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Tree ring recorded May–August temperature variations since A.D. 1585 in the Gaoligong Mountains, southeastern Tibetan Plateau

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ABSTRACT

High-resolution proxy data are still scarce in the southeastern Tibetan Plateau, which limit our understanding of climatic variability before instrumental records. In this study, we developed 595-year tree ring-width chronology from *Larix speciosa* near the timberlines of the Gaoligong Mountains, southeastern Tibetan Plateau. Ring-width site chronologies and a well-replicated regional chronology (RC) showed significant positive correlations with warm season temperatures from May to August. Using RC as predictor, we reconstructed mean May–August temperature for the study region that extends back to A.D. 1585. Cold conditions prevailed during the periods 1600s, 1620–30, 1640–50s, 1700s, 1730–40s, 1760s, 1810–20s, 1850s, 1900–10s and 1955–70. Warm episodes occurred during 1610s, 1660–1680s, 1710–20s, 1750s, 1780–90s, 1820–40, 1920–50 and 1980–present. Spatial correlations with gridded land surface temperatures revealed that our reconstruction represents regional temperature signal for the southern Tibetan Plateau. Comparison with other tree ring-based temperature reconstructions from surrounding areas implies a high degree of confidence for our reconstruction.

1. Introduction

Global warming and associated regional climatic changes have attracted much attention in recent years. The Tibetan Plateau (TP), with an average elevation above 4000 m a.s.l., represents a huge heating surface in subtropical latitudes and plays a key role in driving the Asian summer monsoon circulation (Ding, 1992; Webster et al., 1998). Many studies deal with spatial and temporal aspects of climate variations over the TP with seasonal and annual resolutions, based either on meteorological data (e.g. Liu and Chen, 2000; Liu et al., 2006a, 2009a) or model simulations (Chen et al., 2003; Hulme et al., 1994). Statistically significant overall warming trends were found over the TP during recent decades for both mean and extreme surface air temperatures, especially during winter season and at high elevations (Liu and Chen, 2000; Liu et al., 2006a, 2009a). However, instrumental records on the TP are sparse and seldom extend further back than to the 1950s. To improve our understandings of climatic change in a long-term perspective, it is of great relevance to develop high-resolution proxy data over the TP.

Tree rings are annually resolved natural archives that provide proxy data for palaeo-environmental studies and reconstructions of various climate elements (Bradley and Jones, 1992; Luckman, 1996; Jones et al., 2009). Using tree-ring data, surface temperatures have been successfully reconstructed for the past centuries to millennium on both regional (e.g. Büntgen et al., 2005, 2006; Davi et al., 2003; Luckman and Wilson, 2005; Yadav et al., 2004) and hemispheric scales (e.g. Briffa et al., 2004; Esper et al., 2002; Mann et al., 1998). During the past decades, numerous dendroclimatological studies have been conducted on the TP, with respect to precipitation/drought reconstructions for the north-eastern TP (e.g. Li et al., 2008; Liu et al., 2006b; Shao et al., 2005; Sheppard et al., 2004; Zhang et al., 2003) and temperature reconstructions for the eastern and north-eastern TP (e.g. Bräuning and Mantwill, 2004; Gou et al., 2008; Liu et al., 2005, 2009b; Wang et al., 2009). In comparison with arid and semi-arid areas on the northern TP, the southern TP is characterized by a humid climate. However, only limited tree-ring studies have been performed on the southern TP despite its widespread forest cover (Bräuning, 2001, 2006; Fan et al., 2008, 2009; Fang et al., 2009; Liang et al., 2009; Yang et al., 2009). An improved tree-ring network with dense spatial coverage and long time-span for the southern TP is needed.

The north–south oriented Hengduan Mountains form the southeastern rim of the TP. This region is an area that is especially sensitive to climate change (Zheng, 1996). During the past century, mountain glaciers were retreating at a fast rate and alpine tree lines were advancing under the background of climate warming (Baker and Moseley, 2007; Li et al., 2009). Recently, regional drought variability was reconstructed for the past three to five centuries by using tree ring-width data (Fan et al., 2008;

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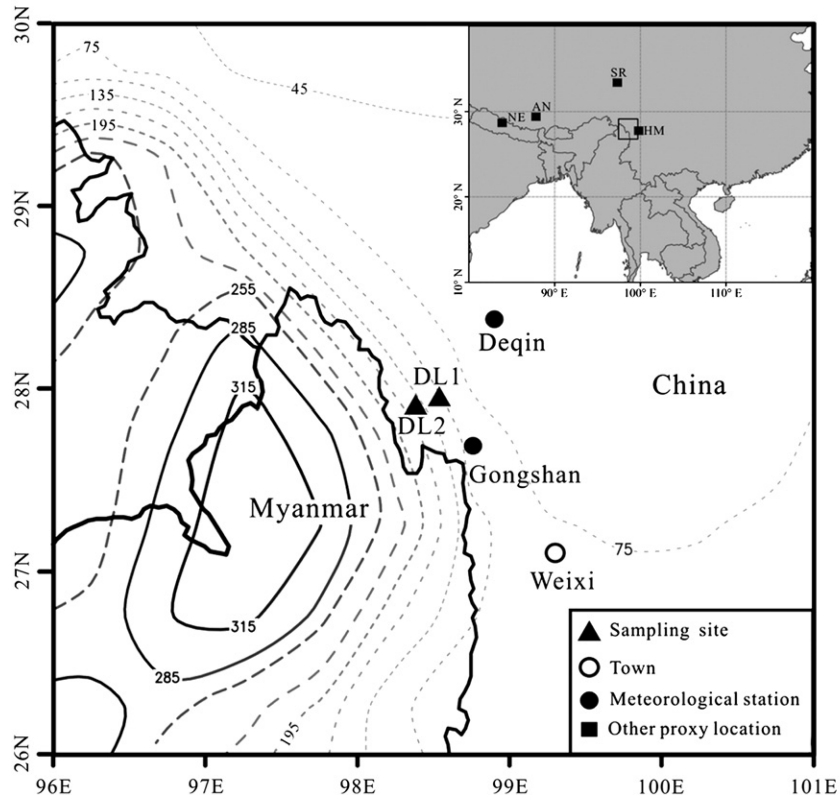

Fig. 1. Map showing the locations of the tree-ring sites, meteorological stations and other proxy sites mentioned in text. Contours represent the mean January–December averaged GPCC v4 0.5 precipitation (mm/month) from 1951 to 2007.

