Tree-ring-based reconstruction of temperature variability (1445–2011) for the upper reaches of the Heihe River Basin, Northwest China

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Abstract: Long-term temperature variability has significant effects on runoff into the upper reaches of inland rivers. This paper developed a tree-ring chronology of Qilian juniper (*Sabina przewalskii* Kom.) from the upper tree-line of the middle Qilian Mountains within the upper reaches of Heihe River Basin, Northwest China for a long-term reconstruction of temperature at the study site. In this paper, tree-ring chronology was used to examine climate-growth associations considering local climate data obtained from Qilian Meteorological Station. The results showed that temperatures correlated extremely well with standardized growth indices of trees ($r=0.564$, $P<0.001$). Tree-ring chronology was highest correlated with annual mean temperature ($r=0.641$, $P<0.0001$). Annual mean temperature which spans the period of 1445–2011 was reconstructed and explained 57.8% of the inter-annual to decadal temperature variance at the regional scale for the period 1961–2011. Spatial correlation patterns revealed that reconstructed temperature data and gridded temperature data had a significant correlation on a regional scale, indicating that the reconstruction represents climatic variations for an extended area surrounding the sampling sites. Analysis of the temperature reconstruction indicated that major cold periods occurred during the periods of 1450s–1480s, 1590s–1770s, 1810s–1890s, 1920s–1940s, and 1960s–1970s. Warm intervals occurred during 1490s–1580s, 1780s–1800s, 1900s–1910s, 1950s, and 1980s to present. The coldest 100-year and decadal periods occurred from 1490s–1580s and 1780s–1800s, respectively, while the warmest 100 years within the studied time period was the 20th century. Colder events and intervals coincided with wet or moist conditions in and near the study region. The reconstructed temperature agreed well with other temperature series reconstructed across the surrounding areas, demonstrating that this reconstructed temperature could be used to evaluate regional climate change. Compared to the tree-ring reconstructed temperature from nearby regions and records of glacier fluctuations from the surrounding high mountains, this reconstruction was reliable, and could aid in the evaluation of regional climate variability. Spectral analyses suggested that the reconstructed annual mean temperature variation may be related to large-scale atmospheric–oceanic variability such as the solar activity, Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO).

Keywords: tree-ring; climatic response; temperature reconstruction; upper reaches of Heihe River Basin

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Climate change has a significant impact on the processes of water resources and ecosystems in arid regions, especially in Northwest China (Stewart et al., 2004; Chen et al., 2010; Xu et al., 2011). Climate warming would speed global water cycle and strengthen rainfall and evaporation (Shi et al., 2002). The different warming conditions and the change of atmospheric oscillations will consequentially result in changes in the distribution of precipitation and runoff. The ascending of temperature in a mountainous area will accelerate snow melting, and therefore make surface flow and ground water increase (Li et al., 2006). Likewise, it will cause reduction of river flow by evaporation under the same precipitation condition in a plain area (Shi and Zhang, 1995; Gong and Wang, 2000). Therefore, temperature change has a significant effect on runoff in inland river areas, and it is also important for maintaining downstream ecosystems (Li et al., 2010; Zhou et al., 2010).

The Heihe River Basin is the second largest arid inland drainage basin in Northwest China. It is located in the transition zone between the monsoon and westerlies, and is important because of its ecological fragility and climatic sensitivity (Wang et al., 2003). The natural ecological environment in the Heihe River Basin has encountered serious degradation due to global climate change and human activities (Ma et al., 2005). Ecological environment in the upper reaches of a river is key to the protection of the whole watershed (Kundzewicz et al., 1997). There is a close relationship between the surface runoff and the air temperature in the upper reaches of Heihe River Basin, and the variation in air temperature will affect the socio-economic development and wildlife habitats in the Heihe River Basin to a certain extent (Kang et al., 1999). For this reason, researches on the variation characteristics and the trend of temperature has great significance to the future planning, utilization and management of water resources in the upper reaches of the Heihe River Basin.

