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# April–September minimum temperature reconstruction based on *Sabina tibetica* ring-width chronology in the central eastern Tibetan Plateau, China

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**Abstract**   Minimum temperatures have remarkable impacts on tree growth at high-elevation sites on the Tibetan Plateau, but the shortage of long-term and high-resolution paleoclimate records inhibits understanding of recent minimum temperature anomalies. In this study, a warm season (April–September) reconstruction is presented for the past 467 years (1550–2016) based on *Sabina tibetica* ring-width chronology on the Lianbaoyeze Mountain of the central eastern Tibetan Plateau. Eight warm periods and eight cold periods were identified. Long-term minimum temperature variations revealed a high degree of coherence with nearby reconstructions. Spatial correlations between our reconstruction and global sea surface temperatures suggest that warm season minimum temperature anomalies in the central eastern Tibetan Plateau were strongly influenced by large-scale ocean atmospheric circulations, such as the El Niño-Southern Oscillation and the Atlantic Multidecadal Oscillation.

**Keywords**   Tree-ring analysis · *Sabina tibetica* · Minimum temperatures · Central eastern Tibetan Plateau · Climate change

## Introduction

Tree growth is a complex biological process, whereas climate is a key determinant of tree adaptation and productivity. IPCC (2021) reported that global surface temperatures during the past decade (2011–2020) were 1.1 °C above those during 1850–1900. Among all the factors that affect tree growth, temperature is the most critical in high latitudes and alpine regions. As a result, tree-ring records of high elevation sites often bear important imprints of temperature variabilities.

Tree-ring parameters provide an opportunity to evaluate past climate changes when instrument observations are unavailable (Davi et al. 2015; Asad et al. 2016; Zhang 2015; Zhang et al. 2019, 2020). As an annual climate proxy, tree rings have been widely used in climate reconstructions at local to global scales (Esper et al. 2002; Mann et al. 2008;

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Cook et al. 2010; Gou et al. 2013; Fang et al. 2014; Li et al. 2014a; Wilson et al. 2016; Sun et al. 2018; Chen et al. 2019). Dendroclimatological research has developed rapidly in China in recent decades (Shao et al. 2010; Yang et al. 2014; Zhang et al. 2015; Liu et al. 2017a; Yang et al. 2017; Fan et al. 2019; Yu and Liu 2020; Jiao et al. 2022). Numerous studies have reconstructed temperature, precipitation, moisture, and streamflow across China (Shao et al. 2005; Liang et al. 2009; Liu et al. 2009, 2017b; Bao et al. 2012; Peng and Liu 2013; Zhang et al. 2014a; Chen et al. 2016; Fang et al. 2017; Li et al. 2017; Shi et al. 2017; Wang et al. 2019). In particular, tree-ring studies in the eastern Tibetan Plateau started in the 1990s (Shao and Fan 1999), but most were concerned with the reconstruction of winter or annual temperatures (Wu et al. 2005; Song et al. 2007; Yu et al. 2012; Li et al. 2014b, 2015a, 2015b; Xiao et al. 2015; Yin et al. 2015; Zhu et al. 2016) or the variability of drought (Deng et al. 2016, 2017). Growing season temperature reconstructions are relatively rare in the eastern Tibetan Plateau, and there is a need to expand the tree-ring coverage, especially for the growing season minimum temperatures.

The central eastern Tibetan Plateau has an average altitude of 4000 m a.s.l. It is characterized by complex topography, thin air with low oxygen levels, and high annual solar radiation (Hu and Zeng 2003). Abundant sunshine makes up, to some extent, for heat loss at high altitudes and cold weather. As a result, trees can grow to a higher elevation, which makes minimum temperatures a key limiting factor on tree growth.

The objective of this study was to reconstruct growing season minimum temperatures based on tree-ring analysis of *Sabina tibetica* Kom. collected from the Lianbaoyeze Mountain in central eastern Tibetan Plateau and to investigate the long-term variations of minimum temperatures and their potential climate driving factors.

## Materials and methods

### Study region

The Lianbaoyeze Mountain (33.08° N, 101.18° E) belongs to the southern branch of the Bayan Har Mountains and is located in the northwest of Aba County of Sichuan Province, bordering Jiuzhi County and Banma County of Qinghai Province. The average elevation is over 4000 m and the highest peak is 5141 m a.s.l. Based on nearby meteorological records from the China Meteorological Data Service Centre (http://data.cma.cn/), the annual average temperature is 3.3 °C, annual total rainfall 712 mm, and annual total