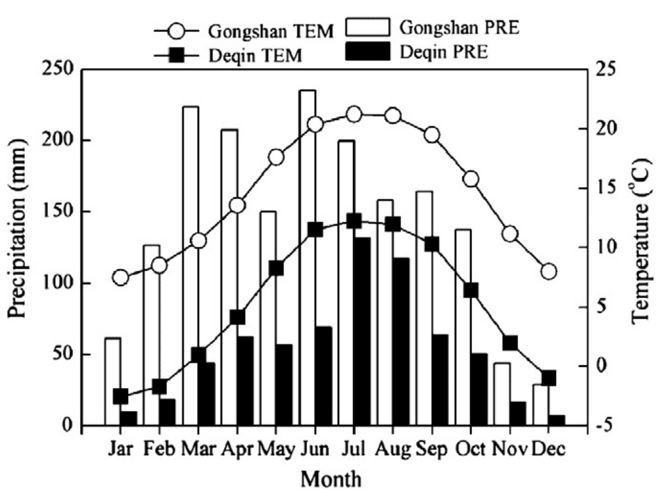

Fig. 2. Monthly total precipitation (bars) and mean temperature (dotted lines) at the Gongshan (1961–2004, 1583 m a.s.l.) and Deqin (1957–2004, 3320 m a.s.l.) stations.

Fang et al., 2009). By using maximum latewood density data of *Picea brachytyla*, Fan et al. (2009) reconstructed warm season (April–September) temperatures during the past 250 years in the central Hengduan Mountains. In this study, we present newly developed larch tree ring-width chronologies covering the past 595 years in the Gaoligong Mountains at the western margin of the Hengduan Mountains, and investigate May–August temperature variability since A.D. 1585. Particularly, we focus on decadal to multi-decadal climate variations on the southeastern TP.

2. Materials and methods

2.1. Study area and climate

The study area is located in the Gaoligong Mountains, being the west margin of the Hengduan Mountains, China (Fig. 1). The Gaoligong Mountains lie in the border area between south-west China and northern Myanmar at the southeastern rim of the Tibetan Plateau. It is the drainage divide of the Nujiang River (upper Salween) and Irrawaddy River that flow in deeply incised north-south oriented gorges. The Gaoligong Mountains are one of the global biodiversity hotspots (Myers et al., 2000), where the rich flora includes at least 4303 seed plant species (Li et al., 2000). Along the elevation gradient, vegetation from low to high altitudes is subtropical evergreen broad-leaf forest (1000–2600 m a.s.l.), temperate deciduous broad-leaf forest (1000–3000 a.s.l.), sub-alpine coniferous forest (2700–3500 m a.s.l.) and alpine meadow (>3400 m a.s.l.). The upper forest limit is located around 3500 m a.s.l. (Wang et al., 2007).

Table 1
Site information and tree-ring chronologies statistics.

Site	Location (Lat./Lon.)	Elev. (m)	Cores/Trees	Time span (A.D.)	MSL	AGR (mm)	SD	MS	AC1	R_{bt}	EPS>0.85
DL1	27.89/98.44	3300	38/19	1411–2005	365	0.71	0.31	0.19	0.80	0.55	1555/13
DL2	27.81/98.41	3200	30/19	1486–2005	327	0.72	0.32	0.23	0.79	0.45	1595/7
RC			68/38	1411–2005	348	0.71	0.31	0.21	0.80	0.48	1585/24

Lat., latitude; Lon., longitude; Elev., elevation; MSL, mean segment length; AGR, average growth rate; SD, standard deviation; MS, mean sensitivity; AC1, first-order autocorrelation; R_{bt}, mean inter-series correlation; EPS>0.85, year/number of cores when expressed population signal exceeds the 0.85 threshold.

