Millennial Mean Temperature Variations in the Qilian Mountains, China: Evidence from Tree rings

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Abstract:

A 1342-year-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 and response function analyses. The chronology was significantly positively correlated with temperature variables during the pre- and current growing seasons. The variability of the mean temperature from July to September since AD 670 was then reconstructed based on the tree-ring chronology. The reconstruction explained 59% of the variance in the instrumental temperature records during the calibration period (1951-2012) and captured the variation patterns in mean temperature at the annual to centennial time scales over the past millennium. The most recent 50 years were the warmest period, while 1690-1880 was the coldest period since AD 670. 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 wavelet analysis showed the occurrence of significant quasi-periodic behaviour at a number of periods (2-4, 40-50, and 90-170 years), which were consistent with those associated with El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and solar activity. The Comparison between reconstructed temperature and the index of tropical volcanic radiative forcing indicated some cold events recorded by tree ring may be due to the impact of tropical volcanic eruptions.

Key words: tree rings; temperature; reconstruction; Qilian Mountains

1. Introduction

Understanding temperature variations over the past 1000 years 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., 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., 2011), 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 years. 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 AD 1000. The two reconstructions showed the occurrences of generally low temperatures during AD 1600-1800 and the abrupt warming toward the end of past millennia. However, there were some discrepancies between these series before AD 1500, and the long-term trends were even reversed in the period of A.D. 1060-1200. Yadav et al. (2011) reconstructed the mean summer temperature extending back to AD 940 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 from 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 years. However, the small sample size led to substantial uncertainties for the period of approximately AD 700-900 (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 years, especially before AD 1050, 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. This reconstruction should improve our understanding of temperature variability in the north-eastern TP for the past millennium.

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 mm 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 mm 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 to -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).

Figure 1 near here

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 living 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 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. Signal strength of the standard chronology was assessed by the mean inter-series correlation (Rbar), and the associated expressed population signal (EPS) (Wigley, 1984). 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). The SSS estimates the agreement between an average series made from a few samples with one made from an optimum or larger number of series.

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). 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 (TS3.21) (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, latest access on May 15, 2014).

Figure 2 near here

2.4 Statistical methods

Correlation and response function analyses (Fritts, 1976) were used to investigate the relationships between the tree-ring data and climatic variables for the 12-month period extending from October of the prior year to September of the current year using the program DENDEOCLIM2002 (Biondi and Waikul, 2004).

To reconstruct the past climate variations, the instrumental climatic records were regressed against the HY chronology. The climate variables for the successive months from the previous October to current September in two stations were examined to identify the best climatic variable and season for reconstruction. The accuracy of the model was evaluated by splitting the samples into two sub periods for separate calibration and verification. Statistical tests, including Pearson's correlation coefficients (r), explained variance (R^2), reduction of error (RE), and coefficient of efficiency (CE) (Cook et al., 1999) were applied.

Wavelet analysis, using a Morlet wavelet coupled with a 5% red-noise reduction, was employed to reveal the variability of the temperature reconstruction in the frequency domain (http://paos.colorado.edu/research/wavelets/; Torrence and Compo, 1998).

3. Results

3.1 STD chronology statistics

The chronology covers the period from AD 450 to 2012 (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 AD 670 to 2012. The median segment length of the chronology was 516 years, 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, respectively, indicating that the chronology was appropriate for dendroclimatic studies (Wigley et al., 1984).

Figure 3 near here

Table 2 near here

Figure 4 near here

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, left) 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. 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, right). 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 temperature variables in two stations with tree-ring index indicated that the tree-ring growth in our sites was temperature-sensitive.

Figure 4 near here

Figure 5 near here

3.3 Calibration and reconstruction of the mean temperature

The resulting statistics of split-sample calibration-verification test for different seasonal and annual mean temperature variables in the two stations were shown partially in Table 3, where all values of RE and CE were significant at the 0.1 level. The regression models based on temperature variables in Zhangye and tree-ring index were more reliable. Although the elevation of Zhangye station is much lower than that of Yeniugou station, the correlations between monthly temperature variables of two stations for the same months are high, especially in warm season. The mean of correlation coefficients of Tmean in 12 months is 0.628 (Tmin: 0.717; Tmax: 0.607). Additionally, Temperature data in Zhangye station can be a good representative of temperature variations in agricultural region of the Hexi Corridor in China, therefore, temperature data in Zhangye station was employed to reconstruct the past temperature history. Based on the phonological investigation of Qilian Juniper in the Qilian Mountains (Liu et al., 2006), the Qilian Juniper leaves sprout in late May or early June when average daily temperature reaches 8-10℃, radial growth will continue into middle September , and stop in late September. Considering the effects of precipitation in early spring and the reliability of the regression model, we finally chose the mean temperature at Zhangye from current July to current September for the reconstruction. A transfer function was estimated by linear regression using July-September mean temperature at Zhangye as the dependent variable and the standard tree ring chronology as the independent variable.