**Fig. 1** Study area showing the sampling site (star) and nearby meteorological stations (circles)
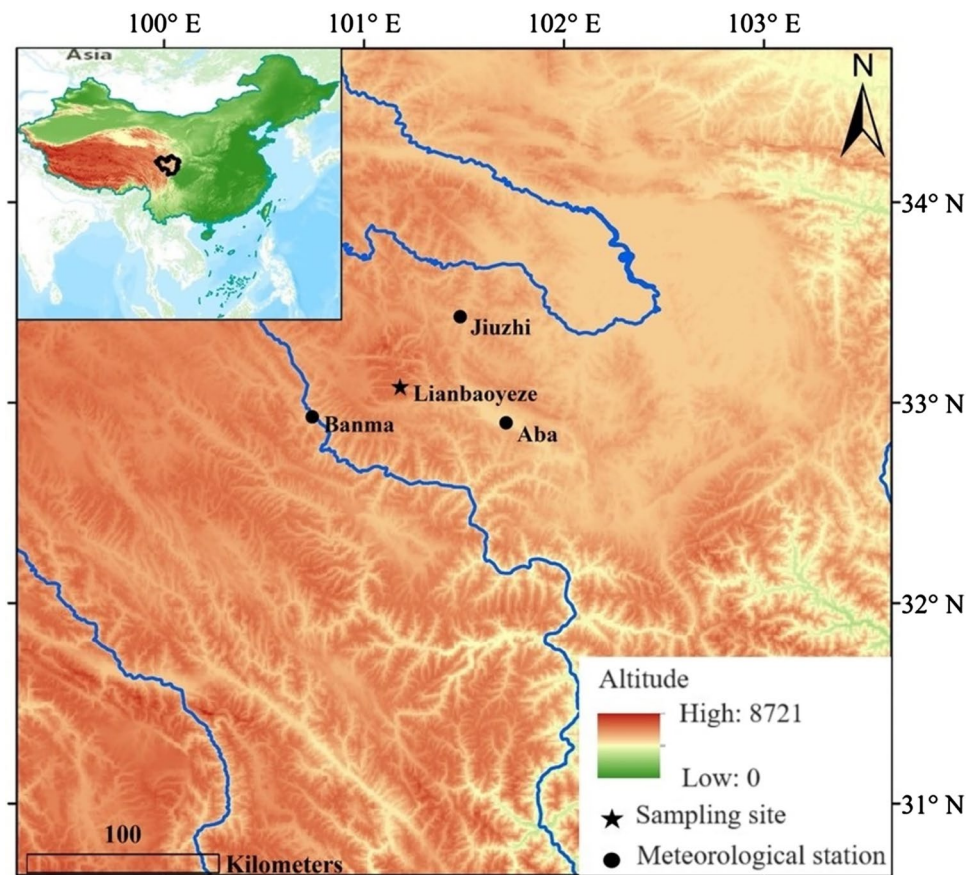
sunshine 2383 h. *S. tibetica* is mainly distributed on sunny slopes from 2800 to 4500 m a.s.l. (Fig. 1).

### Tree-ring data

A total of 83 cores from 40 trees (2–3 cores ind$^{-1}$) of *S. tibetica* were collected from living and dead trees in 2017. Following standard dendrochronological procedure (Stokes and Smiley 1968), the cores were glued to wooden mounts, air dried, and sanded with fine sandpaper until the ring boundaries were clearly seen under a microscope. Rings were visually cross-dated, and then measured using the Velmex measuring system with a precision of 0.001 mm. The cross-dating and ring-width measurements were checked using the COFECHA program (Holmes 1983) for quality control.

The cross-dated ring-width sequences were conservatively detrended using negative exponential or linear curves of any slope (Cook and Kairiukstis 1990). The tree-ring indices were calculated as residuals after performing an adaptive power transformation, which stabilizes the variance in heteroscedastic raw ring-width series (Cook and Peters 1997). The tree-ring indices were merged to generate tree-ring chronologies by ARSTAN program (Cook and Holmes

1986) and a standard chronology used (Fig. 2). The reliable period of the chronology was determined by the expressed population signal (EPS) threshold value of 0.85 (Wigley et al. 1984), a commonly used criterion to assess whether a chronology is statistically reliable for climate reconstruction (Cook and Kairiukstis 1990).

### Climate data

Monthly climate data spanning 1963–2016 were collected from the Jiuzhi meteorological station (31° N, 102°12′ E, 2370 m a.s.l.). Climate factors include monthly mean ($T_{mean}$), maximum ($T_{max}$), minimum ($T_{min}$) temperatures, and monthly total precipitation (P) (Fig. 3). In addition, the Climatic Research Unit (CRU) TS4.04 temperature dataset (Harris et al. 2020) and Hadley Centre sea surface temperature dataset (HadISST1; Rayner et al. 2003) were adopted for spatial correlation analyses.

### Statistical analysis

Pearson's correlation analyses between standard chronology and regional climate factors ($T_{mean}$, $T_{max}$, $T_{min}$ and P) from
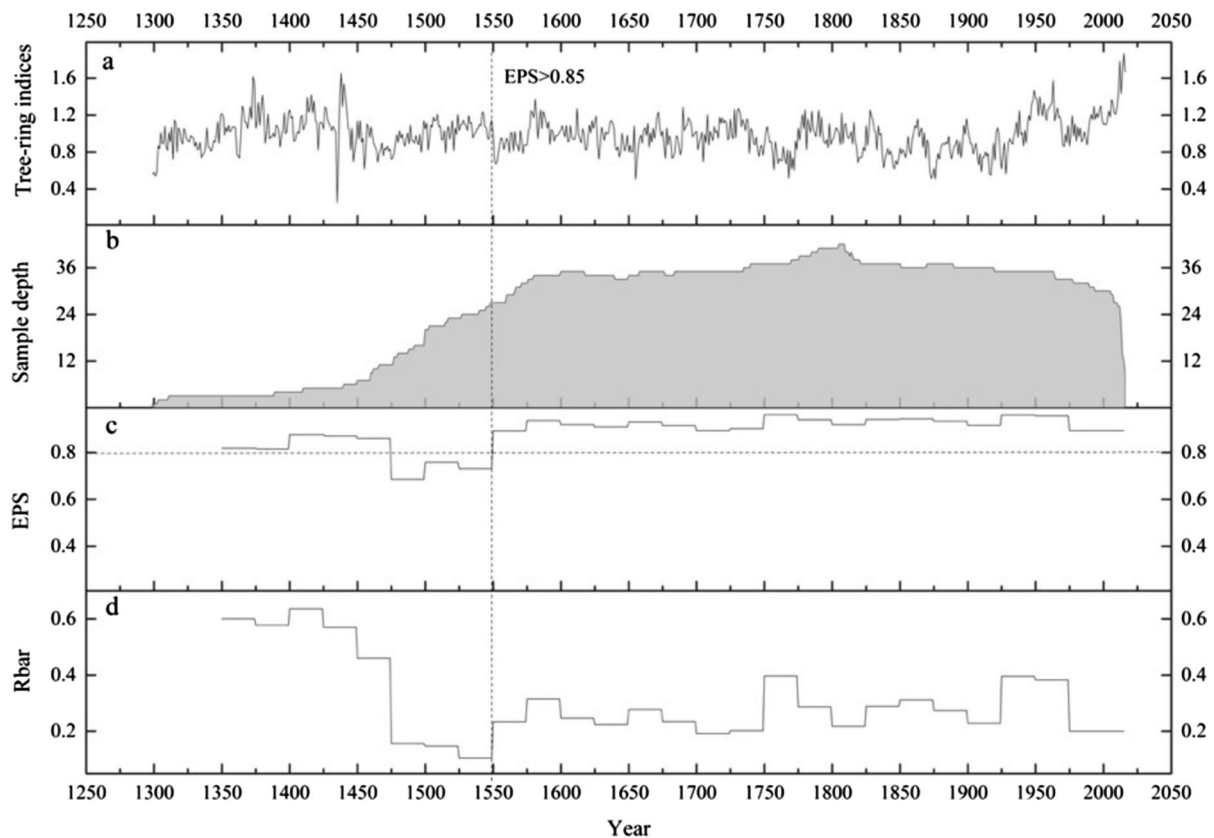


