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Tree-ring reconstruction of summer temperature for A.D. 1475–2003 in the central Hengduan Mountains, Northwestern Yunnan, China

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Abstract Development of long tree-ring records is an important task in paleoclimate studies. Here we presented a five-century long reconstruction of summer (June to August) temperature based on a tree ring-width chronology of *Picea brachytyla* var. *complanata* originating from the Hengduan Mountains of China. Climate-growth response analysis showed that summer temperature was the main climatic factor limiting tree-ring growth in the study area. The reconstructed summer temperature accounted for 47.6% of the variance in actual temperature during their common period A.D. 1958–2002. Analysis of the temperature reconstruction showed that major warm periods occurred in the A.D. 1710s–1750s, 1850s, 1920s–1950s and 1990s to present, whereas cold intervals occurred in the A.D. 1630s–1680s, 1790s–1800s, 1860s–1880s and 1950s–1980s, respectively. The low-frequency variation of the reconstruction agreed fairly well with tree-ring reconstructed temperature from nearby regions and with records of glacier fluctuations in the surrounding high mountains, suggesting that our reconstructed summer temperature was reliable, and could aid in the evaluation of regional climate variability.

1 Introduction

During the past two decades, there have been great progresses in paleoclimate studies on the Tibetan plateau (TP). A substantial increase of tree-ring records has been achieved throughout the mainland of TP, from the Qilian mountains at the northern rim of the TP (Gou et al. 2005; Liang et al. 2009, 2010; Liu et al. 2009a; Zhang et al. 2009) and the northeastern part of TP (Zhang et al. 2003; Shao et al. 2005; Huang and Zhang 2007; Zhang and Qiu 2007; Liu et al. 2006, 2009b; Gou et al. 2007, 2008) to central and southern Tibet (Bräuning 2001, 2006; Bräuning

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and Mantwill 2004; Wang et al. 2008; Yang et al. 2003, 2009, 2010a, b) and the Himalayan mountains, including the related regions of Pakistan (Treydte et al. 2006; Esper 2000; Esper et al. 2002, 2007), India (Yadav and Singh 2002; Singh et al. 2006, 2009; Bhattacharyya et al. 2007; Bhattacharyya and Shah 2009; Yadav 2009) and Nepal (Cook et al. 2003). So far, the southeastern rim of the TP, the Hengduan Mountains, which mainly stretch across the northwestern Yunnan province of China, have received less attention in dendroclimatic research (Wu and Lin 1987; Fan et al. 2008a, b, 2009; Fang et al. 2009).

The Hengduan Mountains are located in the southeastern margin of TP, where several major Asian rivers (Yangtze, Mekong and Salween) run roughly parallel through the deep gorges (Fen and Zhu 2010). This region is also a world-renowned temperate biodiversity hotspot (Myers et al. 2000; Ying 2001), with an astonishing diversity in habitats ranging from warm-temperate, evergreen, broad-leaved to coniferous forest communities (Buntaine et al. 2006; Wang et al. 2007). As a response to the recent intensified global warming, Baker and Moseley (2007) have observed strong evidence of the retreat of glaciers and evident rise of alpine treeline in northwestern Yunnan, indicating the climatic sensitivity of this region to global climate change (He et al. 2003; Zhang et al. 2004). Thus, tree-ring studies conducted in the Hengduan Mountains might add important information about past climate variability on the TP, and may potentially contribute to a better understanding of large-scale atmospheric circulation systems.