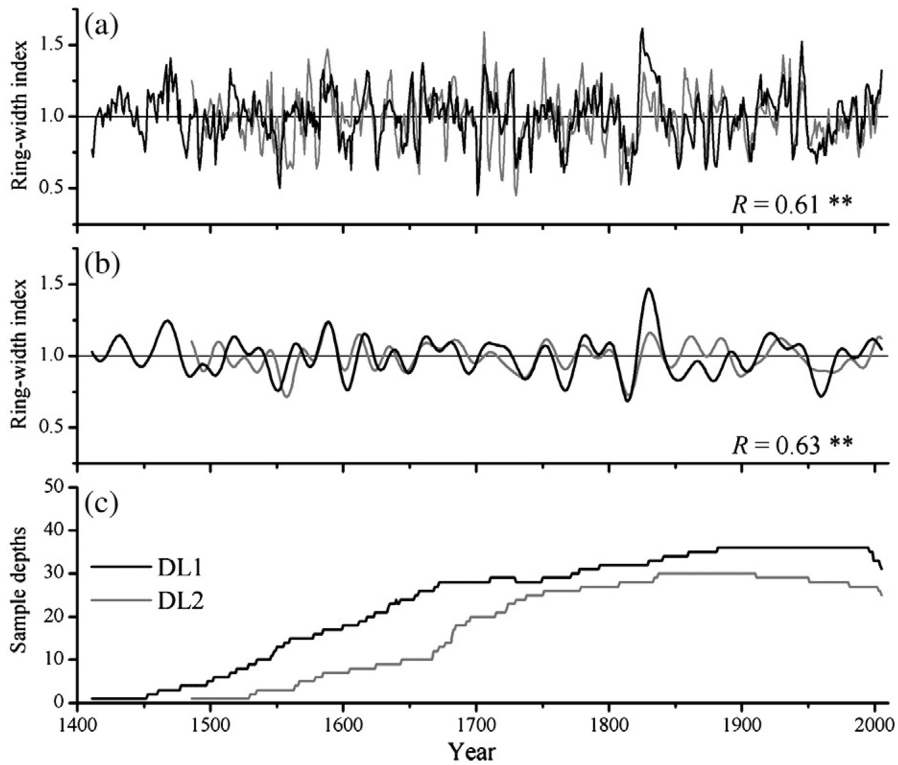

Fig. 3. Comparison of the two ring-width chronologies of *Larix speciosa* in the Gaoligong Mountains, southeastern Tibetan Plateau. (a) Tree ring-width standard chronologies; (b) 20-yr low-pass filters; (c) sample depths. *R* indicates the correlation coefficients between the two site chronologies over the period 1585–2005.

The climate in this region is strongly influenced by the south-west Asian monsoon from the Indian Ocean. The north-south oriented relief appears to block moisture advecting from south-west, resulting in sharply increased rainfall on the windward side and a rain shadow effect on the leeward side of the mountain ranges (Fig. 1). From the south-western lowlands in Myanmar to the Tibetan Plateau, the averaged January–December precipitation for 1951–2007 ranges from 315 to 45 mm/month based on the gridded GPCC full data reanalysis (v4,

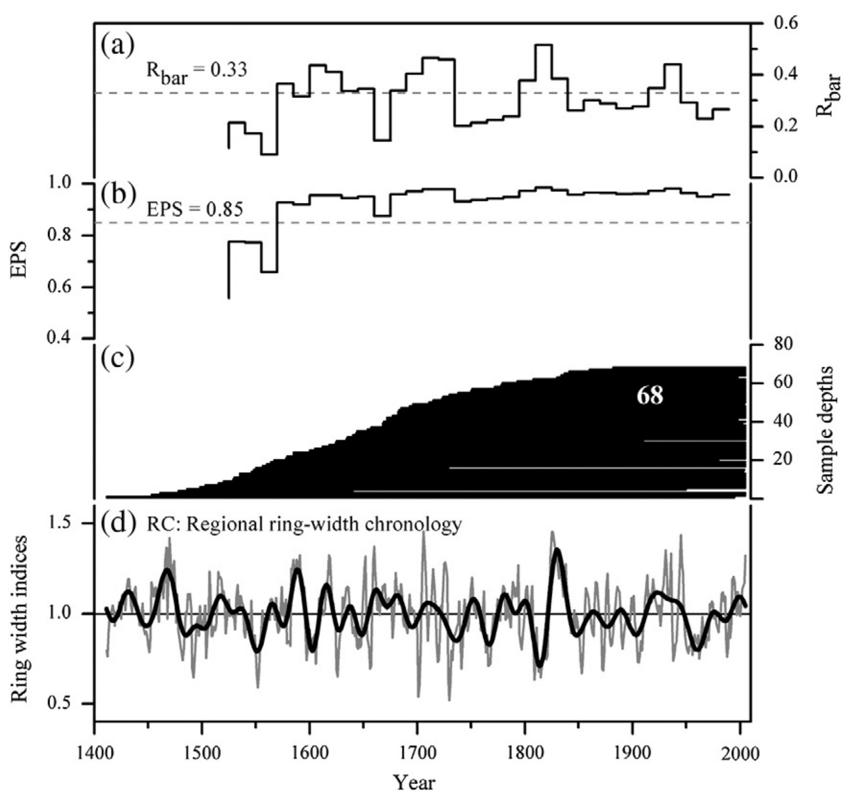

Fig. 4. Regional ring-width chronology (RC) of *Larix speciosa* and signal strength statistics. (a) Running inter-series correlation (R_{bar}, mean = 0.33); (b) running expressed population signal (EPS, dashed line is 0.85 cutoff); (c) sample depths; (d) regional ring-width standard chronology with its 20-year low-pass filer (thick line).

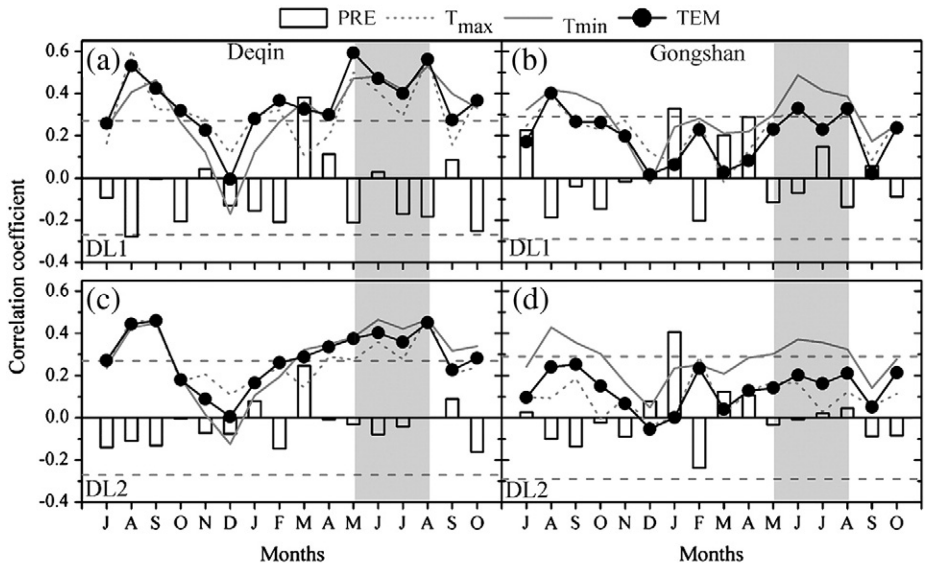

Fig. 5. Correlation coefficients between site ring-width chronologies of *Larix speciosa* and mean climatic variables at the Deqin (a, c; 1957–2004) and Gongshan (b, d; 1961–2004) station. Correlations were calculated from July of the previous year to October after ring formation. Horizontal dashed line denotes the 95% confidence limits.