Fig. 5 compared the observed and estimated Tmean series during 1951-2012, the scatter plot clearly presented the linear relationship between the instrumental and estimated data (Fig. 5a), the estimated temperatures closely matched the instrumental record in most of years except in 4 abnormal years(1952,1979,1993,1995)(Fig. 5b). According to instrumental records of Zhangye stations, the observed July-September precipitation in the first 3 years were abnormally high during the past 62 years (122mm in 1952, 141mm in 1979, 130 mm in 1953, while the mean during 1951-2012 is 75 mm), abnormally high precipitation will lead to low temperature, but in some extent, will reduce the influence of lower temperature on tree-growth, which might explain the discrepancies between actual and estimate values in the 3 years. Both spring precipitation in

1995 (6 mm) and summer precipitation in 1994 (70 mm) were very low, total precipitation in July and August of 1994(28 mm) was the lowest in the same months during 1951-2012. The severe droughts in growing period in previous year and pre-growing period in current year would influence the tree-growth significantly although temperature in growing season was nearly normal in this year. Considering these abnormal years, a new transfer function was re-estimated by linear regression excluding the 4 years, the final transfer function was

$$T_{7\text{-}9} = 15.6 + 2.43STD$$

where $T_{7\text{-}9}$is the average July-September mean temperature and STD is the index of HY chronology.

The final calibration model accounted for 59% ($p<0.001$) of the total variance of the mean July-September mean temperature over the calibration period from 1951 to 2012. As shown in Table 3(bottom), both RE and CE are positive, indicating that our regression model is stable and reliable, and is acceptable to reconstruct the annual-to-centennial variability of the mean July-September mean temperature in the central Qilian Mountains since AD 670.

Table 3 near here

Figure 5 near here

The 31-year running means of the reconstructed series revealed multi-decadal to centennial-scale variation patterns (Fig. 6a). The July-September mean temperature fluctuated with relatively low variability from approximately AD 670 to 780 and from AD 1100 to 1400, while some larger fluctuations were found in the periods of approximately AD 850-1100 and AD 1400-1600. A significant long-term cooling occurred with several short warmer periods, from the late 1500s to the end of the 19^{th} century. Temperature increased gradually after AD 1850, and the increase during the most recent 100 years was the most rapid in the past millennium with a warming trend of 0.26℃ per 100 years. Based on the overall mean and 31-year running means, several distinct warm and cold periods were identified. The warm periods included approximately AD 920-1000, 1310-1450, 1490-1570, and 1930-2011, while the cold periods were approximately AD 780-890, 1000-1060, 1110-1170, 1260-1300, 1450-1490, 1570-1650, 1690-1880, and 1900-1930. The most recent 50 years was the warmest period, and AD 910-1000 was the second-warmest period over the past 1342 years. The period from AD 1690 to 1880 was the coldest period over the past millennium. There seemed to be a centennial scale cyclic pattern in the reconstructed series, especially during AD 1000-1700 (Fig. 6a). Wavelet analysis was then used to analyse the reconstruction series jointly in the time and frequency domains for time-varying signals. The results revealed the persistence of high-frequency (appr. 2-4 years, mainly exists during AD 1000-1600) trends and low-frequency century-scale (appr. 90-170 years, mainly exists during AD 1350-1700; appr. 40-50 years, exists during AD 900-1000) (Fig. 6b).

Figure 6 near here.

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). 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 in the early growing season or some abnormal years, and tree growth is mainly influenced by temperature at our study sites.

4.2 Validation of the reconstruction

4.2.1 Spatial representativeness of the reconstructed series

Figure 7 shows the results of spatial pattern of the correlations of the CRU gridded mean July-September Tmean over western China with the actual and reconstructed July-September Tmean for the period 1951-2012. The instrumental data significantly ($p<0.1$) correlated with the gridded mean July-September Tmean over most areas in western China, with stronger correlations being found mainly in the TP and the north-central part of western China (Fig. 7). 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. 7). 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.