Until today, only a few tree-ring studies have been conducted in the Hengduan Mountains. Based on tree ring-width data from the Haba Snow Mountain of northwestern Yunnan, Wu and Lin (1987) reported a reconstruction of fluctuations of air temperature during the last 400 years and indicated the existence of a similar mode of temperature variation to the Tibetan plateau. In comparison, Fan et al. (2008a) and Fang et al. (2009) recently found that radial growth of conifers growing at low-elevation sites was generally limited by moisture availability in the central Hengduan Mountains, and presented reconstructions of regional drought variability for the past 350 and 568 years, respectively. Because of the complex landscape in this mountainous region, more tree-ring data are required for better understanding of the regional climate variability. Clearly, an overall appraisal of climate trends in Hengduan Mountains must await a more comprehensive analysis, based on expansion of tree-ring data in both spatial and temporal coverage. Here, we present a new tree-ring width chronology from the Hengduan Mountains of northwestern Yunnan. We analyze the relationships between the tree growth and climatic variables, and to examine the regional climate variability during the past 529 years.

2 Materials and methods

Our study area is located in Geza (28°22′ N, 99°46′ E, 3,440 m a.s.l.) in northwestern Yunnan, China (Fig. 1). Records from the nearby meteorological station in Zhongdian (27.83° N, 99.71° E, 3,444 m a.s.l.) show that mean annual air temperature during the period 1958–2002 is 5.2°C, with a mean maximum of 12.3°C in July and a minimum of −2.5°C in January. Mean annual total precipitation is 644 mm, with a maximum monthly sum of 158 mm in July (Fig. 2). The growing season of trees covers approximately May-September, during which about 80% of the annual precipitation

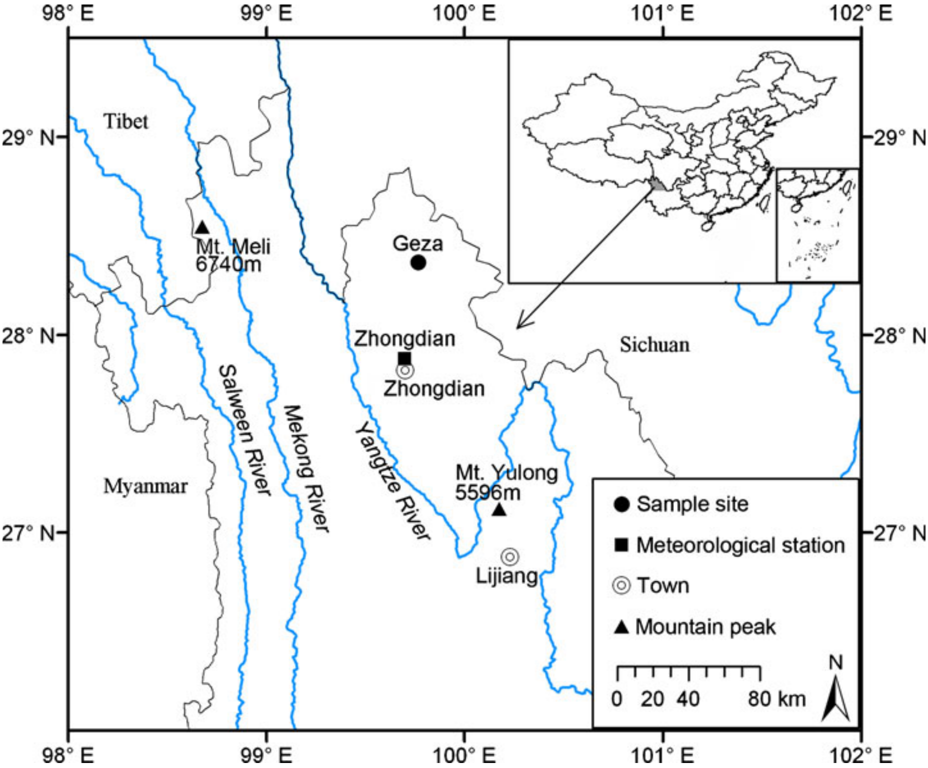
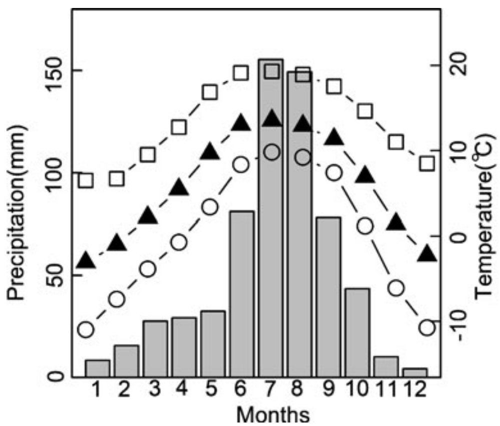


