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Asymmetric variability between maximum and minimum temperatures in Northeastern Tibetan Plateau: Evidence from tree rings

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Ecological systems in the headwaters of the Yellow River, characterized by hash natural environmental conditions, are very vulnerable to climatic change. In the most recent decades, this area greatly attracted the public's attention for its more and more deteriorating environmental conditions. Based on tree-ring samples from the Xiqing Mountain and A'nyêmagên Mountains at the headwaters of the Yellow River in the Northeastern Tibetan Plateau, we reconstructed the minimum temperatures in the winter half year over the last 425 years and the maximum temperatures in the summer half year over the past 700 years in this region. The variation of minimum temperature in the winter half year during the time span of 1578—1940 was a relatively stable trend, which was followed by an abrupt warming trend since 1941. However, there is no significant warming trend for the maximum temperature in the summer half year over the 20th century. The asymmetric variation patterns between the minimum and maximum temperatures were observed in this study over the past 425 years. During the past 425 years, there are similar variation patterns between the minimum and maximum temperatures; however, the minimum temperatures vary about 25 years earlier compared to the maximum temperatures. If such a trend of variation patterns between the minimum and maximum temperatures over the past 425 years continues in the future 30 years, the maximum temperature in this region will increase significantly.

Tibetan Plateau, tree-ring, minimum temperature, maximum temperature, asymmetric variability, warming trend

1 Introduction

The interior Tibetan Plateau where the two longest rivers of China, the Yangtze River and Yellow River, originate is called the headwaters of rivers. The headwaters are characterized by unique natural environmental conditions and rich natural resources. The headwater of the Yellow River gives birth to the second longest river in China and deeply influences the ecological systems of the drainage area of the Yellow River. However, studies of ecological issues in this area are relatively limited for various reasons. Over the recent years, the public has paid much attention to the more and more deteriorating environmental conditions in the area[1,2]. The environmental conditions gradually deteriorated partly from the inherited vulnerable hash natural conditions in the headwater of the Yellow River, and partly from climatic

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change interacting with human activities[3]. In the headwater of the Yellow River, the glaciers retreated[4], the grasslands degraded[5], the desertification area expanded, and the area of lakes shrank[6]. Since the 1950s, the warming trend in the headwater of the Yellow River has resulted in permafrost degradation, along with higher evaporation, and pasture degradation[7]. The ecological environmental changes in the headwaters of Yellow and Yangtze rivers not only affect the ecosystems in the headwaters, but also deeply affect the ecosystem and human activities in their entire drainage areas.

It is fundamentally important to understand the variability of past climatic change. In so doing, we can try to detect the reasons for the undergoing ecological changes and to predict possible future ecological changes in the study region. However, the meteorological records in Western China are generally limited to 50 years, situations are even worse in the Tibetan Plateau where the meteorological stations, even with shorter time spans, are sparse. It is obvious that the limited measured records are insufficient for understanding longer-scale climatic change in this region. Fortunately, high-resolution tree-ring records, one of the most valuable, high-resolution archives, can be used to extend our knowledge on the past climatic change in the area. Based on the accurately dated, continuous, high-resolution, precisely measured ring-widths, and sensitive relations to climate, the sampling and replication of tree rings have been widely applied in reconstructing past climatic change. By using tree-ring proxies, Liu et al.[8,9] reconstructed precipitations of different seasons in various parts of Inner Mongolia, and investigated variations of precipitation induced by East Asian summer monsoon over the 160 years[10]. In addition, Liu et al.[11] reconstructed precipitation variations beginning from A.D. 850 in the northeastern Tibetan Plateau and analyzed the connections to temperature variations in the Northern Hemisphere. By investigating relationships between ring-width indices and meteorological factors, Gou et al.[12−14] suggested that rainfall in spring is the major limiting factor for tree growth in the Qilian Mountain, and reconstructed variations of spring rainfall by using ring-width indices. Based on these results, the climatic information recorded by tree rings and glaciers was comparatively analyzed[15]. The minimum temperatures in the winter half year in the eastern Tibetan Plateau were reconstructed, suggesting a significant warming trend over the past 50 years[16]. Because there are many missing rings and false rings when crossdating samples from arid areas in China, Shao et al.[17] discussed in detail the technological methods to build chronologies in arid areas of China. They reconstructed the variations of precipitation in the past 1000 years in the Delingha area[18], temperature variations in the center Qilian Mountain[19], and spring moisture index variations over the nearly 500 years in southern Qinghai Province[20]. Based on the tree-ring network, the 1920s severe drought event occurring in arid and semiarid areas in north China was also analyzed[21]. Using the tree-ring samples taken from *Juniperus przewalskii* in the Dulan area in Qinghai Province, Zhang et al.[22] established a ring-width chronology of a length of 2326 year. By performing tree-ring analyses, researchers reconstructed precipitation[23] and PDSI[24] in the Tianshan area in the Xinjiang Uygur Autonomous Region. In addition to tree-ring studies carried out in China, researchers have not only reconstructed long-term climatic variations[25−29] but also climatic reconstructions over wide spatial scales[30−32].

Global warming, regarded as undoubted fact[33,34], is one of the key issues addressed by the global change researches. Under the global warming background, the annual mean ground temperatures increased by 0.5—0.8℃ in the past 100 years[35]. Recent studies suggested that variations of the maximum temperatures and minimum temperatures were asymmetric during the warming processes[36−40]. In most regions of the Northern Hemisphere, the significant warming mainly occurred at night, and the increase of the daily average minimum temperature is more than that of the daily maximum temperature[36]. Even reverse variation trends have been observed between maximum and minimum temperatures[38]. These measured records showed that global warming has occurred mainly in the minimum temperatures and at night, however, evidence of the warming trends on the maximum temperatures was not that evident. Wilson and Luckman[41,42] reconstructed the variability of summer maximum and minimum temperatures in British Columbia in Canada by employing tree-ring proxies, and emphasized that we should reconstruct various temperature variables (e.g. maximum and minimum temperatures, etc.) but not the mean temperature. The headwater of the Yellow River, characterized by its harsh natural environmental conditions and located in a remote region, has flourishing, widespread forests. This made it possible to study climatic change history by employing tree-ring widths. In this study, based on tree-ring samples in the headwater of Yellow River from the northeastern Tibetan Plateau, the minimum temperatures in the winter half year and the maximum temperatures in the summer half year were reconstructed and their asymmetric variation patterns are also discussed.

2 Site description and chronology development

2.1 Site description and sample collection

The tree-ring cores were collected from the Xiqing Mountain and A'nyêmaqên Mountains, in the headwater of the Yellow River in the northeastern Tibetan Plateau (Figure 1). The study region is dominated by subalpine grasslands and dark coniferous forests, displaying obvious vertical distribution patterns with simple vegetation bands. The forests in this area are distributed within narrow bands on both sides of the valley. Most cores were sampled from sites featuring conditions of barren soil, low concentrations of humus, and bared rocks. The dominant arborescent species in the study region is *Juniperus przewalskii* which is sparsely distributed with the distances from each other ranging over 5—10 m. The sampled healthy trees have branches near to the ground that is covered by sparsely distributed subalpine herbaceous species.

