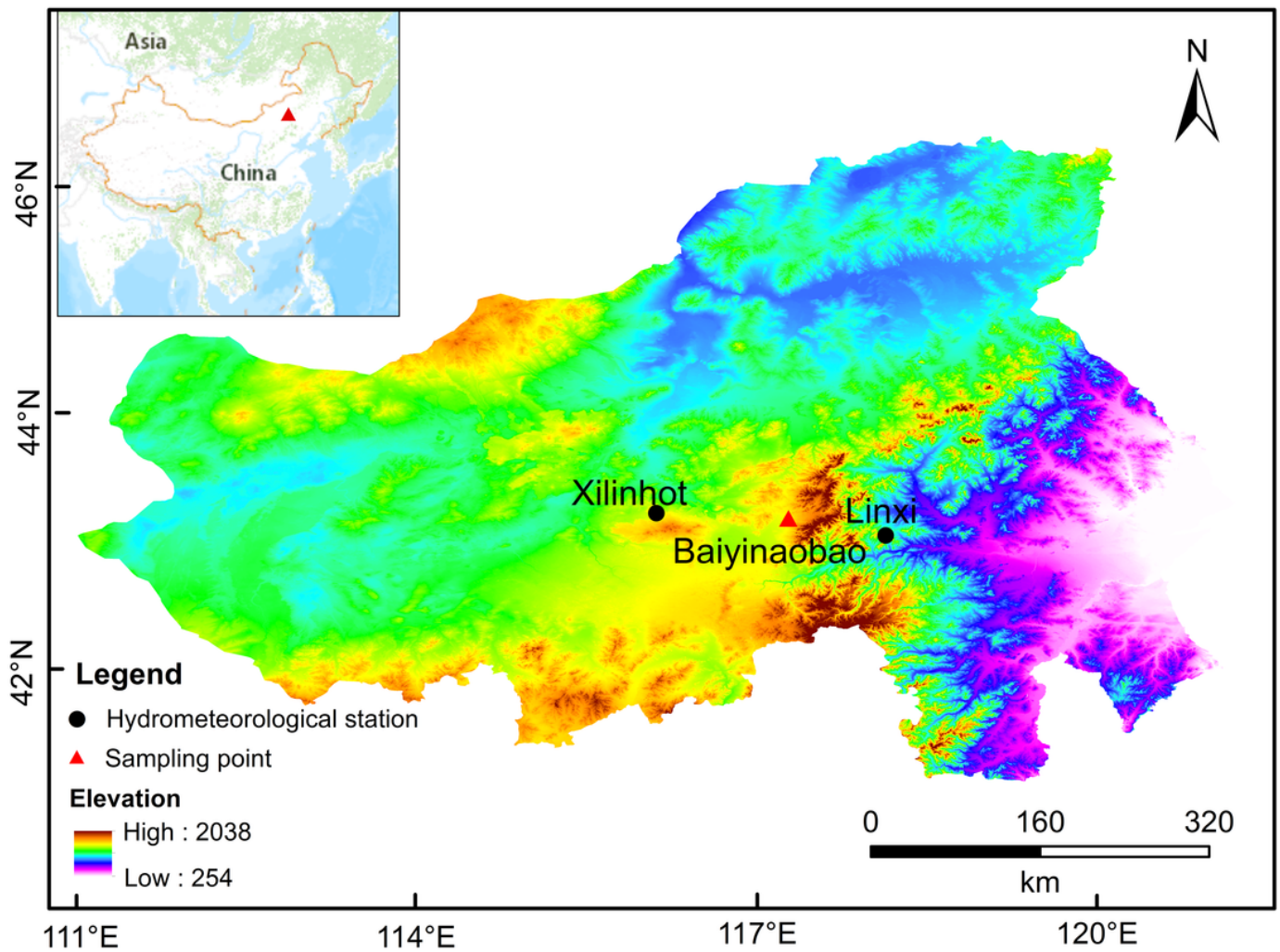


Figure 1

Distribution of sampling point, hydrological stations, and meteorological stations in the study area

