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Reconstructing mean maximum temperatures of May–August from tree-ring maximum density in North Da Hinggan Mountains, China

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Tree-ring samples from Dahurian Larch (*Larix gmelinii* (Rupr.) Rupr.) were collected at three sites in the northern Da Hinggan Mountains. Using samples measured by X-ray densitometry, measurements of tree-ring maximum latewood density chronologies of two sites were found to be significantly correlated with summer temperature. These two sites' tree-ring series were combined to form a single standard regional chronology. This was used to reconstruct the May–August monthly mean maximum temperature for the period 1855–2008 AD, and it explained 39.5% of the total temperature variance. In the past 154 years, there were 4 cold periods (1874–1893, 1927–1948, 1951–1960 and 1992–2002) and 4 warm periods (1855–1873, 1894–1916, 1961–1991 and 2003–2008). The summer temperature rose more obviously than that of winter in this region. Having been validated by other temperature reconstructions from the surrounding area, the reconstruction could indicate the summer temperature changes of large-scale regions.

Dahurian Larch (*Larix gmelinii*), maximum latewood density, summer temperature reconstruction, tree rings

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Global warming has been having large impacts on human activities since the 20th century, resulting in the temperature variations at both global and regional scales, which became one of the important research field in PAGES [1,2]. Northeast China, which is one of the most sensitive region to climate change, has the highest latitudes in China [3,4]. As an important natural proxy, tree rings may have recorded climate tendencies during the past on a scale of centuries and even millennia [5–7]. Dendroclimatology has been used to study historical climate change in Northeast China [8–12], and for the reconstructing of past temperatures [13–16]. However, most previous studies are based on tree-ring width which indicate winter-spring temperature fluctuations. To date, no reconstructions have been reported yet on temperatures during growing seasons based on tree-ring data in this area. Moreover, former studies suggested winter temperatures increased remarkably since the 1980s, but not so in summer [17,18]. Therefore, it is necessary to investigate the summer temperature in Northeast China.

Tree-ring densities appeared to be highly sensitive in cold-wet regions, which is of special significance with maximum latewood density, corresponding very well to summer temperatures, making them an important indicator in dendroclimatological studies [19–21]. The process of cell wall thickening in latewood tracheids in many conifers is mainly affected by growing season temperatures [22,23]. Wang et al. [24] indicated that tree-ring maximum density of *Larix gmelinii* (Rupr.) Rupr. are highly sensitive to temperature variations during the late growing season in Mohe County, Heilongjiang, China, which makes it feasible to extrapolate historic variations of summer temperatures using maximum tree-ring density data from *L. gmelinii* in this

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area.

We employed maximum densities of tree rings in *L. gmelinii* from the northern Da Hinggan Mountains to reconstruct the variations in the mean maximum temperature from May to August during the past 154 years. This reconstruction documents previously unknown summer temperature patterns and provides basic information for studying the history of summer climates in northeastern China.

1 Materials and methods

1.1 Tree ring materials

The Da Hinggan Mountains form a volcanic mountain range in the northeastern part of China. The range extends roughly 1200 km from north to south, narrowing toward the south. It divides the Manchurian plain of northeastern China to the east from the Mongolian Plateau of Inner Mongolia to the west. The area has an elevation of 1100–1400 m, with the highest peak reaching 2035 m. *Larix gmelinii*, *Pinus sylvestris* var. mongolica and *Betula platyphylla* dominate this important forest region.

Tree-ring samples were collected at sites within the northern Da Hinggan Mountains (Figure 1), in which the GL and WM sites located close to upper treeline and the BM site located in lower elevation forest. Two 12 mm cores in diameter were collected from each *L. gmelinii* tree (Table 1).

1.2 Meteorological data

Climate data were collected at a meteorological station close to the sampling sites in Mohe (52.97°N, 122.52°E, 433 m a.s.l.), including monthly mean temperature, monthly mean maximum temperature, monthly mean minimum temperature, and total monthly precipitation. The 1957–2008 mean annual temperature was –4.3°C with mean annual precipitation at about 430.3 mm that 70% falling from June to September (Figure 2).