**Fig. 2** **a** Tree-ring width chronology developed from *S. tibetica*, **b** Sample depth, **c** Running EPS, **d** Running Rbar; vertical dashed line denotes EPS > 0.85

**Fig. 3** Monthly mean ($T_{mean}$), maximum ($T_{max}$), minimum ($T_{min}$) temperatures and monthly total precipitation (P) from the Jiuzhi meteorological data (1963–2016)
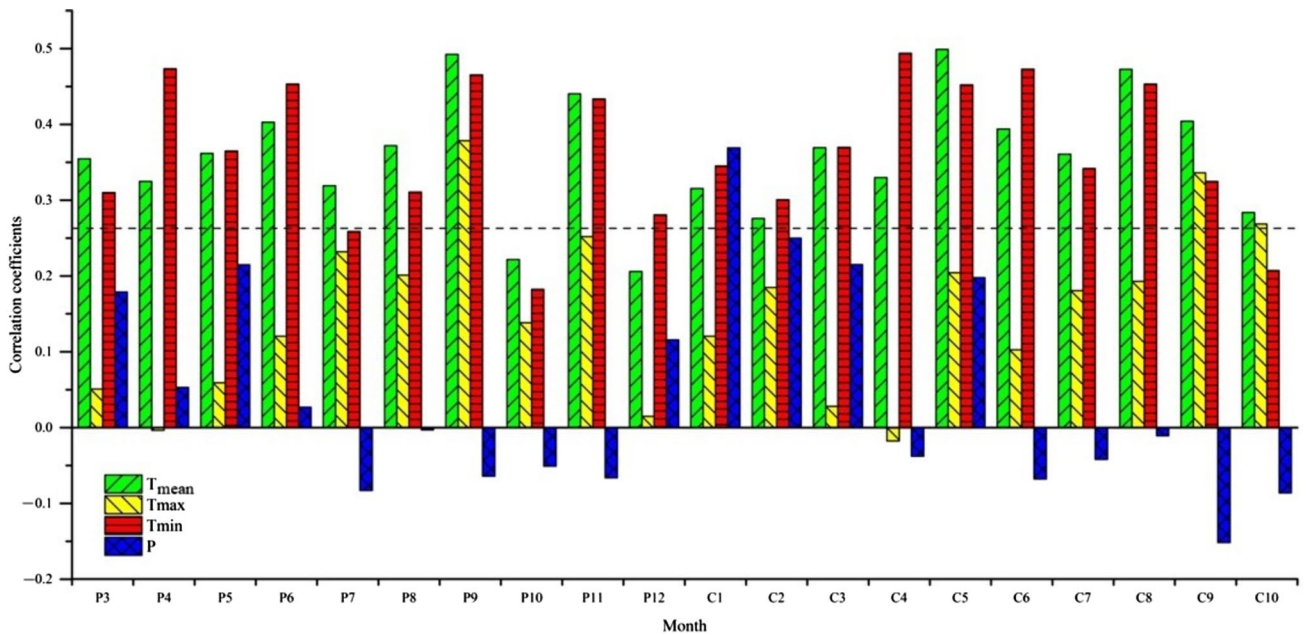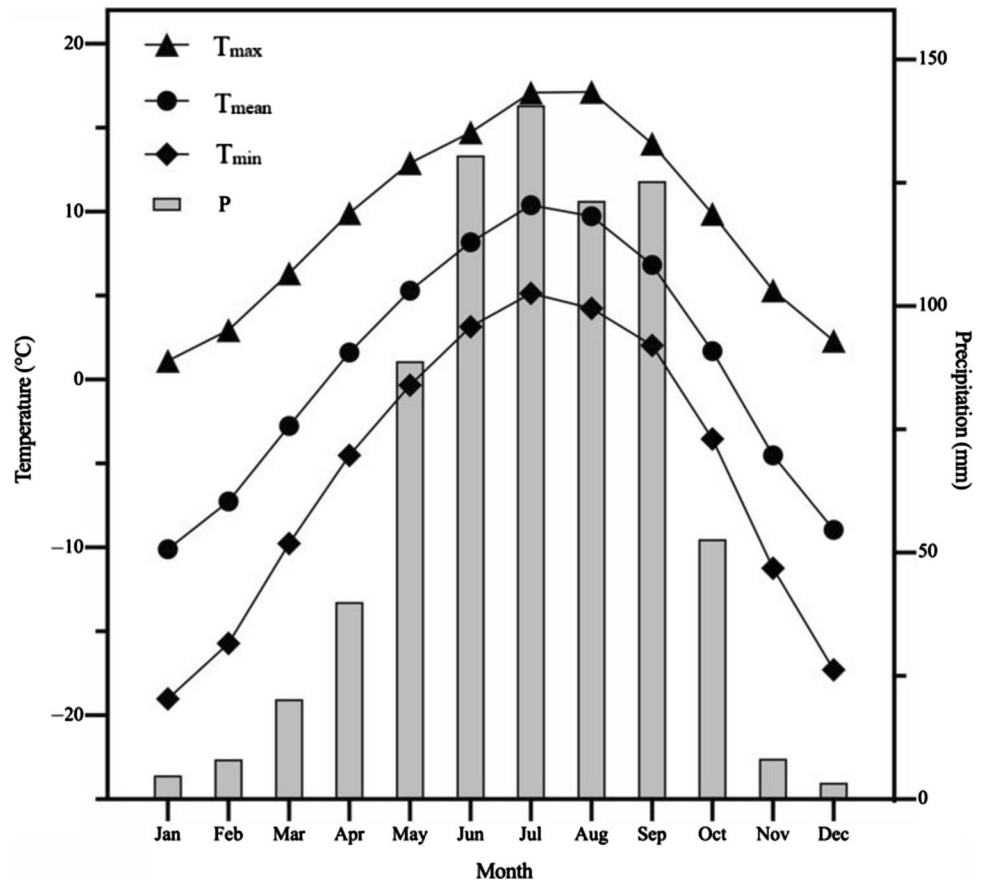




