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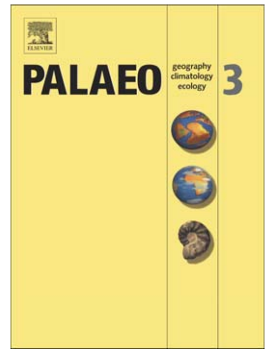


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# Unprecedented January-July warming recorded in a 178-year tree-ring width chronology in the Dabie Mountains, southeastern China

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**ABSTRACT**

Previous tree-ring studies indicate that tree growth at high elevations is strongly limited by temperatures in the southeastern China, where the climate is dominated by the East Asian monsoon. Based on this result, we built a highly replicated 202-year tree-ring width chronology from high elevation sites in the Dabie Mountains, southeastern China. The most reliable period of the chronology is from 1834 to 2011 according to a subsample signal strength cutoff of 0.85. Based on this chronology, January-July minimum temperature was reconstructed for the last 178 years, with an explained variance of 57.6% during the instrumental period 1956-2010. The reconstructed temperature series matches reasonably well with three other tree-ring

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based temperature reconstructions at decadal time scales in the region. The coldest periods are 1891-1898 and 1904-1914, however, the longest cold period is from 1948 to 1973. The warmest period is 1990-2010. Both the recent (1990-2010) warming and recent (1948-2010) temperature increase rate are unprecedented during the past 178 years in the study region.

*Keywords:*

*Pinus taiwanensis* Hayata; Tree ring; Minimum temperature; Southeastern China

## 1. INTRODUCTION

Tree rings play an important role in reconstructing past temperature change over the past millennium, providing a long-term background of natural temperature variability at regional, hemispheric or even global scales (Briffa et al., 2008; Cook et al., 2012; Esper et al., 2002; Mann et al., 2008). Depending on their location, tree growth may be sensitive to temperature for different seasons. Ring widths of trees growing in cold environments usually reflect the influence of warm-season temperatures (Esper et al., 2002). However, in some cases, they also reflect temperatures in the cool seasons before the growing season (Jacoby et al., 1996).

Dendroclimatic investigation of pine species in the eastern China has received increasing attention over the past several years (Chen et al., 2011; Duan et al., 2012; Shi et al., 2010; Zhu et al., 2009). The sampled tree species include *Pinus massoniana*, *P. taiwanensis* Hayata (Taiwan pine), and *P. koraiensis*, and the elevations of the sampling sites range from 450 to 1200 m above sea level (a.s.l.) in these studies. Winter and spring temperatures prior to the growing season are the main limiting factors on tree growth. The investigation of growth response of *P. tabulaeformis* to climate showed that temperature stress effects increased with elevation in the eastern Qinling Mountains, central China (Shi et al., 2012). *P. armandii* Franch at a high elevation site also show a strong prior growing season temperature stress in the eastern Qinling Mountains (Shi et al., 2009). Here we expand our investigations of Taiwan pine in eastern China to the Dabie Mountains.

The Dabie Mountains extends 270 km from southeast to northwest in southeastern China, forming an important watershed divider of the Yangtze River to the south and the Huai River to the north (Fig. 1). The highest peak is Baima Peak, 1777 m a.s.l.

The climate is characterized by subtropical monsoon climate. The radial growth of Taiwan pine growing at 1500 m a.s.l. responds positively to temperature from February to July (Zheng et al., 2012). In this study, we sampled old Taiwan pine trees at higher elevation sites i.e., from 1650-1750 m a.s.l., along mountain ridges in the Dabie Mountains. Our sampling strategy was based on our understanding that 1) trees growing on high elevation sites are more sensitive to temperature than those on low elevation sites (Fritts, 1976), and 2) the highest sites in mountains have less montane microclimate. We built the longest possible tree-ring chronology by sampling the oldest available trees, which may include more low-frequency signals after the traditional detrending process was made (Cook et al., 1995). The purposes of this study are (1) building a long tree-ring width chronology at high elevation sites in the Dabie Mountains, (2) determining the most important limiting factor of tree growth at the sites, and (3) reconstructing temperature variability of the past 178 years for exploring spatial and temporal variability in temperature in southeastern China.