From 2002 to 2003, we collected *Juniperus przewalskii* tree-ring cores from 4 sites at the Xiqing Mountain and A'nyêmaqên Mountains at the headwater of the Yellow River. Detailed sampling information is in Table 1, while Figure 1 displays locations of sampling sites and their surrounding meteorological stations. All the samples were collected from south-facing slopes in the valley of different tributaries. The vertical limits when sampling were limited to 100 m to maintain consistent climatic signals. In order to obtain old and climate-sensitive, long-lived cores, we were careful in selecting the sampling plots to avoid microsites with various non-climatic disturbances and trees attacked by insect pests. Moreover, most cores were collected from isolated trees in open-canopy forests. Some samples, which were sensitive to microenvironments, e.g. collected from plots near to streams, were only used for dat-

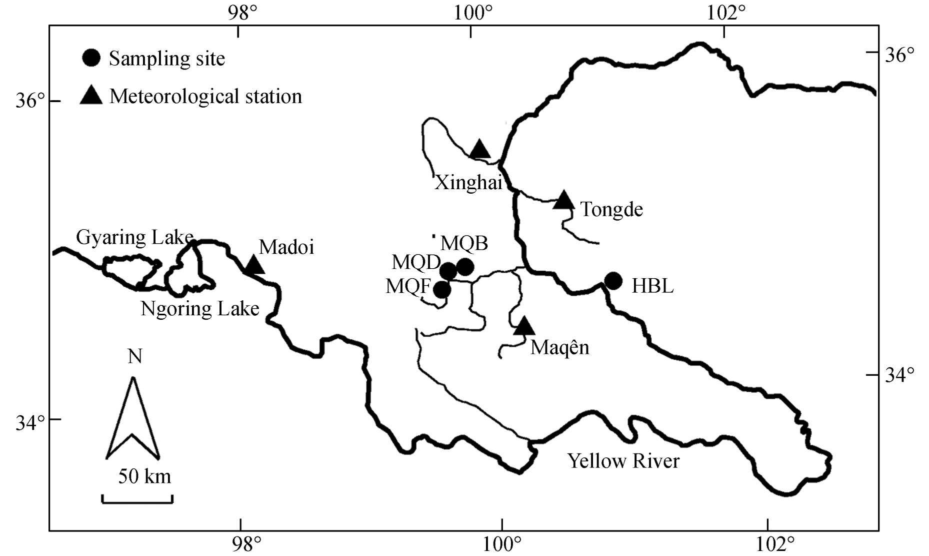

Figure 1 Locations of the sampling sites and nearby meteorological stations.

Table 1 Sample collection information and statistical characteristics of the standardized chronology

Sample site	Longitude/Latitude	Elevation (m)	Sample size (core/tree)	Mean sensitivity	Absent rate (%)	Mean correlations among all radii	Skewness	Kurtosis	PC1[a] (%)	SSS	EPS
MQB	99°47′21″E, 34°47′08″N	3550—3650	53/38	0.543	2.597	0.363	0.592	0.271	38.54	1264(8)	0.95
MQD	99°40′01″E, 34°43′25″N	3600—3700	34/22	0.400	1.074	0.335	0.251	0.326	37.66	1308(5)	0.87
MQF	99°41′29″E, 34°45′15″N	3650—3700	52/37	0.365	1.068	0.281	0.513	0.708	31.38	1301(9)	0.88
HBL	100°45′44″E, 34°45′57″N	3500—3615	39/24	0.348	0.441	0.281	0.324	1.456	32.09	1578(7)	0.89

a) PC1 is the variance of first eigenvector.

ing assistances and finally discarded when building chronologies. Sampling sites at the Xiqing Mountain (HBL) were located at the downstream end of river valley, with a relatively low elevation.

2.2 Cross-dating and chronology development

All the tree-ring cores were taken back to our tree-ring laboratory, air-dried, glued in prepared wooden mounts, sanded with fine sand papers to produce a polished surface allowing the identification of all cells; and then we started to visually cross-date our samples. In this study, we employed skeleton plots and multiple-line plots for visual cross-dating. Subsequently the preliminarily-dated cores were measured using a Velmex measurig stage with the precision of 0.001 mm. The measured data were processed using the program COFECHA[17,43,44] for dating quality control to test the accuracy of each ring date. The cross-dated samples with unusual growth patterns or unique growth releases and/or suppressions were eliminated. In addition, we also discarded samples with shorter time spans (shorter than 200 years) when the sample depth met our needs to better retain low-frequency signals. It is common for trees to experience missing rings in arid areas, and studies indicated that the situation was extreme for *Juniperus przewalskii* in northwestern China[17]. In our study areas, this is the case (Table 1).

We employed program ARSTAN[44] to remove age-related growth trends before calculating the chronologies with standard tree-ring principals[45]. In this study, we adopted, in most cases, negative exponential function or straight line to model the growth trends, with the exception of some slightly anomalous that samples were detrended using spline functions. The detrended series were finally processed to produce the mean standard chronologies (STD) using bi-weight mean methods. Therefore, the four ring-width chronologies from 4 sites were established (Figure 2).