Fig. 1 Location map of tree-ring sampling site and meteorological station in northwestern Yunnan, China

is received. *Picea brachytyla* var. *complanata* is the regionally dominant tree specie in this area, which forms a prominent forest belt in humid mountain environments in a belt between 3,000 and 3,800 m a.s.l. The tree-ring samples used in this study

Fig. 2 Monthly variation of total precipitations (*bars*), mean maximum temperature (*line with squares*), and mean temperature (*line with triangles*) and mean minimum temperature (*line with circles*) for Zhongdian meteorological station of northwestern Yunnan, China



were collected from living trees on north-facing slopes. Increment cores (one core per tree) were collected from trees at breast height. In order to build a long tree-ring chronology and to minimize non-climate signals, mature trees that showed no obvious injury or disease were selected for sampling. In total, 35 core samples for *P. brachytyla* var. *complanata* were retrieved.

The tree-ring samples were processed following standard dendrochronological practices (Stokes and Smiley 1968). Samples were mounted and polished with progressively finer sandpaper to make the ring boundaries clearly visible. To assign an exact calendar year to each growth ring, tree-ring sequences were carefully cross-dated by visually inspecting marker years to ensure year-to-year correspondence. Ring widths were subsequently measured to 0.001 mm precision using a Velmex measuring system (Velmex Inc., Bloomfield, NY, USA). The quality of the cross-dating was further checked using the COFECHA program (Holmes 1983). Tree rings in four samples could not be cross-dated with the master series and were excluded from chronology building. The final chronology was developed from 31 samples. Ring-widths were standardized with the program ARSTAN (Cook and Kairiukstis 1990). Standardization removed the age-related growth trend by fitting negative exponential curves or linear curves of any slope. The detrended individual series were finally combined into a site chronology using a biweight robust estimate of the mean. In this study, the standard ring-width chronology was used for climate-tree growth response analysis and for reconstruction of past climate. In order to reduce the potential influence of changing sample size, the chronology variance was stabilized using the method described in Osborn et al. (1997). Expressed Population Signal (EPS) with a threshold value of 0.85 was employed to evaluate the most reliable period of the chronology (Wigley et al. 1984).

Climate-growth relationships were determined by examining the correlation coefficients between tree-ring indices and climate variables. The climate data were obtained from the nearest weather station in Zhongdian with the record length from 1958 to 2002 (Fig. 1). Correlations between standard tree-ring chronology and temperature and precipitation data were calculated on a 13-month period beginning in October of the prior growth year to October of the growth year. Correlations were also calculated between the tree-ring chronology and temperature and precipitation over various multi-month seasons and a full-year scale.

Past climate was reconstructed from tree rings by a linear regression model. The reliability of the regression model was evaluated by statistics on calibration and verification periods and by employing leave-one-out cross verification method (Michaelsen 1987). Evaluative statistics provided for the calibration period are the Pearson correlation coefficient (R), the coefficient of determination (R^2), and F-test (F) and for the verification period are reduction of error (RE), coefficient of efficiency (CE), sign test (ST), product mean test (Pmt) and Durbin-Watson test (DW) (Fritts 1976; Cook et al. 1994). R^2, RE, and CE are all measures of shared variance between climate and tree rings, and a positive RE or CE is evidence for a valid regression model. The sign test counts the number of agreements and disagreements between the reconstructed and the instrumental climate data, while Pmt measures the level of agreement between the actual and estimated values and takes into account the sign and magnitude of departures from the calibration average. The DW statistic tests for autocorrelation in the residuals between model and target climate data.