1.3 Data analysis

Tree-ring samples were prepared for the densitometric analysis [25,26]. Cores were cut into thin 1.0 mm sections with the twin-blade of DENDROCUT, using angles vertical to the wood fiber, and adjusted by a DENDROSCOPE. Resin was extracted for 48 h with water at 80°C. The thin wood sections were kept at a constant temperature and humidity for least 2 h before X-ray photography was taken

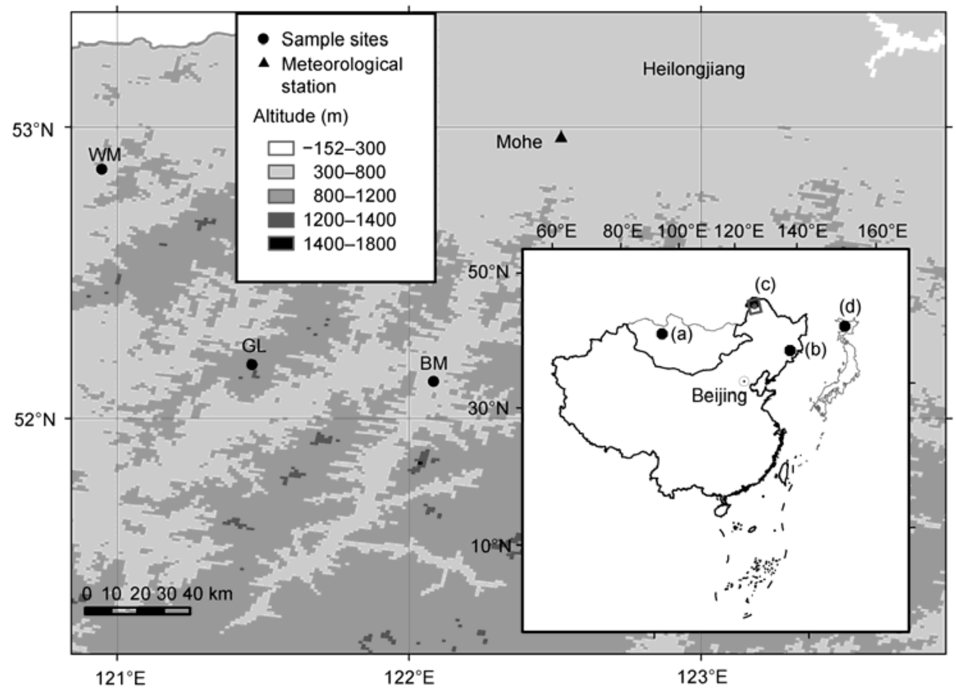

Figure 1 Locations of tree-ring sampling sites, meteorological stations and of other climate reconstruction studies circumjacent to the study area.

Table 1 Dahurian Larch sample sites

Code	Tree species	Location	Altitude (m)	Sample (tree/core)
GL	*Larix gmelinii* (Rupr.) Rupr.	52.19°N, 121.46°E	1260	24(48)
BM	*L. gmelinii*	52.13°N, 122.08°E	713	21(42)
WM	*L. gmelinii*	52.86°N, 120.95°E	655	25(50)

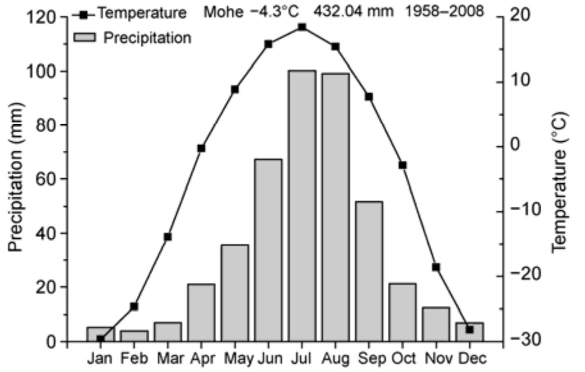

Figure 2 Climate diagram for the Mohe meteorological station.