## 2. MATERIALS AND METHODS

### *2.1. Study area and climatic data*

The climate data used in this study include local monthly mean, maximum, and minimum temperatures and monthly total precipitation records. The instrumental data were obtained from Liuan meteorological station (31º45′N, 116º30′E, 60.5 m a.s.l.) (Fig. 1). According to this station, the region has a mean annual temperature of 15.8 $^{o}$C and an annual precipitation of 1107.0 mm over the 1956-2011 period (Fig. 2a). Peak monthly precipitation is found in July, followed by June and August, and the hottest month is July, followed by August and June, while the coldest month is January, followed by February and December. While all the observed annual maximum, mean, and minimum temperatures show an increasing trend, minimum temperature has increased the fastest (Fig. 2b).

*2.2. Tree-ring data*

We collected radial increment cores of Taiwan pine from two close sites at almost the same elevation along mountain ridges of two highest peaks in the Dabie Mountains (Fig. 1). The sampling sites are Baimajian (BMJ0102, 31º7′N, 116º11′E, 1640-1760 m a.s.l.) and Duoyuanjian (DYJ01, 31º7′N, 116º12′E, 1680-1750 m a.s.l.), which are close to the maximum elevation of Baima Peak (1777 m a.s.l.). The linear distance between them is 3 km. Taiwan pine trees occupy a narrow band along mountain ridges above the deciduous forests growing there. Most of the pine trees are sparsely distributed.

Following standard dendrochronological techniques (Cook and Kairiukstis, 1990), two cores per tree were extracted using increment borers. When a core was found to come from a young tree under field observation or it was dangerous to take more samples, only one core per tree was extracted. In total, 93 cores from 56 trees were collected at BMJ0102 and 37 cores from 25 trees at DYJ01. All the samples were processed using standard procedures (Stokes and Smiley, 1996), and were visually cross-dated under microscope. Each tree-ring width was measured to 0.001 mm precision with LINTAB 5.0 system at Nanjing University. Dating and measurement errors were further checked with the COFECHA computer program (Holmes, 1983). Subsequently, each ring-width chronology was developed using the ARSTAN program (Cook, 1985) by removing biological growth trends while preserving variations that were likely related to climate. All the measurement series were detrended by fitted negative exponential curves or linear regression curves of any slope. A cubic smoothing spline with a 50% frequency response cutoff equal to 67% of the series length was also used in a few cases when anomalous growth trends occurred. The ratios between original ring widths and the fitted curves are calculated as the detrended series. The crossdated and detrended series for each site were then averaged together into mean chronologies using the biweight robust mean. As the sample size generally declines in the early portion of a tree-ring chronology, we used the subsample signal strength (SSS) statistic (Wigley et al., 1984) with a threshold of 0.85 to evaluate the most reliable time span of each chronology. Considering that the correlation coefficient between these two site chronologies is 0.70 during their common most reliable period 1847 to 2011, that the correlation coefficient between the average measurement series of two sites is 0.90 during that period, and that they are close to each other at almost the same elevation, we merged their samples to form a single chronology. The maximum wavelength of recoverable climatic information is generally related to the individual tree-ring series used to construct the chronology (Cook et al., 1995). In order to preserve more low frequency, only the tree-ring series extending back before 1900 were kept in the final chronology construction. The same processes used in building site chronologies were also used to build the overall chronology (RC) (Fig. 3).

*2.3. Climate modeling and reconstruction methods*

The relations between tree growth and climate were explored by Pearson correlation analyses. The dominant factor on tree growth was reconstructed using a principal component regression model. The fidelity of this model was examined by split sample calibration-verification tests (Meko and Graybill, 1995).

## 3. RESULTS AND DISCUSSION

### *3.1. Tree-ring width chronology*

The statistics of the standard ring-width chronology (AD 1810-2011) and the results of the common interval analysis (AD 1900-2010) were computed on the detrended data. Relatively large values were obtained for all the between-core (R1), within-tree (R2), and between-tree (R3) correlations which are 0.27, 0.58, and 0.27, respectively. The statistical values of signal-to-noise ratio (SNR), expressed population signal (EPS), and percent variance explained by the first principal component (PC1) are 23.63, 0.96, and 30.1%, respectively. These statistics indicate that the trees show a common signal likely associated to climate. The RC standard chronology consists of 84 cores from 54 trees, ranging from 1810 to 2011 with the most reliable period 1834 to 2011 when SSS > 0.85.