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 reconstructed climate series was also verified by comparing it with glacier fluctuations and other tree-ring chronologies of the surrounding regions.

3 Results

The chronology spanned the period from A.D. 1475 to 2003 in which at least five sample replications were included (Fig. 3). Based on the arbitrary EPS cutoff value of 0.85 (Wigley et al. 1984), the chronology was considered reliable when sample size exceeded 12 cores, corresponding to the period from A.D. 1530 to 2003. The mean segment length of the chronology was 393 years, indicating its ability to resolve interannual to interdecadal-scale tree growth variations that are likely related to climate change (Cook et al. 1994). The mean sensitivity, which is a measure of relative difference in ring widths between adjacent rings, was about 0.1. The average correlation among individual tree-ring series was 0.46 and the signal to noise ratio was 5.25, indicating that the tree-ring chronology contained common growth-limiting signals, and that the chronology was useful for dendroclimatic studies.

Analysis of the climate-growth relationship showed a general positive correlation between the radial growth of *P. brachytyla* var. *complanata* and temperature of all months from November of the prior growth year to October of the growth year with the highest correlations to winter and summer months (Fig. 4). There were no persistent patterns of correlation between tree-ring growth and precipitation. Because seasonally averaged climate may be more representative than just one single

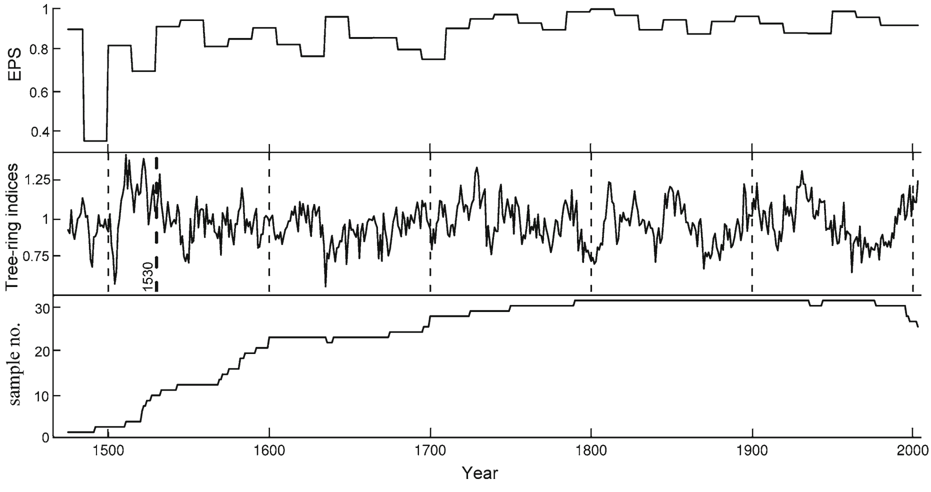


Fig. 3 Ring-width chronology of *Picea brachytyla* var. *complanata* from A. D. 1475–2003 at northwestern Yunnan of China, and changing sample depth and EPS (Expressed population signal) over time. The *vertical bold dashed line* at the time of A. D. 1530 indicated that the running EPS value was rather stable and well above the arbitrary cutoff value of 0.85. So the chronology was more reliable for the period from A.D. 1530 to 2003, when sample depth exceeded 12 cores