$0.5° \times 0.5°$ resolution). Our tree-ring sites are located along the windward regions, where precipitation is around 135 mm/month (Fig. 1). According to the meteorological records from the study area, mean annual temperature at Deqin (1957–2004) and Gongshan (1961–2004) station are 5.2 °C and 14.6 °C, respectively (Fig. 2). Mean annual total precipitation at Deqin is 644 mm, which is much lower than that recorded at Gongshan station (1736 mm). The seasonality of temperature and rainfall at Deqin exhibits a monsoonal-type pattern, whereas a second rainfall maximum during February–April is obvious at Gongshan, where the climate condition is probably influenced additionally by the south branch of the westerlies (Ding, 1992).

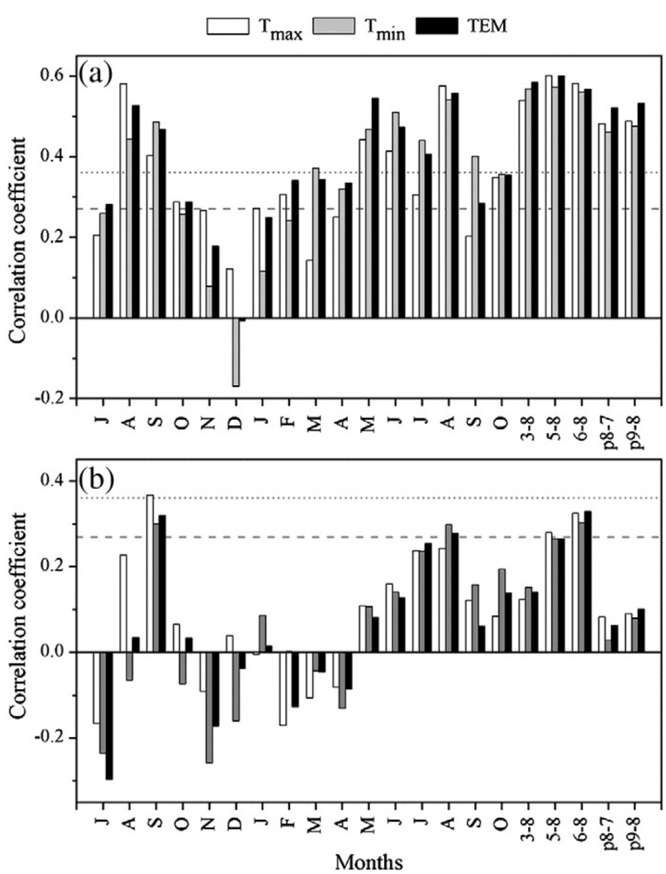

Fig. 6. Correlation coefficients between regional ring-width chronology (RC) and temperatures (T_{max}, T_{min} and TEM) at the Deqin station before (a) and after (b) pre-whitening the time series by applying the autoregressive model (AR). Correlations were calculated from previous year July to current year October, as well as various seasonal means, over the 1957–2004 common period. Horizontal dashed and dotted lines denote the 95% and 99% confidence limits, respectively.

2.2. Tree-ring sampling and chronology development

Larix speciosa W.C. Cheng is a deciduous, shade intolerant pioneer tree species. Larch forests usually occur at sunny, fire-initiated and well-drained slopes in the 2500–3800 m a.s.l. vegetation belt. Two sites (DL1 and DL2) were chosen near the upper timberline on the west-facing slope of the Gaoligong Mountains (Fig. 1). The sampling sites are open stands with no evidence of fire and insects disturbances. Dense bamboo (*Fargesua* spp.) thickets dominate the underground vegetation. In total, 68 increment cores from 38 trees were extracted at breast height, with a minimum of 19 trees at each site (Table 1).

After air-drying, the cores were mounted on sample holders. The wood surfaces were prepared with sharp razor blades and the surface contrast was enhanced with chalk. Ring widths were measured with an LINTAB II measuring system with a resolution of 0.01 mm, and all cores were cross-dated visually and using statistical test (sign test and

Table 2
Statistics of calibration and leave-one-out verification results for the common period 1957–2004.

Calibration (model: $Y = 7.171 + 3.941X$)							
Period	R	R^2	R^2_{adj}	F	SE	DW	
1957–2004	0.601 **	0.361	0.347	25.95 **	0.658	0.656	
Standard verification (1957–2004)				1st difference verification (1958–2004)			
r	ST	Pmt	RE	r	ST	Pmt	RE
0.56 **	$37^{+}/11^{-**}$	2.51 *	0.31	0.32*	$29^{+}/18^{-*}$	2.33 *	0.10

R is correlation coefficient; SE is standard error; DW is Durbin–Watson statistic for residual autocorrelation; r is the correlation coefficient between the recorded data and the leave-one-out-derived estimates; ST is sign test which counts the number of agreements and disagreements between the reconstructed and instrumental series; Pmt is product mean test; RE is the reduction of error, any positive value of RE indicates that there is confidence in the reconstruction (Fritts, 1976). The 0.05 and 0.01 significant levels are indicated by * and **, respectively.