### *3.2. Tree-growth-climate relationship*

Fig. 4 shows the correlation coefficients between the RC chronology and monthly total precipitation and monthly minimum, mean, and maximum temperatures during a two-year dendroclimatic year over 1956-2011. An obvious feature is that both prior and current January-July minimum temperatures correlate significantly positive with tree growth at 0.01 level. Monthly mean and maximum temperatures influence on tree growth is similar to that of monthly minimum temperature, but to a lesser extent. In contrast, no monthly precipitation correlation except for prior September exceeds 0.01 significant level (Fig. 4a). The correlation analysis clearly shows that tree growth at these high-elevation sites is strongly stressed by temperature.

Increased winter temperatures in areas of inconsistent snow pack may mean less winter damage to roots and, thus, less of a growth limitation (Pederson et al., 2004). The influences of winter to spring temperature on tree growth were also discovered for *Pinus tabulaeformis* and *Pinus armandii* Franch in the eastern Qinling Mountains (Shi et al., 2012; Shi et al., 2009), *Pinus massoniana* in southeastern China (Duan et al., 2012; Chen et al., 2012), *Pinus taiwanensis* Hayata in the lower reaches of the Yangtze River (Shi et al., 2010), *Pinus tabulaeformis* in the southern Qinling Mountains (Liu et al., 2009), *Juniperus przewalskii* in the Xiqing Mountains of the northeastern Tibetan Plateau (Gou et al., 2007), and *Sabina przewalskii* and *Picea crassifolia* on the northeast Tibetan Plateau (Liang et al., 2006). Therefore, winter-spring temperatures have a strong influence on tree growth for many tree species on a large scale from subtropical to temperate climate. Summer temperature was reconstructed using tree-ring width chronologies in temperate East Asia (Cook et al., 2012), indicating that summer temperature is also a limiting factor on tree growth in large spatial regions including the research area in this study.

### *3.3. Reconstruction of the January-July minimum temperature*

Based on the results of the correlation analysis, the January-July average minimum temperature was selected as the predictand for reconstruction. The chronologies of the current year and the following year were chosen as the predictors. The calibration model for the early 1956-1983 period shows a correlation coefficient (CC) of 0.523, and the statistics of the CC, reduction of error (RE), and coefficient of efficiency (CE) during the 1984-2010 verification period are 0.652, 0.673, and 0.142 (Table 1). The calibration model using data from the late 1984-2010 period shows a CC of 0.653 and the CC, RE and CE values during the remaining verification period are 0.521, 0.767, and -0.079. Positive values of RE and CE indicate significant reconstruction accuracy (Cook et al., 1999). CE is slightly negative in the latter verification period. The same situation was also found in a previous tree-ring study in southeastern China (Shi et al., 2010). The possible reason is the short calibration and verification periods and the big temperature difference between these two periods. However, the final calibration including the full overlapping period between tree-ring and temperature series could overcome this drawback to some extent. Generally, the overall test results sufficiently demonstrate the validity of our regression mode. The reconstruction accounts for 57.6% of the actual temperature variance during 1956 to 2010, which is the strongest signal found in southeastern China until recently. The 'divergence problem' (D'Arrigo et al., 2008) detected in many circumpolar northern latitude sites since the mid-20th century was not encountered in this study. This may be related to the lack of certain factors that have been associated with the 'divergence problem', such as drought stress (Barber et al., 2000) and delayed snow melt (Vaganov et al., 1999), in our humid subtropical study region. Tree-ring-based reconstruction captures observed temperature quite well at inter-annual to multi-decadal time scales (Fig. 5a). Based on this model, the January-July temperature history was reconstructed with large sample depth for the period of 1834 to 2010 (Fig. 5b).