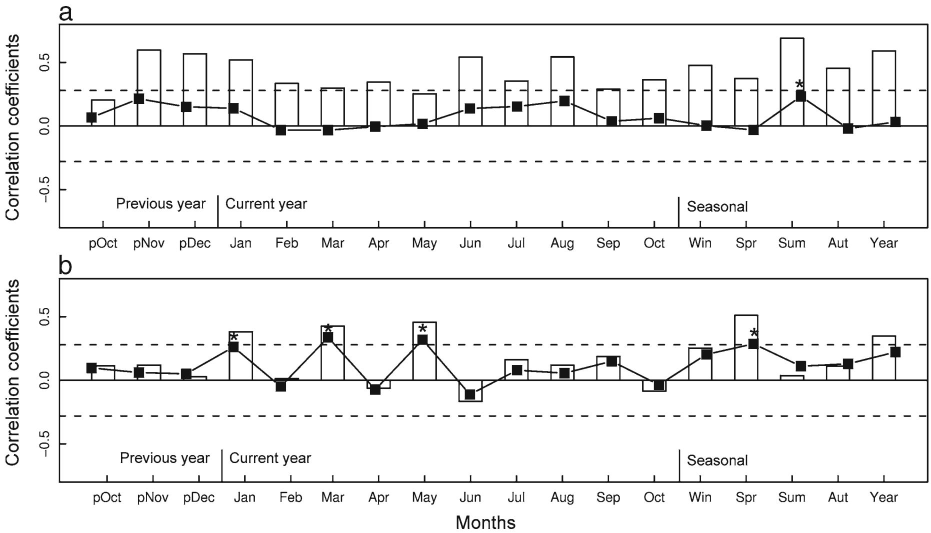


Fig. 4 Correlation and response function analysis between tree-ring chronology and the climate data. **a** Correlation analysis with a monthly mean temperature, **b** correlation analysis with monthly total precipitation. *Bar* diagrams are the results of correlation analysis and line graph is the results of response function analysis. The *dashed lines* represent significant effects ($p < 0.05$) for correlation analysis, and the *asterisks* above columns represent significant effects ($p < 0.05$) for response function analysis

month, we tested different seasonal combinations of temperature and precipitation for climate reconstruction. The highest correlation between tree rings and the seasonalized climate was found in summer (June to August) for temperature ($r = 0.69$; $p < 0.01$). Therefore, we used summer temperature as the climate variable for reconstruction.

A simple linear regression model ($Y = 2.415X + 10.815$) was obtained to reconstruct summer temperature history of the study area (Cook and Kairiukstis 1990). This regression model accounted for 47.6% of the actual temperature variance in the common period of the tree-ring chronology and temperature data (1958–2002; Fig. 5). Despite the general fact that trees tend to underestimate extreme climate conditions (D'Arrigo et al. 1998), our reconstruction successfully captured both high- and low-frequency variations of temperature variability (Fig. 6a). The statistics from splitting samples into calibration-verification intervals and leave-one-out cross-validation both showed a significant correlation between the reconstructed and the actual temperatures during the calibration and verification periods (Table 1). Values of the two most rigorous tests of model validation, RE and CE, were both positive, indicating a significant skill in the estimates of summer temperature. The results of the sign test and product mean test also exceeded the 95% confidence level. For additional verification, DW value was about 1.5, indicating insignificant autocorrelation in the model residuals and target climate data. These results demonstrated the reliability of our regression model.

Using the above model, the summer temperature history in the study area was reconstructed for the period A.D. 1475–2003 (Fig. 6b). The mean summer temperature during A.D. 1475–2003 was 13.2°C and the standard deviation was 0.31°C.

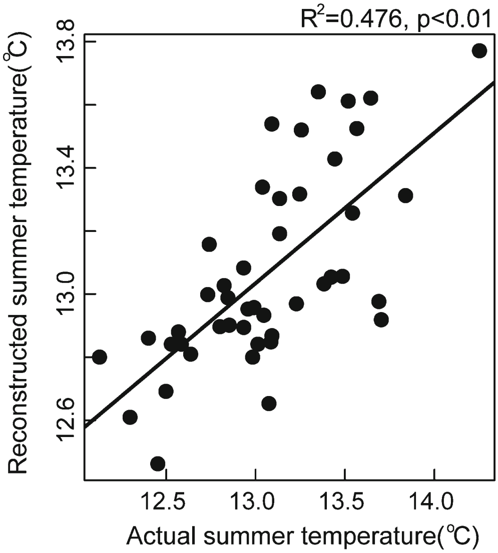


Fig. 5 Scatter plot of actual and tree-ring reconstructed summer (June–August) temperature with a linear relationship highlighted during the period of 1958–2002.

