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Millennial Minimum Temperature Variations in the Qilian Mountains, China: evidence from Tree rings

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Abstract

A 1342 yr-long tree-ring chronology was developed from Qilian junipers in the central Qilian Mountains of the north-eastern Tibetan Plateau, China. The climatic implications of this chronology were investigated using simple correlation, partial correlation and response function analyses. The chronology was significantly positively correlated with temperature variables during the pre- and current growing seasons, especially with minimum temperature. The variability of the mean minimum temperature from January to August since 670 AD was then reconstructed based on the tree-ring chronology. The reconstruction explained 58.5 % of the variance in the instrumental temperature records during the calibration period (1960–2011) and captured the variation patterns in minimum temperature at the annual to centennial time scales over the past millennium. The most recent 50 yr were the warmest period, while 1690–1880 was the coldest period since 670 AD. Comparisons with other temperature series from neighbouring regions and for the Northern Hemisphere as a whole supported the validity of our reconstruction and suggested that it provided a good regional representation of temperature change in the north-eastern Tibetan Plateau. The results of multi-taper spectral analysis showed the occurrence of significant quasi-periodic behaviour at a number of periods (2–3, 28.8–66.2, 113.6–169.5, and 500 yr), which were consistent with those associated with El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and solar activity. Some reconstructed cold events may have close relationship with the volcanic eruptions.

1 Introduction

Understanding temperature variations over the past 1000 yr is imperative for evaluating the current global warming and forecasting future temperature changes. Numerous temperature reconstructions based on multiple proxies make it possible to understand the temperature changes during the past millennium (Esper et al., 2012; Jones et al.,

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

CPD
10, 341–380, 2014

Evidence from Tree rings

Y. Zhang et al.

1998; Mann et al., 1999; Crowley, 2000; Moberg et al., 2005; D'Arrigo et al., 2006). However, due to the uneven distribution of sample locations, knowledge of temperature variations during the past thousand years remains poor for some areas of the world, such as the Tibetan Plateau (TP).

The TP is well known for its profound influences on both regional and global climate through thermal and dynamical forcing (Ding, 1992; Manabe and Broccoli, 1990; Webster et al., 1998; Zhou et al. 2009). Since the mid-1950s, most of the Plateau has experienced a dramatic warming of the climate (Liu and Chen, 2000), which has caused significant changes in the environmental conditions and ecosystems of this area (Yao et al., 2004, 2012; Cyranoski, 2005; Cheng and Wu, 2007; Xu and Liu, 2007). High-resolution millennium-long records of past temperature variation are urgently needed to better understand recent warming trends in the TP. Tree rings are natural records with annual resolution that provide proxy data for palaeo-environmental studies and reconstructions of various climatic events (Jones et al., 2009). During recent decades, many multiple-century-long temperature reconstructions have been established for areas within the TP, such as the Qilian Mountains (Tian et al., 2009), the Anemaqin Mountains (Gou et al., 2007a, b), the Hengduan Mountains (Fan et al., 2008, 2009, 2010; Li et al., 2012), the Nyainqentanglha Mountains (Zhu et al., 2011a), the Tanggula Mountains (Zhu et al., 2011b; Liang et al., 2008), the Sygera Mountains (Liang et al., 2009), and the Himalaya Mountains (Yang et al., 2009a, 2010; Cook et al., 2003; Hughes, 2001; Yadav et al., 2004). However, few millennial-scale temperature series are available. Using the ring widths and stable carbon isotope ratios ($\delta^{13}C$) of Qilian juniper from the upper treeline, Liu et al. (2007) reconstructed the December–April temperature in the Qilian Mountains with a 3 yr resolution over the past 1000 yr. Zhu et al. (2008), using ring width data from Qilian juniper at the upper treeline, reconstructed mean September-to-April temperatures for the Wulan area, Qinghai Province, since 1000 AD. The two reconstructions showed the occurrences of generally low temperatures during 1600–1800 AD and the abrupt warming toward the end of past millennia. However, there were some discrepancies between these series before 1500 AD,

CPD
10, 341–380, 2014
Evidence from Tree rings
Y. Zhang et al.

and the long-term trends were even reversed in the period of 1060–1200 AD. Yadav et al. (2011) reconstructed the mean summer temperature extending back to 940 AD derived from tree-ring width data in the western Himalaya, and the centennial-scale variations in the reconstruction revealed the warm periods encompassing the 11–15th centuries, which was different with those in the two reconstructions mentioned above. In addition, combining samples of archaeological wood and living trees in eastern Qaidam Basin, Qinghai Province, Liu et al. (2009), reconstructed the annual mean temperature in a large region of the mid-eastern Tibetan Plateau over the past 2485 yr. However, the small sample size led to substantial uncertainties for the period of approximately 700–900 AD (Liu et al., 2009). Additionally, it was controversial whether the archaeological samples used in the research were temperature-sensitive or moisture-sensitive (Shao et al., 2010). The temperature variability in the TP during the past 1500 yr, especially before 1050 AD, remains poorly understood and substantially uncertain (Ge et al., 2010). Whether temperatures were higher in the earlier periods than today or whether the current warming is unprecedented in the context of the past millennium is still unclear in this area.

Previous studies have indicated that tree ring samples obtained from low-temperature sites, such as mid-latitude upper treelines and high latitude regions, tend to best reflect past temperature variations (Fritts, 1976; Körner and Paulsen, 2004; Di Filippo et al., 2007; Sazler et al., 2009). To address the need to expand spatial coverage of millennial length proxies of past temperatures, we collected tree-ring samples from the upper treeline in the Qilian Mountains in the north-eastern TP and developed a new ring-width chronology to investigate the temperature variability in the past. The objectives of this study are (1) to develop a new tree-ring chronology for the timberline forests of the Qilian Mountains in the north-eastern TP, (2) to evaluate the validity of this millennial-scale reconstruction; and (3) to reveal the characteristics of past temperature changes using the tree-ring chronology. We hope that this reconstruction will improve our understanding of temperature variability in the north-eastern TP for the past millennium.

CPD
10, 341–380, 2014

2 Data and methods

2.1 Study area

The study area is located in the Qilian Mountains National Nature Reserve, which are located along the north-eastern boundary of the TP bordering the Inner Mongolia-Xinjiang Plateau and the Loess Plateau, with elevations between 3000 and 5000 m above sea level (hereafter as a.s.l.) in general. The climate of the region varies with elevation, forming distinct zones of different vegetation (Chen, 1990). The lower portion of the mountains (2000–2600 m) has a semi-arid steppe climate, with annual mean temperature ranging from 2 to 5° and annual precipitation of approximately 235 to 330 mm; the upper portion of the mountains (2600–3200 m) has a semi-humid forest and steppe climate, with annual mean temperature ranging from −0.7 to 2° and annual precipitation of approximately 400 to 500 mm; and the subalpine and alpine zones (3200 m and higher) have a cold and humid climate, with annual mean temperature of approximately −1.5–−0.7° and annual precipitation of approximately 500 mm (Chen, 1990).The dominant tree species in the study area are Qilian juniper (*Sabina przewalskii* Kom.) and Qinghai spruce (*Picea crassifolia* Kom.) (Yang et al., 2008).

2.2 Tree-ring data

The tree-ring samples were collected on the northern slope of the central Qilian Mountains (Fig. 1). Based on repeated field observations, we found that Qilian junipers grow between approximately 2700 m and 3600 m a.s.l. in this area. Because most of the trees in the upper treeline are located around 3400 m a.s.l., four sampling sites were selected with elevations above 3300 m (Table 1). Standard 5 mm increment cores were collected from healthy and relict trees along the local upper treeline and taken to the laboratory for processing. The samples were prepared using standard dendrochronological techniques (Stokes and Smiley, 1968). After measuring each ring to the nearest 0.01 mm, we statistically verified the cross-dating accuracy using the program

CPD
10, 341–380, 2014
Evidence from Tree rings
Y. Zhang et al.

COFECHA (Holmes, 1983). Because the four sites were located with close proximity (the longest distance is 6 km between sites HY0 and HY6) and the mean correlation of all cores was 0.6, all of the raw measurements were used to develop a single standard chronology (hereafter as HY). Two criteria were used to exclude certain series in order to ensure high signal-to-noise level and obtain the strong temperature signal from the tree-ring series. First, series that exhibited low correlations with the master series ($r < 0.4$) were excluded from being used in the chronology. Second, series from trees growing in rocks or crevices with mean sensitivity values greater than 0.45 were also excluded. The reason for this is because the mean sensitivity values of most sample series are range from 0.15–0.45, while these excluded tree ring series show higher mean sensitivity values with more absent rings. Mean sensitivity is a measure of the relative difference in ring width between adjacent rings, and precipitation-sensitive ring width samples tend to have high variability between adjacent rings (Fritts, 1976). After applying these criteria, 152 cores from 82 trees (out of 250 cores/118 trees, Table 1) were selected to construct the chronology using the program ARSTAN (Cook, 1985), which had the potential to be temperature sensitive.