in a constant-temperature-and-humidity room. The grey-scale X-ray film was then measured with a Dendro2003 (Walesch Electronic) workstation, and then the data sets of seven parameters were obtained (earlywood and latewood widths, earlywood and latewood average densities, maximum and minimum densities, and total tree-ring widths). The COFECHA [27] program was used for cross-dating, which was verified with thin wood sections when inconsistencies appeared. Detrending was carried out with a smoothing spline with two thirds of the series length with ARSTAN program [28]. Table 2 shows the statistical summary and common period analysis of tree-ring maximum density chronologies (MXD).

Pearson's correlation analysis was used to test the response of MXD to climatic factors. MXD of GL (GLMXD) and WM(WMMXD) were significantly positively correlated at the 0.99 level, and their variations were similar, so these two MXD tree-ring index series were combined to construct

Table 2 Tree-ring chronology statistics and common interval analysis of GL, BM, WM & RC[a)]

	GL	BM	WM	RC
Sample (tree/core)	21/43	20/40	25/50	46/93
Mean sensitivity	0.045	0.033	0.031	0.038
Mean index	1.003	1.002	1.001	1.003
Standard deviation	0.184	0.163	0.160	0.182
Sample of common interval analysis (tree/core)	19/36	34/20	16/12	31/52
Rar	0.258	0.249	0.148	0.171
Rbt	0.251	0.242	0.142	0.166
Rwt	0.509	0.540	0.328	0.466
SNR	12.528	11.298	2.777	10.729
PC1	30.8%	29.1%	21.4%	22.3%
EPS	0.926	0.919	0.735	0.915

a) Rar, Mean inter-series correlation; Rbt, correlation between trees; Rwt, correlation within trees; SNR, signal to noise ratio; EPS, expressed population signal; PC1, variance in 1st eigenvector.

a single standard regional chronology (RC) as shown in Figure 3. Because there was no significant correlation between MXD of BM (BMMXD) and climatic factors, we discarded the BMMXD in the regional chronology (Figure 4). The growth-climate relationship between RC and climatic factors was tested by Pearson's correlation analysis and partial analysis. Based on growth-climate analyses, we calculated a transfer function by linear regression using May–August maximum temperatures in the past 154 years as the dependent variable and the RC as the independent variable. Due to the short period of the available climate series, cross verification (leave-one-out) was used to check the validity of the derived temperature reconstruction. Then we compared reconstruction and other temperature series nearby.