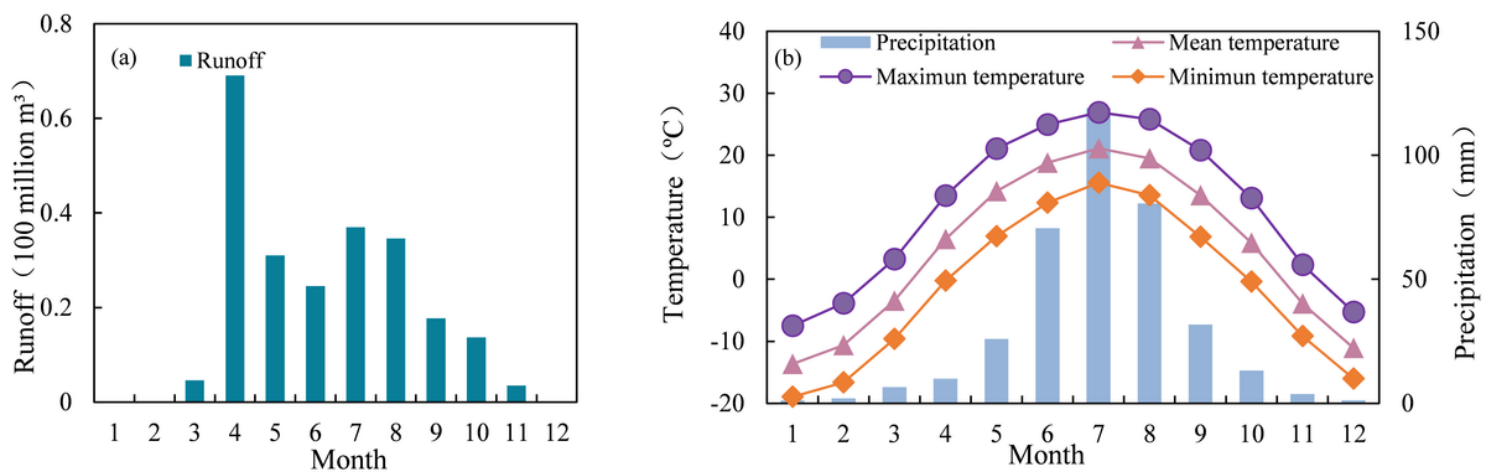


Figure 2

(a) Distribution of runoff data from Xilinhhot Hydrological Station from 1972 to 2016; (b) climate data from Linxi Meteorological Station from 1951 to 2016