**Fig. 4** Correlations of ring-width chronology of *S. tibetica* with monthly climate factors ($T_{mean}$, $T_{max}$, $T_{min}$ and P) from the previous March to the current October over 1963–2016; horizontal dashed line denotes the 0.05 significance level
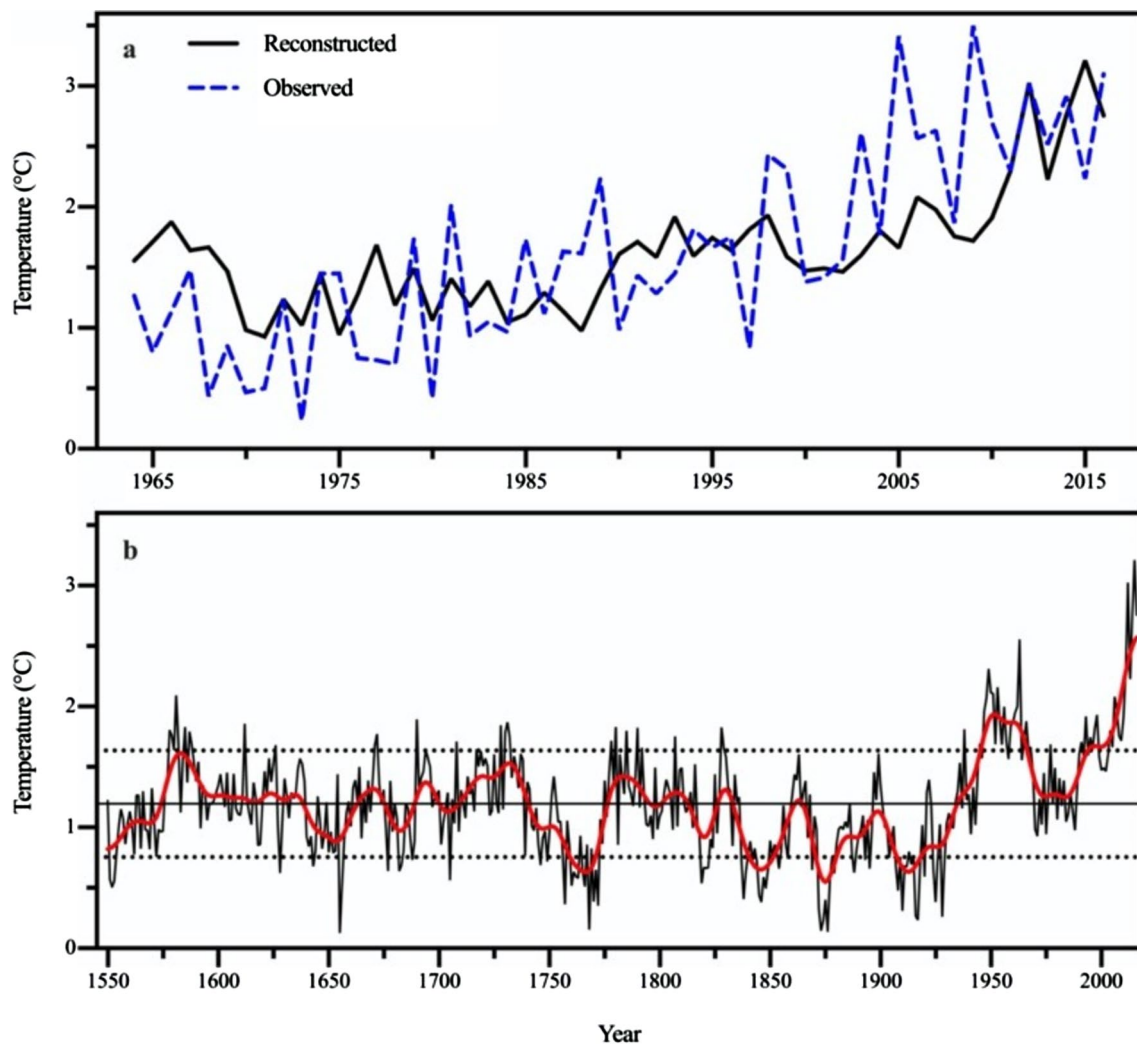
**Fig. 5** **a** Comparison of observed (dash line) and reconstructed (solid line) $T_{min}$ 1964–2016, **b** The reconstructed $T_{min}$ and its 21-year low-pass filter (thick line) 1550–2016

the previous March to the current October were performed over 1963–2016. Based on the results of the climate-growth relationship, the dominant limiting factor was selected for reconstruction with a simple linear regression method (Fritts 1976; Cook and Kairiukstis 1990). The leave-one-out cross-validation (LOOCV) method was employed to test the robustness of the reconstruction model because of the short common period between tree-ring width chronology and meteorological records (Michaelsen 1987). A positive value of the reduction of error (RE) denotes the fidelity of reconstruction model.