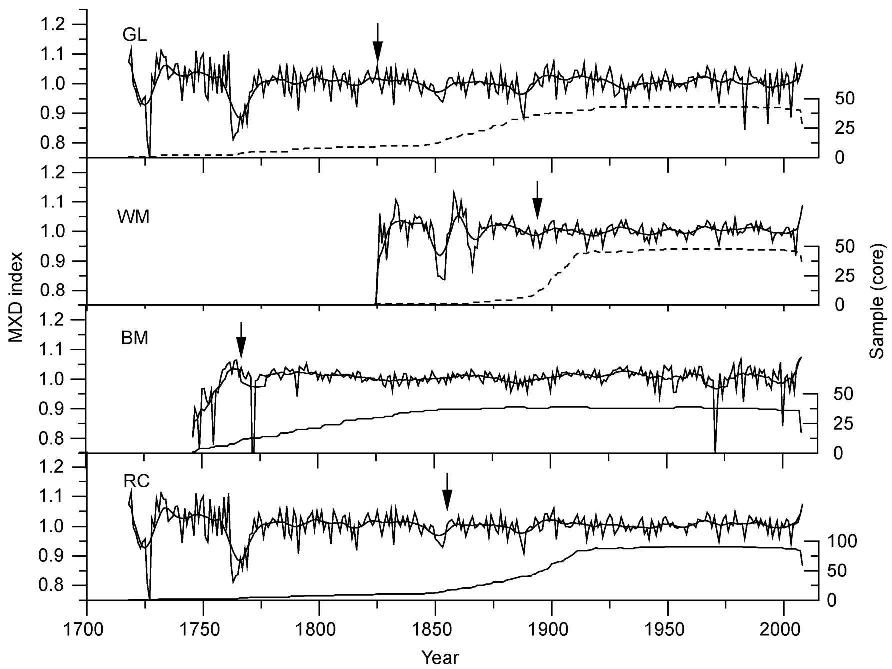

Figure 3 MXD standard chronologies from three sites (GL, WM and BM) and the regional chronology (RC) with 11-year smoothing (thick line) and sample depth. The arrows pointed out the beginning year at SSS <0.85.