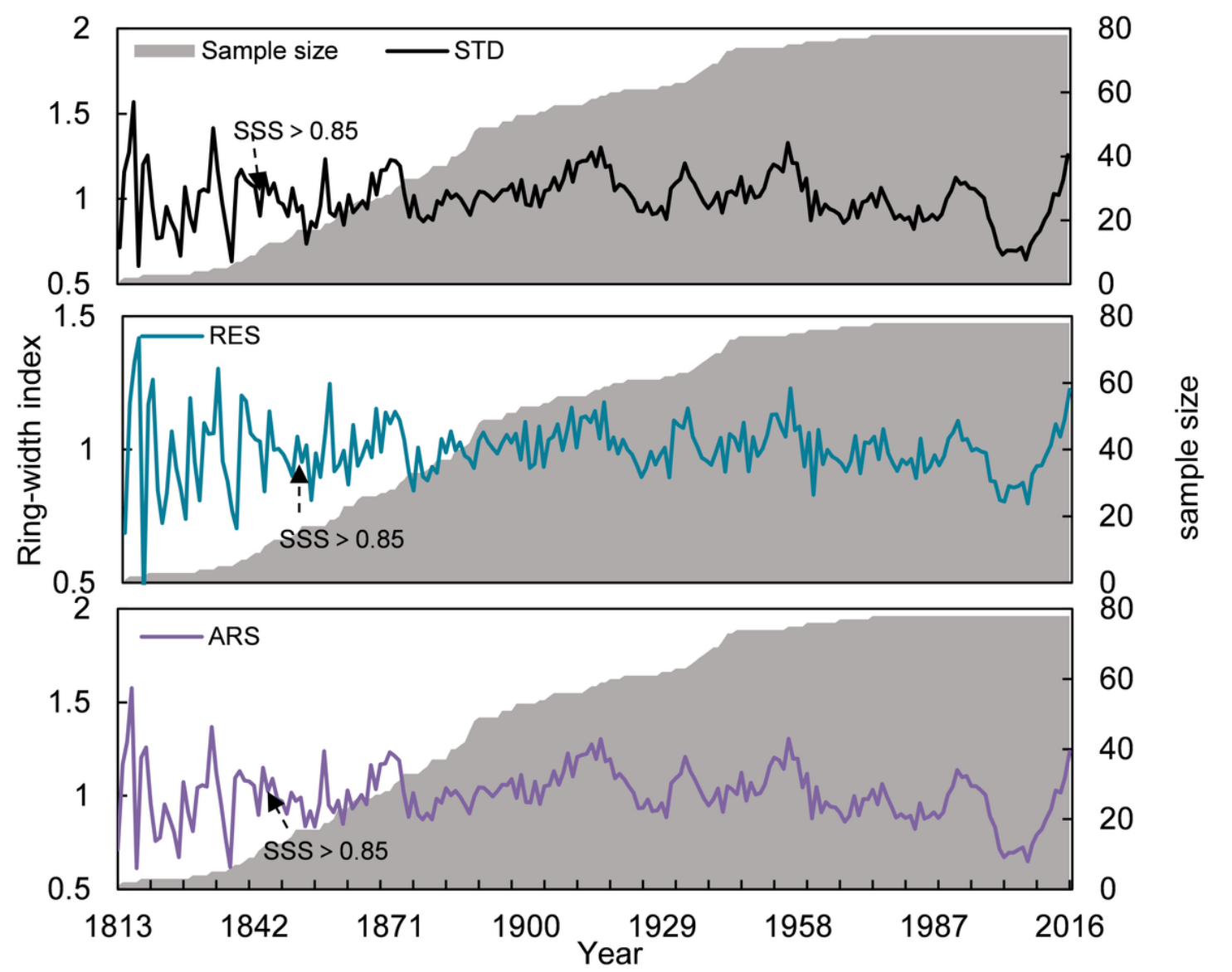


Figure 3
The tree-ring width chronology of Korean spruce and the number of samples