3 Maximum and minimum temperatures reconstructions

3.1 Reconstruction of the minimum temperature in the winter half year

Correlation analyses between meteorological records

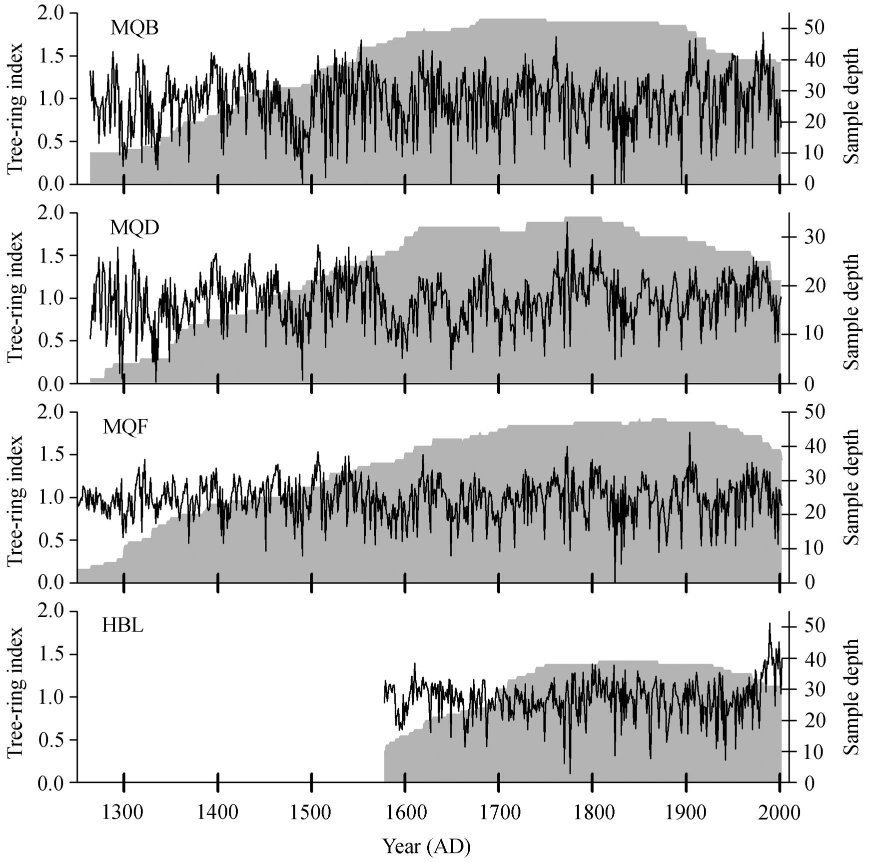

Figure 2 Chronologies (MQB, MQD, MQF and HBL) and their corresponding sample depths.

and ring-width indices showed that HBL chronology, which was located at the lower forest limit near Hebei of Tongde, was most highly correlated with the minimum temperature at Xinghai meteorological station (Figure 3). This sampling site is located at the eastern boundary of Xiqing Mountain where the rainfall is relatively abundant. No significant correlations were found between ring-width indices and precipitation (Figure 3). However, the minimum temperatures in the winter half year (previous October to current April) correlated significantly with ring-width indices, suggesting that the minimum temperature in the winter half year was the limiting factor for tree-growth[16].

The highest correlation occurred between previous autumn and winter temperatures indicating that the minimum temperature within that time span is closely related to tree-growth. Some possible interpretations may account for the results: firstly, trees can accumulate carbohydrate through photosynthesis for the tree-growth of the next year; secondly, the trees from high-elevation environments tended to be limited by minimum temperatures, even during dormancy of the trees in winter; the extremely lower temperatures can also cause, for example, roots and trunk to be mechanically destroyed, inhibiting tree-growth the next year; finally, severely low minimum temperatures in winter form a much deeper frozen earth and thus delay the time of thawing, the growth-season would be shortened and subsequently result in narrow rings.

Based on the above correlation analyses, Gou et al.[16] reconstructed the minimum temperatures in the winter half year (previous October to current April) for nearly 425 years (Figure 5) using the standard chronology (STD) of HBL and observed records from Xinghai meteorological station. The reconstruction can explain 39.7% of the observed minimum temperature variances in the winter half year during the common period from 1960—2001. The comparisons between the reconstruction and observed data over the common period (from 1960—2001) indicated that the reconstruction agrees well with the observed data[16]. In some cases, these data were even the same. In addition, the regression was tested using cross-verification methods. The leave-one-out method was employed to construct series that were independent of the calibration equation. Then the validity of the reconstruction equation was also tested using the sign test, reduction of error, product mean, etc. The statistical results suggested that the reconstructions were reliable[16].

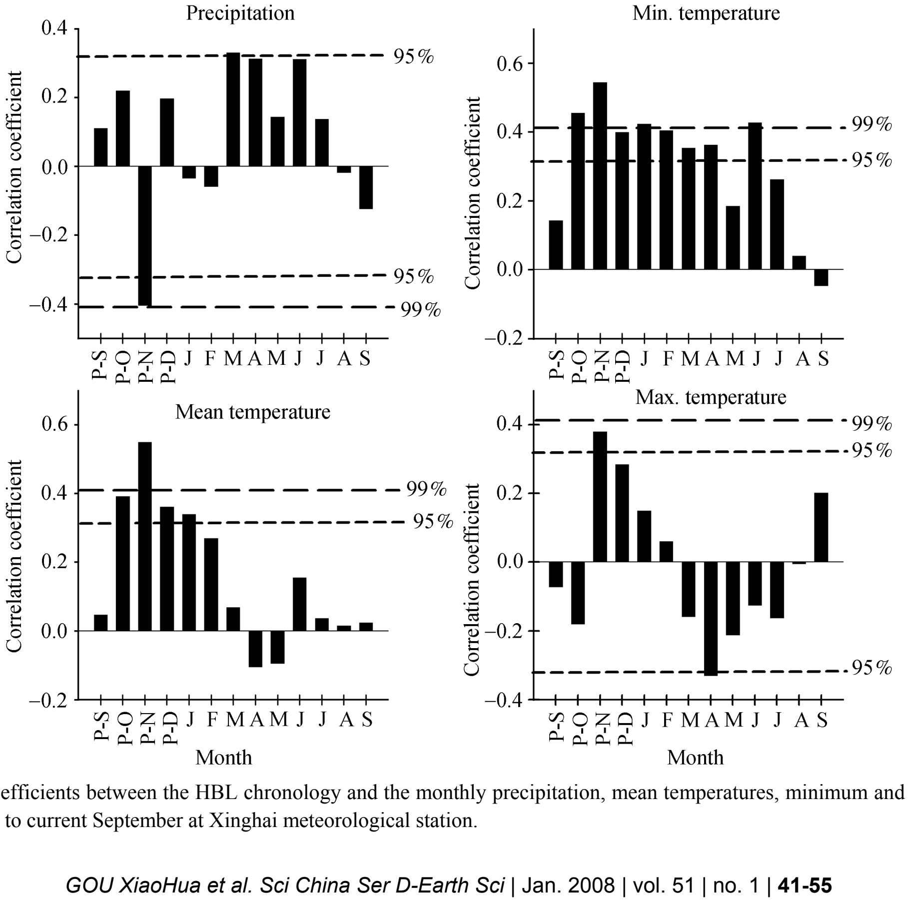

Figure 3 correlation coefficients between the HBL chronology and the monthly precipitation, mean temperatures, minimum and maximum temperatures from previous September to current September at Xinghai meteorological station.

3.2 Reconstruction of the maximum temperatures in the summer half year

Correlation analysis results indicated that the chronologies of MQB, MQD and MQF at the Maqên Mountain were significantly correlated with temperature records from four nearby meteorological stations (Madoi, Maqên, Tongde and Xinghai). In order to better reflect regional fluctuations, we calculated the arithmetic mean chronology of the chronologies of MQB, MQD and MQF. The regional average series was also calculated[46] based on the four nearby meteorological stations (Madoi, Maqên, Tongde and Xinghai) to represent regional observed data. Then the correlation coefficients between each chronology (MQB, MQD, MQF and their mean chronology) and the regional climate series were calculated. The results demonstrated that the chronologies (MQB, MQD, MQF and mean chronology) were negatively correlated with the summer half year (April to September) monthly mean temperature and monthly mean maximum temperature[47]. The correlation between the mean chronology and mean maximum temperatures (April to September) was highly significant (p<0.001). The correlation coefficient is –0.67 (Figure 4). In comparison to correlations with the maximum temperature, the correlations between chronologies and precipitation are not as good[47]. Although the precipitation in May and June is significantly correlated with the chronologies, correlation is higher between maximum temperature in May and June and the chronologies. The observed records from the surrounding meteorological stations indicate that the maximum temperature and precipitation are negatively correlated significantly (p<0.01). Higher temperature often goes with low precipitation.