### *3.4. Comparisons with other East Asian monsoon region temperature reconstructions and temperature variations*

In order to evaluate the reliability of the reconstruction and its spatial representative, we compared the reconstruction with three nearby tree-ring based temperature reconstructions (Duan2012 series, Shi2009 series, and Shi2010 series) in the East Asian monsoon region (Fig. 6). All the three recent below-average temperature periods since 1940 match among the four reconstructions, showing a good degree of spatial homogeneity over the past 70 years. This is likely due to the fact that all the four research sites are located in the East Asian monsoon region, with high annual precipitation, where tree growth is mainly limited by temperatures at elevations. The 1900s and 1890s below-average temperature periods likewise appear in all the reconstructions. In contrast, the 1930s below-average temperature period found in the Duan2012, Shi2009, and Shi2010 series is not in this study. In addition, the 1860s and 1880s below-average temperature periods in Duan2012 and this reconstruction do not agree with reconstructed above-average temperatures in Shi2012 series, which is explained as due to local temperature differences(Duan et al., 2012). However, other factors may also be involved in causing these differences, such as forest disturbances, juvenile problems, and the decreasing number of tree cores in the early parts of tree-ring chronologies(Wigley et al., 1984). To date, it is difficult to attribute the exact reasons of these differences because there are only a few annually-resolved temperature reconstructions from southeastern China for comparison. In general, the common multi-decadal scale temperature signals are clearly shown in all the four temperature reconstructions.

Based on our low-pass filtered reconstruction (Fig. 6), we have defined here five or more years with temperature higher than average as high-temperature periods, and lower than average as low-temperature periods (Table 2). The coldest periods are 1891-1898 and 1904-1914, both with a temperature departure from the average of -0.62 $^{o}$C. However, the longest cold period is from 1948 to 1973 with a temperature departure of -0.45 $^{o}$C. The warmest period is 1990-2010 with a temperature departure of 0.73 $^{o}$C, which exceeds any other periods in the reconstruction. From 1948 to 2010, minimum temperature has also increased at a rate of 0.026 $^{o}$C per year, which is the rate of slope of a linear regression analysis and is the fastest during the reconstructed temperature series. In total, both the recent (1990-2010) warming and its rate of increase (1948-2010) are unprecedented during the past 178 years in our study region.

## 4. CONCLUSIONS

A robust 202-year Taiwan pine tree-ring width chronology was developed from two sites on the highest peaks of the Dabie Mountains in southeastern China, with its most reliable interval covering the 1834-2011 period. This chronology explains 57.6% variance of actual January-July minimum temperature. The high explained variance can be attributed to the high-elevation sampling sites. Besides the prior growing season temperature influence on growth which has been found in several recent studies, this temperature influence extends into the early growing season. Both the high explained variance and long temperature response window show that tree growth at the sampling sites is strongly limited by temperature. In addition, the match between tree growth and instrumental temperatures is excellent, thus indicating a lack of tree growth "divergence", which has been documented in certain northern-hemisphere high-latitude regions. This enabled January-July minimum temperature to be reconstructed using our regional chronology. Mostly, the chronology shows common variations with other nearby temperature reconstructions in the East Asian monsoon region. The recent warming and warming rate are unprecedented during the past 200 years. However, some discrepancies between the reconstructed temperature series cannot be explained until more temperature reconstructions are developed in southeastern China, and the unprecedented recent warming cannot be evaluated beyond 200 years until longer tree-ring width chronologies are built.

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**Figure Captions:**

**Fig. 1.** Map of the tree-ring sampling sites, the meteorological station, and three nearby tree-ring width based temperature reconstructions used for comparisons

**Fig. 2.** Observed precipitation and temperature variations in the Liuan meteorological station for the period 1956-2011. (a), monthly averaged mean temperature and total precipitation records; and (b), annual maximum, mean, and minimum temperatures and their linear regression functions and corresponding explained variances

**Fig. 3.** The tree-ring width standard chronology (solid line) and the corresponding number of cores (dashed line)

**Fig. 4.** Correlation coefficients between the tree-ring width standard chronology and climatic parameters from previous January to current December over the period of 1956 to 2011. (a), monthly total precipitation (gray bar) and monthly minimum temperature (black bar); and (b), monthly mean (blank bar) and maximum (black bar) temperatures. “pJ” means previous January; horizontal dotted line indicates statistical significance level at 0.01

**Fig. 5.** January-July minimum temperature reconstruction in the Dabie Mountains, southeastern China. (a), comparison of actual and reconstructed temperatures for 1956 to 2010; and (b), the reconstructed temperature from 1834 to 2010

**Fig. 6.** Comparison of the reconstructed January–July average minimum temperature with other nearby temperature reconstructions in the East Asian monsoon region. (a), mean January-April temperature reconstruction in the southeastern China (namely, Duan2012 series) (Duan et al., 2012); b, mean temperature reconstruction of prior December to current April in the eastern Qinling Mountains (namely, Shi2009 series) (Shi et al., 2009); c, mean temperature reconstruction of prior December to current March in the lower reaches of the Yangtze River in southeast China (namely, Shi2010 series) (Shi et al., 2010); and d, temperature reconstruction of this study. The curves are the 10-year cubic smoothing spline filters with 50% frequency response cutoff. Blue bars are the below-average temperature periods and the red bar represents an above-average temperature period according to the reconstructed curve from this paper.