The reconstructed temperature series for the last 529 years showed annual to multi-year fluctuations punctuated with cool and warm periods. Because the EPS value of the tree-ring chronology was below 0.85 for the period A.D. 1475–1529, caution should be taken when interpreting the reconstructed temperature for this period. The reconstructed temperature showed that warm episodes occurred in the intervals A.D. 1680s–1750s, 1850s, 1920s–1950s and 1990s to present (Fig. 6b). Although punctuated by a slim cold interval in 1700s, the persistently warm episode in 1680s–1750s, lasting about 70 years, is the most notable warm anomaly of the reconstruction. In the last warm period from A.D. 1991 to present, the temperatures of all the years were above the long-term mean. In contrast, four periods of prolonged cold episodes occurred in A.D. 1630s–1680s, 1790s–1800s, 1860s–1880s and 1950s–1980s, respectively. Superimposed on these decadal to multi-decadal scale temperature

Table 1 Statistics of calibration and verification for tree-ring reconstruction of summer temperature in the common period 1958–2002 in northwestern Yunnan, China

Split-sample calibration-verification									
Calibration				Verification					
Period	R	R^2	F	Period	Sign-test	Pmt	RE	CE	DW
1958–1981	0.55	0.3	14.88*	1982–2002	14+/7−	2.65*	0.21	0.12	1.64
1982–2002	0.49	0.25	12.11*	1958–1981	19+/5−*	1.87*	0.14	0.06	1.52
1958–2002	0.69	0.48	39.16**						
Leave-one-out verification									
1958–2002	0.66	0.44	39.16**		34+/11−*	3.65*	0.43	0.24	1.42

R correlation coefficient, R^2 explained variance, *F* F-test, *Sign-test* sign of paired observed and estimated departures from their mean on the basis of the number of agreements/disagreements, *Pmt* product mean test, *RE* reduction of error, *CE* coefficient of efficiency, *DW* Durbin–Watson test

* $p < 0.05$, ** $p < 0.01$

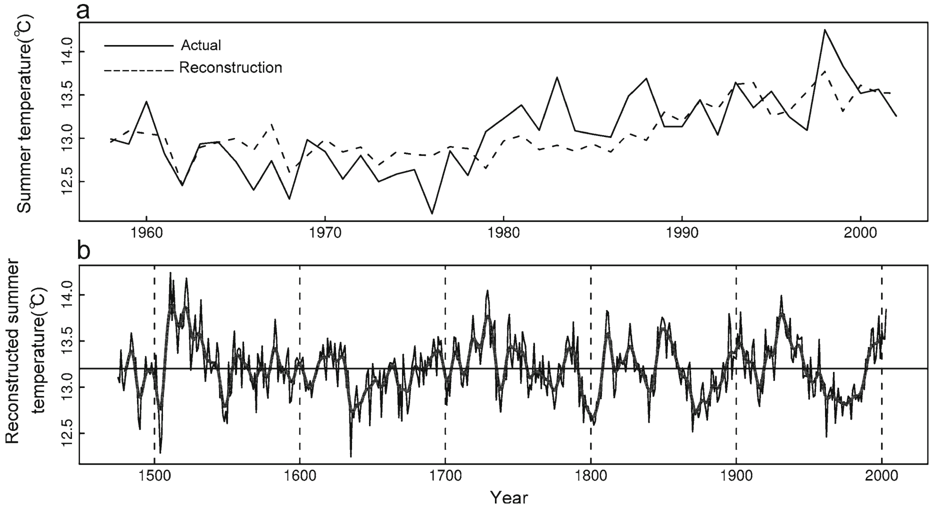
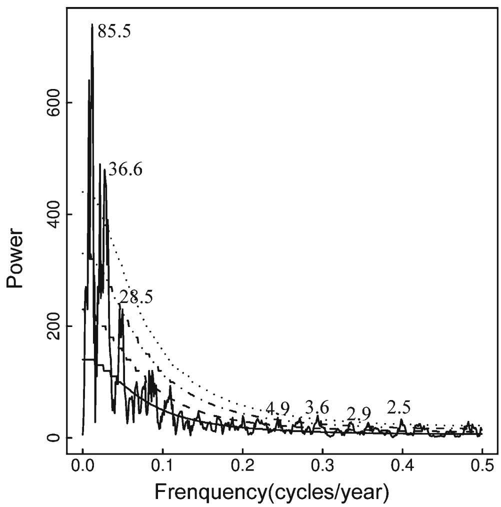