Figure 7 near here

4.2.2 Comparisons with other reconstructions and Northern Hemisphere temperature

To further assess the validity of our temperature reconstruction for the Qilian Mountains (Fig. 8a), 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-year resolution (Fig. 8b). This reconstruction agreed closely with ours (Fig. 8a) with a correlation coefficient of 0.58 ($p < 0.01$) between the two series for the period of AD 1066-1999 and the variation patterns were similar on an interdecadal time scale. However, some differences in the low-frequency domain exited during AD 1100-1200 and 1350-1410, which may be due to the different standardisation methods used and the response mechanisms of carbon isotope and radial growth to climate factors. Figure 8c 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 AD 1060-2004 ($r=0.44$, $p<0.01$). 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 AD 1100-1200. Since the differences mainly existed before AD 1200 when the sample depth of Wulan reconstruction was low, the sample depth may also contribute to these discrepancies (Shao et al., 2010). Additionally, inner-annual variability may have caused discrepancies between the series as the seasons covered by the reconstructions were different (current July - September vs. previous September-current April).

Figure 8 near here

In addition to the tree-ring-based reconstructions, we compared our reconstruction to an ice-core $\delta^{18}O$ series with a 10-yr resolution reflecting the temperature variations at Dunde in the Qilian Mountains (Thompson et al., 2003) (Fig. 8d). Both series showed strong warming trends since the late 18th century. The cold periods of approximately AD 1100-1200, 1250-1300, 1450-1500, and 1750-1800 and the warm periods of approximately AD 1050-1100, 1500-1600, and 1950-2009 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. 8e, the temperature reconstructions for the NH generally showed a cold period during approximately AD 700-950 and a warm period during approximately 950-1100 (the Medieval Climate Anomaly). Another cold period can be seen during approximately AD 1100-1400, 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 years. Certain decadal-scale cold and warm episodes in the NH, including those of the AD 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 (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 AD 840s and 910s 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 AD 1240s, 1540s and 1990s 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 Medieval Climate Anomaly 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 2-4 years (Fig. 6b) in our reconstruction are typically associated with El Ni˜no-Southern Oscillation (ENSO) (Allan et al., 1996), similar periodicities can be identified in other 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, it seems that the relationship between ENSO and temperature was unstable for the past millennium. 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 years ($r=-0.017$, lag = 0), while some significant correlations between ENSO index and reconstructed temperature were found in some periods using 50yr moving-correlation. A series of significant positive correlations ($p<0.01$) were found in approximately AD 1340-1410, 1553-1631, and 1798-1869, the highest correlation coefficient was 0.32 in AD 1355-1404, and meanwhile, continuous significant negative correlation ($p<0.01$) were found in AD 1060-1130, 1591-1656, and 1840-1927, with the highest correlation coefficient of -0.33 during AD 1849-1898.

The significant cycles at around 40-50 years (Fig. 6b) might be linked to Pacific Decadal Oscillation (PDO) (Mantua et al. 1997; Minobe, 1997). We then 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 AD 1068-1210, 1282-1386, and 1509-1654, and the highest positive correlation coefficient was 0.456 ($p<0.01$) for AD 1528-1627. 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). The centennial cycles identified in our study were possibly associated with the frequencies of solar variations (Stuiver and Braziunas, 1989; Hoyt and Schatten, 1997; Raspopov et al., 2008). The cycles similar to the periodicities of 90-170 years have been found in other tree ring reconstructions in China (Wang et al., 2008; Gou et al., 2010; Zhang et al., 2011). These significant low-frequency cycles were prominent in the periods of AD 1350-1650 and before AD 1150, corresponding to the Sporer minimum (AD 1460-1550) and Oort minimum (AD 1040-1080) period of lower solar activities. Although the low-frequency signal depressed since AD 1650, low temperatures during the LIA should be linked to the Maunder Minimum of solar activity (Shindell et al., 2001).

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 AD 1000-1999. 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 AD 1815. 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. More temperature-related tree-ring series are urgently needed for the further analysis.

5. Conclusion

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. The correlations between the tree ring chronology and mean temperatures at near-by weather stations can be as high as 0.6 and, therefore, it can be used to infer the variations in mean July-September mean temperature over the past millennium for the study region. For the calibration period of 1951-2011, the transfer function explained 59% of the total variance in average July-September mean temperature. This temperature reconstruction covered the period AD 670-2011 and revealed temperature variation patterns at the inter-annual to centennial timescales over the past 1342 years. 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 AD 920-1000, 1310-1450, 1490-1570, and 1930-2011, while cool periods were identified in AD 780-890, 1000-1060, 1110-1170, 1260-1300, 1450-14900, 1570-1650, 1690-1880, and 1900-1930. The warming during the most recent 50 years was unprecedented within the past millennium; even during the dramatic warming from AD 900 to 1100, the reconstructed temperatures did not exceed those observed today. The period from AD 1690 to 1880 was the coldest and longest-lasting cold period during the past 1342 years.