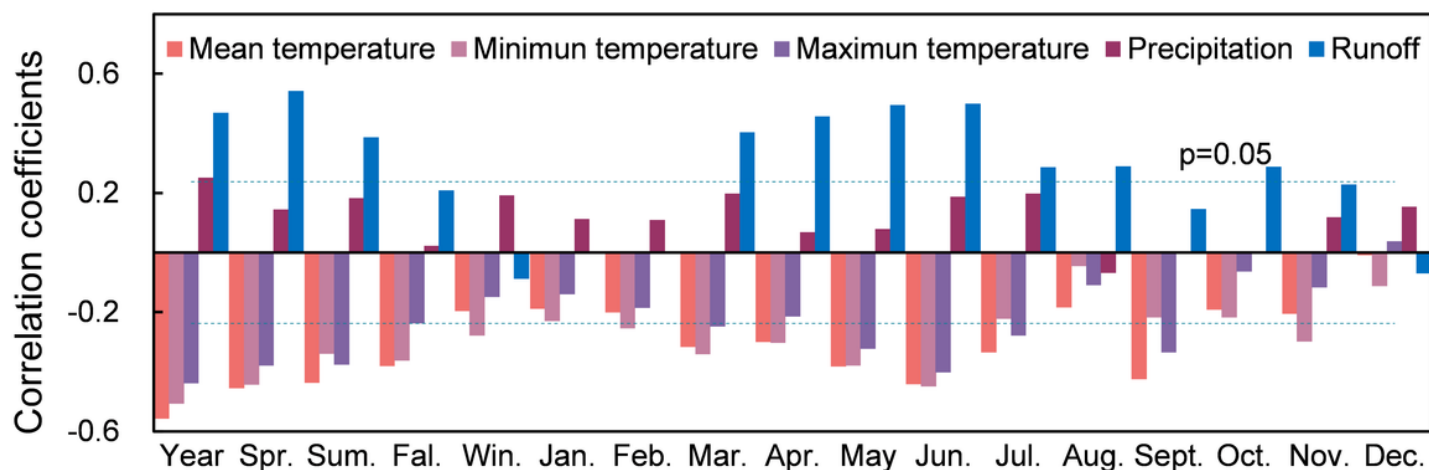


Figure 4

Correlation coefficients between the tree-ring width index of Korean spruce and the annual, seasonal, and monthly data of climatic factors