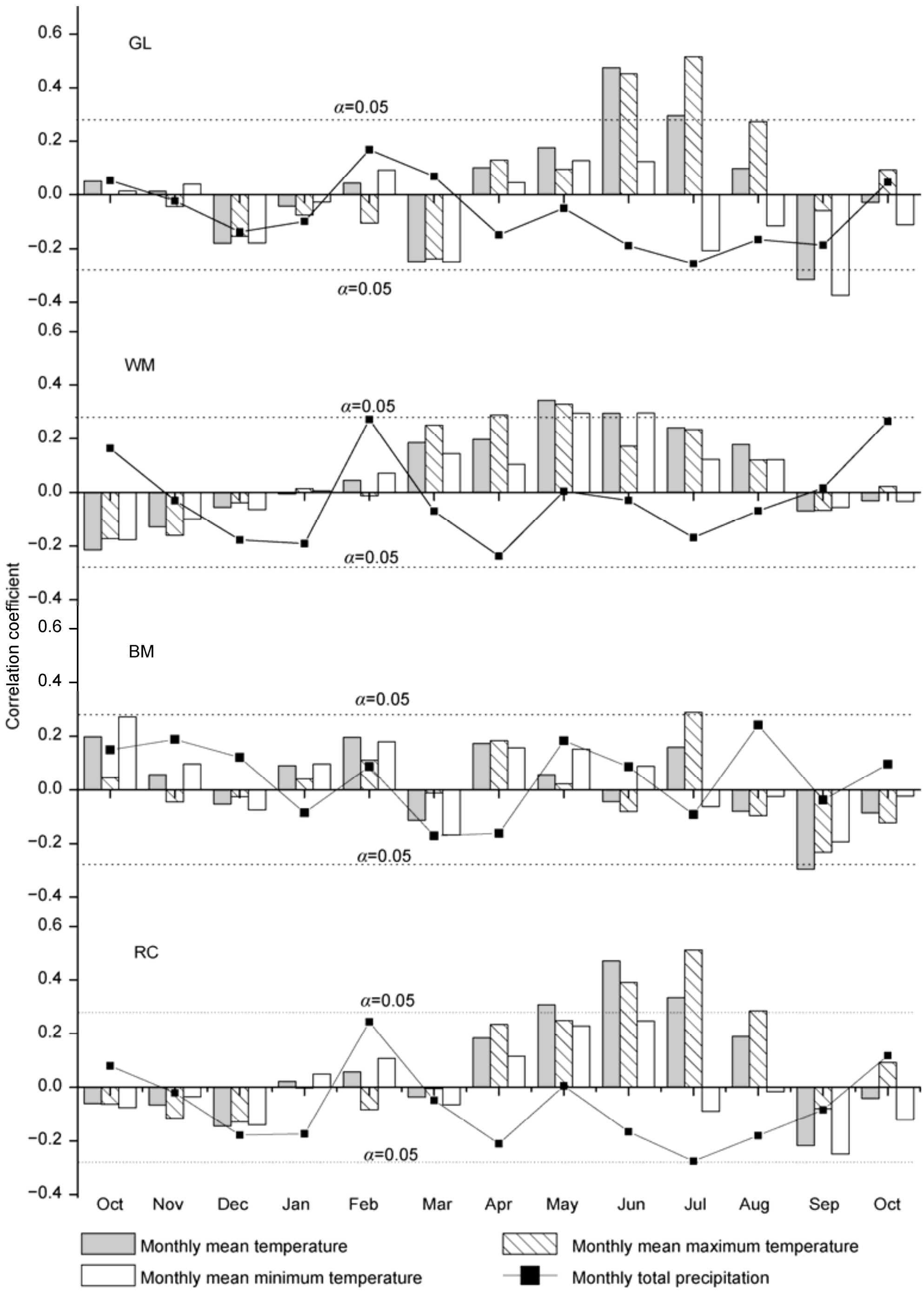

Figure 4 Pearson's correlation analysis between MXD chronologies and meteorological data in Mohe.

1.4 Wavelet analysis

We used wavelet analysis to obtain data related to the time evolution of the spectral properties of a quantity. This analysis is now becoming increasingly common in climatology [29,30]. The potential value of this method is supported by several recently published studies in the field of atmospheric sciences [31,32]. In China, this technique has been applied in several reports on precipitation [33–35] and temperature [36] analysis. An interactive program on a wavelet website (http://paos.colorado.edu/research/wavelets/) was used to calculate the oscillation cycles along with time of the reconstructed series in this study.

2 Results

Regional chronology (RC) has a significant positive correlation with most monthly temperature in the summer (Figure 4), especially with the mean maximum monthly temperature and mean monthly temperature. The correlation coefficient between RC and mean maximum temperature from May to August is much higher (at 0.01 level) than those with any other months. Although the regional chronology was significantly negatively correlated with precipitation in some months, partial correlation demonstrated that the coincident variation of MXD was probably controlled by temperature. This indicates the negative correlation between RC and precipitation may caused by the correlation between temperature and precipitation in the summer. The tree-ring maximum density of Dahurian Larch in the northern Da Hinggan Mountains seemed be directly affected by the mean maximum temperature from May to August.

Historical climate reconstruction was built by linear regression. The result of leave-one-out cross-validation shows the calibration model accounts for 39.5% (R^2_{adj}=38.3%) of total May–August temperature variance over the calibration period, 1957–2008. During this period, the correlation coefficient between RC and mean May–August temperature was 0.628 (P<0.01). The reduction error reached 0.342, and the sign test results of the first order of difference and the original were all significant ($P\leqslant0.01$). These results indicate the validity of the reconstruction [37]. As Figure 5 shows, the reconstructed temperature fits very well with the original temperature curve, except for some extraordinarily high values.

Having made an 11-year smoothing average, the reconstruction showed four cold periods (Figure 6) (1874–1893, 1927–1948, 1951–1960 and 1992–2002) and four warm periods (1855–1873, 1894–1916, 1961–1991 and 2003–2008). There were obvious rapidly alternating cold and warm periods from the middle of the 19th century to the early part of the 20th century. While a 10-year cold period occurred in the 1950s, the longest warm period lasted for 30 years from the 1960s to 1980s, then the last 10 years of the 20th century turned colder. Since the beginning of the 21st century, summer temperatures have started to rise rapidly.

As Figure 7 shows, the Morlet wavelet transform from temperature reconstruction presented different periodicities.

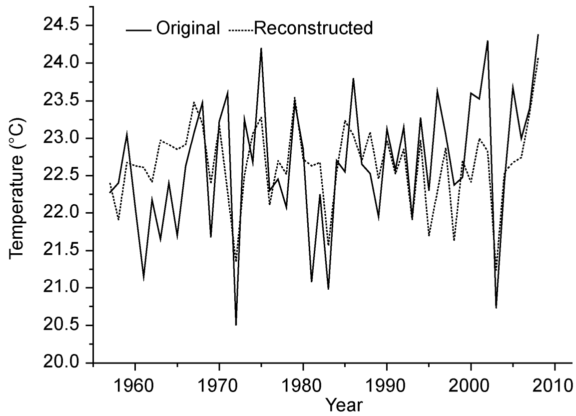

Figure 5 Comparison of the actual (black line) and reconstructed (gray line) May–August temperature.