Significant periodicities were found in the reconstructed series using the wavelet analysis, including those of 2-4, 40-50, and 90-170 years. We examined the relationships between the reconstructed 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 the influences of both ENSO and 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 relationships with the cold events recorded by our reconstruction.

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Tables

Table1 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	1960-2012	
	Zhangye	100.43	38.93	1482.7	1951-2012	

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)

Table3 Calibration and verification statistics of the monthly/seasonal temperature models for the reconstruction

Station	Season	Calibration period	R^2	Verification period	r	RE	CE
Yeniugou	C6-C9	1960-1986	0.157 [b]	1987-2012	0.504[a]	0.474[a]	-0.873[c]
	C6-C9	1987-2012	0.254[b]	1960-1986	0.396[a]	0.501[a]	-1.719[c]
Zhangye	P10-C9	1952-1981	0.14[b]	1982-2012	0.683[a]	0.469[a]	-0.536[c]
		1982-2012	0.466[a]	1952-1981	0.375[a]	0.571[a]	-0.881[c]
	P11-C8	1952-1981	0.138[b]	1982-2012	0.614[a]	0.449[a]	-0.678[c]
		1982-2012	0.377[a]	1952-1981	0.371[a]	0.523[a]	-1.107[c]
	P11-C4	1952-1981	0.15[b]	1982-2012	0.437[a]	0.497[a]	-0.353[c]
		1982-2012	0.191[b]	1952-1981	0.387[a]	0.374[a]	-0.59[c]
	C2-C4	1951-1981	0.141[b]	1982-2012	0.396[a]	0.431[a]	-0.089[c]
		1982-2012	0.157[b]	1951-1981	0.376[a]	0.402[a]	-0.349[c]
	C7-C9	1951-1981	0.153[b]	1982-2012	0.641[a]	0.517[a]	0.17[b]
		1982-2012	0.41[a]	1951-1981	0.391[a]	0.584[a]	-0.005[c]
After excluding the 4 years(1952,1979,1993,1995)							
Zhangye	C7-C9	1951-1979	0.41[a]	1980-2008	0.718[a]	0.68[a]	0.44[a]
		1980-2008	0.516[a]	1951-1979	0.641[a]	0.789[a]	0.369[a]
		1951-2008	0.59[a]	--	--	--	--

r：Pearson's correlation coefficient; R^2: the explained variance; RE: the reduction of error; CE: coefficient of efficiency.

[a] significant at P<0.01; [b] significant at P<0.05;[c] significant at P<0.1

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

	Year (Tropical Volcanic Radiative Forcing, W/m2) (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 (1641 Jan 4) 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) (1815 Apr 10) Java (Indonesia) (1817 Jan 16)
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 (1883 Aug 27)
14	1969(-1.06),1970(-0.51),1971(-0.2)	1971(<-0.5)	Java (Indonesia) (1982 May 17) Sulawesi (Indonesia) (1983 Jul 23)
15	1993(-1.39), 1994(-0.56),1995(-0.26)	1995(<-1.5)	Northern Chile (1993 Apr 19), New Britain (1994 Sep 19)

*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/).