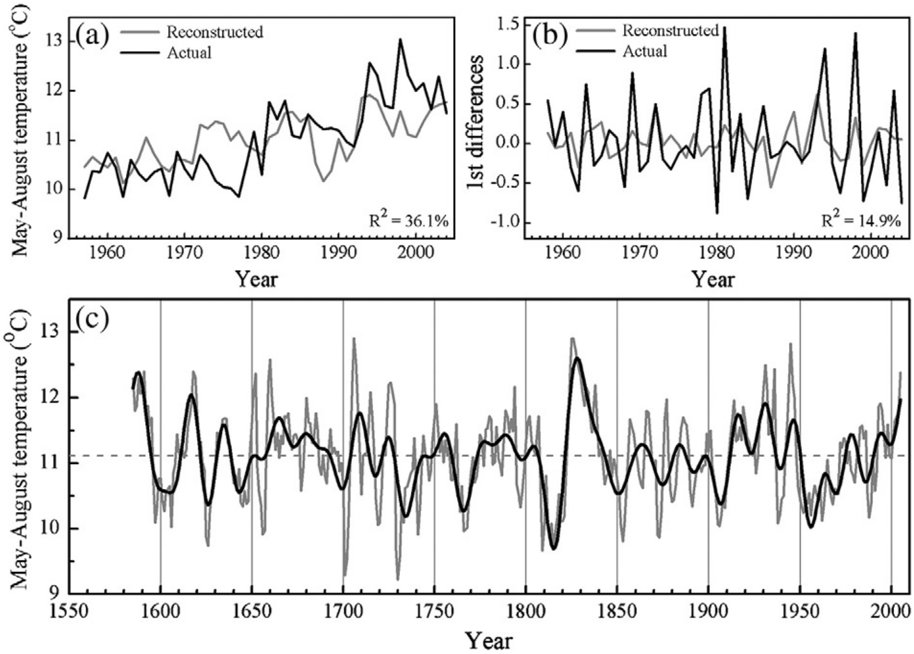

Fig. 7. (a) Comparison between the instrumental and reconstructed mean May–August temperature for their common period 1957–2004. (b) Comparison between the first differences (year-to-year changes) of instrumental and reconstructed mean May–August temperature for their common period 1957–2004. (c) May–August mean temperature reconstruction in the Gaoligong Mountains since A.D. 1585. The dashed horizontal line represents the long-term mean. The bold line indicates the smoothed data with a 15-year low-pass filter to emphasize long-term fluctuations.

t-test) with the software package TSAP-Win (Rinn, 1996; Stokes and Smiley, 1996). The tree-ring measurements were standardized to remove the biological growth trends while preserving variations that were likely related to climate. Prior to standardization, a data-adaptive power transformation was employed to stabilize the variance in heteroscedastic raw ring-width series (Cook and Peters, 1997). Most series were conservatively detrended by adjusting a negative exponential or a linear regression function with negative slope. A cubic spline with a 50% frequency-response cutoff equal to 67% of the series length was used in a few cases (5 series for each site) when anomalous growth trends occurred. This approach emphasized the inter-annual to multi-decadal scale variations. The tree-ring indices were calculated as differences between transformed ring-width measurements and the curve-fitted values. All detrended series were averaged to chronologies by computing the biweight robust means to reduce the influence of outliers (Cook and Kairiukstis, 1990). Variance stabilization was applied to minimize the effect of changing sample size through time by the method described by Osborn et al. (1997). Standardization of ring-width data and chronology building was performed with the ARSTAN program (Cook, 1985).

The reliability of each chronology was evaluated by inter-series correlation (R_{bar}) and the expressed population signal (EPS; Wigley et al., 1984). Both R_{bar} and EPS were computed over 30 years lagged by 15 years. A threshold of EPS>0.85 was employed to determine the most reliable period of the chronology (Wigley et al., 1984). Since a high correlation ($R = 0.61$, $p < 0.01$) was found between the two site chronologies, we decided to combine all raw ring-width data from both study sites following the methods described above, enabling to develop a longer and better replicated regional ring-width standard chronology (RC).

2.3. Growth-climate response and reconstruction

Monthly mean (TEM), maximum (T_{max}), minimum (T_{min}) temperatures and total precipitation (PRE) data were obtained from the National Meteorological Information Centre (NMIC) of China. Climate data from two stations nearby our sample sites, Deqin (28.48 °N, 98.92 °E, 3320 m a.s.l.) and Gongshan (27.75 °N, 98.67 °E, 1583 m a.s.l.), were used to calibrate our tree-ring data. The climate–growth relationships were investigated by correlating ring-width chronologies with monthly climate series for their common period for a 16-month period from previous July to current October. In order to discount the fortuitous correlation of trend in data, correlations were also calculated after pre-whitening both climate and tree-ring data, by applying the autoregressive model (AR) with the AR order objectively determined by the minimum Akaike information criteria (ACI) procedure (Meko, 1981). In addition, we calculated various seasonal means of climate variables and their correlations with tree-ring data.

A linear model was developed to reconstruct mean May–August temperature by using RC as the predictor. The leave-one-out cross-validation (Michaelsen, 1987) was employed to verify our reconstruction, since the available meteorological data were too short to carry out a robust split-sample calibration (Fritts, 1976). Evaluative statistics include the Pearson's correlation coefficient (r), sign test (ST), product mean test (Pmt) and reduction of error (RE) (Fritts, 1976). To demonstrate that our reconstruction and instrumental records represent regional-scale temperature variability, we correlated these series with gridded CPC CHCH/CAMS dataset (t2m analysis, $0.5° \times 0.5°$; Fan and van den Dool, 2008) during the period 1957–2004. Correlations were calculated after removing the linear trends of data, by using the detrending option of the KNMI Climate Explorer (http://climexp.knmi.nl).