Low-frequency cycles were not detected by wavelet analysis; instead there were high-frequency cycles of 2–8 years in this study.

3 Discussion

Near the upper treeline, the tree-ring densities appeared to be positively correlated to temperature with the maximum tree-ring density during the growing season [36,38–40]. In this study, the tree-ring maximum density of Dahurian larch near the treeline revealed a strong relationship with mean maximum temperature during May–August, which was very similar to the results of Schrenk Larch in the Tianshan Mountains at high altitudes in northwestern China [20]. From a physiological perspective, the tree cambium develops tracheids and lengthens rapidly the earlywood cells in the early growing season, representing tree-ring width sensitive to winter and spring temperatures prior to the current growing season [13,15,41]. During the later part of the growing season, radial growth of trees tends to process cell-wall thickening and nutrition accumulation. The maximum latewood density mainly depends on the latewood cell dense

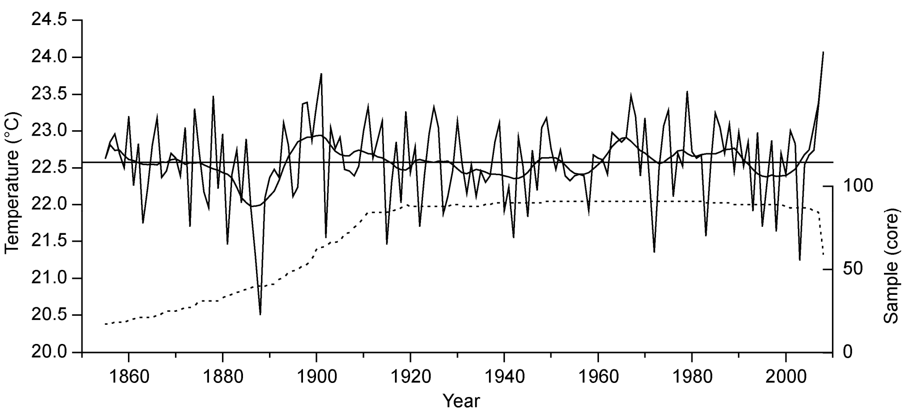

Figure 6 Reconstructed May–August temperature with 11-year smoothing (thick line) and number of samples.

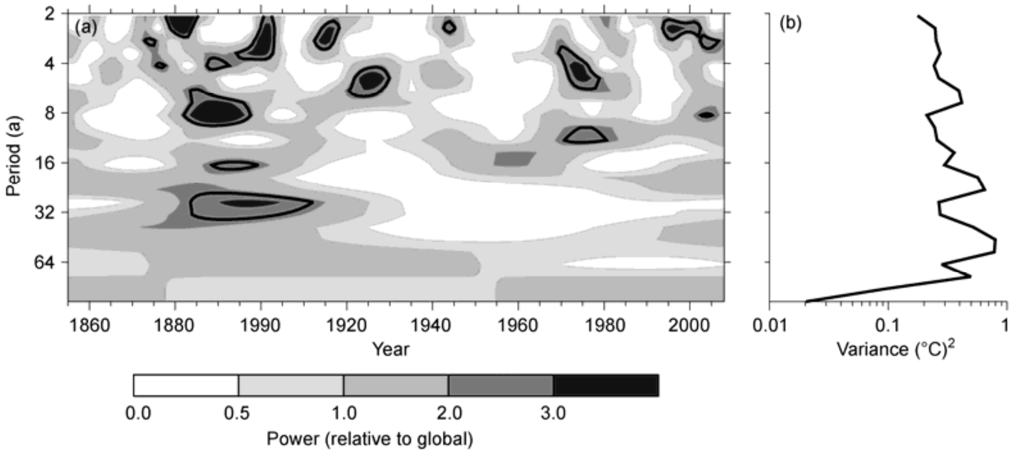

Figure 7 (a) The wavelet power spectrum. The power has been scaled by the global wavelet spectrum (right). The black contour is the 10% significance level, using the global wavelet as the background spectrum. (b) The global wavelet power spectrum.

and latewood cellwall thickness. The strong relationship between tree-ring maximum density and temperatures during the growing season indicates temperature plays an important role as a control factor on tree-ring density. Similar results have been reported in earlier studies [20,21,24]. However, the BM sampling site, located in the lower elevation larch forest, did not show a relationship between maximum tree-ring density and climate data.