However, most instrumental meteorological records in arid regions, especially in Northwest China, are less than 60 years, which is too short for investigating multi-decadal or longer-term climate variability (Yang et al., 2010). Hence, it is difficult to evaluate the characteristics of climate changes in the past. An enhanced understanding of past climatic variability in arid regions must rely on climatic proxies. Tree-ring is a valuable tool for the study of climate variability beyond the short period normally covered by instrument-recorded data, because of their easy availability, high resolution, and reliability (Fritts, 1976). So, time series of tree-ring growth measurements spanning several centuries serve as proxy records of past climatic conditions (Cook et al., 1999). The annual growth of a tree is the net result of many complex and interrelated biochemical processes. Trees interact directly with the microenvironment of their leaves and root surfaces. The fact that there exists a relationship between these extremely localized conditions and larger scale climatic parameters offers the potential for extracting some measures of the overall influence of climate on growth from year to year (Bradley, 1985). Growth of trees may be affected by many aspects of the microclimate, such as sunshine, precipitation, temperature, wind speed, and humidity (Fritts, 1976; Bradley, 1985). Long-term records produced by tree-ring studies have been used to extend these limited meteorological records, and can serve to evaluate the past frequency and severity of climatic anomalies (Pederson et al., 2001; D'Arrigo et al., 2003; Liu et al., 2009; Mann et al., 2009; Cook et al., 2010; Davi et al., 2010) and help anticipate the future probability of such events. Several tree-ring-based climate reconstructions have been developed in China (Zhang et al., 2003; Liu et al., 2004, 2006; Shao et al., 2005; Wang et al., 2005; Liang et al., 2006; Gou et al., 2007; Yuan et al., 2007; Cai et al., 2010; Li et al., 2012). The Qilian mountainous area, where patched forests of long-lived Qilian juniper (*Sabina przewalskii* Kom.) grow, has particularly been of recent interest for tree-ring studies in China (Kang et al., 1997, 2000; Shao and Fan, 1999, 2005; Zhang et al., 2003; Sheppard et al., 2004; Shao et al., 2005; Liu et al., 2005, 2006, 2009; Gou et al., 2008; Yang et al., 2010). As the upper reaches of Heihe River Basin, the middle Qilian Mountains had a multitude of tree-ring chronologies developed, which have revealed the variation of temperature, precipitation, drought, and runoff in the historic period (Kang et al., 2002, 2003; Gou et al., 2005; Liu et al., 2005, 2009; Tian et al., 2007; Liang et al., 2009; Chen et al., 2011; Qin et al., 2011; Yang et al., 2011; Zhang et al., 2011). However, most of the

chronologies are used to reconstruct precipitation, runoff, and drought events. Long-term climate records for temperature variability still remain lacking in the upper reaches of Heihe River Basin.

In this study, a new temperature reconstruction, which derived from a new tree-ring-width chronology of Qilian juniper, was reported for the middle Qilian Mountains in the upper reaches of Heihe River Basin. Variations in terms of tree-ring width, geographical position, and characteristics and climate response patterns of the tree-ring were analyzed. The most responsible climate for tree radial growth was then identified and past climate changes were reconstructed using well calibrated and verified tree growth–climate relationships. The results were compared with previously developed temperature reconstructions from the surrounding regions. This reconstruction should improve our understanding of climate variability in this high and remote region.

1 Study area and methods

1.1 Sampling site

A tree-ring-width chronology was developed using increment cores extracted from Qilian juniper trees growing in the middle Qilian Mountains (Fig. 1). As the upper reaches of Heihe River Basin, the middle Qilian Mountains are sensitive to climate change (Wu and Shao, 1995). The tree growth is mainly limited by temperature at the upper tree-line and by precipitation at the lower tree-line (LaMarche, 1974; Fritts, 1976; Tessier et al., 1997). The tree-ring sampling site was located at the upper tree-line in the middle Qilian Mountains, which was higher in elevation and receives comparatively more precipitation than previous sampling sites. In alpine areas, temperatures are usually decreasing with increasing elevation, while precipitation usually increases (Glickman, 2000). Therefore, samples were collected from trees found growing in an alpine forest located between 3,246 and 3,484 m asl on southeast- and east-facing slopes adjacent to the Yuanbai valley of the middle Qilian Mountains (38°01'08"N, 100°04'03"E; Fig. 1). The tree-ring cores were collected from the dominant Qilian juniper, a tree species that has been widely used in dendroclimatology and dendrohydrology (Kang et al., 2002; Tian et al., 2007). The dominant tree species at the sampling site appeared healthy and were relatively isolated at and close to their upper limit. The trees grew under poor soil conditions, and the forest stands were rather open. The soils are generally shallow and poor in organic matter (Sheppard et al., 2004). Field measurements and sampling were carried out in June 2012.