Figures and captions

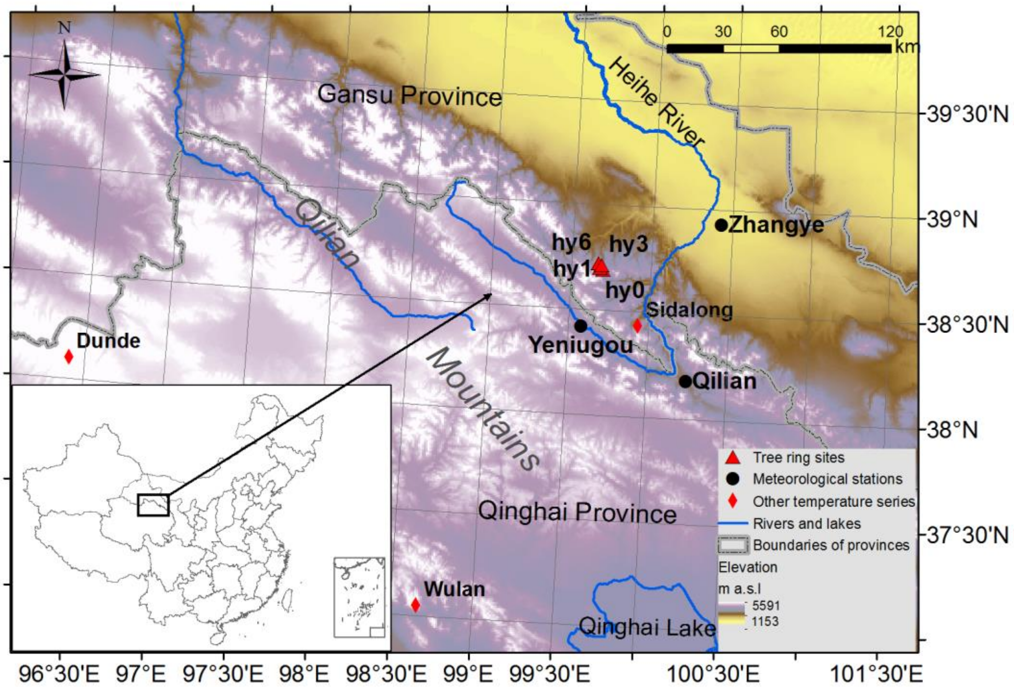

Fig. 1 Locations of tree-ring sampling sites, meteorological stations, and other temperature-related series in the Qilian Mountains (Sidalong: Liu et al., 2007; Wulan: Zhu et al., 2008; Dunde: Thompson et al., 2003)

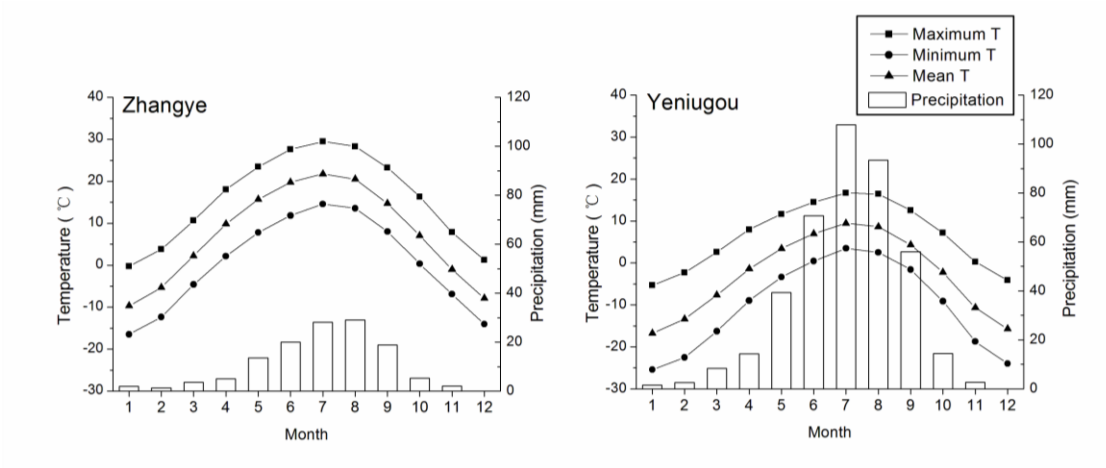

Fig. 2 Monthly maximum, minimum, and mean temperatures and precipitation at Zhangye and Yeniugou meteorological stations.