The negative exponential curve and linear curve with negative slope were used to fit age-related growth trends from the individual tree-ring series for cores that were close to the piths (93 cores). For cores that were not close to the piths (47 cores), their growth trends were fitted based on the horizontal lines through the mean. For cores that reached the piths, the Hugershoff growth curve (4 cores) or a general negative exponential curve (8 cores) was used to fit the growth trends (Cook and Kairiukstis, 1990; Fritts, 1976; Warren, 1980). The final ring-width chronology was obtained by calculating the ratios of the ring-width measurements over the fitted values for each year, producing dimensionless indices with a mean of 1.0. To reduce the possible influence of the variable sample size, the variance of the chronology was stabilised using the method described by Osborn et al. (1997). The subsample signal strength (SSS) with a threshold value of 0.85 was used to assess the adequacy of the replications in the early years of the chronology (Wigley, 1984).

2.3 Climatic data

Base on the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do), four climatic variables from two meteorological stations (Yeniugou and Zhangye) near our tree-ring sites were used here (Table 1), including monthly mean temperature (Tmean), monthly minimum temperature (Tmin), monthly maximum temperature (Tmax), and monthly total precipitation (PRCP) (Fig. 2). The beginning years of the instrumental climate data at these meteorological stations varied, but we used the data during the common period of 1960–2011 in the following unless otherwise noted. To be mentioned, the nearest meteorological station before 2012 was Sunan station, however, its climatic data now is unavailable in the China Meteorological Data Sharing Service System, and accordingly, is not considered in this study.

To assess the regional significance of our reconstruction, the CRU gridded dataset (TS3.0) (Mitchell and Jones, 2005) was correlated with the instrumental and the reconstructed series, respectively, using the research tool known as KNMI Climate Explorer (http://climexp.knmi.nl, last access: 10 June 2013).

2.4 Statistical methods

Correlation and response function analyses were used to investigate the relationships between the tree-ring data and climatic variables using the program DENDEOCLIM2002 (Biondi and Waikul, 2004). Partial-correlation analysis was employed to separate the confounding influence of the inter-correlation of temperature and precipitation using the program SEASCORR (Meko, 2011). Correlation coefficients and response-function analysis between the tree-ring and climatic variables were calculated for the 12 month period extending from October of the prior year to September of the current year. Correlations and partial-correlations between the tree-ring chronology and climatic variables were also calculated for various multi-month periods and on a full-year scale.

CPD
10, 341–380, 2014

To reconstruct the past climate variations, the instrumental climatic records were regressed against the HY chronology. Compare to the climate variable at single station, 2-station means of the climate variable have better spatial representation, therefore we examined all the subsets of 2-station means of the climate variables for the successive months from the previous October to current September to identify the best climatic variable and season for reconstruction. Because the time span covered by the instrumental data was too short for a meaningful division into two subsets for calibration and verification, the leave-one-out procedure (Michaelsen, 1987) was used to validate the calibration function. The evaluative statistics included Pearson's correlation coefficient (r), the explained variance (R^2), the adjusted explained variance (R^2_{adj}), the sign test (ST), the first-differences sign test (FST), the product-mean test (PMT) and the reduction of error (RE) (Fritts, 1976).

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). The MTM used here derive from the Tree-Ring Laboratory of Lamont-Doherty Earth Observatory in Columbia University (http://www.ldeo.columbia.edu/res/fac/trl).

3 Results

3.1 STD chronology statistics

The chronology covered the period from 450 to 2012 AD (Fig. 3). Based on the subsample signal strength threshold of 0.85, the chronology was considered reliable when the sample size reached 11 cores, corresponding to the period from 670 to 2012 AD. The mean segment length of the chronology was 516 yr, indicating its ability to resolve inter-annual to centennial variations in tree growth that were likely related to climate variability. The mean sensitivity was approximately 0.175 that was relatively low due to the criteria applied in selecting the sample cores used in chronology construction. The signal-to-noise ratio and the expressed population signal were 30.83 and 0.969,

CPD
10, 341–380, 2014

respectively, indicating that the chronology was appropriate for dendroclimatic studies (Wigley et al., 1984).

3.2 Correlation and response-function analyses between tree growth and climate

The results of the correlation analyses between the ring width index and the climatic variables (Fig. 4) indicated strong relationships between tree growth and temperature at the two stations. Except for the negative correlations between the tree ring chronology and Tmax at Yeniugou during May of the current year, all of the temperature variables were positively correlated with the tree-ring index. Significantly positive correlations with Tmean and Tmin occurred in almost all months. In general, the correlation coefficients between the tree-ring index and Tmin at the two stations were stronger than those between the tree-ring index and Tmean or Tmax. The correlations between the tree-ring index and PRCP were weak and not statistically significant in most months except for a positive correlation in current March and current May at Yeniugou and current January at Zhangye.

The response-function analysis showed a similar pattern (Fig. 4). The tree-ring index was not significantly correlated with PRCP at the two stations in all months, while the monthly temperature variables in most of months were positively correlated with the tree-ring index. The most significant relationships occurred at February, June and July of the current year.

The results of Correlation and response-function analyses of the mean of temperature variables between two stations with tree-ring index were very similar with those in single station (Fig. 4, bottom), and the relationships between the mean Tmin anomalies at Zhangye and Yeniugou and the tree-ring index for different months were generally stronger than the others too, indicating that Tmin is more likely to be the control factor radial growth of trees in this region.

Figure 5 shows the results of correlation and partial-correlation analyses between the tree-ring index and the mean Tmin and PRCP anomalies at Zhangye and Yeniugou at different time scales. We found statistically significant relationships between the tree-ring data and Tmin in different months and multi-month periods (Fig. 5a). The correlation between the tree-ring index and Tmin as the length of the averaging period increased, reaching its maximum value for the 8 month period ending in August of the current year for the period of 1962–2011($r = 0.78$, $p < 0.01$).

When Tmin was the control variable, the relationships between the tree-ring index and precipitation were weak and not statistically significant at the 0.05 level for the 1, 3, 8, and 12 month periods (Fig. 5b). Inversely, if we use precipitation as the control variable, Tmin has strong relationships with the tree ring data for these periods (Fig. 5c). Based on the above results, we can conclude that our tree-ring series represented the temperature variation in the study area, especially the variation of Tmin.

3.3 Calibration and reconstruction of the mean January–August minimum temperature

Based on the above analysis results, we finally chose the mean January–August minimum temperature anomalies at Zhangye and Yeniugou ($r = 0.765$ with the tree ring series for the period of 1960–2011, $p < 0.01$) for the reconstruction. A transfer function was estimated by linear regression using January–August Tmin at Zhangye and Yeniugou (T_{c18}) as the dependent variable and the standard tree ring chronology (STD) as the independent variable. The final transfer function was

$$T_{c18} = -4.0414 + 2.7707\text{STD}, \quad (1)$$

where T_{c18} is the mean January–August minimum temperature anomalies and STD is the index of HY chronology.

The final calibration model accounted for 58.5 % ($p < 0.01$) of the total variance of the mean January–August minimum temperature over the calibration period from 1960 to 2011 (Fig. 6a). As shown in Table 3, the ST and PMT statistics were significant at the 0.01 level, and FST was significant at the 0.05 level. The leave-one-out correlation

CPD
10, 341–380, 2014

coefficient is 0.745. Additionally, the RE statistic (0.555) was greater than 0.3 over the full calibration period (1960–2011).

Figure 6b compared the observed and reconstructed Tmin series during 1960–2011. The reconstructed values matched the observed values particularly well after 1985 with a correlation coefficient for 1985–2011 as 0.8 ($p < 0.01$). The agreement between the observed and reconstructed series was not as good before 1985. This discrepancy between the reconstructed and observed data may be partly due to the uncertainties in the instrumental data for the earlier years. Additionally, averaging values for multi-month period may obscure the effects of short events. For example, according to temperature anomalies of Zhangye and Yeniugou stations, the observed January–August minimum temperature in 1962 (−2.1°) was the lowest recorded during the past 50 yr, but our reconstruction did not reflect this observation (Fig. 6b). The temperature records at the two stations showed that the months from January to May (−2.7°) were much colder than normal (0°), while the temperature from June to August (−1°) was nearly normal in this year. Tree growth may be more sensitive to temperature variation during the growing season than to temperature variation before the onset of growth. Therefore, the reconstructed data series may fail to capture the variations in a few years when temperatures prior to and during the growing season varied in different directions.

Regardless the issues in the earlier part of the calibration period, the evaluative statistics in Table 3 indicated that our regression model was stable and reliable, and was acceptable to reconstruct the annual-to-centennial variability of the mean January–August minimum temperature anomalies in the central Qilian Mountains since 670 AD.