1.2 Tree-ring sampling and data analysis

Standard 5-mm increment cores were taken from living trees, stumps, and logs. The trees were sampled at breast height with an increment borer. A total of 104 cores or sections were taken from 52 trees within a range of nearly 8.5 km. All cores were mounted, air-dried, sanded, and cross-dated using standard dendrochronological methodology (Stokes and Smiley, 1968). The LINTAB 6 measuring system was used to measure tree-ring widths for all series. The width of each annual tree-ring was measured to the nearest 0.01 mm. The measurements and visual cross-dating underwent quality control using the International Tree-Ring Data Bank software program COFECHA (Holmes, 1983).

The tree-ring-width series were standardized using the program ARSTAN (Cook, 1985). A double-detrending method was used to enhance the climate signal contained in the tree-ring-width series by reducing the noise caused by biological growth trends and endogenous disturbance events (Cook and Kairiukstis, 1990). The initial detrending was completed by fitting an exponential or linear regression curve of any slope to each individual tree-ring-width series. A secondary detrending was accomplished by fitting a cubic spline with a 50% frequency-response cutoff equal to 67% of each series length (Cook and Kairiukstis, 1990). After detrending, individual series of each tree were averaged into single tree indices. This detrending method was able to remove long-timescale variance but could retain variance over periods up to a century using these trees. Only the prewhitened residual tree-ring-width series

were used for further analysis.

The Expressed Population Signal (EPS) statistic was used to determine the change in chronology quality that occurred as sample size varied through time (Wigley et al., 1984; Briffa and Jones, 1990). EPS value was calculated using a 30-year moving window with 15-year overlaps to determine the most suitable parts for climate reconstruction. The tree-ring-width chronology was truncated at the decade interval, in which the running EPS fell below the standard value of 0.85, as proposed by Wigley et al. (1984).

Fig. 1 Locations of the sampling site and the meteorological station

1.3 Climate data

The study area is characterized by a semi-arid continental climate and affected by the Tibetan Plateau climate (Liu et al., 2006). The climate in the upper reaches of Heihe River Basin is dominated by westerly flow and partially affected by the southerly monsoon (Wang et al., 2003). Climate data from nearby regional meteorological stations were obtained from the China Meteorological Data Sharing Service System (<http://www.esiience.gov.cn/metdata/page/index.html>). Monthly temperature and precipitation records were obtained from the Qilian Meteorological Station (38°01′08″N, 100°02′05″E; 2,787.4 m asl), which was the closest meteorological station (Fig. 1). The annual mean temperature during the period 1961–2011 was 1.1°C, with a monthly mean minimum in January and maximum in July. The mean annual precipitation was 405.7 mm, and the precipitation between June and August accounted for 90% of the annual precipitation (Fig. 2). The annual mean relative humidity was 46.5%, with an equable distribution in each month.

To demonstrate that tree-ring chronology and the climate records reflect large-scale climate variability, we correlated the measured data with the regional monthly gridded climate dataset

obtained from the high-resolution 0.5°-gridded climate data set CRU TS 3.1 (Mitchell and Jones, 2005). The historical monthly temperature data for the region were defined by grid coordinates 80°–120°E and 30°–50°N for the period 1961–2005. The analyses were achieved using the KNMI climate explorer, a web-based collection of climate data analysis tools maintained by the Royal Netherlands Meteorological Institute (Royal Netherlands Meteorological Institute; <http://climexp.knmi.nl>).

Fig. 2 Monthly mean temperature and monthly precipitation for the Qilian Meteorological Station during the period 1961–2011

1.4 Analysis methods of climate-growth responses

Pearson's correlation analysis, bootstrap correlation and bootstrap response function analysis were used to explore the climate-growth relationships between the tree-ring-width indices and the climate factors using Dendroclim 2002 software (Biondi and Waikul, 2004). A 95% confidence interval was used to determine the statistical significance of the correlations. The tree-ring-width chronologies were compared with a 17-month window of climate data spanning the period from May of the previous year through September of the current growing season. Climate data used for the bootstrap response function and correlation analysis included monthly mean temperature and total monthly precipitation. The tree-ring-width chronologies were also compared with the temperature and precipitation over various multi-month seasons and a full-year scale.