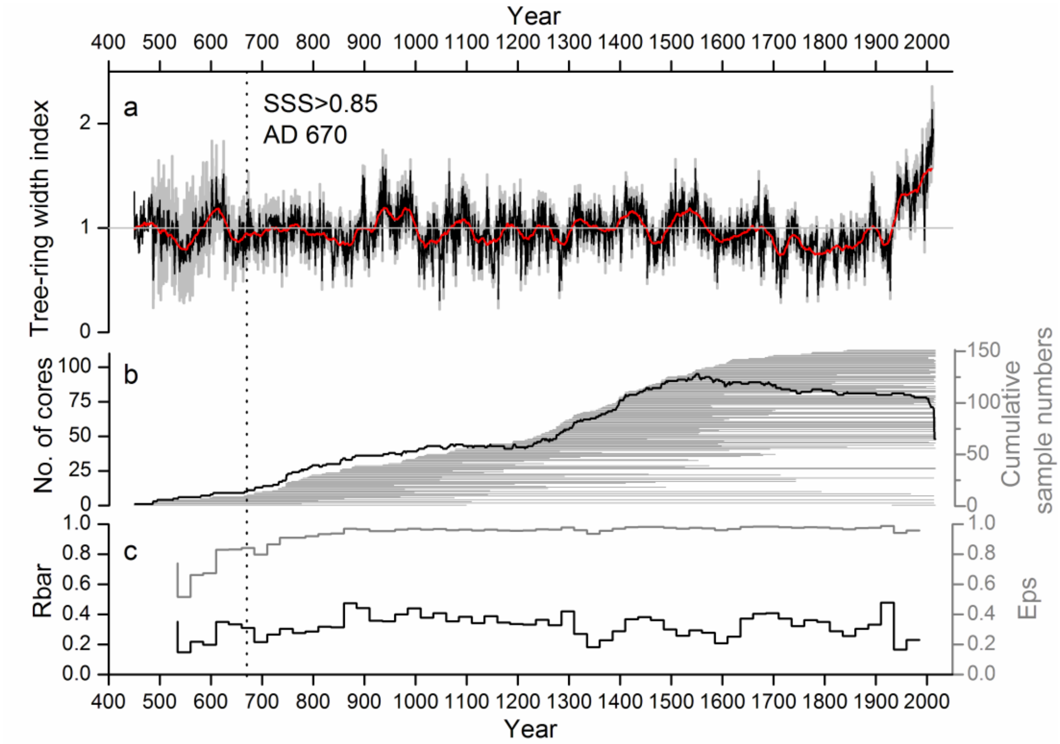

Fig. 3 a. Ring-width chronology (HY), the red line indicates the 31-year running mean, the grey area indicates the 2-standard errors of the ring-width chronology. b. Changing sample size over time (dark line) and cumulative sample numbers. c. Expressed Population Signal (EPS) (Wigley et al., 1984) and the mean inter-series correlation (Rbar) values. The dotted vertical line denotes the year AD 670, when the SSS value exceeded the threshold of 0.85(SSS means the subsample signal strength).

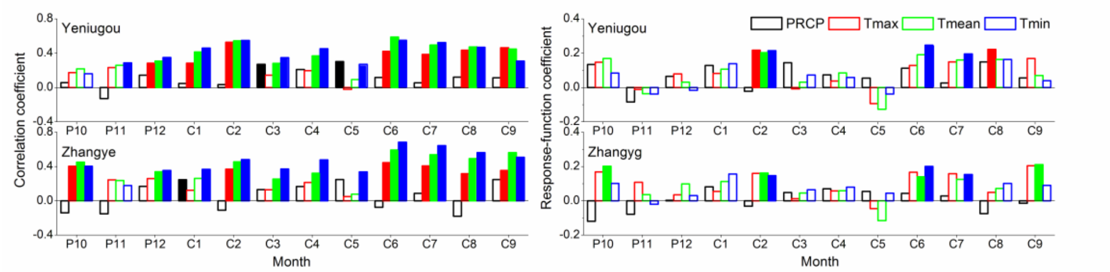

Fig. 4 Correlation (left) and response-function (right) analysis plots between the HY chronology and the monthly climatic data from Yeniugou and Zhangye. Months P10 through P12 are October through December of the previous year, and months C1 through C9 are January through September of the current year. 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).

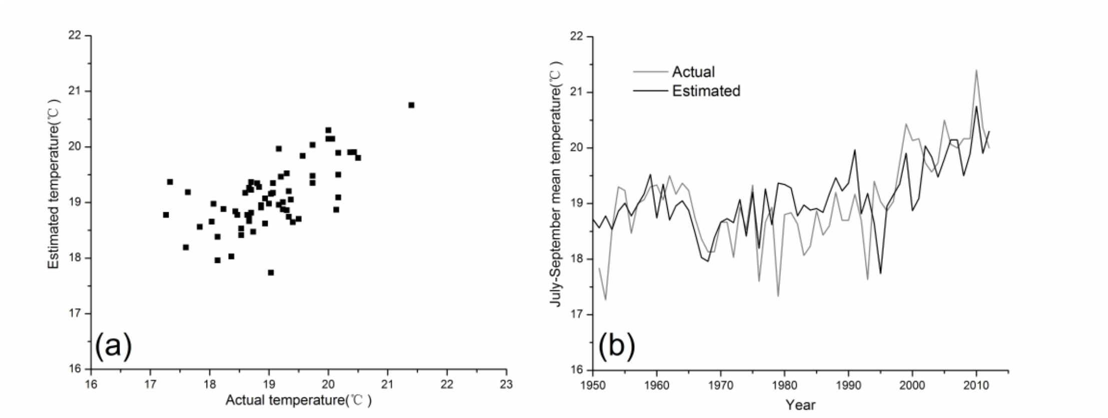

Fig. 5 Scatter plot (a) and time series (b) of the actual and estimated mean temperature during the calibration period from 1951 to 2012.