The 31 yr running means of the reconstructed series revealed multi-decadal to centennial-scale variation patterns (Fig. 7a). The January–August minimum temperature anomalies fluctuated with relatively low variability from approximately 670 to 780 AD and from 1100 to 1400 AD, while some larger fluctuations were found in the periods of approximately 850–1100 AD and 1400–1600 AD. A significant long-term cooling occurred with several short warmer periods, from the late 1500s to the end of

CPD
10, 341–380, 2014

the 19th century. The January–August minimum temperature increased gradually after 1850 AD, and the increase during the most recent 100 yr was the most rapid in the past millennium with a warming trend of 0.26° per 100 yr. Based on the overall mean and 31 yr running means, several distinct warm and cold periods were identified. The warm periods included approximately 920–1000, 1310–1450, 1490–1570, and 1930–2011 AD, while the cold periods were approximately 780–890, 1000–1060, 1110–1170, 1260–1300, 1450–1490, 1570–1650, 1690–1880, and 1900–1930 AD. The most recent 50 yr was the warmest period, and 910–1000 AD was the second-warmest period over the past 1342 yr. The period from 1690 to 1880 AD was the coldest period over the past millennium. There seemed to be a centennial scale cyclic pattern in the reconstructed series, especially during 1000–1700 AD (Fig. 7a). The MTM spectrum indicated the occurrence of significant (99 % based on an assumed underlying red noise null spectrum model) quasi-periodic behaviour at a number of periods, including 2–3, 28.8–66.2, 113.6–169.5, and 500 yr (Fig. 7b).

4 Discussion

4.1 Climatic implications of the upper treeline chronologies

The significant positive correlations between the tree-ring data and Tmean and Tmin in most months (Fig. 4) indicated that the HY chronology was temperature-sensitive. A similar climatic response has been reported for the timberline forests on the eastern and north-eastern TP (Shao and Fan, 1999; Bräuning, 2006; Liu et al., 2007; Liang, 2006, 2008, 2009). Low temperature limited respiration, photosynthesis, and other biochemical process which were essential for rapid growth of trees (Fritts, 1976). For instance, low summer soil temperatures at the timberline can limit the growth of roots and their function in water uptake (Körner, 1999; Mayr, 2007). In addition, even though the cambium tissues of trees are dormant in winter and early spring, the phloem sap may have freezing damage when temperatures are low during this period (Kimmins, 1987).

CPD
10, 341–380, 2014

Accordingly, tree growth at the upper forest limit responded strongly to temperature variation in our study region. However, the influence of growing-season precipitation should be noted in this area as well. The positive correlations of the tree-ring index with precipitation and negative correlations with maximum temperature in May indicated the presence of moisture stress when the trees begin to grow in the early growing season. Although precipitation is higher and temperatures are lower at the upper forest limit than at low elevations, rainfall during this time may not meet the demand for tree growth in the arid and semi-arid areas. Nevertheless, the influence of precipitation seems to occur only at the early growing season, and tree growth is mainly influenced by temperature, especially minimum temperature both prior to and during the growing season, at our study sites.

4.2 Validation of the reconstruction

4.2.1 Spatial representativeness of the reconstructed series

Figure 8 shows the results of spatial pattern of the correlations of the CRU gridded mean January–August minimum temperature over western China with the actual and reconstructed January–August Tmin for the period 1960–2009. The instrumental data significantly ($p < 0.1$) correlated with the gridded mean January–August minimum temperature over the entire western China, with stronger correlations being found mainly in the TP and the north-central part of western China (Fig. 8, left). For the reconstructed series, the spatial pattern of the correlation was quite similar to that of the instrumental data, with somewhat lower correlation coefficients and smaller spatial coverage of statistical significance (Fig. 8, right). However, the TP was still a prominent area with high correlation coefficients. The spatial correlation results demonstrated that our temperature reconstruction could reflect temperature variability in a large region, especially in the TP.

CPD
10, 341–380, 2014

4.2.2 Comparisons with other reconstructions and Northern Hemisphere temperature

To further assess the validity of our minimum temperature reconstruction for the Qilian Mountains (Fig. 9a), we compared it with several millennium-long temperature reconstructions in the region. Closest to our study sites is the Sidalong reconstruction series of December–April temperature (Liu et al., 2007), based on a combination of ring width and stable carbon isotope with a 3 yr resolution (Fig. 9b). This reconstruction agreed closely with ours (Fig. 9a) with a correlation coefficient of 0.58 ($p < 0.01$) between the two series for the period of 1066–1999 AD and the variation patterns were similar on an interdecadal time scale. However, some differences in the low-frequency domain exited during 1100–1200 and 1350–1410 AD, which may be due to the different standardisation methods used and the response mechanisms of carbon isotope and radial growth to climate factors. Figure 9c shows another millennial-scale temperature reconstruction of previous September to current April (Zhu et al., 2008), using Qilian juniper samples from the upper treeline in Wulan approximately 200 km south of our sites. Like our temperature reconstruction, this reconstruction series indicated that cold conditions prevailed from the early 17th century to the middle of the 19th century and that the rate of warming rapidly increased during the most recent century. The Wulan reconstruction was also significantly correlated with our reconstruction for the period of 1060–2004 AD ($r = 0.44$, $p < 0.01$). This series and our series also showed consistent multi-decadal variations, such as the cold period at the end of the 13th century, warm period during the 16th century, cool period from the end of the 16th century to the early 17th century, and the cold period during the 1800s. The two reconstructions showed certain discrepancies in multi-decadal trends during several periods, such as 1100–1200 AD. Since the differences mainly existed before 1200 AD when the sample depth of Wulan reconstruction was low, the sample depth may also contribute to these discrepancies (Shao et al., 2010). Additionally, inner-year variability may have caused

CPD
10, 341–380, 2014

discrepancies between the series as the seasons covered by the reconstructions were different (January–August vs. previous September – current April).

In addition to the tree-ring-based reconstructions, we compared our reconstruction to an ice-core δ^{18}O series with a 10 yr resolution reflecting the temperature variations at Dunde in the Qilian Mountains (Thompson et al., 2003) (Fig. 9d). Both series showed strong warming trends since the late 18th century. The cold periods of approximately 1100–1200, 1250–1300, 1450–1500, and 1750–1800 AD and the warm periods of approximately 1050–1100, 1500–1600, and 1950–2009 AD in our reconstruction were all confirmed by the corresponding cold and warm periods in the ice-core series. In general, the overall agreement between our reconstruction and other temperature reconstructions suggests that our series is reliable over the past millennium.

We also compared our reconstruction to broad-scale temperature reconstructions for the Northern Hemisphere (NH) (Jones et al., 1998; Mann et al., 1999; Crowly, 2000; Moberg et al., 2005; D'Arrigo et al., 2006). As shown in Fig.'9e, the temperature reconstructions for the NH generally showed a cold period during approximately 700–950 and a warm period during approximately 950–1100 (the Mediaeval Climate Anomaly). Another cold period can be seen during approximately 1100–1400 AD, followed by the Little Ice Age (LIA) (approximately 1450–1850). Temperature then rapidly increased after approximately 1810. Our reconstruction showed a similar long-term trend of temperature variability over the past 1300 yr. Certain decadal-scale cold and warm episodes in the NH, including those of the 840s (cold), 910s (cold), 980s (warm), 1090s (warm), 1210s (cold), 1240s (warm), 1290s (cold), 1420s (warm), 1470s (cold), 1540s (warm), 1590s (cold), 1710s (cold), and 1990s AD (warm) were also found in our reconstruction, suggesting that the temperature variations in the north-eastern TP were highly synchronous with those of the NH. Several of these cold or warm events are recorded by temperature series in other regions. For example, the cold periods during approximately the 840s and 910s AD can be seen in a stalagmite series from Beijing (Tan et al., 2003) and in historical documents from eastern China (Ge et al., 2003). The warm periods during approximately the 1240s, 1540s and 1990s AD were recorded both in eastern China and in the TP (Yang et al., 2002, 2009b). These agreements not only suggested the occurrence of climatic events at a continental or even semi-hemispheric scale but also reinforced the validity of our temperature reconstruction. The differences between the NH temperature series and our reconstruction probably reflected local climatic variability. For example, our series showed that the Mediaeval warm period was not as continuous in the Qilian Mountains and that it probably occurred earlier in this region than elsewhere in the NH. The magnitudes of the temperature fluctuations and the multi-decadal trends during some periods also differed between our series and the NH temperature series.

4.3 The periodicity of the reconstruction and the possible forcing factors of temperature variations

The cycles of 2–3 yr (Fig. 7b) in our reconstruction represent the common mode of interannual variability associated with atmospheric and oceanographic conditions caused by various forcing mechanisms, such as El Niño-Southern Oscillation (ENSO), thermal contrasts of land mass and ocean, intensities of the westerly and/or winter monsoon circulations, The ENSO band of 2–8 yr (Allan et al., 1996) has been in many temperature and precipitation reconstruction series in China (Fang et al., 2009; Li et al., 2011; Zhang et al., 2011; Sun and Liu, 2012; Deng et al., 2013). The results of instrumental data based researches on ENSO and temperature in the Qilian Mountains showed air temperature in the El Niño years was increased while in the La Niña years air temperature was distinctly decreased in this area (Lan et al., 2003; Zhang et al., 2011; Yang and Zhao, 2012). However, cross correlation between a reconstructed inter-decadal ENSO variation series (Li et al., 2011) and our reconstruction for the period 900–2002 was not statistically significant with lags up to 10 yr ($r = -0.017$, lag = 0), indicating that the relationship between the variations of ENSO and minimum temperature in Qilian Mountains might be more complex.