1.5 Temperature reconstruction and verification methods

Linear regression models were used to construct the past values of climate variables based on the tree-ring-width chronologies. The reliability of the regression models was evaluated by statistics on calibration and verification periods and by employing leave-one-out cross verification method (Michaelsen, 1987). A split period verification analysis was deemed inappropriate due to the short length of the instrumental climate record (Gordon, 1982; Michaelsen, 1987). The following statistics were used to evaluate the quality of the reconstruction: Pearson correlation coefficient (r), explained variance adjusted for loss of degrees of freedom (adjusted R^2), the reduction of error (RE) statistic for validation, and coefficient of efficiency (CE) (Fritts, 1976; Cook et al., 1999). The values of CE are normally lower than those of RE except that its benchmark for determining model skill is the verification period and not the calibration period, which demonstrated CE is more rigorous than RE. These tests proved the validity of the regression model. Once the final regression model was successfully validated, it was calibrated on the full instrumental period (1961–2011) used for the final reconstruction model.

1.6 Multi-taper method spectral analysis

The variability of the temperature reconstruction in the frequency domain was examined using the multi-taper method (MTM) of spectral analysis (Mann and Lees, 1996). MTM is non-parametric. It uses a series of tapers that reduce the variance of spectral estimates, which is an advantage over other spectral window methods (Percival and Walden, 1993).

2 Results

2.1 Tree-ring chronology

Ninety-two ring-width series from 46 individual trees were included in the final analysis (Table 1). The mean sensitivity, which is a measure of the relative differences in width between adjacent tree-rings, was 0.30. The first order auto-correlation was 0.65, suggesting that Qilian juniper tree-ring growth in one year influenced its growth in the following year. The average correlation among tree-ring series was 0.72, indicating that the tree-ring chronology contained common growth-limiting signals, most likely the large-scale climate signal. The chronology spanned the period from 1395 to 2011 (Fig. 3). Based on EPS statistics (Wigley et al., 1984), the chronology was considered reliable when the sample size exceeded 7 cores, corresponding to the period from 1445 to 2011. The mean segment length of the chronology was 566 years, indicating its ability to resolve interannual- to interdecadal-scale tree growth variations that are likely related to climate change (Cook et al., 1994).

Table 1 Statistics for the residual tree-ring-width chronology

Statistical item	Standard dendrochronological (STD)
Mean sensitivity	0.303
Standard deviation	0.171
First-order autocorrelation	0.650
Mean correlations among all series	0.720
Mean correlations between trees	0.529
Expressed population signal (EPS)	0.980
First year where EPS>0.85 (No. of cores)	1,445 (7)

Fig. 3 Standard tree-ring-width chronology and sample size of Qilian juniper in the middle Qilian Mountains (the red curve superimposed on the tree-ring-width indices is an 11-year smoothing line) from 1395 to 2011

2.2 Climate-growth relationship

Consistent relationships between tree growth and climate variables (monthly average temperature and precipitation) through time and across plots are shown in Fig. 4. The relationship between tree-ring-width and temperature showed a positive correlation, while the correlations between tree-ring-width and monthly precipitation totals were relatively weak. All temperatures were associated with positive growth responses except in the previous August. Correlation analysis results demonstrated that temperature is the limiting climate factor most strongly associated with tree growth at the upper tree line. Significant positive correlations ($P < 0.05$) with temperature in May ($r = 0.302$) and September ($r = 0.323$) of the previous year were weaker, and those in January, February, March, April, June, July, and August of the current year were higher (r values from 0.486 to 0.598). The highest correlation was found between tree ring and annual mean temperature ($r = 0.641$, $P < 0.001$). Therefore, annual temperature was used as the climate variable for reconstruction.

Fig. 4 Correlation coefficient (a) and bootstrap response coefficient (b) of standard chronology with mean temperature and precipitation measured at the Qilian Meteorological Station from 1961–2011. The prefix “p” and “c” in horizontal axis denotes previous year and current year, respectively. The asterisks indicate significant correlation at the 95% confidence level.

2.3 Temperature reconstruction

Basing on the results of the growth-climate analysis, we used a simple linear regression function to reconstruct annual mean temperature for the upper reaches of Heihe River Basin: $T = -0.673 + 2.689W$. Where T is the annual mean temperature and W is the tree-ring index.

Reconstruction accounted for 57.8% (Fig. 5a) of the actual temperature variance over the common calibration period (1961–2011) of the tree-ring chronology and temperature data. The reconstructed temperatures closely matched the instrumental record. Although the explained variance is not very high, low-frequency as well as high-frequency temperature variations were adequately captured by the reconstruction. It is seen that the significant increase during 1961–2011 recorded in observed instrumental temperatures were captured by estimated values derived by the reconstruction model. The reconstruction closely tracks the observed temperatures (Fig. 5b) and the decreasing sensitivity to temperature. All the values of R^2 , R_{adj}^2 , F , and P in Table 2 are quite close to the values of the original dataset. These indicated that the regression model was stable and reliable during the calibration period. The validation results showed that the reconstruction was reliable because RE and CE had positive values and the values of CE normally were lower than those of RE. Correlation coefficients for the split-sample validation periods were also large and significant, exceeding the 99% confidence level. These results demonstrated the reliability of the regression model.