3. Results

3.1. Chronology statistics

Descriptive statistics of the two larch ring-width chronologies and their regional composite (RC) are shown in Table 1. The mean segment lengths of these two site chronologies are 365 years (DL1) and 327 years (DL2), respectively. Thus, the resulting regional chronology is capable to reflect climatic variations of multi-decadal length. Based on the 0.85 threshold of EPS statistics, the site chronologies met signal strength acceptances after A.D. 1555 for DL1 (>13 cores) and A.D. 1595

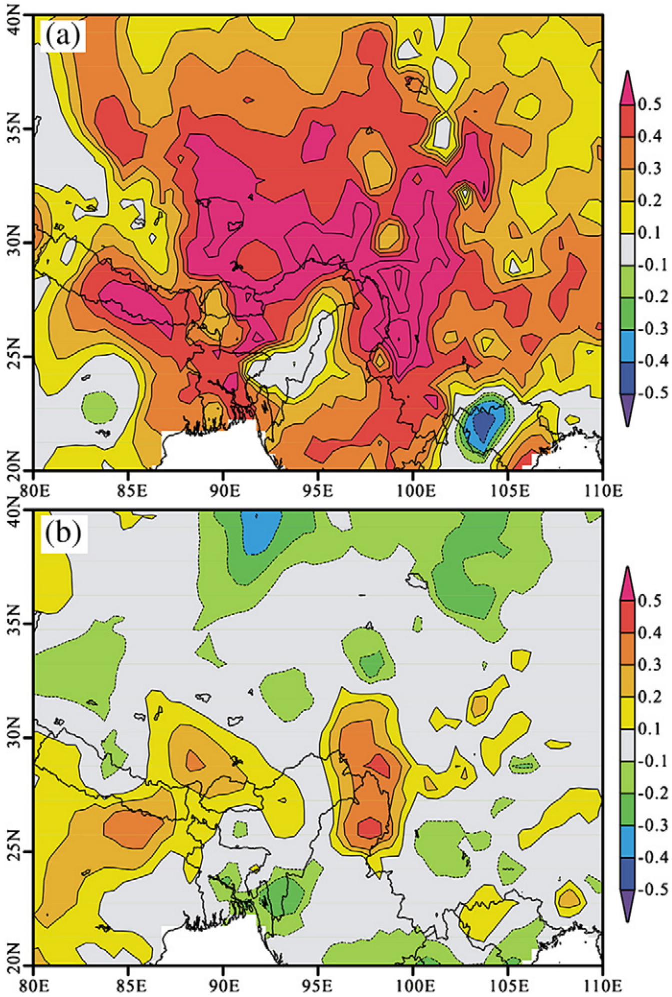

Fig. 8. Spatial correlations of (a) instrumental and (b) reconstructed May–August temperature with the concurrent gridded CPC CHCN/CAMS t2m dataset (Fan and van den Dool, 2008) for the period 1957–2004. Correlations were calculated after removing the linear trends of data, by using the detrending option of the KNMI Climate Explorer (http://climexp.knmi.nl).

for DL2 (>7 cores). The site chronologies showed a low year-to-year variability (MS, range from 0.19 to 0.23), which is typical for conifers growing in humid environments. Comparable high inter-series correlations ($R_{bt}=0.45$–0.55) indicated that the developed chronologies contain considerable common signals and were thus suitable for climate change studies. The two site chronologies show similar growth patterns, both at inter-annual and decadal scales (Fig. 3). Over the 1585–2005 period, the two site chronologies and their 20-year low-pass filter components correlated with $R=0.61$ ($p<0.01$) and $R=0.63$, respectively. The developed regional chronology (RC) extends back to A.D. 1411, showing a sufficient signal strength (EPS>0.85) after A.D. 1585, when more than 24 cores were included (Table 1, Fig. 4). The mean segment length is 348 years and ranges from 124 to 585 years. The average growth rate is very low (0.71 mm/year), which results from the high ages of the studies trees.

3.2. Response to climatic variables

The two ring-width site chronologies and the RC show positive correlations with monthly temperatures in most months (Figs. 5 and 6). Significant correlations ($p<0.05$) were found during the growing season from May to August of the current year and late summer (August–September) of the year before growth. The importance of precipitation on radial growths was weak, although positive effects of March rainfall were found for site DL1. Correlations with monthly maximum temperatures are generally lower than with monthly mean and minimum temperatures (Fig. 5). Compared with higher elevation site DL1, larch trees growing at site DL2 appear to be less sensitive to summer temperatures (Fig. 5). Relatively high correlations were found with climate records from Deqin station, possibly due to the fact it has a similar altitude than the sampling sites (Table 1). On the other hand, Gongshan station is around 1600 m lower than the sampling sites, which may not well represent the climate conditions for higher elevations. Therefore, we correlated the regional standard chronology (RC) with temperature records from the Deqin station for the period 1957–2004. The RC showed similar correlation patterns with temperatures as the individual site chronologies; however, higher correlation coefficients were obtained (Fig. 6a). Correlation patterns with temperatures are similar before and after pre-whitening both of the climate and tree-ring data, although correlations are lower for the latter (compare Fig. 6a and b). The highest correlation was found between RC and mean May–August temperature ($r=0.601$, $p<0.01$).