The significant cycles at around 29–66 yr (Fig. 8b) might be linked to Pacific Decadal Oscillation (PDO) (Mantua et al. 1997; Minobe, 1997; Grigholm et al., 2009). We then

CPD
10, 341–380, 2014

calculated the correlation between our reconstruction and PDO index (MacDonald and Case, 2002) for the period of 993–1996, but the relationship between the two series was not significant ($r = 0.08$). However, it was interesting to note that significantly negative correlation were found in several periods when we calculated the moving-correlation between the two series for different 100 yr intervals, especially during 1370–1510, when continuous highly negative correlation coefficients were found with the highest value of −0.564 ($p < 0.01$) in 1389–1488. Meanwhile, a series of significantly positive correlations were found during 1068–1210, 1282–1386, and 1509–1654 AD, and the highest positive correlation coefficient was 0.456 ($p < 0.01$) for 1528–1627 AD. Hence the relationship between PDO and temperature variability in our study area probably changed over time.

It is well known that solar irradiance and volcanism are the important forcing factors of global temperature variations (Crowley, 2000; Jones and Mann, 2004). For example, low temperatures during the LIA have been linked to the Maunder Minimum of the 22 yr sunspot cycle (Shindell et al., 2001). The centennial cycles identified in our study, i.e. those of 113.6–169 and 500 yr (Fig. 8b), were possibly associated with the frequencies of solar variations (Stuiver and Braziunas, 1989; Raspopov et al., 2008). The cycles similar to the periodicities of 113.6–169 yr have been found in other tree ring reconstructions in China (Wang et al., 2008; Gou et al., 2010; Zhang et al., 2011), while the very long period of 500 yr visible in our reconstruction was not found in other tree-ring series in China, which may be due to the lack of millennial tree ring records with low-frequency signals. The relationship between volcanism and temperature variations cannot be revealed via the spectrum analysis, however, some extreme cold events in our reconstruction maybe associate with the volcanic eruptions. Because the effects of some volcanoes may take a couple of years to impact around the globe (Robock and Mao, 1995; Salzer and Hughes, 2007), the reconstructed cold events which occurred in current and/or the next two years of volcano eruptions were counted (Table 4). The tropical volcanic radiative forcing (Mann et al., 2005) were used here, and a single negative value year or successive negative value years was regarded as a volcanic event, 21 volcanic events were then identified during the period of 1000–1999 AD. Meanwhile our reconstruction series was normalized by its mean and standard deviation, the years with the value less than 0.5 were regarded as cold years in this standardized series. In this case, the corresponding cold events can be found in 15 volcanic event years for the past millennium. Some of them were also supported by the factual evidences, such as these volcanic eruptions since 1815 AD. It seems that the volcanic eruption in Indonesia played an important role in temperature change in our study area. Undoubtedly, solar activity and volcanism have great influences on global temperature change. However, the forcing mechanism of both factors on local temperature variations is complex and still unclear to us. More temperature-related tree-ring series are urgently needed for the further analysis.

5 Conclusions

In this study we sampled four upper-treeline sites (> 3300 m a.s.l.) for tree ring cores of Qilain juniper in the Qilian Mountains of the north-eastern Tibetan Plateau. After carefully screening sample cores that are less sensitive to precipitation, we selected 152 cores from 82 trees to construct a potentially temperature-sensitive ring width chronology through correlation and response-function analyses between the chronology and climatic variables (Tmax, Tmin, Tmean, and PRCP), we determined that the radial growth of the trees was mostly controlled by temperature, especially minimum temperature. The correlations between the tree ring chronology and mean and minimum temperatures at near-by weather stations can be as high as 0.77 and, therefore, it can be used to infer the variations in mean January–August minimum temperature anomalies over the past millennium for the study region. For the calibration period of 1960–2011, the transfer function explained 58.5 % of the total variance in mean January–August minimum temperature. This temperature reconstruction covered the period 670–2011 AD and revealed temperature variation patterns at the inter-annual to centennial timescales over the past 1342 yr. The comparisons with other reconstructions in the region and those of the Northern Hemisphere displayed strong consistencies, suggesting good reliability.

According to the reconstructed series, distinct warm periods were identified during 920–1000, 1310–1450, 1490–1570, and 1930–2011 AD, while cool periods were identified in 780–890, 1000–1060, 1110–1170, 1260–1300, 1450–1490, 1570–1650, 1690–1880, and 1900–1930 AD. The warming during the most recent 50 yr was unprecedented within the past millennium; even during the dramatic warming from 900 to 1100 AD, the reconstructed temperatures did not exceed those observed today. The period from 1690 to 1880 AD was the coldest and longest-lasting cold period during the past 1342 yr.

Significant periodicities were found in the reconstructed series using the MTM spectral analysis, including those of 2–3, 28.8–66.2, 113.6–169.5, and 500 yr. We examined the relationships between the reconstructed minimum temperature series and several forcing mechanisms of temperature variability at different temporal scales, including ENSO and PDO, solar activities, and volcanic eruption records. We found that ENSO was not correlated with minimum temperature variation in our region, while the influence of PDO might have been variable over time. The periodicities of solar activity have good agreement with those in our reconstruction. The tropical volcanic eruptions have good corresponding relationship with the cold events recorded by our reconstruction.

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References

Allan, R., Lindesay, J., and Parker, D.: El Niño-Southern Oscillation and climatic variability, Common wealth Scientific and Industrial Research Organisation, Melbourne, Vicoria, Australia, p. 405, 1996.

Biondi, F. and Waikul K.: DENDROCLIM2002: a C++ Program for statistical calibration of climate signals in tree-ring chronologies, Comput. Geosci., 30, 301–311, 2004.

Bräuning, A.: Tree-ring evidence of "Little Ice Age" glacier advances in southern Tibet, Holocene, 16, 369–380, 2006.

Chen, C. Y.: The distribution of climate and vegetation in the north slope of the Qilian Mountains, Arid Meteorol., 2, 28–33, 1990 (in Chinese).

Cheng, G. and Wu, T.: Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau, J. Geophys. Res., 112, F02S03, doi:10.1029/2006JF000631, 2007.

Cook, E. R.: A time-series analysis approach to tree-ring standardization, PhD dissertation, The University of Arizona, Tucson, 1985.

Cook, E. R. and Kairiukstis, L. A.: Methods of dendrochronology: Applications in the environmental sciences, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1990.

Cook, E. R., Krusic, P. J., and Jones, P. D.: Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal, Int. J. Climat., 23, 707–732, 2003.

Crowley, T. J.: Causes of Climate Change Over the Past 1000 Years, Science, 289, 270–277, 2000.

Cyranoski, D.: The long-range forecast, Nature, 438, 275–276, 2005.

D'Arrigo, R., Wilson, R., and Jacoby, G.: On the long-term context for late twentieth century warming, J. Geophys. Res., 111, D03103, doi:10.1029/2005JD006352, 2006.

Deng, Y., Gou, X., Gao L., Yang, T., and Yang, M.: Early-summer temperature variations over the past 563 yr inferred from tree rings in the Shaluli Mountains, southeastern Tibet Plateau, Quaternary Res., doi:10.1016/j.yqres.2013.08.002, 2013.

Di Filippo, A., Biondi, F., Cufar K., de Luis, M., Grabner, M., Maugeri, M., Saba, P. E., Schirone B., and Piovesan G.: Bioclimatology of beech (Fagus sylvatica L.) in the Eastern Alps: spatial and altitudinal climatic signals identified through a tree-ring network, J. Biogeogr., 34, 1873–1892, 2007.

Ding, Y. H.: Summer monsoon rainfalls in China, J. Meteor. Soc. Japan., 70, 373–396, 1992.