The annual mean temperature in the study area for the 1395–2011 period was then reconstructed based on the above model (Fig. 5c). Because the EPS value of the tree-ring chronology was above 0.85 for the period 1445–2011, the reconstructed temperature for this period should be interpreted. The annual mean temperature for the 1445–2011 period is 0.99°C , with a standard deviation of 0.21°C . The reconstructed temperature series for the last 566 years showed annual to multi-year fluctuations punctuated with cool and warm periods. In the warm-cold criteria of $\text{mean} \pm \text{SD}$, the mean value for “cold” is less than 0.78°C , and the mean

value for “warm” is more than 1.2°C . There were 85 cold years (15.02%), 88 warm years (15.55%), and 393 normal years (69.43%) defined during the entire period.

Table 2 Statistics of different calibration and verification periods for the regression model

	Calibration (1961–1986)	Verification (1987–2011)	Calibration (1982–2011)	Verification (1961–1981)	Full calibration (1961–2011)
R^2	0.61	0.57	0.53	0.57	0.578
R_{adj}^2	0.59	0.56	0.50	0.56	0.569
F					15.12
P					0.001
RE	0.84		0.81		0.58L
CE		0.42		0.37	

Note: R^2 , variance explained by the regression model; R_{adj}^2 (adjusted R^2), variance explained adjusted for loss of degrees of freedom; F , F statistic for the statistical significance of the regression models; P , P -value is a function of the observed sample results (a statistic) that is used for testing a statistical hypothesis; RE, reduction of error statistic; CE, coefficient of efficiency; L, the leave-one-out verification.

Fig. 5 Correlation of actual and reconstructed annual mean temperatures during the period of 1961–2011 (a); comparison of actual and reconstructed annual mean temperatures from 1961 to 2011 (b); tree-ring reconstruction of annual mean temperature, plotted annually (thin line) from 1462 to 2011, along with a smoothed 11-year moving average (thick line) (c).

Reconstruction of the annual mean temperature revealed lower temperatures from 1445 to 1482, followed by a warmer period from 1483 to 1567. There has been a general cooling trend since 1540s, with pronounced cooling from 1570 to 1890. Although punctuated by a slim cold interval since 1540s, a persistently warm episode occurred in 1640s–1670s, which lasted about 30 years and was the most notable warm anomaly in the reconstruction. During the last warm period (from 1987 to present), the temperatures for all the years were above the long-term mean. The 20th century is the warmest hundred years (mean temperature (T_{em})= 1.97°C), and 1990–2011 was the warmest period (T_{em} = 2.41°C) during the past 566 years. The warmest 100- and 10-year periods before the 20th century were 1480–1570 (T_{em} = 2.29°C) and 1650–1660 (T_{em} = 2.23°C),

respectively, and the coldest 100- and 10-year periods were 1800–1899 ($T_{em}=1.95^{\circ}\text{C}$) and 1642–1651 ($T_{em}=1.92^{\circ}\text{C}$), respectively. After a 30-year moving average, the reconstruction showed that the cold and warm intervals appeared to be alternative on a decadal scale. Several cold episodes occurred during 1450s–1480s, 1590s–1770s, 1810s–1890s, 1920s–1940s, and 1960s–1970s. Marked periods with high temperatures occurred during 1490s–1580s, 1780s–1800s, 1900s–1910s, 1950s, and 1980s to present. The years that had five top high-temperature extremes (anomaly ≥ 2 STD) were 1486, 1525, 1528, 2006, and 2010. The reconstructed temperature had five cold extremes in 1763, 1824, 1857, 1861, and 1962.

2.4 Spatial representativeness of the reconstructed temperature

To demonstrate that our reconstruction and instrumental records reflected regional-scale temperature variability, we correlated these data with the CRUTs 3.1 dataset (Mitchell and Jones, 2005). The reconstructed temperature was significantly correlated with the annual mean temperature over large areas of the upper reaches of Heihe River Basin (Fig. 6a). It is demonstrated that the highest correlation coefficients were concentrated mainly in the upper reaches. Although correlations were lower for the actual temperature, the spatial pattern of the correlation is quite similar to that of the instrument-recorded data (Fig. 6b). The results showed significant correlations with gridded climatic variables on a regional scale, indicating that the reconstruction represents climatic variations for an extended area surrounding the sampling sites, and even a larger territory in northeastern Tibetan Plateau. The annual mean temperature reconstruction in the upper reaches of Heihe River Basin can also provide base data for historical droughts analysis, water resources planning, and management in the arid inland drainage basin or even to a greater extent.