The significant negative correlations between chronologies and maximum temperatures may be related to soil moisture transpiration. In some cases, temperature is not yet the limiting factor when trees grow in their peak season. However, warming temperatures might result in intensive transpiration, and may become the limiting factor when soil moistures are insufficient[12,18,29], it is thus that temperatures negatively correlate with ringwidth[48]. The Maqên Mountain is located in the northwestern A'nyêmaqên Mountains. The precipitation in the Maqên Mountain is less than that in the eastern A'nyêmaqên Mountains. The effective soil moisture in the growing season may be the limiting factor for tree growth. The higher the temperatures in the summer half year, the more intensive the soil evaporations and plant transpirations are, and this leads to worse

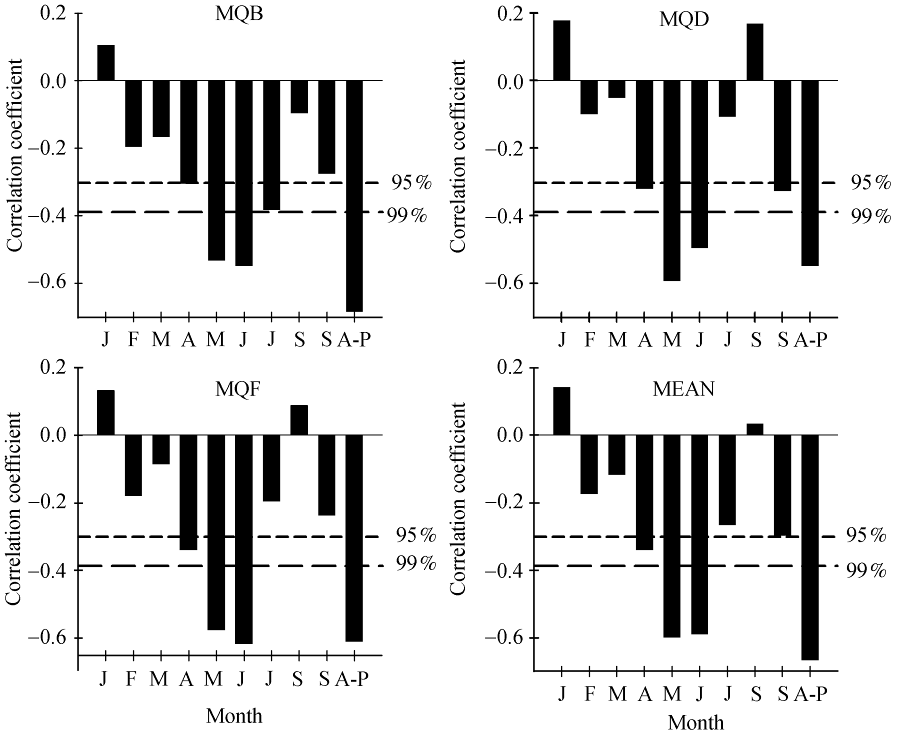

Figure 4 Correlation coefficients between the chronologies (MQB, MQD, MQF and their mean chronology) and the monthly mean maximum temperatures and their average from April to September.

conditions for tree-growth. In contrast, lower temperatures in the growing season would induce lower transpiration, and higher soil moisture conditions should favor tree-growth.

According to the above statistical analyses, the maximum temperature in the summer half year (April to September) was reconstructed by using the principal components regression model[49] based on the three standard chronologies (MQB, MQD and MQF). The reconstructions can explain 47% of the variances of the maximum temperatures during the period of 1959—2001 when the observed data were available. The reconstructions and the observed data agree well with each other[47]. Before 1982, the maximum temperatures showed a downward trend, while an upward trend was detected from 1983—2001. It is possible that tree-ring reconstructions may underestimate some extreme events[45]. Our results were also in line with this general fact, e.g. there were disagreements between reconstructions and actual data when some extreme events occurred, particularly when the maximum temperature reconstructions underestimated some extremely cold years. There were only limited meteorological records in this region (the time duration was from 1959—2001). Cross-verification was used to test the validity of the reconstruction. We used the leave-one-out method to construct a new series independent of the transform equation. The statistical methods such as sign test, reduction of error, product mean, etc. were employed. Statistical results indicated that our reconstruction was reliable[47]. Therefore, the maximum temperature in the summer half year (April to September) over the past 700 years were reconstructed (Figure 5).

4 Maximum and minimum temperatures variability

The reconstructed minimum temperature in the winter half year over the past 425 years revealed some strong low-frequent variations (Figure 5). The minimum temperatures from 1578 to 1940 displayed relatively gentle variations. There are two evident warming and cooling periods. From 1610 to 1776, the reconstructed minimum temperature decreased gradually with fluctuations. The year 1776 is the coldest (−15.41℃) in the past 400 years. During the period of 1776—1800, an abrupt rising process was observed. From 1800 to 1941, minimum temperature decreased with fluctuations. The magnitude of temperature decreasing during 1800—1941 is similar to that of the prior 200 years. However, the minimum

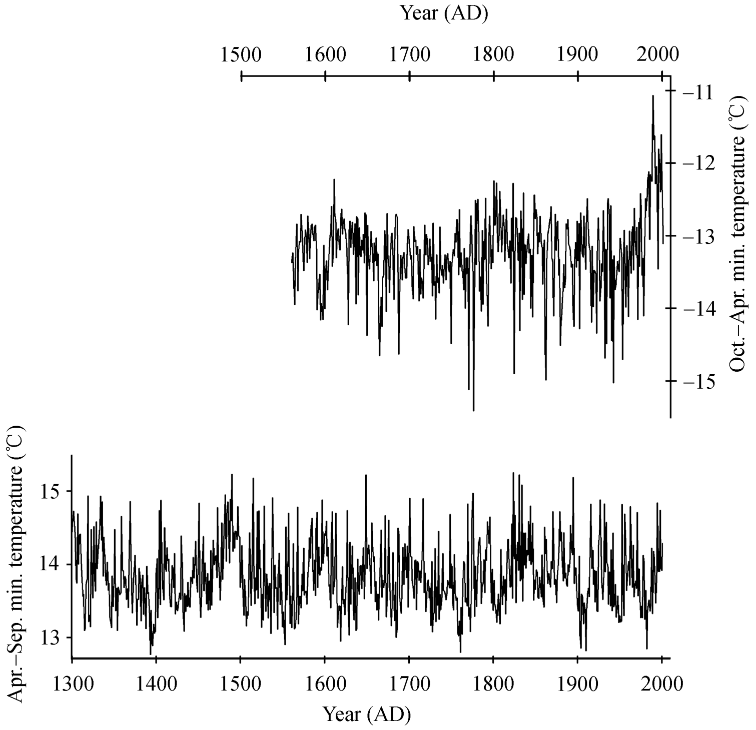

Figure 5 Reconstructed minimum temperatures in winter half year (October to April) and maximum temperatures in summer half year (April to September).

temperature increased abruptly since 1941 (p<0.001). During the 60 years from the 1940s—1990s, the minimum temperature has increased up to about 1.6℃. This is a surprisingly dramatic temperature rise.