Esper, J., Frank, D. C., imonen, M., Zorita, E., Wilson, R. J. S., Luterbacher, J., Holzkämper, S., Fischer, N., Wagner, S., Nievergelt, D., and Versteg, A.: Orbital forcing of tree-ring data, Nat. Clim. Change., 2, 862–866, doi:10.1038/nclimate1589, 2012.
Fan, Z. X., Bräuning, A., and Cao, K. F.: Annual temperature reconstruction in the central Hengduan Mountains, China, as deduced from tree rings, Dendrochronologia, 26, 97–107, doi:10.1016/j.dendro.2008.01.003, 2008.
Fan, Z. X., Bräuning, A., Yang, B., and Cao, K. F.: Tree ring density-based summer temperature reconstruction for the central Hengduan Mountains in southern China, Global. Planet. Change., 65, 1–11, 2009.
Fan, Z. X., Bräuning, A., Tian Q. H., Yang, B., and Cao, K. F.: Tree ring recorded May-August temperature variations since A.D. 1585 in the Gaoligong Mountains, southeastern Tibetan Plateau, Palaeogeogr. Palaeocl., 296, 94–102, 2010.
Fang, K., Gou, X., Chen, F., Yang, M., L, J., He, M., Zhang, Y., Tian, Q., and Peng J.: Drought variations in the eastern part of northwest China over the past two centuries: evidence from tree rings, Clim. Res., 38, 129–135, 2009.
Fritts, H. C.: Tree Rings and Climate, London, Academic Press, 1976.
Ge, Q. S., Zheng, J. Y., Fang, X. Q., Ma, Z. M., Zhang, X. Q., Zhang, P. Y., and Wang, W. C.: Winter half-year temperature reconstruction for the middle and lower reaches of yellow river and Yangtze river, China, during the past 2000 years, Holocene, 13, 933–940, 2003.
Ge, Q. S., Zheng, J. Y., Hao, Z. X., Shao, X. M., Wang, W. C., and Luterbacher, J.: Temperature variation through 2000 years in China: An uncertainty analysis of reconstruction and regional difference, Geophys. Res. Lett., 37, L03703, doi:10.1029/2009GL041281, 2010.
Gou, X., Chen, F., Jacoby, G., Cook, E., Yang, M., Peng, J., and Zhang, Y.: Rapid tree growth with respect to the last 400 years in response to climate warming, northeastern Tibetan Plateau, Int. J. Climat., 27, 1497–1503, doi:10.1002/joc.1480, 2007a.
Gou, X., Chen, F., Yang, M., Jacoby, G., Fang, K., and Tian, Q.: Asymmetric variability between maximum and minimum temperatures in Northeastern Tibetan Plateau: Evidence from tree rings, Sci. China. Ser. D., 50, 1–15, 2007b.
Gou, X., Deng, Y., Chen, F., Yang, M., Fang, K., Gao, L., Yang, T., and Zhang, F.: Tree ring based streamflow reconstruction for the Upper Yellow River over the past 1234 years, Chin. Sci. Bull., 55, 4179–4186, 2010.
Grigholm, B., Mayewski, P.A., Kang, S., Zhang, Y., Kaspari, S., Sneed, S. B., and Zhang, Q.: Atmospheric soluble dust records from a Tibetan ice core: possible climate proxies

and teleconnection with the Pacific Decadal Oscillation, J. Geophys. Res., 114, D20118, doi:10.1029/2008JD011242, 2009.
Holmes, R. L.: Computer-assisted quality control in tree-ring dating and measurement, Tree-Ring B., 43, 69–95, 1983.
Hughes, M. K.: An improved reconstruction of summer temperature at Srinagar, Kashmir since 1660 AD, based on tree-ring width and maximum latewood density of Abies pindrow (Royle) Spach, Palaeobotanist., 50, 13–19, 2001.
Jones, P. D. and Mann, M. E.: Climate over past millennia. Rev. Geophys., 42, RG2002, doi:10.1029/2003RG000143, 2004.
Jones, P. D., Briffa, K. R., Barnett, T. P., and Tett, S. F. B.: High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures, Holocene, 8, 455–471, 1998.
Jones, P. D., Briffa, K. R., Osborn, T. J., Lough, J. M., van Ommen, T., Vinther, B. M., Luterbacher ,J., Zwiers, F. W., Wahl, E., Schmidt, G., Ammann, C., Mann, M. E., Wanner, H., Buckley, B. M., Cobb, K., Esper, J., Goosse, H., Graham, N., Jansen, E., Kiefer, T., Kull, C., Mosley-Thompson, E., Overpeck, J. T., Schulz, M., Tudhope, S., Villalba, R., and Wolff, E.: High-resolution paleoclimatology of the last millennium: a review of the current status and future prospects, Holocene., 19, 3–49, 2009.
Kimmins, J. P.: Forest Ecology, MacMillan Publishing Company, New York, 1–531, 1987.
Körner, C.: Alpine Plant Life: Function Plant Ecology of High Mountain Ecosystems, Springer, Berlin, 1999.
Körner, C. and Paulsen, J.: A world-wide study of high altitude treeline temperatures, J. Biogeogr., 31, 713–732, 2004.
Lan, Y., Ding, Y., Kang, E., and Zhang, J.: The relationship between ENSO cycle and temperature, precipitation and runoff in the Qilian Mountain area, J. Geog. Sci., 13, 293–298, 2003
Li, J., Xie, S. P., Cook, E. R., Huang, G., D'Arrigo, R., Liu, F., Ma, J., and Zheng, X.-T.: Interdecadal modulation of El Niño amplitude during the past millennium, Nat. Clim. Change, 1, 114–118, 2011.
Li, Z. S., Zhang, Q. B., and Ma, K. P.: Tree-ring reconstruction of summer temperature for A.D. 1475–2003 in the central Hengduan Mountains, Northwestern Yunnan, China, Clim. Change, 110, 455–467, doi:10.1007/s10584-011-0111-z, 2012.

Liang, E. Y., Shao, X. M., Eckstein, D., Huang, L., and Liu, X. H.: Topography- and species-dependent growth responses of Sabina przewalskii and Picea crassifolia to climate on the northeast Tibetan Plateau, Forest. Ecol Manage., 236, 268–277, 2006.
Liang, E., Shao, X., and Qin, N.: Tree-ring based summer temperature reconstruction for the source region of the Yangtze River on the Tibetan Plateau, Global. Planet. Change, 61, 313–320, 2008.
Liang, E. Y., Shao, X. M., and Xu, Y.: Tree-ring evidence of recent abnormal warming on the southeast Tibetan Plateau. Theor. Appl. Climatol., 98, 9–18, doi:10.1007/s00704-008-0085-6, 2009.
Liu, X. and Chen, B.: Climatic warming in the Tibetan Plateau during recent decades, Int. J. Climat., 20, 1729–1742, 2000.
Liu, X. H., Shao, X. M., Zhao, L. J., Qin, D. H., Chen, T., and Ren, J. W.: Dendroclimatic temperature record derived from tree-ring width and stable carbon isotope chronologies in the middle Qilian Mountains, China, Arct. Antarct. Alp. Res., 39, 651–657, 2007.
Liu, Y., An, Z., Linderholm, H. W., Chen, D., Song, H., Cai, Q., Sun, J., and Tian, H.: Annual temperatures during the last 2485 years in the Eastern Tibetan Plateau inferred from tree rings, Sci. China. Ser. D., 52, 348–359, 2009.
MacDonald, G. M. and Case, R. A.: Variations in the Pacific Decadal Oscillation over the past millennium, Geophys. Res. Lett., 32, L08703, doi:10.1029/2005GL022478, 2005.
Manabe, S. and Broccoli, A.: Mountains and arid climate of middle latitudes, Science, 247, 192–195, 1990.
Mann, M. E. and Lees, J. M.: Robust estimation of background noise and signal detection in climatic time series, Clim. Change, 33, 409–445, 1996.
Mann, M. E., Bradley, R. S., and Hughes, M.K.: Northern hemisphere temperatures during the past millennium: inferences, uncertainties and limitations, Geophys. Res. Lett., 26, 759–762, 1999.
Mann, M. E., Cane, M. A., Zebiak, S. E., and Clement, A.: Volcanic and solar forcing of the Tropical Pacific over the past 1000 years, J. Climate, 18, 447–456, 2005.
Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis R. C.: A Pacific interdecadal oscillation with impacts on salmon production, B. Am. Meteorol. Soc., 78, 1069–1079, 1997.
Mayr, S.: Limits in water relations, in: Trees at their Upper limits, edited by: Wieser, G. and Tausz, M., Springer, Dordrecht, 145–162, 2007.

CPD
10, 341–380, 2014

Meko, D. M., Touchan, R., and Anchukaitis, K. J.: Seascorr: A MATLAB program for identifying the seasonal climate signal in an annual tree-ring time series, Comput. Geosci., 37, 1234–1241, doi:10.1016/j.cageo.2011.01.013, 2011.

Michaelsen, J.: Cross-validation in statistical climate forecast models, J. Climate. Appl. Meteorol., 26, 1589–1600, 1987.

Minobe, S.: A 50–70 year climatic oscillation over the North Pacific and North America. Geophys. Res. Lett., 24, 683–686, 1997.

Mitchell, T. . and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693–712, 2005.

Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko, N. M., and Karlen, W.: Highly variable Northern Hemisphere temperatures reconstructed from low- and high resolution proxy data, Nature, 433, 613–617, 2005.

Osborn, T. J., Briffa, K. R., and Jones, P. D.: Adjusting variance for sample size in tree-ring chronologies and other regional mean time series, Dendrochronologia, 15, 89–99, 1997.

Raspopov, O. M., Dergachev, V. A., Esper, J., Kozyreva, O. V., Frank, D., Ogurtsov, M., Kolström, T., and Shao, X.: The influence of the de Vries (~200-year) solar cycle on climate variations: Results from the Central Asian Mountains and their global link, Palaeogeogr. Palaeocl., 259, 6–16, 2008.

Robock, A. and Mao, J.: The volcanic signal in surface temperature observations, J. Climate, 8, 1086–1103, 1995.

Salzer, M. W. and Hughes, M. K.: Bristlecone pine tree rings and volcanic eruptions over the last 5000 yr, Quaternary Res., 67, 57–68, 2007.

Salzer, M. W., Hughes, M. K., Bunn, A. G., and Kipfmueller, K. F.: Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes, Proc. Natl. Acad. Sci., 106, 20348–20353, 2009.