Fig. 6 Spatial correlations of reconstructed (a) and instrument-recorded (b) annual mean temperatures with the concurrent CRU3.1 land temperature grid dataset over their overlapping periods for the period 1961–2005

3 Discussion

3.1 Growth–climate response

Tree growth–climate relationship analysis indicated that except August of the previous year, all the temperatures in the other months had positive correlations with tree-ring data. Qilian juniper ring-width chronologies from the upper timberline were sensitive to temperature, especially in the summer season (June to September of the current year) and the winter and spring seasons (January to April of the current year) (Fig. 2). This has also been reported for other high-elevation conifers from the same area (Liu et al., 2005) and other areas, such as west Sichuan (Shao and Fan, 1999) and the eastern Tibetan Plateau (Bräuning, 2001; Gou et al., 2007; Liang et al., 2008). The strong influence of temperatures during the winter preceding tree growth is a common feature in high-altitude tree-ring series (Liu et al., 2005; Liang et al., 2006; Zhang and Qiu, 2007). This is generally explained by a shorter vegetation period after a cold winter due to the delayed melting

of soil ice and the delayed warming of the soil until temperatures of $>5^{\circ}\text{C}$ are reached, which are needed for physiological root activity, or by damage to the photosynthetic active plant mass by extremely low temperatures (Körner, 1998). The positive correlation with spring temperature is reasonable due to the fact that high temperatures in the spring season of the growth year favour the formation of early wood cells, which account for the majority of the total tree-ring width (Yang et al., 2010). At the timberline, conifer tracheids divide and enlarge during the warmest period of the growing season when a minimum temperature is a critical factor affecting cambium activity (Deslauriers et al., 2003). Phenologically, early spring is when bud germination and cell production occur and late autumn is when the growing period ends. Temperatures in spring and autumn determine the length of the growing period and the growth increment of the current year. Temperature and light are more important limiting factors than precipitation when precipitation is sufficient and the evaporation rate is low, especially in permafrost areas (Zhang et al., 2011). Low June and July minimum temperatures can even cause the formation of frost rings and missing rings as observed at the northern timberline in Obsko-Tazovskaya forest-tundra (Gurskaya and Shiyatov, 2006). Warm conditions in the late autumn might increase carbohydrate storages in the stem, and thus enhance earlywood growth in the following spring (Gou et al., 2008). However, winter temperatures have been found to constrain radial growth in different temperate species and ecosystems in eastern North America (Pederson et al., 2004). The warmer winters in regions without a regular snow pack may experience increased tree growth and carbon uptake (Groffman et al., 2001). Defoliation and bud mortality would deplete an important pool of stored carbon and reduce a tree's potential for future growth and photosynthetic capture (Lazarus et al., 2004; Misson et al., 2004). Climatic conditions of the previous year may precondition physiological processes within the tree and hence strongly influence tree growth (Bradley, 1985). Besides these, there are other non-climatic factors that may exert an influence, such as competition, defoliators and soil nutrient characteristics.

3.2 Comparison with other temperature reconstructions

To further assess the validity of our temperature reconstruction for the upper reaches of Heihe River Basin, we compared it to other temperature reconstructions from the surrounding regions within the eastern Tibetan Plateau (Fig. 1). The reconstruction was most similar to the December–April temperature reconstruction based on stable carbon isotope ($\delta^{13}\text{C}$) for the middle Qilian Mountains, about 52 km northeast of the sampling site (Fig. 7; Liu et al., 2005). For meeting the replication criterion, the two series were truncated after 1450. The two reconstructions are in good agreement with each other at the same timescales. They both fluctuated at a relatively low temperature level during the middle 15th century, and were warm during the period of the later 15th through 16th centuries. Since the 16th century, temperature fluctuation shows low values until the late 19th century. Temperature is relatively warm in the recent hundred years. The cold episodes found in this study, namely in 1450s–1480s, 1590s–1770s, 1810s–1890s, 1920s–1940s, and 1960s–1970s were in agreement with cold periods that occurred during 1440s–1500s and 1580s–1880s in the upper reaches of Heihe River Basin. The warm episodes in 1900s–1910s, 1950s, and 1980s–2011 prominent in this series matched with the warm period of 1900–2000 in the upper reaches of Heihe River Basin. However, there are some discrepancies between the two reconstructions, possibly due to the different seasonal responses of the tree-ring data used in different reconstructions.