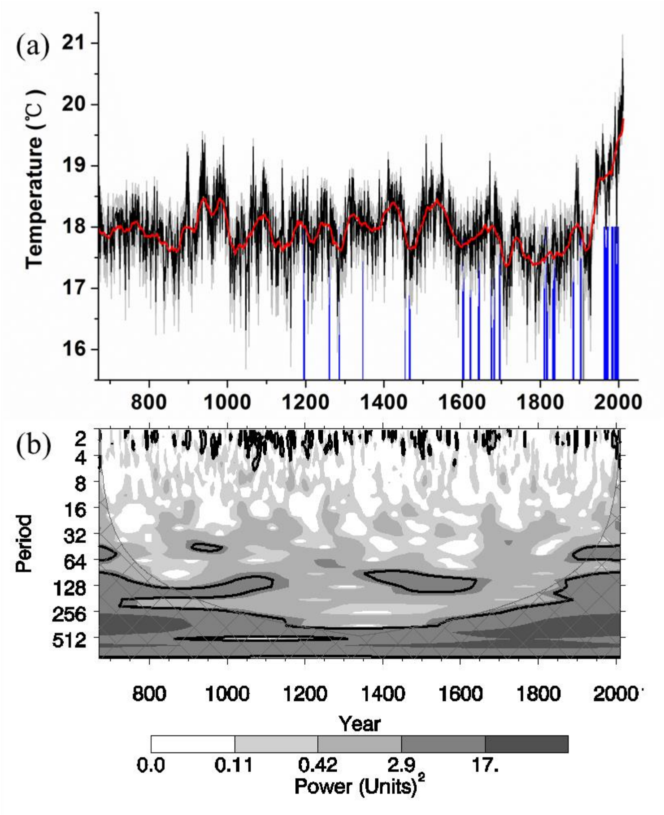

Fig. 6 (a), our reconstructed temperature in the central Qilian Mountains and 95 % confidence level (grey bars), the red dark lines indicate the 31-year running mean of our reconstruction. The vertical blue lines indicate 21 volcanic events during AD 1000-1999. (b), the wavelet power spectrum of our temperature reconstruction series. Cross-hatched regions represent the cone of influence where zero-padding of the data was used to reduce variance using a Morlet wavelet. Black contours indicate significant modes of variance with a 5% significance level using an autoregressive lag-1 red-noise background spectrum (Torrence and Compo, 1998).

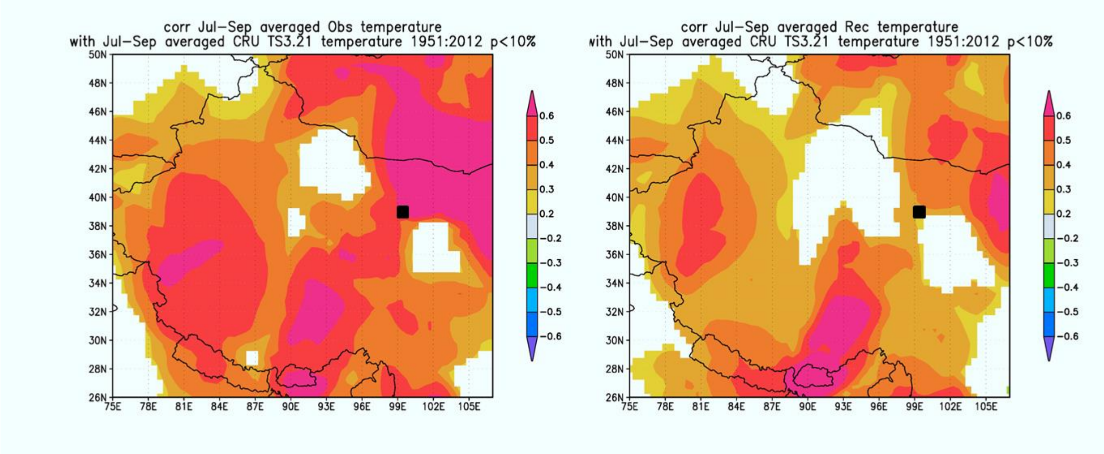

Fig. 7 Correlations of the instrumental (left) and reconstructed (right) July-September mean temperature with the CRU gridded July-September mean temperatures for western China during the period 1951-2012. The black square indicates the location of this study.