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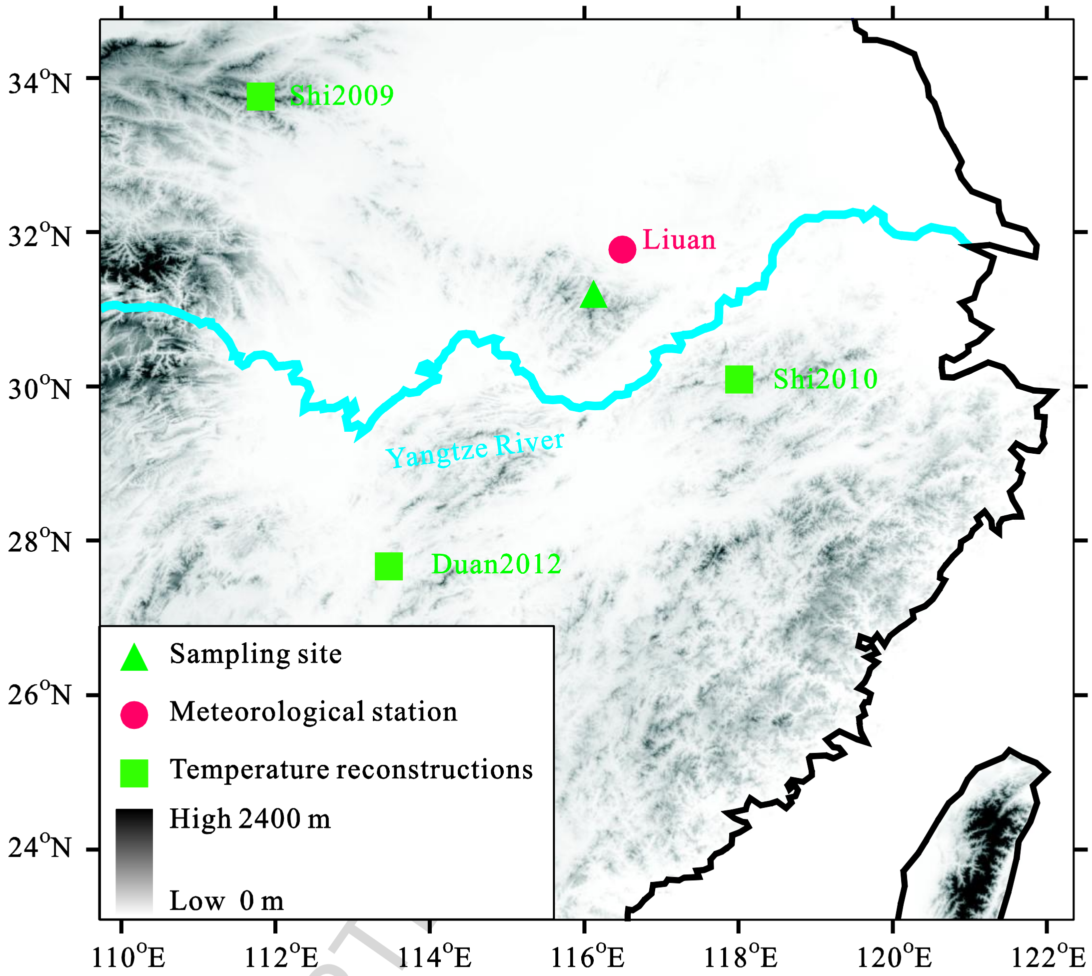
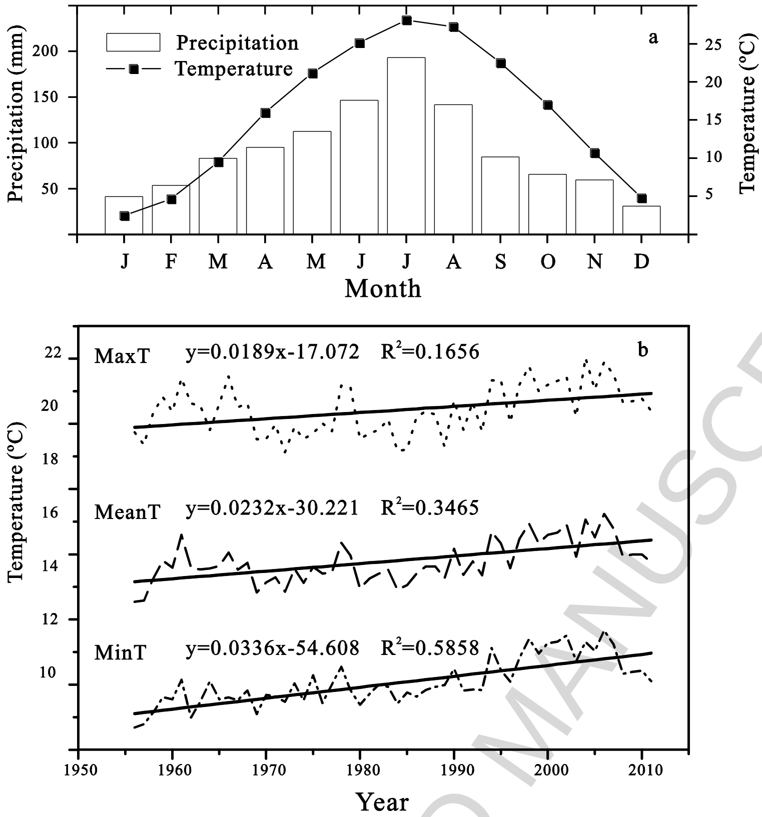