The results of wavelet analysis suggest that there is no frequency oscillation with lower than decade-level periodicity in this study, which differs from an August–September temperature series reconstructed in the Tibetan Plateau [36], which had a strong 20-year oscillation during the period between 1800–1860. It might be due to the short time span of our series, starting in only 1855. Although there are similarities between the summer climates of the Tibetan Plateau and the high-altitude mountains of northeastern China [42], a considerable distance separates these two regions. One is in the inland of a continent as the third pole, impacted by south Asia and subtropical monsoons; the other is located in the far east of Eurasia, mostly influenced by the east Asian monsoon [43,44]. Further study is needed to compare the periodic regularities of the summer temperatures in these two regions.

We compared our reconstructed temperature series (XA) with the temperature series that are circumjacent our study region (see the locations in Figure 1) to test the validity of the reconstruction, as well as to investigate the characteristics of climate change in the study area. These series are: warm-season annual to decadal temperature variability inferred from maximum latewood density of Saghalin Spruce for Hokkaido, Japan (AD 1557–1990) [45]; February–April temperature reconstruction by tree-ring width of red pine for Changbai Mountain in northeastern China [15] and: a Mongolian tree-ring width series of Siberia larch and Siberia pine [46]. We took 11 a smoothing average to these four series, together with a digitalized proximal centurial annual mean temperature anomaly series in northeast China [4], to compare their various tendencies (Figure 8).

The reconstruction of the May–August mean maximum temperature series (c) in our study showed the highest correlation (r = 0.303) with series (d). The two locations are in

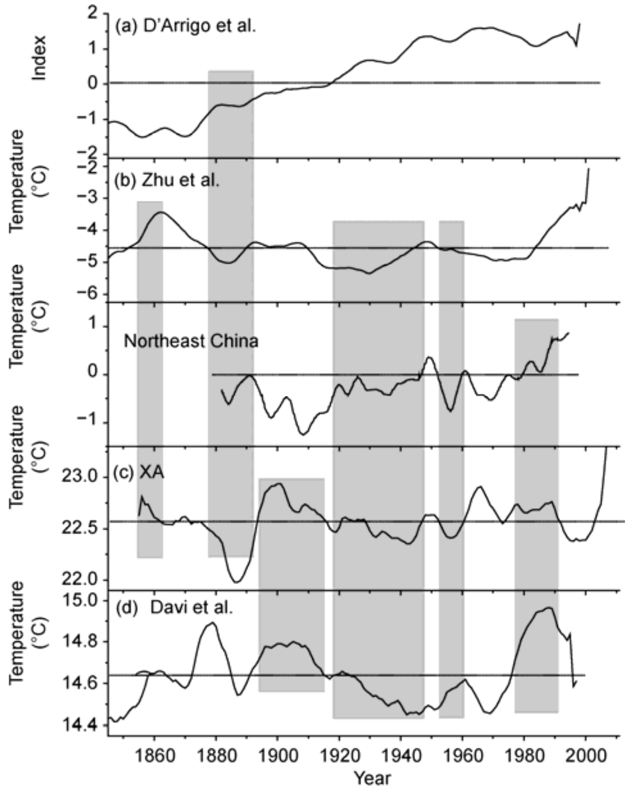

Figure 8 Graphical comparison between the August–September temperature reconstructed in this study and the other temperature records. (a) Mongolian tree-ring width series of Siberia larch and Siberia pine [46]; (b) February–April temperature reconstruction by tree-ring width of red pine for Changbai Mountain in northeastern China [15]; (c) May–August temperature reconstruction from this study; (d) April–September temperature reconstruction from maximum latewood density of Saghalin Spruce in Hokkaido, Japan [45]. The curves (a)–(d) are smoothed values with an 11-year adjacent average and the horizontal lines are the long-term means. “Northeastern China” refers to of mean annual temperature series in northeastern China [4].