Multi-taper method (MTM; Mann and Lees 1996) and wavelet analysis (Torrence and Compo 1998) were used to explore periodic variations of the reconstruction. Spatial correlation analyses were performed between the actual and reconstructed series and CRU TS4.04 temperature dataset to reveal the spatial representativeness of the reconstruction.

In addition, spatial correlations between the reconstructed series and HadSST1 SST dataset were calculated to determine the impact of global SSTs on climate variability in the study area. Spatial correlations were performed using the KNMI Climate Explorer (http//www.knmi.nl).

## Results

### Climate-growth relationships

A ring-width chronology of *S. tibetica* was developed which spans 1299–2016 with a mean segment length of 379.3 years. The reliable portion of the chronology covers 1550–2016 based on the EPS threshold of 0.85 (Fig. 2). The Rbar of the reliable chronology ranges from 0.20 to 0.40, with an average value of 0.27 (Fig. 2). Based on the statistics

**Fig. 6** **a** MTM spectral results of the reconstructed $T_{min}$ 1550–2016. The red and green lines denote 0.01 and 0.05 significance level, respectively; **b** Wavelet analysis of the reconstructed $T_{min}$ 1550–2016. The black line indicates the cone of influence beyond which the edge effect may contort the results. Shading denotes the 0.05 significance level
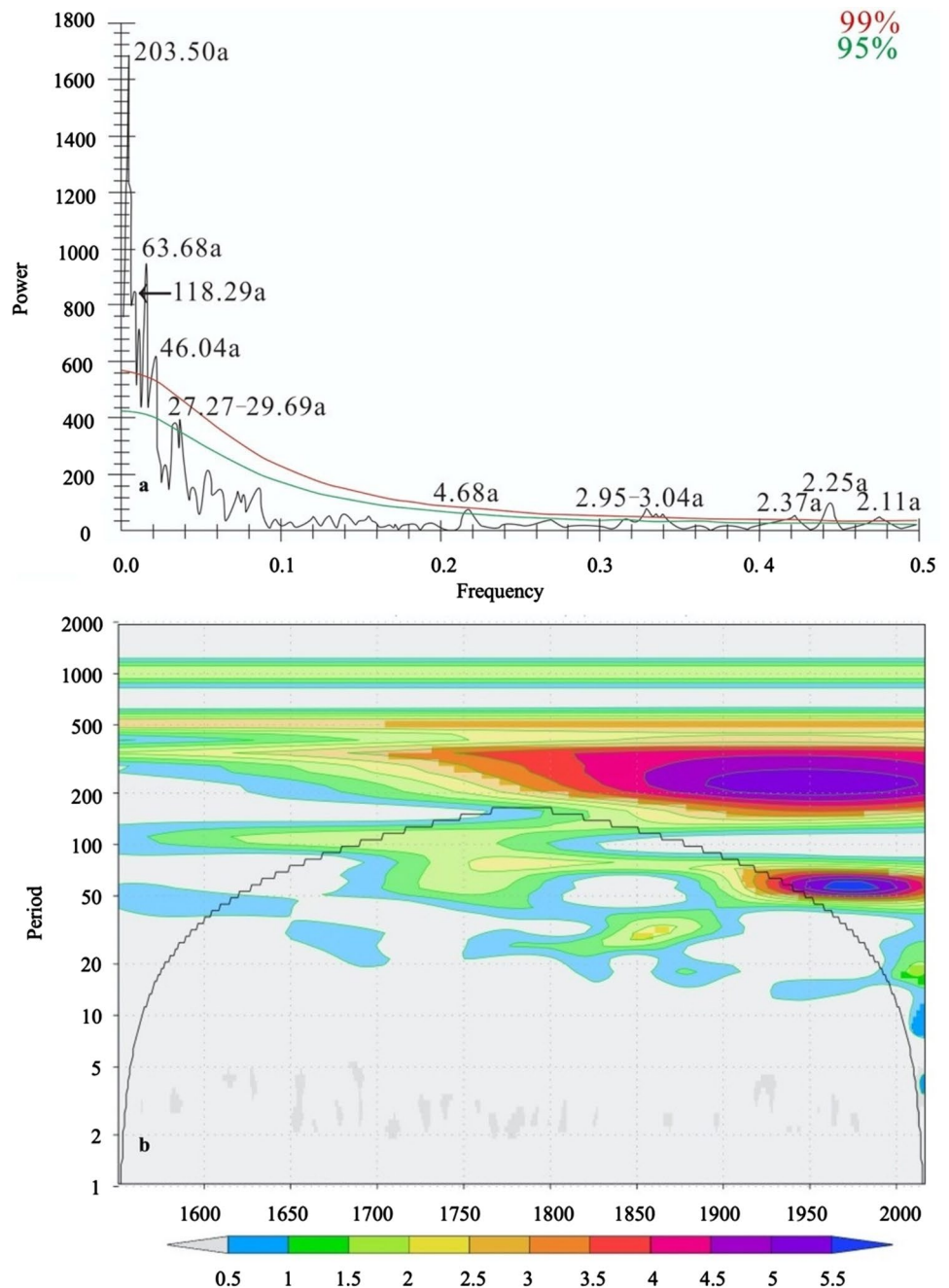
of EPS and Rbar, the chronology holds strong and stable climate signals and is suitable for dendroclimatic studies.

Growth of *S. tibetica* was positively correlated with almost all temperature factors (Fig. 4). It had significant positive correlations with $T_{mean}$ and $T_{min}$ in the previous March to September, previous November, and the current January to October. It also had significant positive correlations with $T_{max}$ in the previous September and in the current September–October. At the same time, growth of *S. tibetica* showed a weak relationship with precipitation, although there was a significant positive correlation in the current January. These results indicate that $T_{mean}$ and $T_{min}$ were the most important limiting factors affecting growth of *S. tibetica* in the central eastern Tibetan Plateau.