Shao, X. M. and Fan, J. M.: Past climate on west Sichuan Plateau as reconstructed from ring-widths of dragon spruce, Quaternary Sci., 1, 81–89, 1999 (in Chinese).

Shao, X. M., Xu, Y., Yin, Z-Y., Zhu, H., and Wang, S.: Climatic implications of a 3585-year tree-ring width chronology from the northeastern Qinghai-Tibetan Plateau, Quaternary Sci. Rev., 29, 2111–2122, doi:10.1016/j.quascirev.2010.05.005, 2010.

Shindell, D., Schmidt, G., Mann, M., Rind, D., and Waple, A.: Solar forcing of regional climate change during the Maunder Minimum, Science, 294, 2149–2152, 2001.

Stokes, M. A. and Smiley, T. L.: An introduction to tree ring dating, The University of Chicago Press, Chicago, 1968.
Stuiver, M. and Braziunas, T. F.: Atmospheric 14C and century-scale solar oscillations, Nature, 338, 405–408, 1989.
Sun, J. and Liu, Y.: Tree ring based precipitation reconstruction in the south slope of the middle Qilian Mountains northeastern Tibetan Plateau, over the last millennium, J. Geophys. Res., 117, D08108, doi:10.1029/2011JD017290, 2012.
Tan, M., Liu, T.S., Hou, J., Qin, X., Zhang, H., and Li, T., Cyclic rapid warming on centennial-scale revealed by a 2650-year stalagmite record of warm season temperature, Geophys. Res. Lett., 30, 1617, doi:10.1029/2003GL017352, 2003.
Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P. N., Henderson, K., and Mashiotta, T. A.: Tropical glacier and ice core evidence of climate change on annual to millennial time scales, Clim. Change, 59, 137–155, 2003.
Tian, Q., Gou, X., Zhang, Y., Wang, Y., and Fan, Z.: May-June mean temperature reconstruction over the past 300 years based on tree rings in the Qilian Mountains of the Northeastern Tibetan Plateau, IAWA J., 30, 421–434, 2009.
Wang, X. C., Zhang, Q. B., Ma, K. P., and Xiao, S. C.: A tree-ring record of 500-year dry-wet changes in northern Tibet, China, Holocene, 18, 579–588, 2008.
Warren, W. G.: On removing the growth trend from dendrochronological data, Tree-Ring Bull., 40, 35–44, 1980.
Webster, P. J., Magaña, V. O., Palmer, T. N., Shukla, J., Tomas, P. A., Yanai, M., and Yasunari, T.: Monsoons: processes, predictability, and the prospects for prediction, J. Geophys. Res., 103, 14451–14510, 1998.
Wigley, T. M. L., Briffa, K. R., and Jones, P. D.: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, J. Clim. Appl. Meteorol., 23, 201–213, 1984.
Xu, W. X. and Liu, X. D.: Response of vegetation in the Qinghai-Tibet Plateau to global warming, Chinese Geogr. Sci., 17, 151–159, 2007.
Yadav, R. R., Park, W. K., Singh, J., and Dubey, B.: Do the western Himalayas defy global warming? Geophys. Res. Lett., 31, L17201, doi:10.1029/2004GL020201, 2004.
Yadav, R. R., Braeuning, A., and Singh, J.: Tree ring inferred summer temperature variations over the last millennium in western Himalaya, India, Clim. Dynam., 36, 1545–1554, 2011.

CPD
10, 341–380, 2014
Evidence from Tree rings
Y. Zhang et al.

Yang, B., Bräuning, A., Johnson, K. R., and Shi Y. F.: General characteristics of temperature variation in China during the last two millennia, Geophy. Res. Lett., 29, 381–384, 2002
Yang, B., Bräuning, A., Liu, J. J., Davis, M. E., and Shao, Y. J.: Temperature changes on the Tibetan Plateau during the past 600 years inferred from ice cores and tree rings, Global. Planet. Change., 69, 71–78, 2009b.
Yang, B., Kang, X., Liu, J., Bräuning, A., and Qin, C.: Annual temperature history in Southwest Tibet during the last 400 years recorded by tree rings, Int. J. Climatol., 30, 962–971, doi:10.1002/joc.1956, 2009a.
Yang, B., Kang, X. C., Brauning, A., Liu, J., Qin, C., and Liu, J. J.: A 622-year regional temperature history of southeast Tibet derived from tree rings, Holocene, 20, 181–190, 2010.
Yang, L. and Zhao, J.-B.: Effect of ENSO events on climate and climate disasters in the Hexi Corridor, Gansu Province, Arid Zone Res., 29, 949–955, 2012 (in Chinese).
Yang, Q., Liu, J., and Wang, Y.: Survey report in the National Nature Reserve of Qilian Mountains, Gansu, Gansu Science & Technology Press, Lanzhou, 2008 (in Chinese).
Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D. B., and Joswiak, D.: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings, Nat. Clim. Change, 2, 663–667, doi:10.1038/NCLIMATE1580, 2012.
Yao, T. D., Wang, Y. Q., Liu, S. Y., Pu, J. C., Shen, Y. P., and Lu, A. X.: Recent glacial retreat in High Asia in China and its impact on water resource in Northwest China, Sci. China. Ser. D., 47, 1065–1075, 2004.
Zhang, C., Zhao, J., Luo, X., and Chen, L.: Correlation between ENSO events and climate impacts in Gansu for 60 years, J. Arid Land Resour. Environ., 25, 106–113, 2011 (in Chinese).
Zhang, Y., Tian, Q., Gou, X., Chen, F., Leavitt, S. W., and Wang, Y.: Annual precipitation reconstruction since AD 775 based on tree rings from the Qilian Mountains, northwestern China, Int. J. Climatol., 31, 371–381, 2011.
Zhou, X. J., Zhao, P., Chen, J. M., Chen, L. X., and Li, W. L.: Impacts of thermodynamic processes over the Tibetan Plateau on the Northern Hemispheric climate, Sci. China. Ser. D., 52, 1679–1693, 2009.
Zhu, H. F., Shao, X. M., Yin, Z. Y., and Huang, L.: Early summer temperature reconstruction in the eastern Tibetan plateau since AD 1440 using tree-ring width of Sabina tibetica, Theor. Appl. Climatol., 106, 45–53, 2011a.

CPD
10, 341–380, 2014

Zhu, H. F., Shao, X. M., Yin, Z. Y., Xu, P., Xu, Y., and Tian, H.: August temperature variability in the southeastern Tibetan Plateau since AD 1385 inferred from tree rings, Palaeogeogr. Palaeocl., 305, 84–92, 2011b.

Zhu, H. F., Zheng, Y. H., Shao, X. M., Liu, X. H., Xu, Y., and Liang, E. Y.: Millennial temperature reconstruction based on tree-ring widths of Qilian juniper from Wulan, Qinghai Province, China, Chinese Sci. Bull., 53, 3914–3920, doi:10.1007/s11434-008-0400-8, 2008.

CPD
10, 341–380, 2014
Evidence from Tree rings
Y. Zhang et al.

Table 1. Tree-ring sampling sites and meteorological stations.

	Name	Longitude (E)	Latitude (N)	Elevation (m a.s.l.)	Time span	Cores (Trees)
Tree-ring sites	Hy0	99.70	38.69	3371–3489	450–2009	64 (27)
	Hy1	99.68	38.70	3300–3420	486–2012	80 (39)
	Hy3	99.69	38.71	3301–3341	490–2009	24 (11)
	Hy6	99.67	38.72	3369–3578	1076–2012	82 (41)
Meteorological stations	Yeniugou	99.58	38.42	3320.0	1960–2011	
	Zhangye	100.43	38.93	1482.7	1951–2011	

CPD
10, 341–380, 2014

Table 2. Statistical features of the HY chronology.

Statistics	HY
Total number of cores	152
Mean sensitivity	0.175
Mean	0.982
Standard deviation	0.22
First-order autocorrelation	0.535
Median length	516
Statistical features of the common-period analyses (1701–2000)	
Number of cores	68
Mean correlation between all series	0.312
Mean correlation between trees	0.306
Mean correlation within trees	0.823
Signal-to-noise ratio	30.83
Variance explained by the first principal component (%)	40.9
Expressed population signal (EPS)	0.969
First year of subsample signal strength > 0.85 (Number of Cores)	670(11)

CPD
10, 341–380, 2014

Y. Zhang et al.

Table 3. Leave-one-out statistics for the reconstructed January–August minimum temperature for the common period 1960-2011.

	r	R^2	R^2_{adj}	RE	ST	FST	PMT
Calibration	0.765[a]	0.585	0.578	–	–	–	–
Verification	0.745[a]	–	–	0.555	$41^+/11^{-a}$	$35^+/16^{-b}$	3.931[a]

r: Pearson's correlation coefficient; R^2: the explained variance; R^2_{adj}: the adjusted explained variance; ST: the sign test; FST: the first-differences sign test; PMT: the product-mean test; RE: the reduction of error. [a] significant at $P < 0.01$; [b] significant at $P < 0.05$.

CPD
10, 341–380, 2014

Evidence from Tree rings

Y. Zhang et al.

Table 4. Tropical volcanic eruptions and the possible corresponding cold events recorded by tree ring (1000–1999 AD).