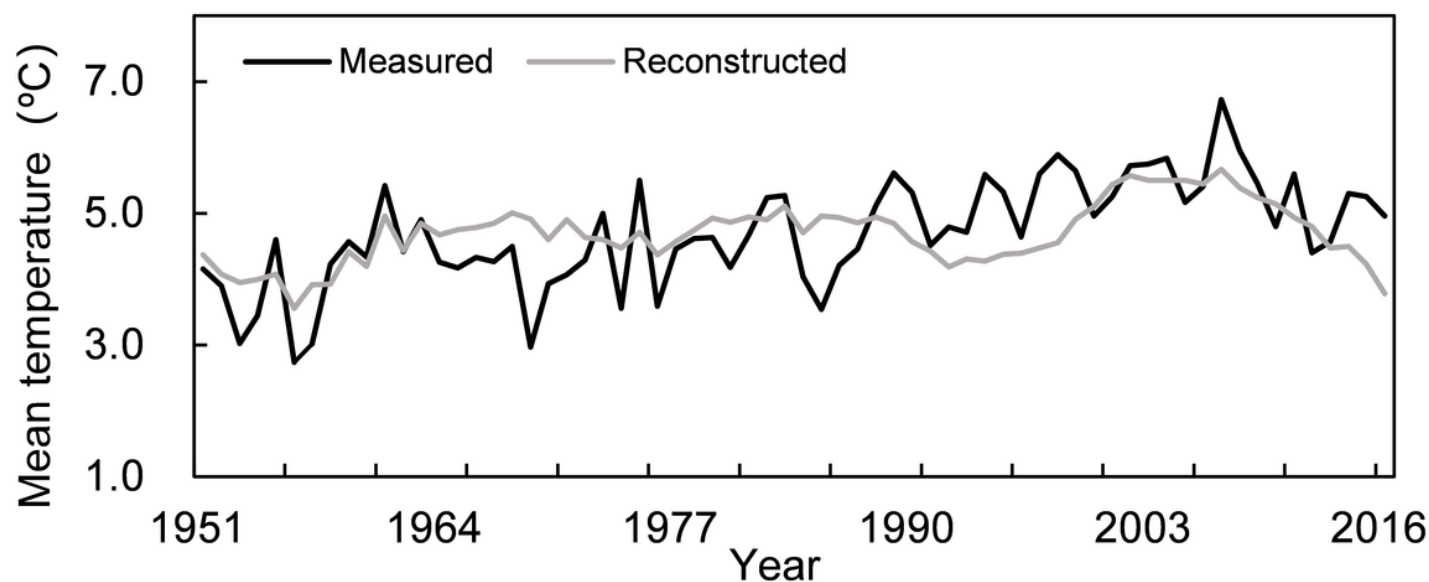


Figure 5

Comparison of the reconstructed and measured annual mean temperature

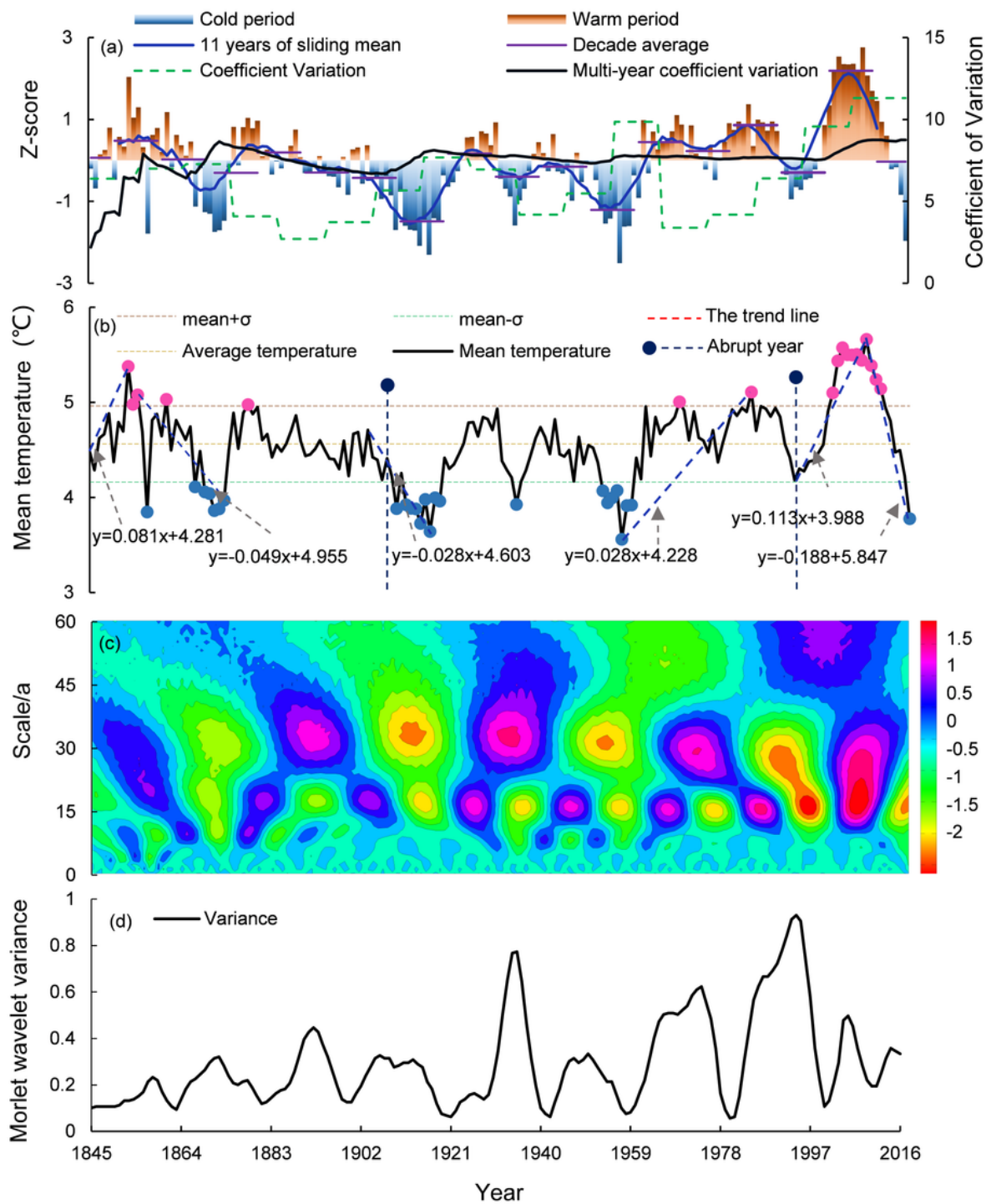


Figure 6

Changes in the reconstructed mean temperature series (a) time distribution of the reconstructed sequence of warm and cold periods; (b) distribution of the changes in the reconstructed sequence; (c) Wavelet analysis time-frequency distribution of the reconstructed sequence; (d) wavelet variance diagram of the reconstructed sequence