## Regional $T_{min}$ reconstruction

Based on the climate-growth relationship, a linear regression model between ring-width chronology and warm season $T_{min}$ was developed for reconstruction (Cook and Kairiukstis 1990). The reconstruction explained 37.8% (36.6% after adjusting for the degree of freedom) of the $T_{min}$ variance

from 1964 to 2016. A comparison between the observed and reconstructed $T_{min}$ showed good consistency during 1964–2016 (Fig. 5a). The LOOCV generated reconstruction had a significant positive correlation with the observed data ($r = 0.58$, $p < 0.01$). The positive RE value (0.29) and low root mean squared error value (0.66) suggest that the reconstruction model is robust. Therefore, the warm season $T_{min}$ for the central eastern Tibetan Plateau was reconstructed for the past 467 years based on the linear regression model (Fig. 5b).

The reconstructed $T_{min}$ ranged from 0.13 to 3.21 °C with a mean of 1.19 °C and a standardized deviation ($\sigma$) of 0.44 °C over the past 467 years (Fig. 5b). An extremely high temperature was defined as above 1.63 °C (mean + 1$\sigma$) and an extremely low temperature as below 0.75 °C (mean − 1$\sigma$). Therefore, there were 70 extremely high temperature years and 69 extremely low temperature years, which accounted for 14.99% and 14.78% of the past 467 years, respectively. Among them, the top ten warmest years were 2015, 2012, 2014, 2016, 1963, 1949, 2011, 2013, 1953 and 1950, ranging from 2.12 to 3.21 °C, and the top ten coldest years were 1655, 1876, 1873, 1768, 1874, 1917, 1928, 1916, 1910 and 1872, ranging from 0.13 to 0.33 °C. Based on the 21-year low-pass filter of the reconstruction, there were 8 warm periods (1575–1638, 1663–1675, 1689–1700, 1709–1740, 1777–1795, 1801–1812, 1827–1833, 1935–2016) and 8 cold periods (1550–1574, 1639–1662, 1676–1688, 1701–1708, 1741–1776, 1796–1800, 1813–1826, 1834–1934) in the past 467 years.

### Periodic variations of the reconstructed $T_{min}$

The MTM spectral analysis showed that the reconstructed $T_{min}$ had inter-annual (2.11a, 2.25a, 2.37a, 2.95–3.04a, 4.68a), multi-decadal (46.04a, 63.68a), centennial (118.29a) and bicentennial (203.5a) cycles significant at 0.01 significance level (Fig. 6a). In addition, a multi-decadal periodicity (27.27–29.69a) at the 0.05 significance level was also found. Wavelet analysis indicated that multi-decadal and bicentennial cycles were the main periodicities of the $T_{min}$ series 1550–2016 (Fig. 6b). The multi-decadal cycles were most pronounced during the 1880–2010s, while the bicentennial cycles were most pronounced during the 1700–2010s.

## Discussion

### Climate-growth relationships

According to the correlations between ring-width chronology and climatic factors, warm season $T_{min}$ is the dominant limiting factor on tree growth on the central eastern Tibetan Plateau. Numerous studies have revealed that tree growth at high-altitude sites reflect minimum temperature signals on the eastern Tibetan Plateau (Gou et al. 2007; Liang et al. 2009; He et al. 2014; Shi et al. 2015; Li and Li 2017; Huang et al. 2019; Li et al. 2021). $T_{min}$ could influence cell division in the cambium and the enlargement of tracheids during the growing season (Deslauriers et al. 2003). Low air temperatures at night reduce soil temperatures and may constrain root growth and water uptake
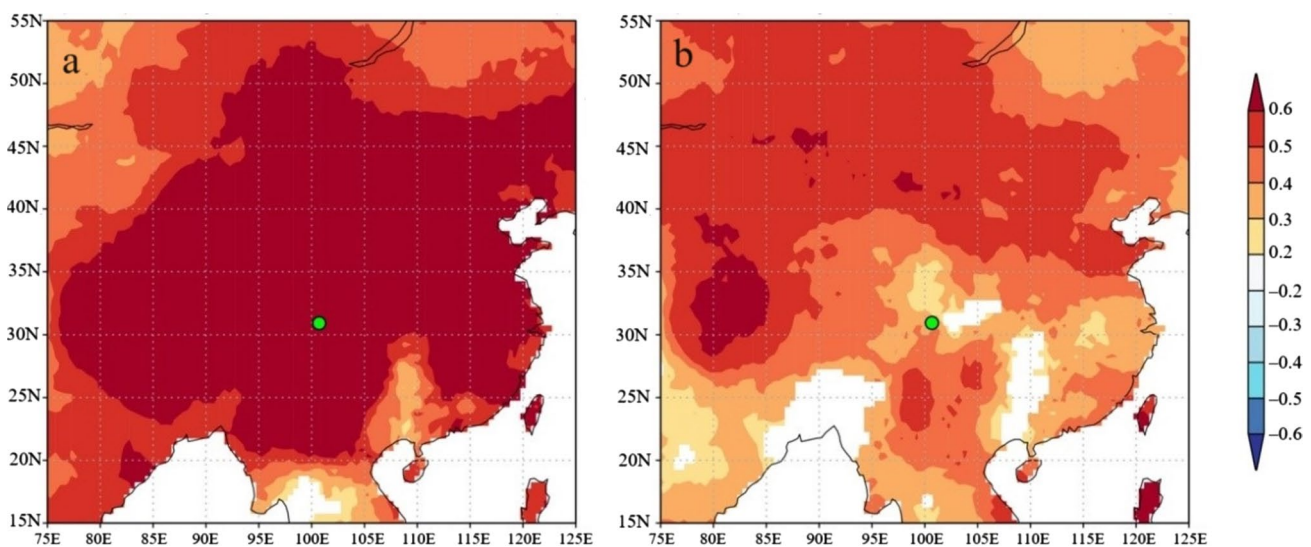