3.3. Temperature reconstruction

Based on a linear regression model, we reconstructed May–August mean temperature for the Gaoligong Mountains region that extends back to A.D. 1585. The regression model accounts for 36.1% ($R^2_{adj}=34.7\%$, $p<0.01$) of the instrumental temperature variances over the calibration period from 1957 to 2004 (Table 2). Although the signal strength in the reconstruction is not very strong, the developed model passes all conventional verification tests. The leave-one-out cross-validation test yielded a positive RE (0.31), indicating predictive skill of the regression model (Fritts, 1976). Statistically significant sign test ($37^+/11^-$, $p<0.01$), product mean test ($t=2.51$, $p<0.05$) and correlation ($r=0.56$, $p<0.01$) between the recorded data and the leave-one-out estimates are all indications of the reconstruction's validity. However, the regression model fails the residual analysis with a significant positive autocorrelation (DW = 0.656), which may induced by the increasing trend of both instrumental and tree-ring data (Fig. 7a). We further calibrated the 1st differences of the tree-ring series with actual data, which explained 14.9% of the actual temperature variances. The leave-one-out validation produced significant verification statistics with positive RE (0.10), indicating that the developed model was able to track the high-frequency temperature variability (Fig. 7b).

This reconstructed May–August temperature series contains inter-annual to multi-decadal variability (Fig. 7c). Several cold episodes occurred during 1600s, 1620s, 1640–50s, 1700s, 1730–40, 1760s, 1810–20, 1850s, 1900–10s and 1955–70s. Marked periods with high temperatures occurred during 1610s, 1660–1680s, 1710–20s, 1750s, 1780–90s, 1825–40, 1920–50 and 1980–present. Spatial correlations with gridded surface temperature dataset produced similar fields for the instrumental and reconstructed series, although correlations were lower for the latter (Fig. 8). The highest correlation fields confined to the area south of 32 °N, i.e. the north-south oriented Hengduan Mountains and the eastern Himalayan arc (Fig. 8b). The spatial correlation results confirm that our temperature reconstruction captures broad-scale regional climatic variations over the southern TP (Fig. 8).

4. Discussion

Warm conditions during the growth season (May–August) generally enhance larch radial growth in the Gaoligong Mountains (Figs. 5 and 6). A similar climatic response was also found in the Himalayas (Chaudhary and Bhattacharyya, 2000) and eastern Tibetan Plateau (Bräuning, 2006; Liang et al., 2008, 2009). Near timberline, conifer tracheids form and enlarge during the warmest period of the growing season (Antonova and Stasova, 1997; Deslauriers et al., 2008; Rossi et al., 2007). Low mean temperature may limit root growth,

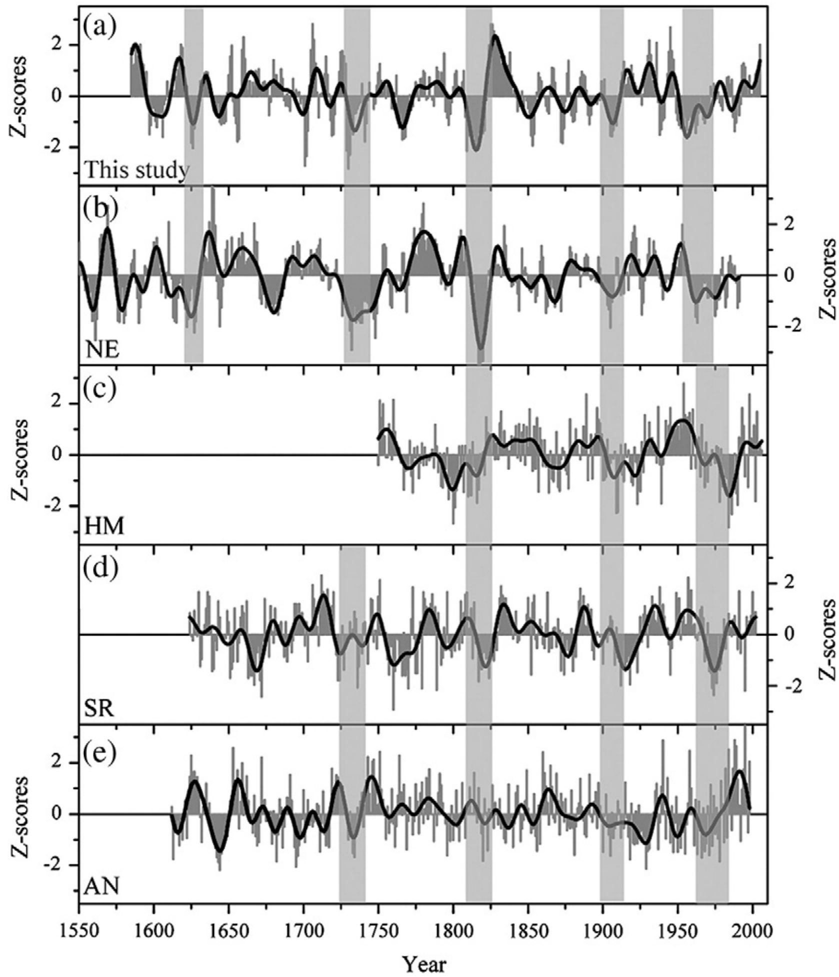

Fig. 9. Comparison of May–August temperature reconstruction in the present study with other tree-ring proxies from surrounding regions. (a) Mean May–August temperature reconstruction in the Gaoligong Mountains (this study); (b) mean February–June temperature reconstruction in east Nepal (NE; Cook et al., 2003; International Tree-Ring Data Bank); (c) warm season (April–September) mean temperature reconstruction in the central Hengduan Mountains (HM; Fan et al., 2009); (d) mean summer (June–August) minimum temperature reconstruction in the upper source region of Yangtze River (SR; Liang et al., 2008); (e) annual (July–June) temperature reconstruction in the Angren region in southern Tibet (AN; Yang et al., 2009). All series were adjusted for their long-term means over the period 1750–1991, and smoothed with a 15-year low-pass filter to emphasize long-term fluctuations.

cambial activity and hence tree growth in our study area. In addition to current growing season warmth, high temperatures during previous late summer appear to have a positive effect on radial tree growth (Figs. 5 and 6). Warm conditions in the late summer and autumn (August–October) might increase carbohydrate storage in the stem, and thus enhance early wood growth in the following spring (Gou et al., 2008).