Reconstruction preserved the inter-annual to multi-decadal annual temperature variability (Fig. 7). The temperature reconstruction from this study has several warm/cold periods that are also reflected in other tree-rings and retreat of glaciers. Cold periods such as 1590s–1770s and 1810s–1890s denoted in the present study agreed reasonably well with cold temperatures measured in the northeast Tibetan Plateau (Kang et al., 2000; Liu et al., 2005; Zhang and Qiu, 2007; Zhu et al., 2008). The most severe cold periods in other tree-ring-based temperature reconstructions correspond well to the cold/warm periods indicated here, particularly 1850s–1860s (Liu et al., 2006; Fan et al., 2009; Cai et al., 2010; Zhang et al., 2011). The extended cold episodes noted here in around 1800–1850, 1890–1930, and 1965–1995 are contemporaneous with cooling in nearly all other regions of the eastern Tibetan Plateau despite the seasonal

differences in the various temperature reconstructions, although some differences can be seen in the amplitude, persistence, and phases of cooling. Decreasing trends in tree-ring width were also detected in the winter-half-year temperature of eastern China during the periods 1750–1816 and 1863–1932 (Ge et al., 2003). Other short regional cold conditions in around 1625, 1685, and 1760 occurred synchronously in each parts of the eastern Tibetan Plateau. Two extended cold periods were found from the 1590s to 1770s and from 1810s to 1890s, and occurred during the Little Ice Age (16th–mid 19th century) (Mann et al., 1999; Mann, 2002). Specifically, the period of 1923–1947 was a low-temperature period, which caused widespread damage to natural vegetation and agriculture in eastern Qinghai province and Hexi region of Gansu province (Yuan, 1994). Frost disasters were derived from the Qilian Mountains, and pointed to the necessity of considering large temperature fluctuations during the crucial spring transitional period as a real threat to terrestrial ecosystem structure and functioning ability (Gou et al., 2005).

Fig. 7 Duration of warm and cold periods in the surrounding and other areas in different proxies. The black bars denote this study. Numerals 1–6 denote the mean temperatures from Qilian Mountains (December–April; Liu et al., 2005), Halihatu National Forest Park (September–April; Zhu et al., 2008), the Dulan region (Kang et al., 2000), eastern China (winter-half-year; Ge et al., 2003), Dunde ice-core ($\delta^{18}\text{O}$; Yao et al., 1991), and the Northern Hemisphere (annual mean; Mann et al., 1999), respectively.

The warm periods 1490s–1580s, 1900s–1910s, 1950s, and 1980s–2011 are in good agreement with compared records. The longest warm period from 1978 to 2011 is not local and has regional characteristics consistent with widespread warming (Jacoby et al., 1996, 2003; Liu et al., 2006; Wang et al., 2007; Fan et al., 2009; Sano et al., 2009; Zhu et al., 2009; Cai et al., 2010; Chen et al., 2010; Zhang et al., 2011). There is little agreement between our reconstruction and the Qamdo area (Zhu et al., 2011) during 1501–1514 and 1794–1804 periods. 1930–1960 is likely the warmest period in the last few centuries as seen in the tree-ring records, and was notable throughout the 20th century over China, especially in the southwestern part of China and on the Tibetan Plateau (Wang et al., 2004). The warming period from 1930–1960 was also detected in North Tibet, as reflected by $\delta^{18}\text{O}$ ice core records (Thompson et al., 2006; Wang, 2006; Yao et al., 2006; Kang et al., 2007), from northwestern Sichuan province of South China (Shao and Fan, 1999), East China and West China (Yang et al., 2002; Ge et al., 2003; Tan et al., 2003; Wang, 2006), and as recorded in temperature composites in the central and western Himalaya (Cook et al., 2003; Yadav et al., 2004).