**Fig. 7** Spatial correlations of **a** observed and **b** reconstructed $T_{min}$ with CRU TS4.04 $T_{min}$ during 1964–2016
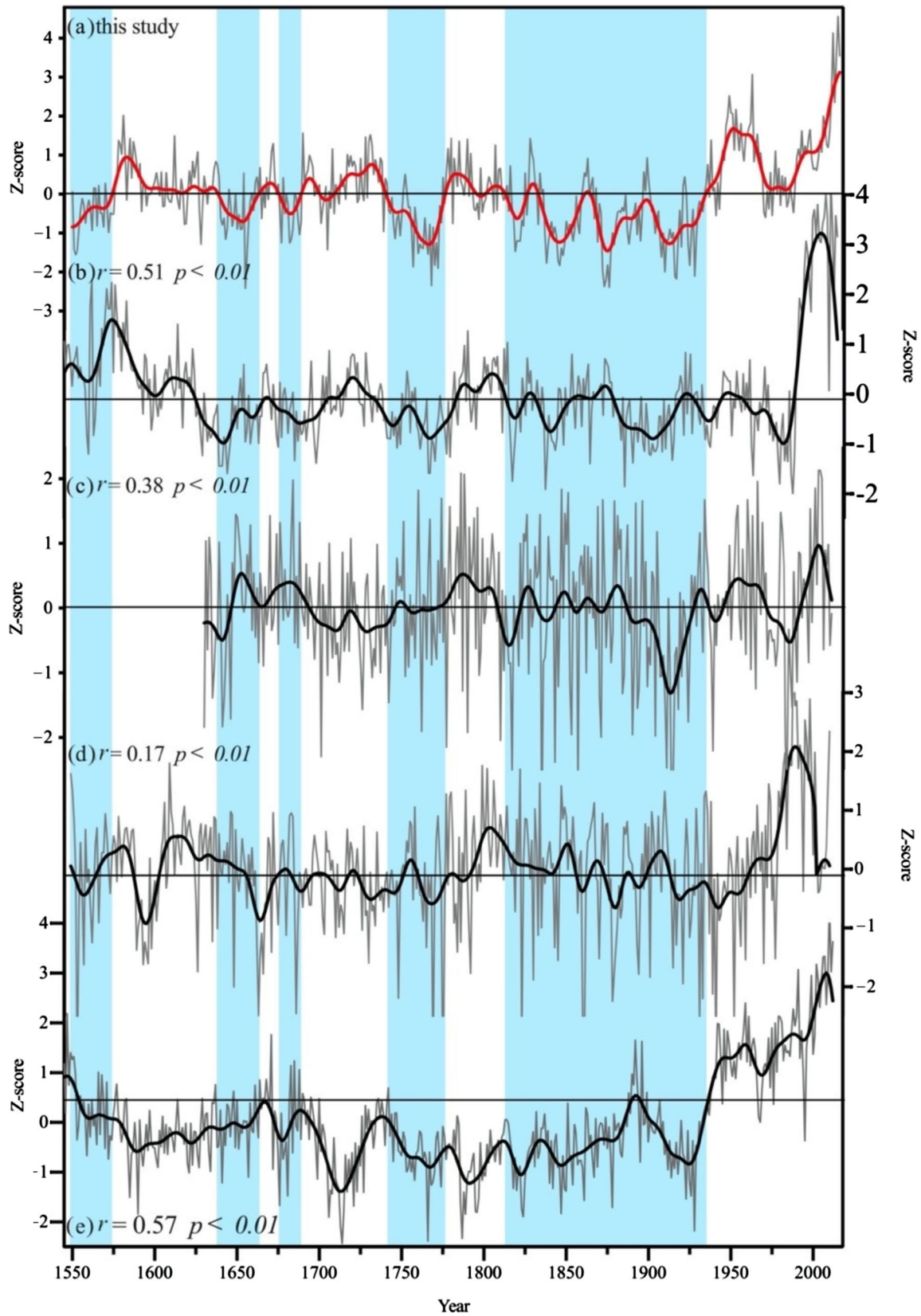
◄**Fig. 8** Comparison of $T_{min}$ reconstruction in this study with $T_{min}$ reconstructions from other studies on the Tibetan Plateau. **a** the $T_{min}$ reconstruction in this study, **b** the previous April to current March $T_{min}$ reconstruction on the east central plateau (Li and Li 2017), **c** August $T_{min}$ reconstruction on the southeastern plateau (Liang et al. 2016); **d** previous October to current April $T_{min}$ reconstruction on the northeastern Tibetan Plateau (Gou et al. 2007), and **e** January–August $T_{min}$ reconstruction on the northern plateau (Zhang et al. 2014b). All reconstructions have been standardized over their common period for direct comparison. In each panel, the grey line represents the raw data and the bold line a 21-year low-pass filter. Light blue shading denotes major cold periods in our reconstruction

(Körner 1999). Therefore, $T_{min}$ influences tree growth at high-altitude sites by affecting root growth and cambium activity during the growing season.

## Spatial representativeness of the reconstruction

Spatial correlation patterns of the observed and reconstructed $T_{min}$ with the gridded CRU TS4.04 $T_{min}$ during 1964–2016 were highly consistent, suggesting that the reconstructed $T_{min}$ can represent large-scale temperature changes on the plateau (Fig. 7). To further validate the reliability of our reconstruction, four tree-ring based $T_{min}$ reconstructions from nearby regions were used for comparison: a 564-year previous April to current March reconstruction on the east central plateau (Li and Li 2017), a 382-year August reconstruction on the southeastern plateau (Liang et al. 2016), a 425-year previous October to current April reconstruction on the northeastern plateau (Gou et al. 2007), and a 1343-year January–August reconstruction on the northern plateau (Zhang et al. 2014b). Similar cold and warm periods were found in these $T_{min}$

reconstructions (Fig. 8). For example, two major cold periods occurred during the 1740–1770s and 1810–1920s. The cold period of the 1550–1560s in our study was consistent with the previous October to current April variations on the northeastern plateau (Gou et al. 2007), and January–August variations on the northern plateau (Zhang et al. 2014b). The cold periods of the 1640–1650s and in the 1680s in this study were also found in the $T_{min}$ reconstructions on the east central Tibetan Plateau (Li and Li 2017) and in the north (Zhang et al. 2014b). However, there are some discrepancies between our reconstructions and other $T_{min}$ reconstructions. For example, the cold period in the 1680s was not captured in the August $T_{min}$ reconstruction on the southeastern plateau (Liang et al. 2016). The differences among these reconstructions may be related to the growth sensitivity of different tree species under different micro-environments (Classen et al. 2015). Pronounced warming since the 1990s has been observed in all the reconstructions. Overall, the above results indicate that our reconstructions are highly consistent with nearby $T_{min}$ reconstructions since the 1550s.