34°N
32°N
30°N
28°N
26°N
24°N
110°E
112°E
114°E
116°E
118°E
120°E
122°E
Shi2009
Liuan
Shi2010
Yangtze River
Duan2012
Sampling site
Meteorological station
Temperature reconstructions
High 2400 m
Low 0 m

**Fig. 1**



Precipitation
Temperature
a
Precipitation (mm)
Temperature (°C)
J F M A M J J A S O N D
Month
b
MaxT y=0.0189x-17.072 R²=0.1656
MeanT y=0.0232x-30.221 R²=0.3465
MinT y=0.0336x-54.608 R²=0.5858
Temperature (°C)
Year


**Fig. 2**

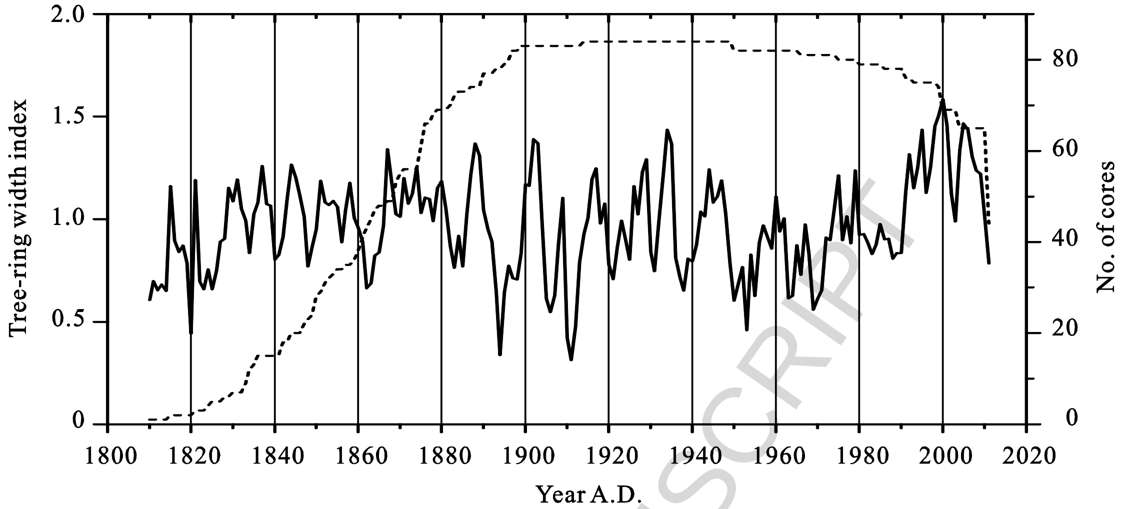
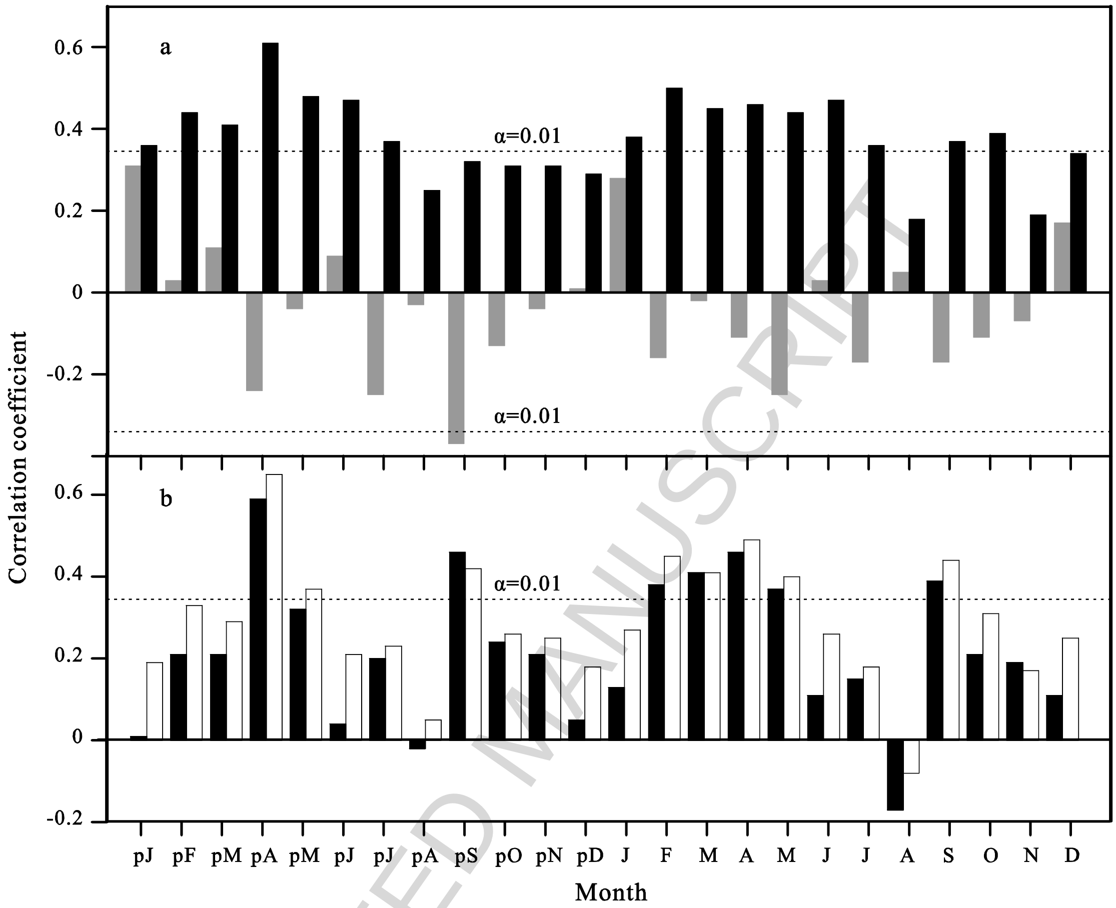
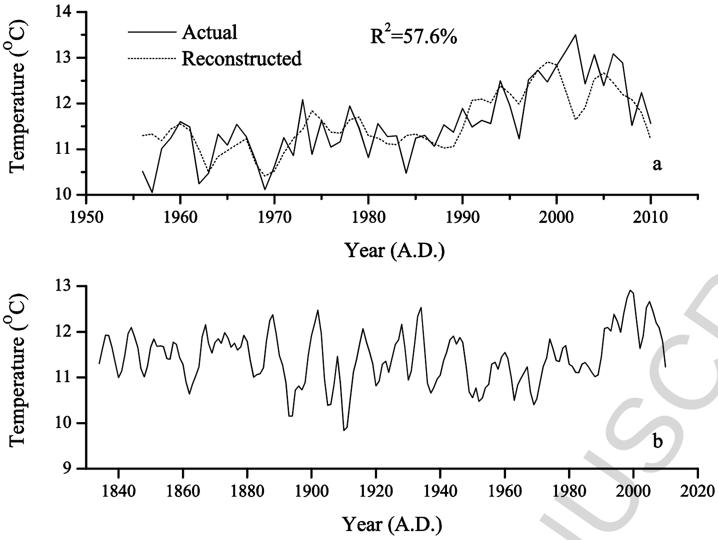

2.0
1.5
1.0
0.5
0
Tree-ring width index
80
60
40
20
0
No. of cores
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year A.D.