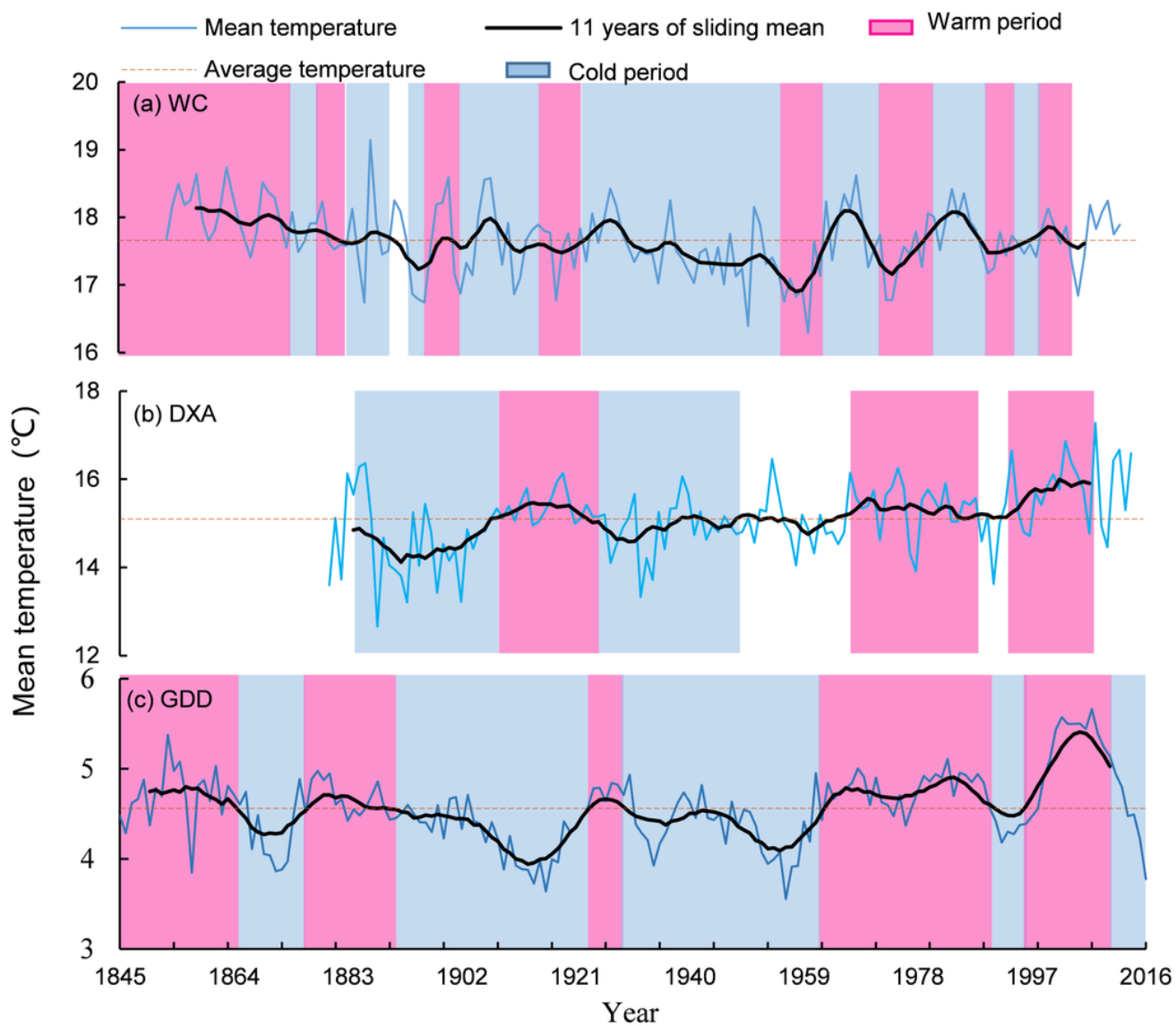


Figure 7

Comparison of the reconstruction results in this study with other reconstruction results in regions in the vicinity of the study area