	Year (Tropical Volcanic Radiative Forcing, $W m^{-2}$) (Mann et al., 2005)	Year (Standardized Tmin)	Volcanic eruption*
1	1195 (−2.42), 1196 (−0.9)	1197 (< −1.5), 1198 (< −1)	
2	1259 (−11.82), 1260 (−4.4), 1261 (−1.6)	1259 (<−1.5), 1260 (<−0.5), 1262 (<−0.5)	
3	1285 (−3.75), 1286 (−1.4)	1285 (<−1.5), 1286 (<−0.5)	
4	1453 (−4.4)	1453 (<−1.5)	
5	1465 (−1.1), 1466 (−0.4)	1465 (<−1), 1467 (<−1.5), 1468 (<−0.5)	
6	1601 (−5.43), 1602 (−2)	1602 (<−1)	
7	1641 (−5.5), 1642 (−2), 1643 (−0.8)	1641 (<−1), 1643 (<−0.5)	Philippines – Mindanao (4 Jan 1641) Java (Indonesia) (1641)
8	1674 (−3.37), 1675 (−1.2)	1674 (<−0.5), 1675 (<−1), 1676 (<−1.5)	
9	1681 (−2.79)	1681 (<−1.5)	
10	1809 (−5.5), 1810 (−2)	1810 (<−1)	
11	1815 (−5.98), 1816 (−2.2), 1817 (−0.8)	1818 (<−1)	Lesser Sunda Islands (Indonesia) (10 Apr 1815) Java (Indonesia) (16 Jan 1817)
12	1831 (−4.86), 1832 (−1.8)	1831 (<−1.5), 1833 (<−0.5)	North of Luzon (Philippines) (1831)
13	1883 (−3.7), 1884 (−1.4)	1883 (<−1.5), 1884 (<−1.5)	Indonesia (27 Aug 1883)
14	1969 (−1.06), 1970 (−0.51), 1971 (−0.2)	1971 (<−0.5)	Java (Indonesia) (17 May 1982) Sulawesi (Indonesia) (23 Jul 1983)
15	1993 (−1.39), 1994 (−0.56), 1995 (−0.26)	1995 (<−1.5)	Northern Chile (19 Apr 1993), New Britain (19 Sep 1994)

* Volcanic eruption data were downloaded from Global Volcanism Program, Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution (http://www.volcano.si.edu/).

CPD
10, 341–380, 2014

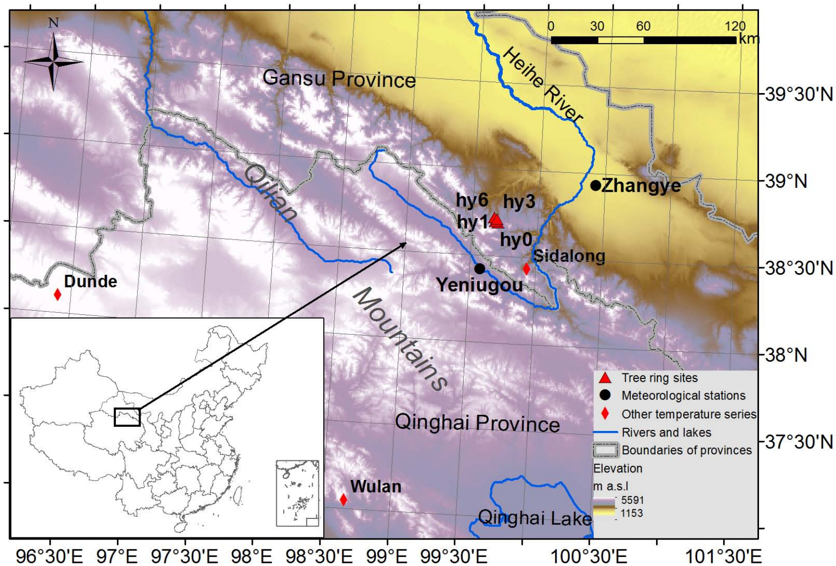

Fig. 1. Locations of tree-ring sampling sites, meteorological stations, and other temperature-related series in the Qilian Mountains (Sidalong: Liu et al., 2007; Wulan: Zhu et al., 2008; Dunde: Thompson et al., 2003).

CPD
10, 341–380, 2014

Evidence from Tree rings

Y. Zhang et al.

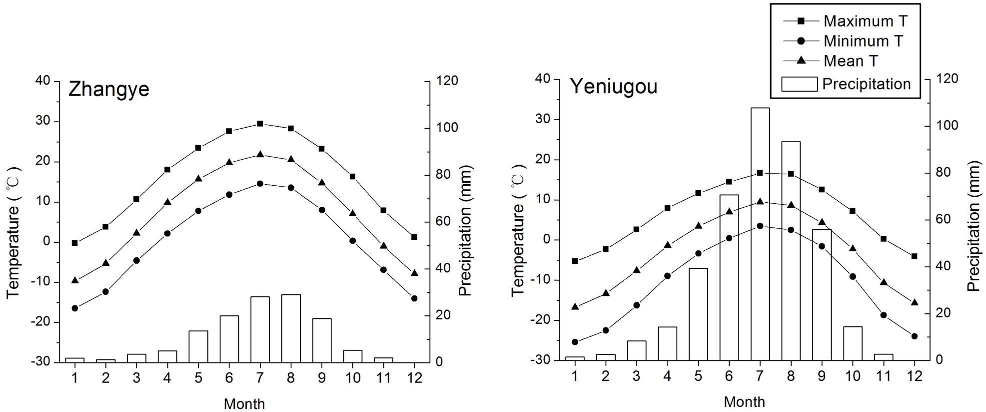

Fig. 2. Monthly maximum, minimum, and mean temperatures and precipitation at Zhangye and Yeniugou meteorological stations.

CPD
10, 341–380, 2014

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◂◂
▸▸
◂
▸
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

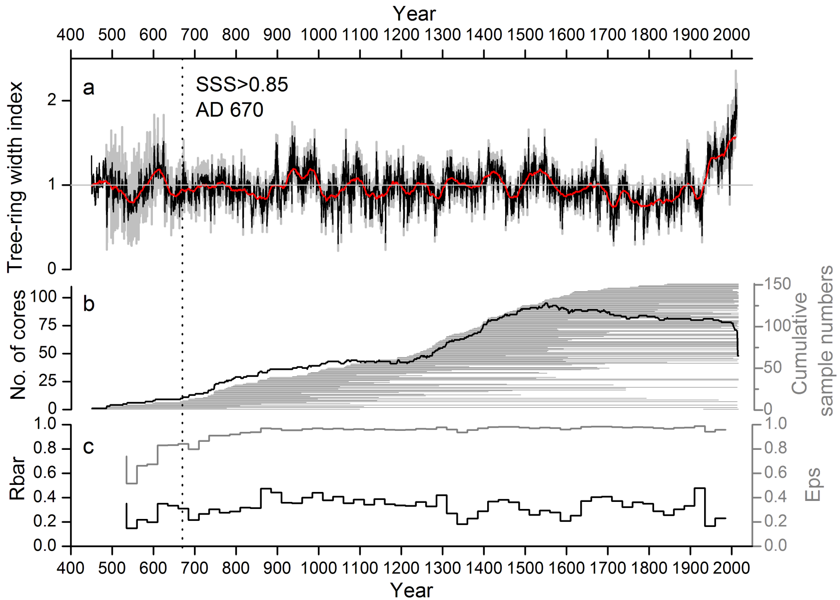

Fig. 3. (a) Ring-width chronology (HY), the red line indicates the 31 yr running mean, the grey area indicates the 2-standard errors of the ring-width chronology. **(b)** Changing sample size over time (dark line) and cumulative sample numbers. **(c)** EPS and Rbar values. The dotted vertical line denotes the year 670 AD, when the SSS value exceeded the threshold of 0.85 (SSS means the subsample signal strength).

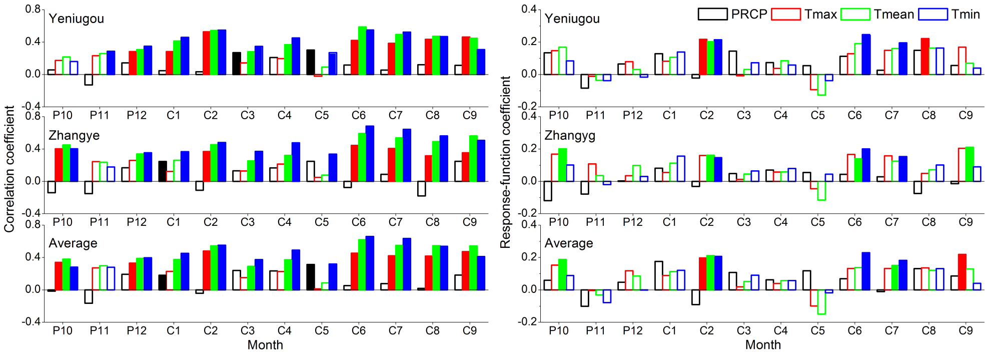

Fig. 4. Correlation (left) and response-function (right) analysis plots between the HY chronology and the monthly climatic data from Yeniugou (top), Zhangye(middle) and the averages of two stations(bottom). Months P10 through P12 are October through December of the previous year, and months C1 through C9 are January through September of the current year. The filled colour bars mean the significance level of 0.05. The monthly climatic data include monthly mean temperature (Tmean), monthly minimum temperature (Tmin), monthly maximum temperature (Tmax), and monthly total precipitation (PRCP).