Fig. 6 Climate reconstruction in northwestern Yunnan, China. **a** The comparison of actual and reconstructed summer temperature from 1958 to 2002, **b** Tree-ring reconstruction of summer temperature, plotted annually from 1475 to 2003, along with a smoothed 11-year moving average

decreases were annual fluctuations of temperature in different amplitudes. The most severe and prolonged cold event occurred in A.D. 1630s–1650s (Fig. 6b).

The results of multi-taper method (MTM) spectral analysis over the full length of our reconstruction revealed peaks significant above 99% level at 85.5, 36.6, 3.6, 2.9, and 2.5 years, and significant above 95% level at 28.5 and 4.9 years (Fig. 7).

Fig. 7 MTM spectral density of the tree-ring based summer reconstruction of northwestern Yunnan, China. The *bold line* indicates the null hypothesis, and the *dash*, *dash-dot* and *dotted lines* indicate the 90%, 95% and 99% significance level from bottom to up, respectively



4 Discussion

The climate-tree growth relationship analysis showed that the radial growth of *P. brachytyla* var. *complanata* correlated to summer (June to August) temperature (Fig. 4). Similar results were reported by various studies in nearby areas (Fan et al. 2009; Liang et al. 2008; Bräuning and Mantwill 2004; Bräuning 2006; Bhattacharyya and Chaudhary 2003). Fan et al. (2009) studied the dendroclimatology of *P. brachytyla* in the central Hengduan Mountains located at about 80 km southwest of our study site. They found that total ring width and maximum latewood density of *P. brachytyla* mainly responded to summer temperature variability. Liang et al. (2008) suggested that mean summer minimum temperature was the major limiting factor to tree-ring growth of *P. likiangensis* var. *balfouriana* in the source region of the Yangtze River on the Tibetan Plateau. Dendroclimatological studies of high-elevation conifer sites on the eastern Tibetan plateau suggested that tree-ring chronologies were an indicator of late summer temperature (Bräuning and Mantwill 2004; Bräuning 2006; Bhattacharyya and Chaudhary 2003). These similarities suggested that summer temperature is a major factor limiting the growth of spruce trees in the study area. We consider that the tracheids of spruce trees enlarge during the warm period of the growing season when temperature is a critical factor affecting cambium activity (Deslauriers et al. 2003). Meanwhile, warm summer can also improve the growth of roots and their function in water uptake (Körner 1998; Mayr 2007), which facilitates the accumulation of photosynthates for cell wall thickening during the late growing season (Hughes 2001).

In order to identify whether our reconstruction represents features that are coherent over a large spatial scale, we compared our reconstruction with other tree-ring based temperature reconstructions from nearby regions. Our reconstruction mirrored decadal-scale patterns of reconstructed summer temperatures in the central Hengduan Mountains, about 80 km southwest of our site (Fan et al. 2009). The warm episodes found in this study, namely A.D. 1780s, 1810s–1820s, 1840s–1850s, 1920s–1940s, 1990s-present, were in agreement with warm periods occurred at 1780s, 1820s–1850s, 1930s and 1990s in the central Hengduan Mountains. The cold episodes of A.D. 1790s–1800s, 1900s–1910s and 1950s–1980s prominent in our series matched with the cold periods A.D. 1790s–1810s, 1900s–1920s and 1970s–1980s in the central Hengduan Mouantains. Discrepancies between the two reconstructions were that our reconstruction showed stronger signals in low frequency variation than that in Fan et al. (2009), possibly reflecting the difference in the procedure of standardization on tree-ring data.