## Linkages of the $T_{min}$ variability with global sea surface temperatures (SSTs)

Based on the results of the multi-taper method (MTM) and wavelet analyses, the reconstructed warm season $T_{min}$ on the eastern plateau has several dominant interannual (2.11a, 2.25a, 2.37a, 2.95–3.04a, 4.68a) and multi-decadal (63.68a) cycles, which are consistent with the 2–7a El Niño–Southern Oscillation (ENSO) cycles and the 60–80a Atlantic Multi-decadal Oscillation (AMO) cycles,

**Fig. 9** Spatial correlations of the reconstructed $T_{min}$ with global April–September averaged sea surface temperatures over 1964–2016
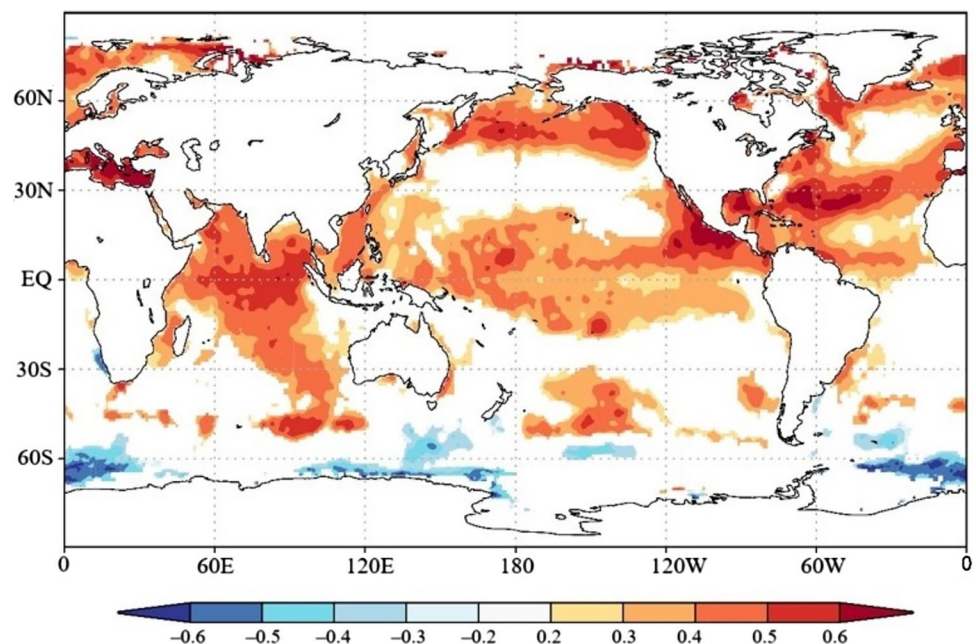
respectively. In addition, our reconstructed $T_{min}$ series exhibits significant positive correlation ($r = 0.54$, $p < 0.01$) with the AMO index over 1870–2006 (Mann et al. 2008). Significant positive correlation ($r = 0.21$, $p < 0.01$) was also found between our $T_{min}$ reconstruction and the Had-ISST1 Niño3.4 SST index from 1870 to 2006 (Rayner et al. 2003). Spatial correlations between the reconstructed $T_{min}$ and global SSTs during 1964–2016 showed that there were significant positive correlations with SSTs in the central and northern Pacific Ocean, Indian Ocean, and the North Atlantic Ocean, suggesting that ENSO and AMO played a key role on temperature changes in the central eastern Tibetan Plateau (Fig. 9). Altogether, these results suggest that the $T_{min}$ variations have a close relationship with ENSO and AMO cycles. Previous studies have shown that climate change on the eastern Tibetan Plateau has been influenced by different large-scale ocean-atmospheric circulations, such as the Asian monsoon, and the ENSO and AMO cycles (Shao and Fan 1999; Song et al. 2007; Duan et al. 2010; Yu et al. 2012; Xiao et al. 2015; Deng et al. 2016; Zhu et al. 2016; Deng et al. 2017; Li and Li 2017; Li et al. 2021), which are consistent with our findings. Nevertheless, further research is needed to reveal the dynamic processes that connect ENSO and AMO cycles with temperature changes on the central eastern Tibetan Plateau.

## Conclusion

In this study, a ring-width chronology was developed for *S. tibetica* from the Lianbaoyeze Mountain in the central eastern Tibetan Plateau. Climate-tree growth analysis showed that growth of *S. tibetica* was mostly limited by the warm season (April–September) minimum temperatures. Based on this relationship, we reconstructed warm season $T_{min}$ for the past 467 years, which revealed 8 warm periods (1575–1638, 1663–1675, 1689–1700, 1709–1740, 1777–1795, 1801–1812, 1827–1833, 1935–2016) and 8 cold periods (1550–1574, 1639–1662, 1676–1688, 1701–1708, 1741–1776, 1796–1800, 1813–1826, 1834–1934). Spatial correlations and comparisons with other $T_{min}$ reconstructions on the plateau confirmed that our reconstruction represented large-scale $T_{min}$ variations on the Tibetan Plateau. Further analyses indicated that temperature changes in central eastern plateau may be affected by large-scale ocean-atmospheric circulations such as ENSO and AMO. Future research should develop a larger tree-ring network with longer chronologies for the central eastern Tibetan Plateau to help better understand long-term associations of regional climates with large-scale ocean-atmospheric circulations.

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