The temperature-increasing trend since 1941 started to fall somehow around 1989. However, the mean temperature of 1980—2001 was still the highest compared with any periods over the past 400 years. Considering the mean temperature for each decade, the warmest decade was the 1800s over the period before the 1970s. However, due to the warming trend since the 1940s, the 1980s became warmer than the 1800s. Moreover, the 1990s was the warmest decade over the past 400 years. As reported by the Third Assessment Report of IPCC, on a global average, the 1990s is likely to have been the warmest decade since the beginning of the observed records in 1861. It is also likely to be the warmest decade of the past millennium in Northern Hemisphere[50]. However, Wang[33] pointed out that the evidence was not enough to make such a statement. Over the past more than 400 years, the coldest decade was the 1590s, and other three sub-coldest decades were the 1660s, 1940s and 1770s, respectively.

The tree-ring data in Mongolia and Siberia also revealed similar abrupt rise of temperatures in the 20th century[51,52]. Compared to those in Mongolia and Siberia, our reconstructions suggested the even more significant warming trend in the winter half year in headwater of Yellow River. The ice core records and the instrumental records in the Tibetan Plateau demonstrate that, compared to lower-altitude area, the Tibetan Plateau with higher elevations tended to be more sensitive to global warming[53,54]. In the Tibetan Plateau at the area above 3500 m a.s.l., the linear rate of temperature rise was 0.25℃/decade over the past 30 years. Our reconstruction suggested that the rate of temperature rise was about 0.32℃/decade in the winter half year from the 1940s to 1990s at the headwater of the Yellow River, higher than that of the mean temperature rise in the Tibetan Plateau.

Over the past 700 years, there was no evident linear trend in the reconstructed maximum temperature in the summer half year, albeit some slightly warm or cold periods were also shown (Figure 5). Additionally, no obvious warming trend since the industrial revolution was exists in our reconstructions. On the contrary, the maximum temperature showed a downward trend with fluctuations from 1824 to 1982, and the temperature has started to rise only since 1982 (p<0.05). Through inspections of our reconstructions, the coldest year is 1393, while the warmest one is 1824. The coldest decade is 1390s, while the warmest decade is 1480s. During the past 200 years, the coldest period spans from 1900 to 1910, the other two sub-coldest period were from 1970 to 1990 and 1940 to 1950, respectively. Since 1982, the maximum temperatures in the summer half year have started to rise. The temperatures in the 1990s are higher than the mean temperature of the past 700 years. Nevertheless, considering temperatures over the past 700 years, the temperatures in 1990s are not unprecedented. The temperatures in 1990s are still lower than the temperatures in the periods of the 1890s, 1820s—1840s, 1790s, 1650s, 1690s—1600s, 1480s—1490s, 1330s and 1300s.

As indicated by Figure 5, the reconstructed maximum temperature can experience dramatic change within a 10-year time scale. From the 1390s to 1400s, the decadal mean temperatures had increased by 0.73℃. From 1393 to 1404, the temperatures had risen by 1.97℃. Another abrupt warming period is from 1980s to 1990s. Relative to temperatures in the 1980s, the temperatures in the 1990s were increased by 0.63℃. Over the past 700 years, the significant cooling processes within the decadal time scale are more frequent. From the 1490s to 1500s, the temperature decreased about 0.89℃. While during the time spans of the 1330s—1340s and the 1890s—1990s, the temperatures decreased 0.74℃ and 0.73℃, respectively.

Wilson and Luckman[42] suggested that the summer maximum temperatures in Canada in the 20th century had been the highest since 1600, which was generally different from our results. But our results indicated that the minimum temperatures in the winter half year had experienced a significant warming trend since the 1940s (p<0.001), and the time period of 1980s—1990s is the warmest over the past 400 years. As suggested by observed records from nearby meteorological stations, high temperatures are negatively correlated to precipitations (p< 0.01). Higher temperatures often go with lower precipitations. This is also the case in Italy[55,56]. Some extreme drought events took place when the reconstructed temperatures are high, such as 1920—30s, 1820—30s, 1590—1600s and 1480—90s, which are also consistent with the historical archives[57]. The cold/warm periods in the reconstructed temperature are basically in line with the dry/humid periods in tree-ring reconstructions from Shepard et al.[29] in northeastern Qinghai Province.

5 Asymmetric variations between the maximum and minimum temperatures

Instrumental data showed that variations of maximum and minimum temperatures were out of phase[36−40]. Through inspections of temperature records from 369 meteorological stations in China, it was suggested that there was no evident trend for the yearly maximum temperatures in the past 40 years. However, the yearly minimum temperatures were significantly increased[39]. In northwestern China, the summer maximum temperature was decreasing from 1930 to 1990. This is the case also in Beijing[40]. No matter at regional or global scales, the minimum temperature rises much faster than the maximum temperature in the 20th century[36−40,58−64], and their variation patterns are inconsistent[37,40]. Certainly, there are some places with more significant warming trend for the spring and summer maximum temperature rise[65]. Some researchers pointed out that the decrease of the summer maximum temperature in Sichuan basin was due to the increase of aerosols[66]. Wilson and Luckman[42,43] demonstrated that when temperature was the major limiting factor, trees tended to be more sensitive to the diurnal maximum temperatures but not to the nocturnal minimum temperatures, it was thus of great importance to reconstruct not only the mean temperature but also various other temperature variables (e.g. maximum temperature, minimum temperature). The meteorological records indicated that the temperature rise was mainly due to the increase of daily minimum temperature. The magnitude of the daily maximum temperature increase is only half of the daily minimum temperature increase[62]. It is more evident for the warming trend in the Northern Hemisphere than that in the Southern Hemisphere[67], and the warming trend is mainly caused by nocturnal temperature increase[36,68]. The observed records showed that, in various places throughout China, the warming climate is mainly because of temperature rise at night or minimum temperatures rise. While the increase of the maximum temperature was not significant, even showed a cooling trend at some places[37−39].