Other temperature-sensitive tree-ring records in surrounding regions provide a reference to validate our reconstruction. Decadal variations in our reconstruction show consistent patterns with tree-ring-based temperature reconstructions from the southern TP and vicinity (Fig. 9). Our temperature reconstruction shows significant correlation ($r = 0.22$, $p < 0.01$ for 1585–1991) with a February–June temperature reconstruction from eastern Nepal (Cook et al., 2003). Cold periods during the 1730–40s, 1810–20, 1900–10s and 1955–70s found in the present study are consistent with low summer temperatures in the source region of Yangtze River (Liang et al., 2008) and the central Hengduan Mountains (Fan et al., 2009), as well as cold phases in eastern Nepal (Cook et al., 2003) and the Angren region in southern Tibet (Yang et al., 2009). Cold conditions in the 1810s, 1900s and 1970s are also reported for the north-eastern TP (Gou et al., 2008), southern TP (Bräuning and Mantwill, 2004) and the Himalayan region (Bhattacharyya and Chaudhary, 2003; Yadav et al., 2004). Warm intervals during the 1710–20s, 1780–90s, 1820–40, 1920–50 and 1980–present are consistent between the compared records (Fig. 9).

The cold periods of 1700s and 1730–60s are consistent with decadal scale droughts found in north Thailand (Buckley et al., 2007) and north Vietnam (Sano et al., 2009) and south India (Borgaonkar et al., 2010). These mid 18th century mega-drought correspond to periods of anomalously warm sea surface temperature (SST) in the central and eastern tropical Pacific, implying that El Niño-like (warm phase) conditions may have broadly weakened monsoon activity in the Asian tropics (Buckley et al., 2007; Sano et al., 2009; Cook et al., 2010). In addition, the cold phases of early and middle18th century correspond to dry conditions in the study region (Fan et al., 2008). These results imply the combination of warm–wet and cold–dry climate pattern in the study regions, where monsoon climate is predominant (Liu et al., 2006b).

The 1810–20 stand out as the coldest period in the 420-year temperature reconstruction (Fig. 7c) and corresponds to a cold event in the southeastern TP (Bräuning and Mantwill, 2004; Liang et al., 2008, 2009), the central Hengduan Mountains (Fan et al., 2009), eastern Nepal (Cook et al., 2003) and the western Himalaya (Hughes 2001; Yadav, 2007). This cold period also widely occurred in other areas in the northern hemisphere and may be linked to unknown volcanic eruptions in 1808 (Chenoweth, 2001) and 1809 (Dai et al., 1991) and the Tambora (Indonesia) eruption in April 1815

(Sigurdsson and Carey, 1992). The 1815 eruption probably influenced the atmospheric circulation patterns (Vupputuri, 1992), causing an extremely cold summer in Europe and North America in 1816 (Briffa et al., 1998; Trigo et al., 2009). Historical documents recorded a serious famine from 1815 to 1817 in Yunnan history (Yang et al., 2005). In Kunming, the capital of Yunnan Province, the mean temperature in August 1816 was estimated to be 2.5–3 °C lower than the long-term mean. In addition, Himalayan ice core records show a strong acidity signal associated with this year (Dai et al., 1991; Thompson et al., 2000), supporting the occurrence of strong volcanic eruptions.

The warming trend of the second half of the 20th century is the longest period of continuous warming (Fig. 7c). During 1951–2005, the linear trend in the reconstructed temperature series is 0.24 °C/decade ($R^2 = 0.53$, $p < 0.01$). However, concerning absolute temperature values it is still within the temperature variability occurring over the past 420 years. In addition, the period of positive tree-ring excursions following the 1820 pessimum seems to be extreme at our study site DL1 in comparison with other *Larix* trees from the same area and with temperature reconstructions from neighbouring regions (Figs. 3 and 9). Thus, it remains to be tested if the warm period of the 1830s is caused by a local tree reaction. If this holds true, the 20th century warming trend is more prominent in the context of the past 420 years as it appears now (Fig. 7c).

5. Conclusions

We developed tree ring-width chronologies from two sites of *Larix speciosa* in the Gaoligong Mountains, southeastern Tibetan Plateau. Correlation analyses indicate that larch trees growing near the timberlines are sensitive to temperature variations during growth season. Therefore, we reconstructed mean May–August temperature for the study region, reflecting inter-annual to multi-decadal scale temperature variability back to A.D. 1585. Our temperature reconstruction improves the spatial coverage of available proxy records in the high-elevation regions of the southern margin of the TP where instrumental records are short and scarce. Spatial correlations with a gridded surface temperature dataset highlight the regional representative of our reconstruction. A comparison with other tree ring-based temperature reconstructions reveals a high coherency in the timing of warm/cold episodes at the decadal scale over the southeastern TP and vicinity, i.e. cold 1730–40s, 1810–20, 1900–10s, 1960–70s, and warm 1780s, 1830s, 1930–50 and recent warming since 1980. The present study first demonstrates the potential of using larch tree-ring data to reconstruct temperature variability at high elevations in the southern TP. Further efforts should take effort to develop more comprehensive tree-ring networks along elevational gradients, as well as to include additional tree-ring parameters (i.e. stable isotopes), to shed more light on the spatial and temporal variability of past temperature changes. In addition, further sampling strategies should aim to be applying other methods like regional curve standardization (RCS; Esper et al., 2003) that allow the preservation of long-term climatic trends in the final tree-ring climate reconstructions.

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