Comparison of our reconstruction with those from further distances could help evaluate the spatial synchrony of climate variation. The release of tree-ring growth in 1510s–1530s coincided with growth release in trees in western Sichuan (Shao and Fan 1999). It should be kept in mind that the number of tree-ring samples in this interval was lower than the years after 1530 and, thus, climate signals at this interval was not as reliable as those after 1530 and the data should be interpreted with caution. In general, warm conditions during 1710s–1730s, 1780s, 1930s and 1930s–1950s found in the present study agreed reasonably well with warm temperatures in western Sichuan (Shao and Fan 1999) and the source region of Yangtze river (Liang et al. 2008). Although all the records showed warm conditions around 1930s–1950s, the relative magnitude of the warmth in this period was most evident in our record. Cold conditions in the 1650s–1680s, 1790s–1800s, 1860s–1890s and 1960s–1980s in the present study were also broadly contemporaneous with tree-ring records in the source region of the Yangtze river (Liang et al. 2008) and the southeastern Tibetan Plateau (Bräuning and Mantwill 2004) although difference existed in the duration of the cold intervals.

Warm and cold periods in our reconstruction were also generally in phase with the periods of advance and retreat of the temperate glaciers in this region. The warm period of the 1920s–1940s coincided with the retreat of glaciers, while the cold period of the 1940s–1980s corresponded to rapid glacier advance in the Jade Dragon Snow Mountain and Meili Snow Mountain (Zheng et al. 1999; He et al. 2003; Baker and Moseley 2007). The impressive feature of the reconstruction was the dramatic temperature increase from the late 1980s to present. It coincided with a growing body of evidence witnessing an accelerated retreat rate of most China's monsoonal temperate glaciers after 1980s (He et al. 2003; Yao et al. 2006). Hence, our tree rings seem to be a good indicator of past glacier fluctuations in the Hengduan Mountains and suggest that temperature signals from our tree rings are not restricted to the sampling site but are indicative of climate variation at a larger spatial scale.

The MTM results indicated the existence of some important cycles for regional temperature variability (Fig. 7). The 85.5-year mode was most significant in our reconstruction, which resembled other reconstructed temperature series (D'Arrigo et al. 2003, 2005a) and suggested an influence of solar forcing (Pederson et al. 2001). One noteworthy feature of our reconstruction was that the cold episodes in 1630s–1670s, 1790s–1800s and 1890s–1910s were in general agreement with the Maunder (1645–1715), Dalton (1790–1820) and Damon (1890s–1920s) periods of low solar irradiance (Eddy 1976). This phenomenon demonstrated the possible association between summer temperature variation in our study area and solar activity. The significant cycle at around 36.6 and 28.5 years might be linked to Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), and our analyses indicated a significant and positive correlation ($r = 0.25$, $p < 0.01$) between the reconstruction and the mean annual PDO index of Mantua et al. (1997) from 1900–2003. This result is consistent with the hypothesis that a large-scale Asian tree-ring network may be able to reflect PDO signals (D'Arrigo and Wilson 2006). Significant spectral peaks were also found at 4.9, 3.6, 2.9 and 2.5 years, which fall within the "classical" ENSO (El Niño-Southern Oscillation) band of 2–8 years (Allan et al. 1996; D'Arrigo et al. 2005b). Consistent with this observation, ENSO have been proven to have potential impact on the glacier accumulation and drought variability in northwestern Yunnan (Zhang et al. 2004; Fan et al. 2008a). These high-frequency cycles may suggest teleconnections of local temperature variability with tropical ocean-atmosphere systems.

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