The summer and winter half years reconstructed temperatures based on tree-ring width and the maximum temperatures in the summer half year (April to September) and minimum temperatures in the winter half-year (October to April) temperatures observed at Lanzhou (36°03′N, 103°53′E, 1517.2 m a.s.l.) and Xi’an (34°18′N, 108°56′E, 397.5 m a.s.l.) meteorological stations during the period of 1932—2001 (Figure 6) demonstrated that their respective variation trends are similar, sometimes even the same fluctuations. For the maximum temperatures, over the past 70 years, no warming trend was observed for either the reconstructions or the meteorological data from the Lanzhou. At Xi’an meteorological station, the summer half-year maximum even decreased (the linear slope is negative). Nevertheless, if we inspect variations for the entire 70-year in detail, it is not difficult to find that these three plots all declined initially and then rose over the 70 years. The maximum temperatures in the summer half year in Xi’an experienced a significant downward trend from 1933—1984 (p<0.05), and then started to increase quickly (p<0.1). The maximum temperature in the summer half year in Lanzhou showed similar variation patterns for the period of 1933—2001, and the coldest year was in 1967. For the past 70 years, the tree-ring reconstructions for the maximum temperatures in the summer half-year indicated a decrease trend with fluctuations initially, and started to increase after about 1982 when the values had already been the lowest. However, for the minimum temperatures in winter half-year, the reconstructions and meteorological records from Xi’an and Lanzhou were increasing significantly with some fluctuations (p<0.001).

There are long meteorological records, over 100 years, in Shanghai (31°10′N, 121°26′E, 2.6 m a.s.l.). Therefore the reconstructed maximum temperatures in the summer half year and minimum temperatures in the winter half year were also compared with the summer half year maximum temperature (Figure 7) and the winter half year minimum temperature (Figure 8) at Shanghai. From 1880 to 1945, the maximum temperatures in the summer half year at Shanghai increased significantly (p<0.001), and then decreased significantly. Since 1982 the temperatures started to rise again. The reconstructed maximum temperatures in the summer half year showed no evident trends for 1880—1945, but since then the trends were similar with variations in meteorological records at

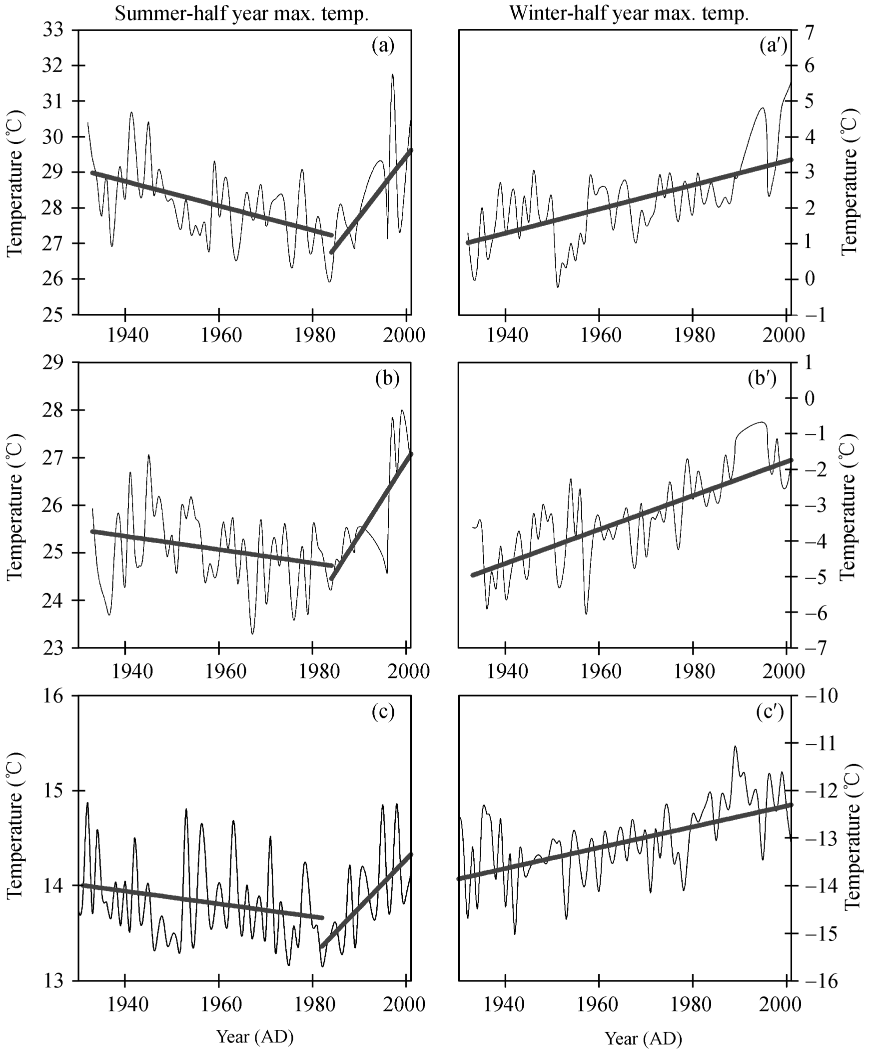

Figure 6 Comparisons between the summer half year (April to September) maximum temperatures at meteorological stations at Xi’an (a), Lanzhou (b), reconstructed maximum temperature (c) and the winter half-year (October to April) minimum temperatures at meteorological stations at Xi’an (a′), Lanzhou (b′), reconstructed minimum temperature (c′).

Shanghai. From 1945 on, the temperature started to decline, and after about 1982, it started to rise again. As for the minimum temperatures in the winter half year (Figure 8), over the past 120 years, both the reconstructions and meteorological records at Shanghai experienced a rising trends (as indicated by the dotted line in Figure 8). But if we re-examine the subsections, the minimum temperatures in the winter half years decreased from 1880 to 1918, and initiated to increase after 1918. The reconstructed minimum temperatures in the winter half year underwent a decline trend for 1880—1941, and rose abruptly from 1941.

The relationships between maximum and minimum temperature variations are complex. Not only the rising amplitudes may be different from each other[36,39,40,62,68], their variation trends can also vary[37], even sometimes are inverse[38,40]. With regard to longer-term climatic change, what are the relationships between maximum and minimum temperatures on earth, and how do they response to global change? Due to the limitations of the short observed data sets, it is difficult to answer these questions using only the instrumental records. Fortunately, the minimum and maximum temperatures over the time duration of 400 years were reconstructed based on the tree-ring widths. Thus, it is possible to address these questions in detail.