However, this temperature reconstruction differed from other temperature records for the beginning and end of the change phases, as well as in the magnitudes of fluctuations, whereas they showed similar variations in warm or cold phases. This discrepancy most likely reflects the different sampling sites and local microclimate influence, the use of different instrument-recorded data, and the different calibration periods (He et al., 2013). Slightly different seasonality (Frank and Esper, 2005) and inconsistent variability between the mean, maximum, and minimum temperatures (Wilson and Luckman, 2003; Luckman and Wilson, 2005) also prevent an adequate estimation of the long-term absolute temperature amplitude. A more complete understanding of the spatial and temporal characteristics of annual temperature variability at the upper reaches of the Heihe River Basin requires more tree-ring records sensitive to annual temperatures.

3.3 Multi-taper method spectral analysis

Multi-taper method (MTM) spectral analysis was employed to examine the characteristics of temperature variability in the frequency domain (Mann and Lees, 1996). The results of the spectral analysis of MTM was performed over the full range of the reconstruction from 1445 to 2011 (Fig. 8). The MTM analysis revealed peaks at 85.7, 75.1, 46.1, 32.9, 8.1, 3.6, 2.9, and 2.1 years ($P<0.01$), and at 11.2 and 5.1 years ($P<0.05$). The MTM results indicated the existence of several important cycles for regional temperature variability. The 85.7-year mode was most significant in this reconstruction, which resembled other reconstructed temperature series (D'Arrigo et al., 2003, 2005) and suggested an influence of solar forcing (Pederson et al., 2001). One noteworthy feature of this reconstruction was that the warm episodes in 1780s–1800s and 1900s–1910s were in general agreement with the Dalton (1790–1820) and Damon (1890s–1920s) periods of low solar irradiance (Eddy, 1976). This phenomenon demonstrated the possible association between annual temperature variation in this study area and solar activity. The significant cycle at 36.6 and 28.5 years might be linked to the Pacific Decadal Oscillation (PDO, http://ds.data.jma.go.jp/tcc/tcc/products/el_nino/decadal/pdo.html) (Mantua et al., 1997), and our analyses indicated a negative correlation ($r = -0.15$, $P<0.01$) between the reconstruction and the mean annual PDO index of Mantua et al. (1997) from 1900–2011. This result is consistent with the hypothesis that a large-scale Asian tree-ring network may be able to reflect PDO signals (D'Arrigo et al., 2006). The PDO has wide-ranging impacts on global climate and marine ecosystems on a decadal time scale (Mantua et al., 1997; Mantua and Hare, 2002). In addition, as the decadal background, it can modulate seasonal and interannual climate variability. The PDO time scale is set by the baroclinic Rossby wave speed (ocean adjustment process). Under global warming, ocean stratification would enhance, Rossby waves would speed up, and the interannual and decadal variability periods might become shorter (Saenko, 2006). Significant spectral peaks were also found at 8.1, 3.6, 2.9, and 2.1 years, which fall within the “classical” ENSO (El Niño–Southern Oscillation) band of 2–8 years (Allan et al., 1996; Li et al., 2012). These high-frequency cycles may suggest teleconnections of local temperature variability with tropical ocean–atmosphere systems.

Fig. 8 Results of MTM spectral analysis of the temperature reconstruction

4 Conclusions

A tree-ring width chronology from 1395 to 2011 was developed using 92 tree-ring cores in the upper reaches of Heihe River Basin in Northwest China. The chronology was most reliable after

1445, for the period in which EPS equals 0.85. The relationships between tree-ring widths of Qilian juniper at the upper tree-line limit and climate variables were analyzed, and the tree-ring width chronology in the upper forest limit appears to be mainly induced by regional annual mean temperature variability. The result proved that the strong influence of temperatures during tree growth is a common feature in high-altitude tree-ring series. Such results suggest a more cautious approach while using tree-ring chronology to reconstruct local or regional climate history. Based on the tree growth-climate relationship, the annual mean temperature before growing season since 1445 was reconstructed for the upper reaches of the Heihe River Basin. The 20th century was the warmest 100 years within the time period studied, while the coldest 100-year and decadal periods occurred in 1490s–1580s and 1780s–1800s, respectively. The recovered temperature history agrees well with other temperature series reconstructed across the northeastern Tibetan Plateau, demonstrating that this reconstructed temperature could be used to evaluate regional climate change. Because the reconstruction is only based on one site of trees, it is very likely that the reconstruction contains site-specified variations. More tree-ring sites and longer chronologies are needed to acquire an accurate and thorough representation of climate variations spatially. The annual mean temperature analysis in this paper suggests that the water resources policy in the Heihe River Basin should be based not only on short-term instrumental records but also on long-term records for regional water resources management. Long-term perspectives on climatic variations should be considered by policy makers.

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