the same general geographic area; these two series are both derived from maximum latewood density of tree rings and reflect spring-summer thermal variations, explaining well the coincidence of low frequency. Both series demonstrated the cold period in 1880s, and the warm interval from the end of the 19th century to the beginning of the 1920s. Also, two decades of cold climate around 1920–1940 can be seen in these chronologies, which have also recorded the later oscillation lasting about 30 years, as well as warm summer periods from the end of the 1970s to 1990s.

Series (b) employed tree-ring width to construct winter temperatures in Changbai Mountain, located in northeastern China and nearest to our study area (Figure 1), and showed a synchronized variation in climate. Both series show the warm period of the 1850s, cold time intervals around the 1870s–1890s and the 1920s, as well as the rapid rise in temperature in the beginning of 21st century. The two series show rising temperatures at the end of the chronologies, but earlier in series (b) than in series (c), indicating the temperature warming trend may have happened earlier in winter than in summer in northeastern China. The correlation coefficient between series (c) and (b) is lower (r = 0.199) than that of series (c) and (d); also the possibility exists that series (b) recorded different seasons and tree species from our study, and the proxy it used was tree-ring width chronology, which might explain the disparity.

Series (c) and (a) show a cold decade around 1880, while our reconstruction and series (a) developed a centuries thermal increasing phase, resulting in the lowest correlation (r = 0.181) with series (c). Series (a) was built on the principal component series of tree-ring width, and highly coincided with the reconstruction of the North Hemisphere temperature [47], but the cause of the visible difference between series (a) and (c) is unclear.

Our reconstruction did not exhibit an obvious warming tendency during the last decade of the 20th century [4], which may due to the difference between two series in season and spatial scales. Ding et al. [3] indicated that temperatures have had a rising trend since the 1980s, particularly in winter, but not as clearly in summer. In some regions, such as in the Liaotung Peninsula and Mohe area, summer temperatures have been even going down [17,48], which was similar to our results. In Figure 8, series (c) and (d) showed consistent summer temperatures in northeast Asia, but declined after the1990s, while series (b) revealed a strong warmer tendency in winter temperatures. Moreover, our reconstruction indicated several cold periods (1880s–1890s, 1920s–1940s, and 1950s–1960s) and a warm period (1970s–1990s) (Figure 8) which were quite similar to the temperatures in northeastern China [4]. So it can be seen, despite the different temperatures and seasons, that these two series still appeared to have coinciding variations in several time periods. This result suggests that sources for reconstructing climate data might be able to reflect similar climate tendencies using discreet data sets, and multiple proxies may be involved in evaluating temperature fluctuation for each season within a year, to study climate change at larger scales.

4 Conclusions

(1) For Dahurian Larch grown near the treeline in the northern Da Hinggan Mountains, the tree-ring maximum latewood density was controlled by summer temperature, and significantly responded positively to the variations of the mean maximum temperatures in May–August.

(2) The maximum latewood density series of Dahurian Larch reconstruct mean May–August temperatures in the northern Da Hinggan Mountains region explained 39.5% of the temperature variance. The result of wavelet analysis showed 2–8 a circulations while no longer periodicity above 10 a was found.

(3) The reconstruction was stable and appeared to show coinciding fluctuations with the chronologies surrounding our study area, which might indicate larger scale climate variations. In the past 154 years, the series indicated four cold periods (1874–1893, 1927–1948, 1951–1960, 1992–2002), and four warm periods (1855–1873, 1894–1916, 1961–1991, 2003–2008) in the northern Da Hinggan Mountains with 22 extremely warm years and 23 extremely cold years. Evidence of climate warming since the end of the 20th century mainly appeared in winter in the study area, with no obvious changes in the summer.

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