The reconstructed minimum and maximum temperatures demonstrate that there are differences between the variation trends of the maximum and minimum temperatures over the past 425 years (Figure 5). The mini-

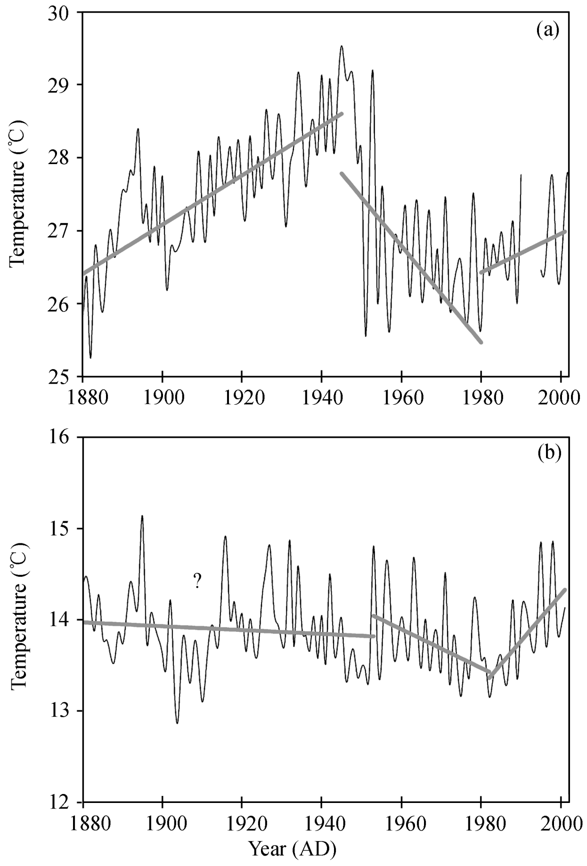

Figure 7 Comparisons between the summer half year (April to September) maximum temperatures at Shanghai meteorological station (a) and reconstructed summer half year maximum temperature (b).

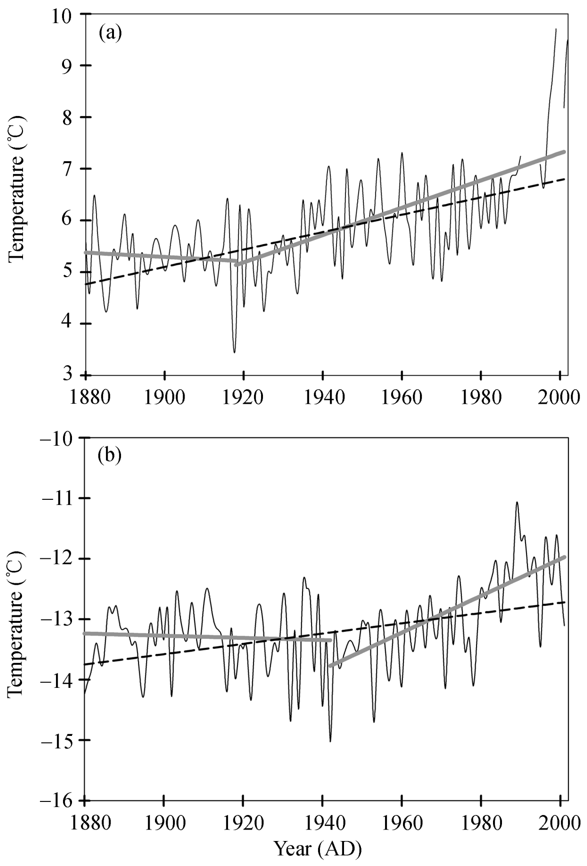

Figure 8 Comparisons of the winter half year (October to April) minimum temperatures at Shanghai meteorological station (a) and the reconstructed winter half year minimum temperature (b).

mum temperatures increased dramatically over the recent 60 years. Such increasing amplitude is beyond any period in the past 425 years. However, the increasing of the maximum temperatures is not that significant, and is much later. Only after about the 1980s, the temperatures started to increase. However, the increasing amplitude is less than that of the minimum temperature. Before the 1940s, the minimum temperatures experienced a slightly decreasing trend. The minimum temperatures decreased by roughly 0.4℃ for the time period of 1800—1940. At the same time, the maximum temperatures also underwent a significant downward trend. Lagging behind the minimum temperatures by about 25 years, the maximum temperatures started to decrease. After experiencing a 150-year decreasing trend from 1824 to 1980, the maximum temperature began to increase. During the 150-year temperature decrease, the maximum temperatures had fallen by about 0.5℃. Both the decreasing amplitude and duration are larger than that of the minimum temperatures for the corresponding periods. Before this temperature-decreasing period, lasting about 150 years, both the maximum and minimum temperatures had undergone an abrupt temperature rise for about 30 years. The 30-year rise with a magnitude of about 0.4℃ for minimum temperature was during the time span of 1770—1800 and for maximum temperatures was during the time duration of 1800—1825, lagging about 25 years. For the 200-year period of 1600—1800, the maximum temperatures decreased by about 0.5℃; while the minimum temperatures declined by about 0.5℃ with fluctuations for the 160-year period from 1610—1770. Based on analyses above, it is concluded that although there are some disagreements between high-frequency variations of maximum and minimum temperatures, the low-frequency variations agree well with each other but with lags in phases. The trends of maximum temperatures lag behind those of minimum temperatures.

Therefore, based on 11-year running average since 1578, the lagging correlation coefficients of the minimum temperatures in the winter half year and the

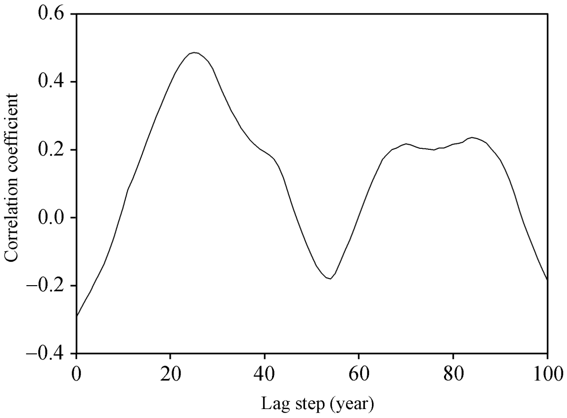

Figure 9 Lagged correlation coefficient of the reconstructed maximum temperatures in summer half-year and minimum temperatures in winter half-year. The lagged step is the years of the maximum temperature lagging behind the minimum temperature.

maximum temperatures in the summer half year were calculated (Figure 9). It demonstrated that when the maximum temperatures lagged behind the minimum temperatures in 25 years, the correlation coefficient is the highest (0.49), indicating that the variations of the maximum and minimum temperatures were highly consistent.

Taking into account the maximum temperatures lagging behind the minimum temperatures in 25 years (Figure 10), the variations of maximum and minimum temperatures coincide with each other very well, and low-frequency variations are also very consistent. Both maximum and minimum temperatures underwent temperature increase and temperature decrease periods. The two also showed similar patterns of more rapid temperature increase while relatively slower temperature decrease. More interestingly, as seen from Figure 10, the minimum temperatures started to rise abruptly after 1941, while the maximum temperatures only began to increase after the 1980s. If such a lag relationship of the past 425 years between maximum and minimum temperatures continues to take effect for the next 30 years, then it is natural for us to predict that the maximum temperatures will continue to increase dramatically in the next 30 years. Should this prediction indeed take in effect, the ecological environment changes induced by the increase of maximum temperatures may be dramatic.

Since transpiration is directly related to maximum temperatures in the summer half year, the increase in maximum temperatures would result in dramatic increasing of transpiration, declining of soil moisture, and thus causing tremendous changes of local moisture regimes. Crucial for tree-growth are the soil-moisture conditions during the transitional period from later spring to early summer, also regarded as the beginning of tree-growth season. Insufficient soil moisture during this period can directly influence the plant growth conditions, and finally cause vegetation degradation. This situation is disadvantageous for regions characterized as vulnerable ecosystems, degrading grasslands, desertification lands, and other serious ecological problems. It is thus of highly importance to conduct researches ad-

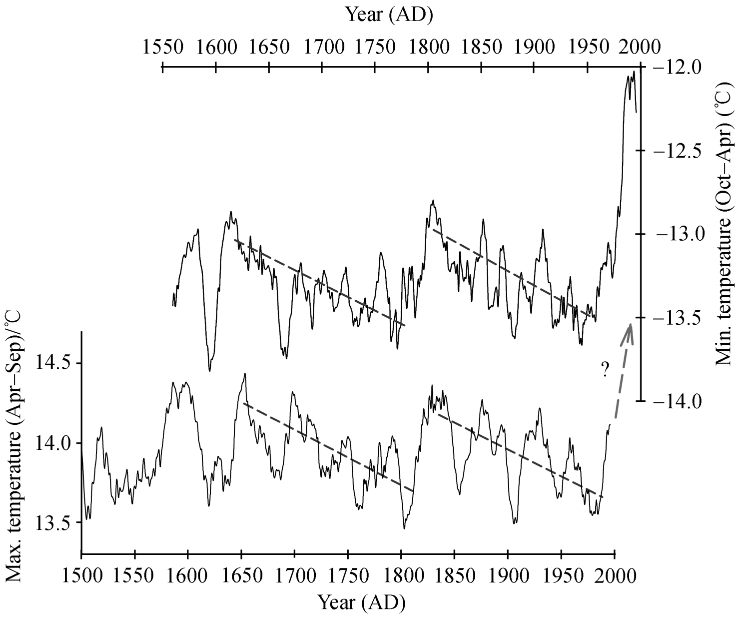

Figure 10 11-year running mean curves for reconstructed minimum temperatures and maximum temperatures over the past 425 years. The coordinate of maximum temperatures lagged behind that of the minimum temperatures in 25 years.

dressing these issues. Based on scientific studies, appropriate countermeasures should be taken to prevent the ecological conditions in the study region from further degrading, and to avoid the possible disastrous consequences in the drainage area of the Yellow River and surrounding areas induced by regional ecological systems degradation.

6 Results and discussions

We reconstructed the minimum temperatures for the winter half year and the maximum temperatures for the summer half year, by using ring-width chronologies developed from the headwater of the Yellow River in the northeastern Tibetan Plateau. The variation trends between the reconstructions and the observed data were very similar. Various verification results indicated that the reconstructions were stable and reliable.

The reconstructed minimum temperatures for the winter half year over the past 400 years indicated that minimum temperatures showed moderate variations for 1578-1940. There are two periods of significant temperature decrease (1610—1776, 1800—1941) and two temperature increasing periods (1776—1800, 1941—?). For the 60-year time span of the 1940s—1990s, the minimum temperatures increased by roughly 1.6℃, a rather high rate of temperature rises. The rising trends started from 1941 and stopped around 1989, but even after 1989, the temperature is still higher than in any time periods over the past 400 years. The 1990s is the warmest decade over the past 400 years. Unlike the variations of minimum temperatures, the low-frequency variations of maximum temperatures for the summer half year during the past 700 years are not that evident, and there are much more high-frequency variations. No significant temperature increase is observed in the 20th century. On the other hand, the maximum temperatures experienced a decreasing trend over the 160-year time period of 1824—1982. Since the 1982, the maximum temperatures have started to rise. The maximum temperatures in the 1990s are already higher than the mean temperature in the past 700 years. For the whole 700 years, however, temperature in the 1990s is not too high. Viewing the entire reconstructed maximum temperature, the lowest decade is the 1390s, while the warmest decade is the 1480s.

In the context of global warming during the recent 100 years, there are significantly asymmetric variation features for extreme temperatures in the study area. It is significantly asymmetric for the temperature variation features in the study region. The studies based on the instrumental records also suggested, in common with the reconstructions, that the variation of the extreme temperature is asymmetric in northwestern China, and even in whole China mainland[39,40].

The asymmetric variation of extreme temperatures and the induced decrease of the daily range of the temperature can inevitably result in significant changes of the ecological environment in the headwater of the Yellow River which is characterized as an arctic-alpine arid region. Recent researches stated that the deteriorations of ecological conditions were often closely tied with the regional temperatures rise[69]. Then what are the responses of regional ecological conditions to the temperature variations in the headwater of the Yellow River? Furthermore, what is the future scenario in the study region? And what are the adjustments of these components, involving the glaciers, snow, permafrost, as well as the fauna and flora, in response to temperature change? How much do the climatic changes contribute to the deteriorations in ecological conditions? These are the key scientific issues with regard to the national economy and people’s livelihood, and need to be further examined by modeling. Thereby, appropriate countermeasures could be established.

Our results also indicated that, at low-frequency variation trends, the variation features of the minimum and maximum temperatures were similar, however with differences in phase. The variation of the minimum temperatures precedes the maximum temperatures for about 25 years. If this lag-variation relationship in the past 425 goes on in the next 30 years, the maximum temperatures in the study region will dramatically increase. If this really takes into effect, it is not difficult to imagine that the mountain glaciers and permafrost, which are strongly affected by summer temperature, will surely experience tremendous changes. The glaciers will rapidly retreat and the permafrost will degrade. Meanwhile, due to the dramatic increase of the maximum temperature, the transpiration in the study area will be intensified. The effective soil moistures will decrease and lead to further deterioration of the regional ecological environment. Regional moisture recycles would be changed and the hydrological processes would consequently be altered. The streamflow of the Yellow River would be reduced. Then not only the headwater but also the entire drainage area of the Yellow River would be affected by climatic changes. At present, the streamflow reduction of the Yellow River has already resulted in stress on the electrical power system of northern China, substantial economic losses, and huge inconvenience for the industrial and agricultural productions in the lower reaches of the Yellow River. If such conditions keep on deteriorating, streamflow reduction of larger area and longer term may occur. Therefore, the losses in ecology, economy, and society caused by climatic change could be of great severity.

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