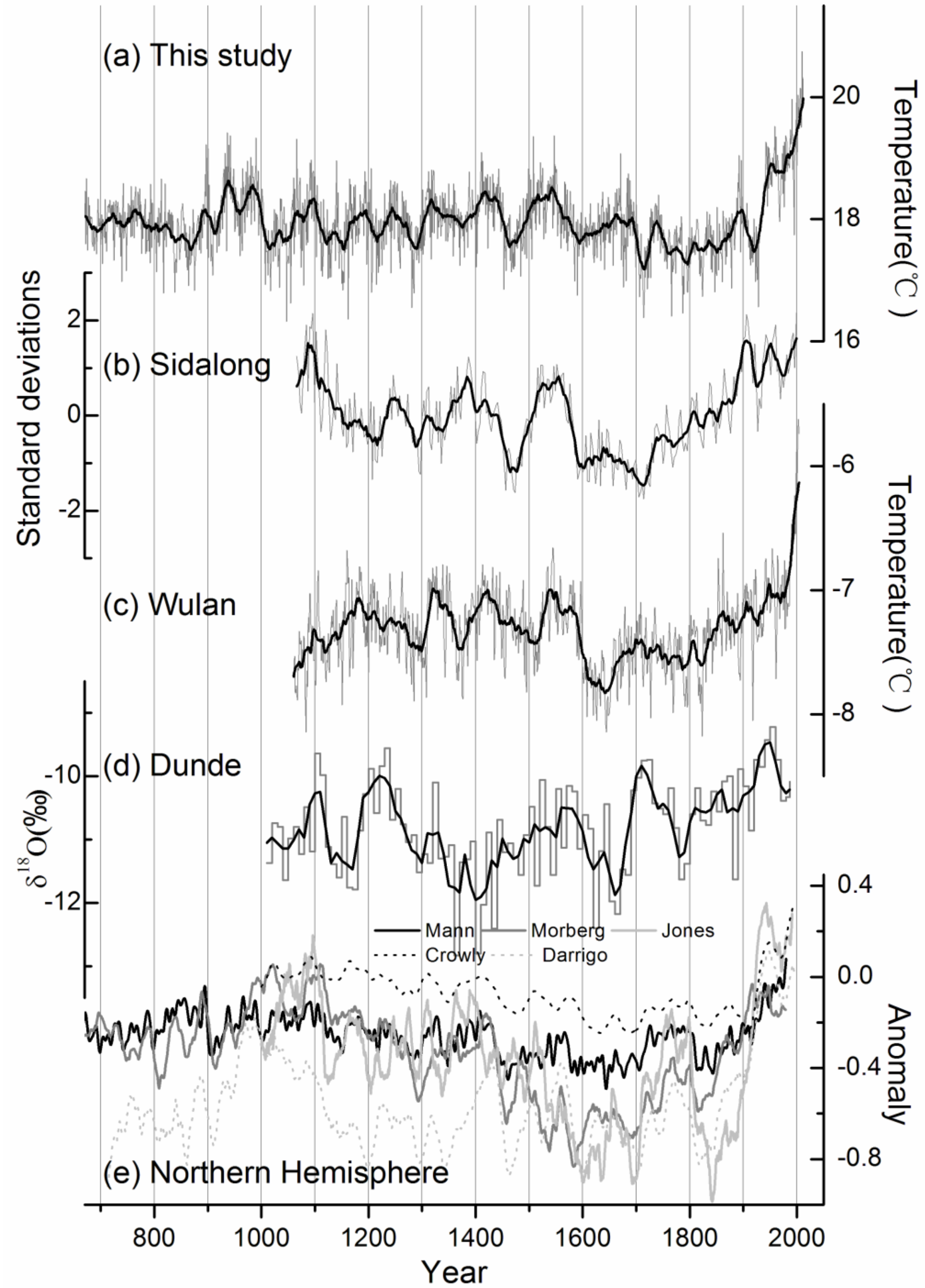

Fig. 8 Comparison between the reconstruction presented here (a) and other temperature series for the Qilian Mountains (b, c, and d) (Liu et al., 2007; Zhu et al., 2008; Thompson et al., 2003), and the Northern Hemisphere (e) (Jones et al., 1998; Mann et al., 1999; Crowly, 2000; Moberg et al., 2005; D'Arrigo et al., 2006). The dark lines indicate the 20-year running mean of each series except for the 21-year running mean of Sidalong series (Liu et al., 2007).