**Fig. 3**



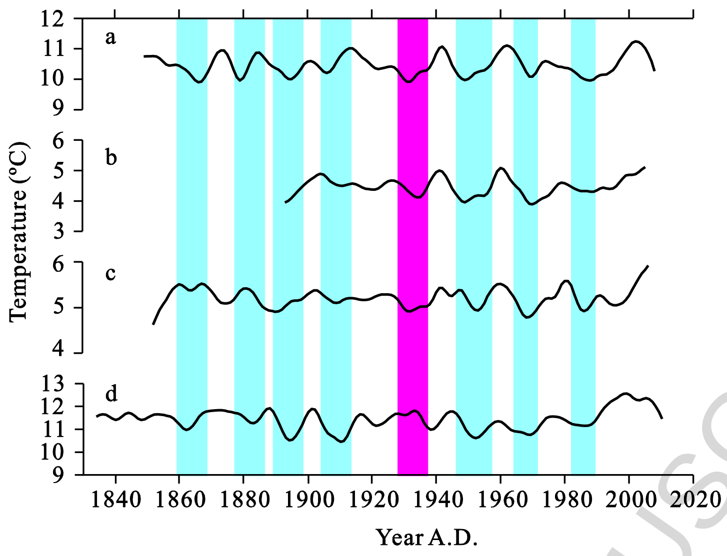
a
b
α=0.01
α=0.01
α=0.01
0.6
0.4
0.2
0
-0.2
Correlation coefficient
pJ pF pM pA pM pJ pJ pA pS pO pN pD J F M A M J J A S O N D
Month


**Fig. 4**



Actual
Reconstructed
$R^2$=57.6%
a
Temperature (°C)
Year (A.D.)
b
Temperature (°C)
Year (A.D.)


**Fig. 5**



12
11
10
9
a
6
5
4
3
b
6
5
4
c
13
12
11
10
9
d
Temperature (°C)
1840 1860 1880 1900 1920 1940 1960 1980 2000 2020
Year A.D.


**Fig. 6**

**Table 1**

Statistics of Calibration and Verification Test Results for the Common Period of 1956-2010 (MinT1_7)

| | Calibration (1956-1983) | Verification (1984-2010) | Calibration (1984-2010) | Verification (1956-1983) | Full calibration (1956-2010) |
|---|---|---|---|---|---|
| r | 0.523 | 0.652 | 0.653 | 0.521 | 0.759 |
| $r^2$ | | | | | 0.576 |
| RE | — | 0.673 | — | 0.767 | — |
| CE | — | 0.142 | — | -0.079 | — |

**Table 2**

Low- and High-Temperature Periods in the Reconstructed January-July Minimum Temperature Series

| Low temperature period | Temperature departure from the average/ $^{o}$C | High temperature period | Temperature departure from the average/ $^{o}$C |
|---|---|---|---|
| 1859-1865 | -0.28 | 1834-1858 | 0.13 |
| 1891-1898 | -0.62 | 1866-1880 | 0.30 |
| 1904-1914 | -0.62 | 1885-1890 | 0.28 |
| 1919-1924 | -0.19 | 1899-1903 | 0.29 |
| 1936-1941 | -0.30 | 1925-1935 | 0.22 |
| 1948-1973 | -0.45 | 1942-1947 | 0.22 |
| 1980-1989 | -0.20 | 1974-1979 | 0.08 |
| | | 1990-2010 | 0.73 |

## Highlights

- We built a 202-year tree-ring width chronology from HIGH elevation sites.
- The chronology explained 57.6% variance of actual January-July minimum temperature.
- The reconstructed temperature matches three nearby temperature reconstructions.
- The recent warming and temperature increase rate are unprecedented.