CPD
10, 341–380, 2014

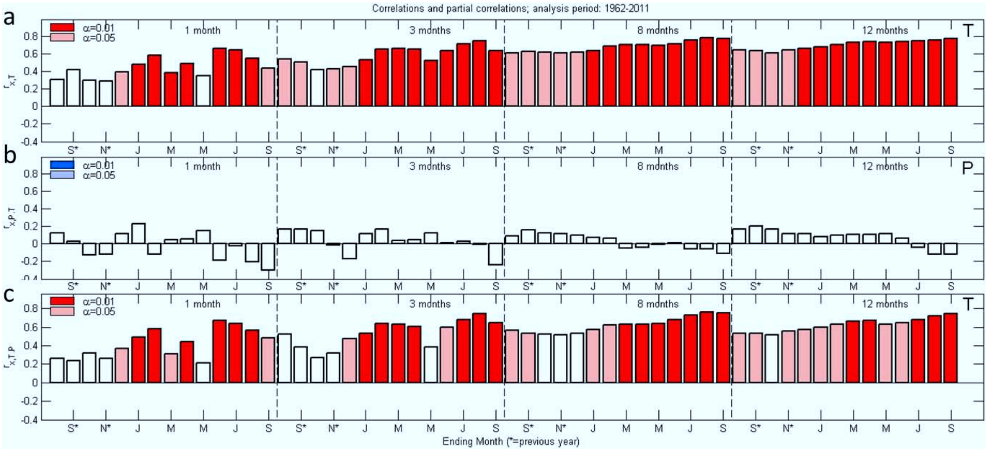

Fig. 5. Correlations and partial correlations between the tree-ring series and the multi-month averages of climatic variables from Yeniugou and Zhangye. **(a)** Simple correlations with the primary climatic variable, the mean minimum temperature anomalies of the two stations (Zhangye and Yeniugou). **(b)** Partial correlations between the tree-ring index and the secondary climatic variable, the mean precipitation anomalies of the two stations, when the minimum temperature was the control variable. **(c)** Partial correlations between the tree-ring index and the secondary climatic variable, the mean minimum temperature anomalies of the two stations, when the mean precipitation anomalies was the control variable. The *x* axis presents months from August of the previous year to September of the current year.

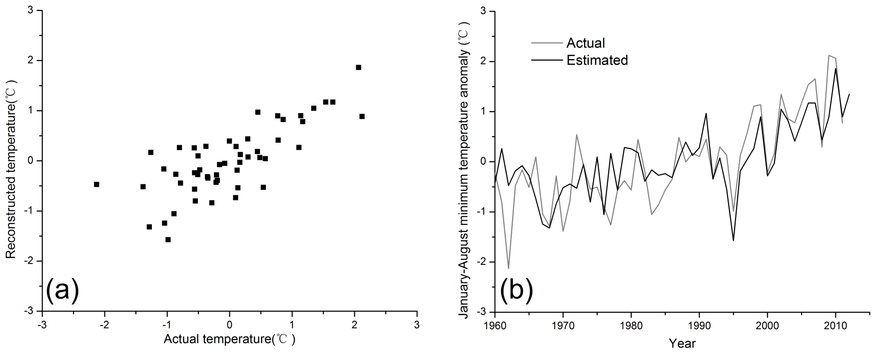

Fig. 6. Scatter plot **(a)** and time series **(b)** of the actual and estimated temperature anomalies during the calibration period from 1960 to 2011.

CPD
10, 341–380, 2014

Evidence from Tree rings

Y. Zhang et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

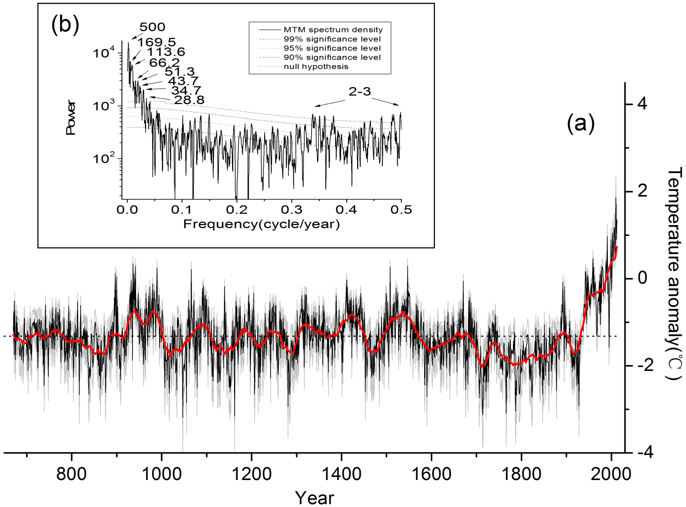

Fig. 7. (a) our reconstructed temperature in the central Qilian Mountains with mean (dotted lines) and 95 % confidence level (grey bars), the red dark lines indicate the 31 yr running mean of our reconstruction. **(b)** MTM spectral density of our temperature reconstruction.

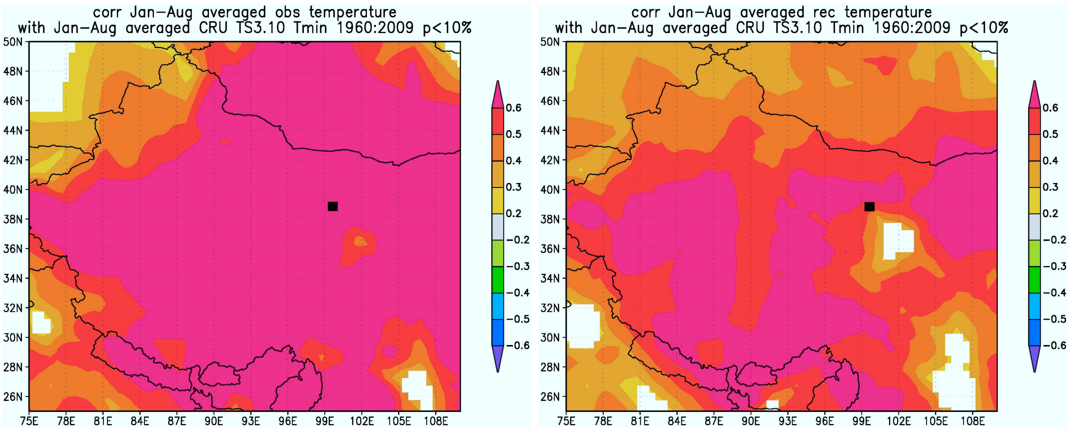

Fig. 8. Correlations of the instrumental (left) and reconstructed (right) January–August mean minimum temperature with the CRU gridded January–August mean minimum temperatures for western China during the period 1960–2009. The black square indicates the location of this study.

CPD
10, 341–380, 2014

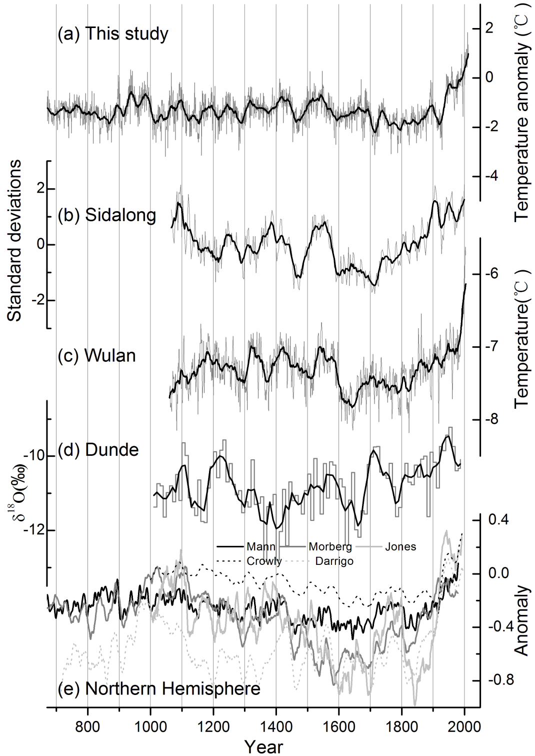

Fig. 9. Comparison between the reconstruction presented here **(a)** and other temperature series for the Qilian Mountains (**b**, **c**, and **d**) (Liu et al., 2007; Zhu et al., 2008; Thompson et al., 2003), and the Northern Hemisphere **(e)** (Jones et al., 1998; Mann et al., 1999; Crowly, 2000; Moberg et al., 2005; D'Arrigo et al., 2006). The dark lines indicate the 20 yr running mean of each series except for the 21 yr running mean of Sidalong series (Liu et al., 2007).

CPD
10, 341–380, 2014

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀I | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion