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Overcoming model instability in tree-ring-based temperature reconstructions using a multi-species method: A case study from the Changbai Mountains, northeastern China

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Abstract. The unstable sensitivity of growth-climate relationships greatly restricts tree-ring-based paleoclimate reconstructions, especially in areas with frequent "divergence" problems, such as the temperate zone in northeast China. Here, we propose an original tree-species mixing method to overcome this obstacle and improve the stability and reliability of reconstruction models. We take the tree-ring based growing-season minimum temperature reconstruction for the northern Changbai Mountains in northeast China as an example to illustrate the method. Compared with previous temperature reconstruction models, our reconstruction model is more stable and reliable and explains up to 68% of the variance. It is also highly consistent with historical records and tree-ring-based temperature reconstructions from the nearby Xiaoxing'an Mountains and from across the Northern Hemisphere. Our reconstruction uses two different tree species and is more accurate than temperature reconstructions developed from a single species. Over the past 259 years (AD 1757-2015), five significant cold periods and five warm periods were identified. The reconstruction indicates rapid warming since the 1980s, which is consistent with other instrumental and reconstructed records. We also found the Atlantic Multidecadal Oscillation plays a crucial role in driving the growing-season minimum temperature in the northern Changbai Mountains.

1 Introduction

Global climates are changing rapidly, with unexpected consequences; in fact, climate change is a major threat to ecosystems and societies in many parts of the world (IPCC, 2018;Allen et al., 2010;Liu et al., 2013). Understanding and quantifying the characteristics, patterns, and driving mechanisms of past climate changes is essential to reducing the uncertainty in predicting future

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Climate of the Past Discussions

climates (Fritts, 1976;Zhu et al., 2020a). However, the lack of long-term instrumental climate data severely limits our ability to understand past climates; for this reason, long climate proxy records are urgently needed.

Tree rings, especially ring widths, are a critically important paleoclimate proxy (Fritts, 1976) and are widely used for reconstructing climate at a high resolution over hundreds to thousands of years (Anchukaitis et al., 2017;Wilson et al., 2016). Such records are invaluable for placing recent climatic changes in a long-term context, which can help considerably with planning appropriate responses to future climate changes and extreme events. However, the statistical calibration and verification of tree-ring based reconstructions is a rigorous process (Fritts, 1976) that requires a relatively stable growth-climate relationship over time.

Over the last several decades, many studies have addressed the "divergence problem", an anomalous reduction in tree-ring indices and temperature sensitivity after rapid warming (D'Arrigo et al., 2008). Other studies have found an increased correlation between tree-ring indices and temperature after rapid warming, such as in the case of *Fraxinus mandshurica* (FM) (Cao et al., 2018) and *Larix gmelinii* (Zhang et al., 2016) in northeastern China. These two types of "unstable sensitivity" in growth-climate relationships challenge the assumption of "uniformity principle" in dendroclimatology (Fritts, 1976), and thus brings more uncertainties in tree-ring-based inferences on past climate.

The Changbai Mountains are the highest in eastern Eurasia, covering nearly 2,000 square kilometers. Climate changes in the region significantly affect human social-economic activities and ecosystem health. A number of tree-ring-based reconstructions have been carried out in the region in the past two decades (Zhu et al., 2009;Shao and Wu, 1997;Lyu et al., 2016;Zhang et al., 2007;Wang et al., 2012;Yu, 2019). These studies have looked at the tree-ring widths of *Pinus koraiensis* (Zhu et al., 2009;Shao and Wu, 1997;Lyu et al., 2016) and *F. mandshurica* (Zhang et al., 2007;Wang et al., 2012;Yu, 2019). However, some other studies report an evident unstable sensitivity in the growth-climate relationships of *Pinus koraiensis* and *F. mandshurica*'s both before and after warming (Cao et al., 2018;Zhu et al., 2020b). These two species typify the two types of unstable growth-climate (temperature) relationships (*P. koraiensis*: reduced sensitivity and *F. mandshurica*: increased sensitivity) in temperate forests, northeastern China (Cao et al., 2018;Zhu et al., 2015b;Zhu et al., 2020b;Wang et al., 2016). For this reason, climate reconstructions that are based on only one species' tree-ring data may be biased toward that species' specific response to climate (Lyu et al., 2016;Wang et al., 2012).

In this study, we propose a hypothesize that the accuracy of reconstruction in areas with frequent "unstable sensitivity" problems can be improved through mixing two species typifying the two types of unstable growth-climate (temperature) relationships. The Changbai Mountains are especially prone to the unstable sensitivity in growth-climate relationships due to rapid warming (Cao et al., 2018;Zhu et al., 2020b;Zhu et al., 2018a). Hence, we use trees from the Changbai Mountains as an example by compositing tree-ring

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data from species experiencing different types of unstable sensitivity. We aim to (1) develop a new tree-ring-based temperature reconstruction for the Changbai Mountains by a mixing multi-species method; (2) verify and compare its accuracy and consistency with other temperature records; (3) identify the patterns of past temperature changes and possible large-scale driving mechanisms.

2 Materials and methods

2.1 Study area

The study area is located in the northern part of the Changbai Mountains (Fig. 1). It is characterized by a temperate continental monsoon climate with four distinct seasons. Based on climate data (http://data.cma.cn/) from the Songjiang and Dunhua meteorological stations, the average annual temperature in the study area ranges from 1.3 °C to 4.85 °C. January (-17.08 °C) and July (20.13 °C) are the coldest and warmest months, respectively (Fig. 2). The mean annual total precipitation is 652 mm (335-734 mm), and 87.05% of the annual precipitation falls during the growing season (April to September) (Fig. 2). Over the past 60 years, the average minimum temperature has increased significantly ($p < 0.01$) at a rate of 0.06 ºC per year. There has been no significant change in the total annual precipitation (Fig. 2a-c).

We carried out our study in the lower and middle elevation areas (700-1100 m a.s.l.) of the northern Changbai Mountains. All sampling sites are characterized by typical broadleaf-Korean pine mixed forests with little human disturbance. Such forests represent the zonal climax vegetation type of the temperate regions in northeastern China. The main tree species include *P. koraiensis*, *Abies nephrolepis*, *Picea jezoensis* var. *microsperma*, *F. mandshurica*, *Phellodendron amurense*, *Juglans mandshurica*, *Tilia amurensis*, *Betula costata*, *Quercus mongolica*, and *Ulmus japonica*. The soils are mainly dark-brown forest soil.

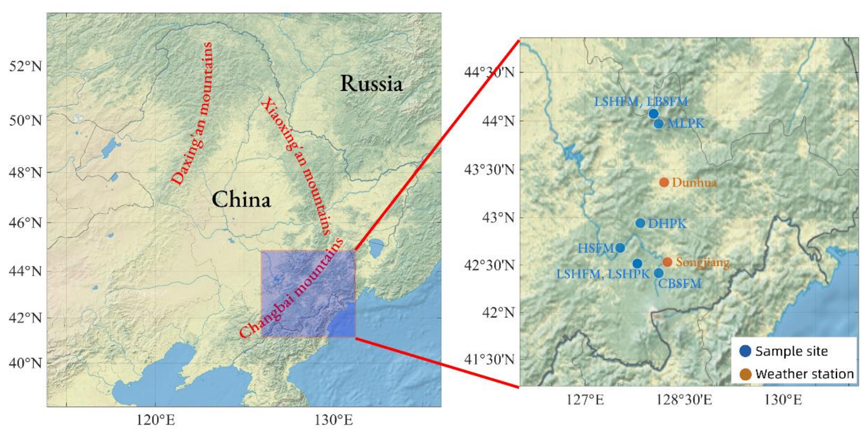

Figure 1. Map showing the distribution of sampling sites and weather stations in the study. This figure was drawn by MATLAB R2017b software (The MathWorks, Inc.). The basemap, presented with a light, natural palette, overlaid with the boundary line, combines satellite-

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derived land cover data, shaded relief, and ocean-bottom relief made with Natural Earth. MathWorks® offers the basemap with geographic axes and charts.

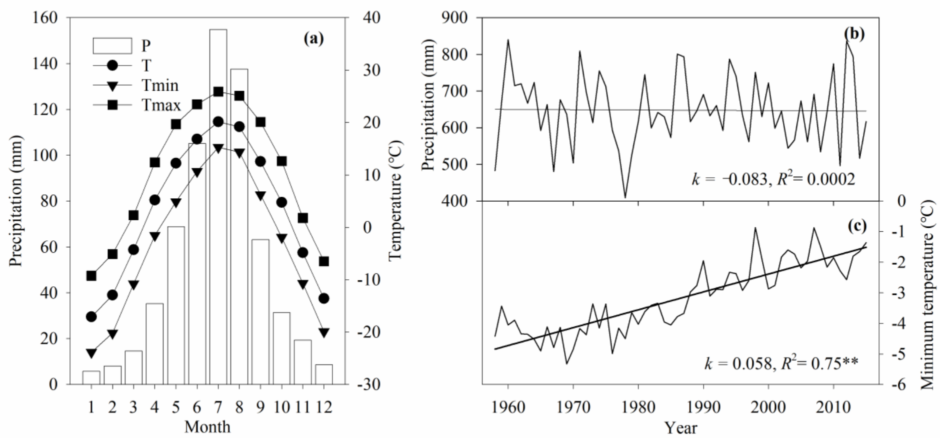

Figure 2. Monthly distribution and inter-annual variability of climate variables in the northern Changbai Mountains. (a) Mean (T), minimum (T_{min}), and maximum (T_{max}) temperature and the monthly distribution of total precipitation (P). The inter-annual variability of (b) total precipitation and (c) minimum temperature. The climate data for the period 1958-2016 were averaged using records from the Songjiang (42.533° N, 128.25° E, 525 m a.s.l.) and Dunhua (43.367° N, 128.2° E, 591 m a.s.l.) meteorological stations.

2.2 Tree-ring data

From May to August in 2012, 2014, and 2016, at least one core per tree was extracted at breast height (1.3 m) from both *P. koraiensis* and *F. mandshurica* trees at six forest sites in the Changbai Mountain using 5.15-mm increment borers. A total of 433 cores from 259 trees were used in this study (Table S1).

All tree-ring cores were mounted, dried, and progressively surfaced in the laboratory until individual cells within annual rings were visible under a dissecting microscope. The cores were then visually cross-dated using the skeleton plot method to identify absent or false rings (Fritts, 1976;Stokes and Smiley, 1968). Ring widths were measured to a precision of 0.001 mm using the Velmex Tree-ring Measurement System (Velmex, Bloomfield, NY, USA). The COFECHA program was used to check the quality of cross-dating and measurement (Holmes, 1983). Conservative negative exponential curves or linear regression curves of any slope were used to remove age-related growth trends. Tree-ring chronologies were developed using the R package 'dplR' (Bunn, 2008). The inter-series correlation (R_{bar}) and expressed population signal (EPS) were used to control the quality of the chronologies (Table S1) (Wigley et al., 1984).

2.3 Climate data and other records

Instrumental climate data, including monthly total precipitation and mean, minimum, and maximum temperature, were obtained for

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the Songjiang and Dunhua meteorological stations from the China Meteorological Data Service Center (http://data.cma.cn/). The distance between the eight sampling sites and its nearest weather station is between 20 and 80 km. The regional climate during the growing season (April to September) was calculated by taking the arithmetic average of the data from the two weather stations (Fig. 2).

The actual (Enfield et al., 2001) and reconstructed (Mann et al., 2009;Gray, 2004) Atlantic Multidecadal Oscillation (AMO) index was downloaded from http://climexp.knmi.nl/ and https://www.ncdc.noaa.gov/paleo-search/study/6324. All reference tree-ring-based temperature sequences used in this study were requested from the authors of the relevant studies.

2.4 Statistical analyses and model verification

Pearson correlation and moving correlation methods were used to check the relationships between the chronologies. Correlation analysis was used to identify the relationship between the tree-ring chronology and regional monthly or seasonal climate records. A simple linear regression model was used to reconstruct the growing-season minimum temperature for the northern Changbai Mountains. A traditional split-period calibration-verification method was used to test the regression model's goodness-of-fit (stability and reliability) (Fritts, 1976).

Statistical parameters including the correlation coefficient (R), explained variance (R^2), reduction of error (RE), coefficient of efficiency (CE) and sign test (ST) were used to verify the model. RE indicates whether a reconstruction provides a better estimate of climate variability than simply using the mean value of the target climate in the calibration period. CE is similar to RE, but it tests reconstruction skill against the mean value of the target climate in the verification period. RE and CE are rigorous verification statistics; any positive RE and CE values indicate sufficient similarity between the estimated and actual sequences. Thus, positive RE and CE values indicate that the model has a considerable predictive skill (Fritts, 1976). The ST was used to test the coherency between the actual and estimated series by calculating the coherence and incoherence (Fritts, 1976).

To explore our reconstruction's spatial representativeness, we performed a spatial correlation between the actual and estimated growing-season minimum temperature and the April-September gridded (0.5°×0.5°) CRU TS4.04 minimum temperature for the period 1958-2015 using the KNMI Climate Explorer (http://climexp.knmi/nl). We defined warm (cold) periods as periods of at least two consecutive years during which the 10-year low-pass filtered temperature value was greater than (less than) high than the average (a) plus (minus) 0.5 times the standard deviation (δ) (8.3 °C for warm periods, 7.7 °C for cold periods). We used the multi-taper method of spectral analysis to identify the periodicity of temperature variability (Mann and Lees, 1996). This method is especially suitable for diagnosing and analyzing weak signals and has been widely used to analyze paleoclimate signals (Liu et al.,

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2019).

To better ascertain the accuracy of our temperature reconstruction and its consistency with regional records, we compared it with nearby temperature records and local historical documents. We used direct comparisons of curve trends and Pearson correlations to evaluate the consistency of our growing-season minimum temperature reconstruction and nearby tree-ring based temperature reconstructions. A 10-year low-pass loess filtering method was used to highlight the low-frequency signals of temperature records and the actual (Enfield et al., 2001) and reconstructed Atlantic Multi-decadal Oscillation (AMO) data. Z-scores were used to normalize the temperature records and ensure that they were kept at the same scale. Pearson correlation was used to evaluate the relationship between our temperature reconstruction and the AMO index. To further verify the influence of the AMO on local temperature, we conducted a spatial correlation between our temperature reconstruction and global gridded sea surface temperatures (SST) (HadISST1 SST dataset, 1°×1°, 1870-2015) using the KNMI Climate Explorer (http://climexp.knmi/nl). The 20th century reanalysis data were used to produce composite maps of the 500-mb vector wind and air temperature from April to September. These maps were then used to explore the linkages between temperature and atmospheric circulation patterns in the Northern Hemisphere.

3 Results

3.1 Consistency of tree growth and its response to climate

For both *P. koraiensis* and *F. mandshurica*, significant correlations exist among all site chronologies over their common period of 1855-2011 (Table S2). Significant correlations between *P. koraiensis* and *F. mandshurica* chronologies, however, only exist for some sites. The mixed-species regional chronology (ALL, in Table S2) correlates significantly with each site chronology and each combined species chronology (Table S2).

Growing-season minimum temperature strongly affects the growth of both *P. koraiensis* and *F. mandshurica* in Changbai Mountains. Most sites' tree-ring indices correlate significantly ($p < 0.05$) with April, May, June, July, August, and September minimum temperatures (Table 1). The radial growth of *P. koraiensis* and *F. mandshurica* at all sites is positively correlated with the mean growing-season (April-September) minimum temperature. The three combined chronologies (PK, FM, and ALL in Table 1) are all significantly correlated with growing-season minimum temperature; the highest positive correlation is found between the mixed-species regional chronology (ALL) and the growing-season minimum temperature ($R = 0.824$, $p < 0.001$).

However, there is a differential temporal instability in the growth-climate relationship between *P. koraiensis* and *F. mandshurica.* For the combined *P. koraiensis* chronology (PK), there is a stronger positive correlation with the growing-season minimum temperature

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during the period 1958-1986 than the period 1987-2015. For the combined *F. mandshurica* chronology (FM), the correlation is stronger during the second period than the first. However, the mixed-species regional chronology (ALL) shows significant correlations in both the first and second periods (Table 1 & Fig. 3).

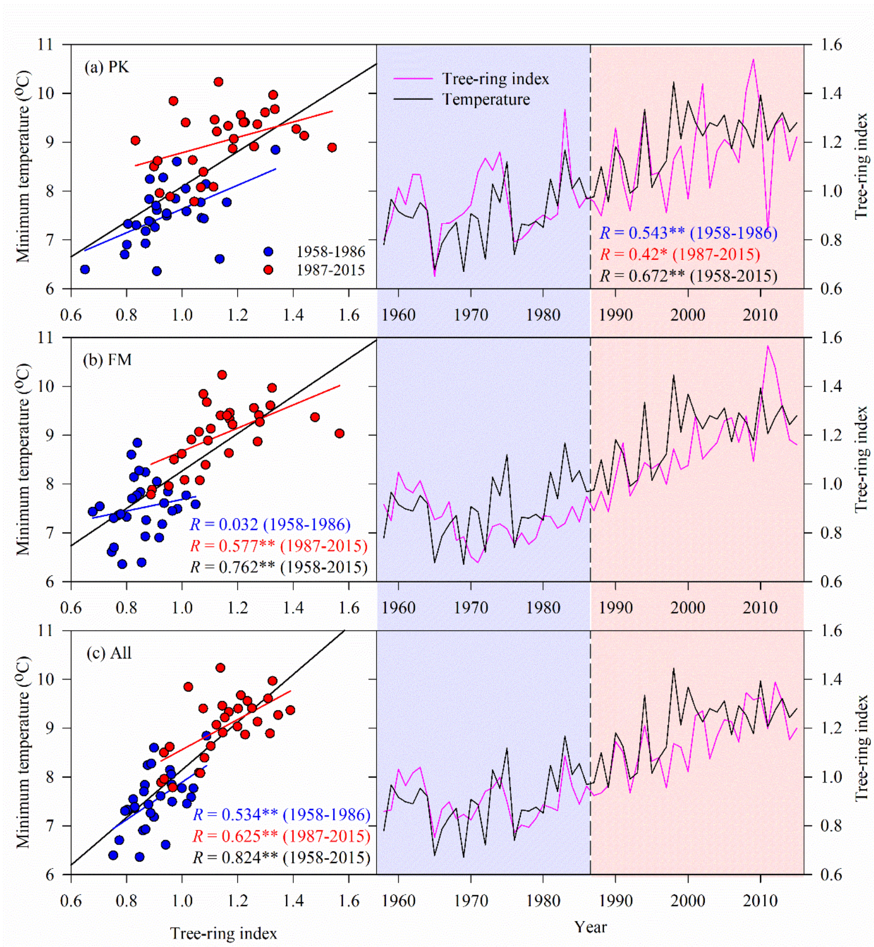

Figure 3. Correlation relationships between the growing-season minimum temperature and the combined *P. koraiensis* (PK), the combined *F. mandshurica* chronology (FM), and mixed-species regional chronologies (ALL) during the first part of the chronology (1958-1986) and second part (1987-2015).

Table 1. Correlations between the site and regional chronologies and regional minimum temperature during the growing season (current April to current September).

	Apr	May	Jun	Jul	Aug	Sep	Apr-Sep
DHPK (*n* = 54)	**0.59****	**0.48****	0.22	**0.28***	0.08	**0.51****	**0.51****
LBSPK (*n* = 58)	**0.58****	**0.66****	**0.65****	**0.53****	0.22	**0.54****	**0.73****
LSHPK (*n* = 57)	**0.34****	0.25	0.19	0.23	0.12	**0.40****	**0.36****
MLPK (*n* = 58)	**0.31***	**0.41****	**0.35****	**0.39****	**0.37****	**0.42****	**0.51****
CBSFM (*n* = 56)	**0.43****	**0.65****	**0.63****	**0.48****	**0.46****	**0.54****	**0.73****

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HSFM (n = 57)	**0.56****	**0.71****	**0.72****	**0.50****	**0.46****	**0.57****	**0.81****
LBSFM (n = 58)	**0.37****	**0.52****	**0.60****	**0.53****	**0.40****	**0.48****	**0.66****
LSHFM (n = 57)	**0.36****	**0.55****	**0.53****	**0.43****	**0.41****	**0.48****	**0.63****
PK (n = 58)	**0.58****	**0.58****	**0.46****	**0.45****	**0.25**	**0.59****	**0.67****
FM (n = 58)	**0.47****	**0.66****	**0.67****	**0.52****	**0.46****	**0.55****	**0.76****
ALL (n = 58)	**0.60****	**0.71****	**0.65****	**0.56****	**0.41****	**0.66****	**0.82****

Notes: * = $p < 0.05$, ** = $p < 0.01$. Tree-ring indices of combined *P. koraiensis* (PK), combined *F. mandshurica* (FM), and mixed species (ALL) were calculated using a simple arithmetic average.

3.2 Tree-ring-based minimum temperature reconstruction

We attempted to reconstruct the growing-season minimum temperature for the northern Changbai Mountains based on the FM, PK, and ALL chronologies using a linear regression model. Neither the FM nor the PK chronology is suitable for the reconstruction due to negative CE and insignificant ST tests (Table 2). However, the ALL chronology combined with the FM and PK chronologies passes the model test. The model equation is the following:

$$T_t = 4.881 * I_t + 3.268, (R = 0.824, N = 57, F = 118.74, p < 0.0001) \quad (1)$$

where the T_t and I_t are the growing-season minimum temperature and regional tree-ring index at the year t, respectively.

Table 2. Calibration and verification statistics for the growing-season mean temperature reconstruction.

	Calibration	*R*	Verification	R^2	RE	CE	ST
PK	1958-2015	0.67**	—	0.45**	0.45	—	(42, 16)**
	1987-2015	0.42*	1958-1986	0.30**	0.84	**-0.22**	**(20, 9)**
	1958-1986	0.54**	1987-2014	0.18*	0.77	**-0.50**	**(20, 9)**
FM	1958-2015	0.76**	—	0.58**	0.58	—	(49, 9)**
	1987-2015	0.58**	1958-1986	**0.03**	0.83	**-0.23**	**(16, 13)**
	1958-1986	**0.18**	1987-2014	0.33**	0.87	0.12	(23, 6)**
ALL	1958-2015	0.82**	—	0.68**	0.67	—	(49, 9)**
	1987-2015	0.63**	1958-1986	0.29**	0.89	0.20	(21, 8)*
	1958-1986	0.53**	1987-2014	0.39**	0.88	0.20	(22, 7)**

Notes: Statistical parameters that are not significant or that failed the verification test are highlighted in bold. * = $p < 0.05$, ** = $p < 0.01$.

The model explains 68% of the temperature variation. A similar or parallel trend is found between the reconstructed and observed growing-season minimum temperatures ($R^2 = 0.68$, $p < 0.01$) and between their first-order differences ($R^2 = 0.13$, $p < 0.01$) during the calibration period from 1958 to 2015 (Fig. 4a & 4b). A significant spatial correlation pattern is found between the actual and reconstructed growing-season minimum temperature and the gridded (0.5°×0.5°) April-September averaged CRU TS4.04 minimum

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temperature over northeast Asia (Fig. S3). The positive RE and CE in the verification periods (Table 2) indicate that our reconstruction model has a robust skill and acceptable reliability in estimating the growing-season temperature (Fritts, 1976). The R^2 and ST statistics are all significant at the 95% or 99% confidence levels, which indicates that our model is stable and reliable in the two calibration periods (Table 2).

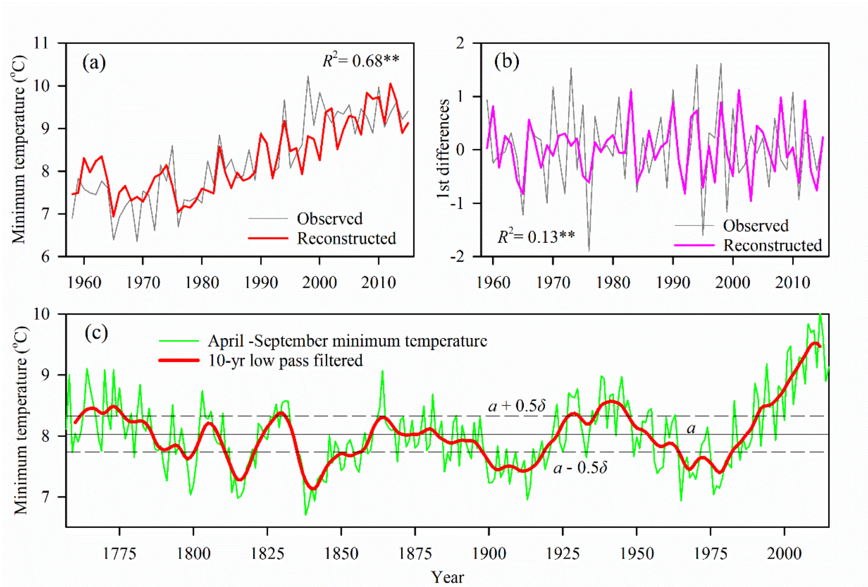

Figure 4. Minimum temperature reconstruction for the northern Changbai Mountains, northeastern China. (a) Comparisons between reconstructed and observed April-September minimum temperature during the calibration period 1958-2015. (b) Comparisons between the first-order differences of reconstructed and observed April-September minimum temperatures for the period 1959-2014. (c) April-September minimum temperatures for the northern Changbai Mountains from 1757 to 2015 (cyan line) with a 10-year low-pass filter (red line). The α and δ indicate the average (8.03) and standard deviation (0.59) values of the minimum temperature during the whole span, respectively.

3.3 Growing season temperature variations

In the northern Changbai Mountains, the growing-season minimum temperature has a high interannual and decadal variance with a mean (a) of 8.03 and a standard deviation (δ) of ±0.59 during the past 259 years (Fig. 4c). The record contains five warm periods (1762-1776, 1828-1831, 1927-1930, 1936-1947, and 1991-2012) and five cold periods (1797-1800, 1811-1820, 1836-1856, 1898-1918, and 1956-1982) (Table 3). The periods 1991-2012 and 1836-1856 are the most prolonged and most severe warm and cold periods, respectively. Most cold years/periods occur during the 19th century, and most warm years/periods occur during the 20th century. There is a clear rapid warming trend after the 1980s. The top ten warmest and coldest years are listed in Table 3. Spectral analysis of the full reconstruction (1757-2015) reveals significant (p <0.01) annual cycle peaks at 2.7, 3, and 3.5 years, and decadal cycle peaks at 59.6

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and 78.4 years (Fig. 5).

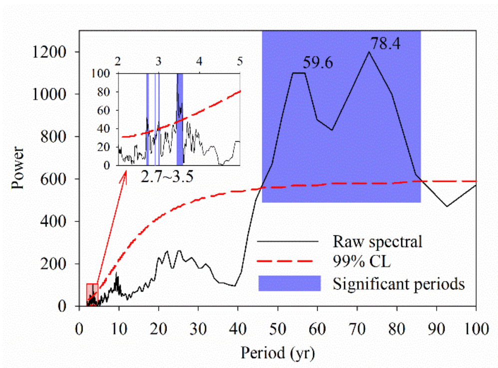

Figure 5. Multi-taper power spectra for the growing-season minimum temperatures from AD 1757 to 2015 in the northern Changbai Mountains. The 99% confidence level relative to red noise is shown by the dashed red line. The lengths of the sig nificant cycles are indicated in the figure.

Table 3. The top 10 most extreme warm/cold years and extreme warm/cold periods in the northern Changbai Mountains.

Warm/Cold years					Warm/Cold periods			
Rank	Cold	Tmin	Warm	Tmin	Period	Duration	Mean	Warm/Cold
1	1838	6.71	2012	10.05	1762-1776	15	8.47	Warm
2	1839	6.88	2008	9.83	1797-1800	4	7.38	Cold
3	1841	6.93	2010	9.74	1811-1820	10	7.39	Cold
4	1965	6.94	2009	9.69	1828-1831	4	8.44	Warm
5	1913	6.96	2013	9.66	1836-1856	21	7.46	Cold
6	1815	6.98	2002	9.47	1898-1918	21	7.50	Cold
7	1816	7.01	2001	9.37	1927-1930	4	8.69	Warm
8	1799	7.03	2005	9.30	1936-1947	12	8.55	Warm
9	1976	7.04	2006	9.26	1956-1982	18	7.47	Cold
10	1813	7.07	1994	9.18	1991-2012	22	8.90	Warm

4 Discussion

4.1 Climate-growth relationships and their stability

We found that the radial growth of *P. koraiensis* and *F. mandshurica* is significantly positively correlated with growing-season minimum temperature. This result is consistent with those of other dendrochronological studies of *P. koraiensis* (Zhu et al., 2009;Shao and Wu, 1997) and *F. mandshurica* (Zhu et al., 2015a;Li and Wang, 2013;Zhu et al., 2020b) in northeastern China, and of other species at high latitudes in the Northern Hemisphere (Zhu et al., 2020b;Anchukaitis et al., 2017;Wilson et al., 2016). High growing-season

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minimum temperatures are often accompanied by a long growing-season and a high photosynthetic efficiency, which results in wider rings (Fritts, 1976). In contrast, trees tend to form narrow rings in years with low growing-season minimum temperatures.

As previous studies have shown, *P. koraiensis* and *F. mandshurica* show contrasting response patterns to rapid warming (Cao et al., 2018;Zhu et al., 2015b;Zhu et al., 2020b;Wang et al., 2016). In the case of *P. koraiensis*, temperature sensitivity is slightly weakened after warming (Zhu et al., 2015b). This divergence phenomenon has been reported by many studies, especially in northern forests (D'Arrigo et al., 2008;Zhu et al., 2018a). Although many previous tree-ring studies from the surrounding area have suggested that this divergence phenomenon is associated with temperature-induced drought stress (Zhu et al., 2018a;Zhu et al., 2015b), the exact causes are still unknown. Other possible causes include nonlinear thresholds or time-dependent responses to rapid warming, the delayed snowmelt and related changes in seasonality, the differential growth-climate relationships inferred for mean, maximum, and minimum temperatures, and global dimming (D'Arrigo et al., 2008).

Unlike *P. koraiensis,* the growth of *F. mandshurica* has been significantly enhanced by warming, a result that is consistent those of other studies of *F. mandshurica* in northeastern China (Cao et al., 2018;Zhu et al., 2020b). The reasons for this enhancement are still not clear. Zhang et al. (2016) pointed out that the radial growth of *Larix gmelinii* is more sensitive to temperature after rapid warming because of changes in the moisture availability caused by the permafrost thaw. Previous studies have shown that drought stress in early spring is a key factor limiting vessel formation and tree growth (Zhu et al., 2020b). The enhanced temperature sensitivity of *F. mandshurica* is likely related to the temporal coincidence between cambial activity and snowmelt and related changes in seasonality.

The unstable sensitivity of *P. koraiensis* or *F. mandshurica* to temperature (Fig. 3) has been proved widespread in northeast China (Cao et al., 2018;Zhu et al., 2015b;Zhu et al., 2020b;Wang et al., 2016). Hence, previous temperature reconstructions based only on tree-ring widths of *P. koraiensis* (Zhu et al., 2009;Shao and Wu, 1997;Lyu et al., 2016) or *F. mandshurica* (Zhang et al., 2007;Wang et al., 2012;Yu, 2019) may have some uncertainty. Our results confirmed that the unstable sensitivity of *P. koraiensis* or *F. mandshurica* to temperature before and after warming hindered the possibility of paleoclimate reconstruction based on single species tree-ring data. Both two reconstruction models based on the combined *P. koraiensis* and combined *F. mandshurica* chronologies do not pass the model test (Table 2). However, the opposite patterns in temperature sensitivity of *P. koraiensis* and *F. mandshurica* make it possible to improve the performance of tree-ring-based temperature reconstruction by multiple tree species (Table 2).

4.2 Higher quality of our reconstruction and its comparison with regional records

In general, our reconstruction reflects warm/cold patterns that have been observed in other temperature records (Fig. 6) and local historical documents (Wen, 2008) from northeastern China. This suggests that similar processes control temperatures across northeast

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China. Spatial field correlations between our reconstructed temperature and the gridded 0.5°×0.5° growing-season temperatures are significant ($p < 0.05$) across much of northeast Asia (Fig. S3). Compared with the existing reconstructed temperatures for the Changbai Mountains, our reconstruction is more consistent with reconstructed temperatures from the nearby Xiaoxing'an Mountains of northeast China (XXA, Zhu et al. (2015a)) and from the extratropical Northern Hemisphere (NH, Wilson et al. (2007)) at low- and high-frequency scales (Fig. 6e-f). Common cold/warm periods and similar fluctuation patterns during the past two centuries indicate that our reconstruction is accurate and reliable.

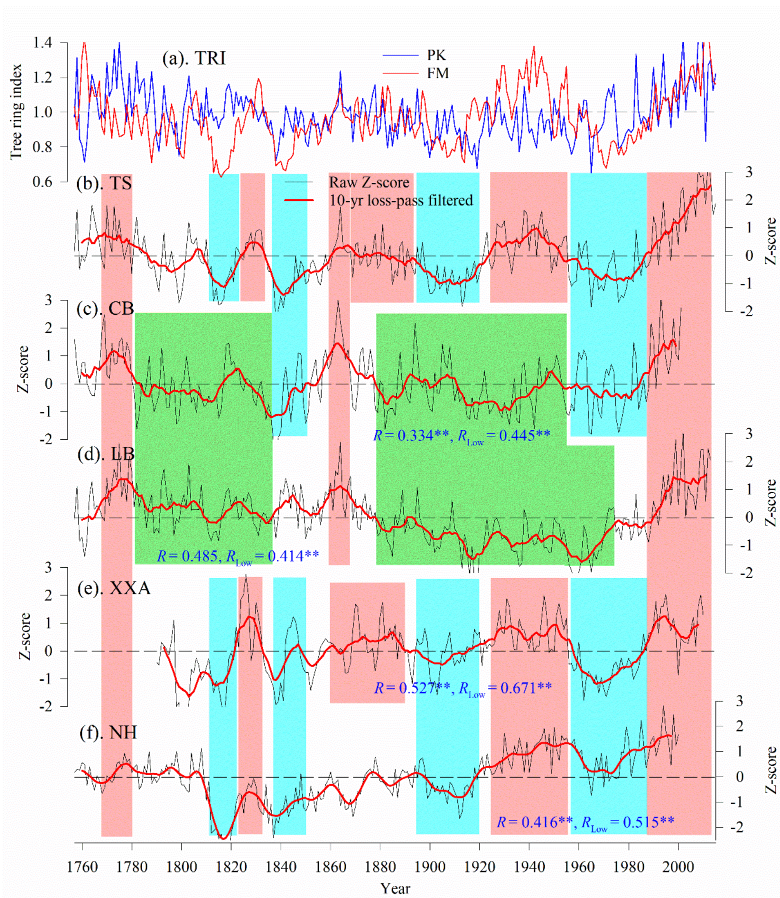

Figure 6. Comparison of temperature records in northeastern China and the extratropical Northern Hemisphere. (a) The tree-ring index (TRI) of combined *P. koraiensis* (PK) and combined *F. mandshurica* (FM) in the northern Changbai Mountains. (b) The April-September minimum temperature reconstruction in the northern Changbai Mountains in this study (TS). (c) The February-April mean temperature reconstruction for the Changbai (CB) Mountains by Zhu et al., (2009). (d) The April-July minimum temperature reconstruction for the Laobai (LB) Mountains by Lyu et al., (2017). (e) The February-March minimum temperature reconstruction for the Xiaoxing'an (XXA) Mountains by Zhu et al., (2015). (e) The extratropical Northern Hemisphere (NH) temperature reconstruction by Wilson et al., (2007). All of the above series were standardized using Z-scores; low-pass filtration was then carried out using a 10-year loess filter. Blue (cold) and red (warm) shading indicate periods with good temperature consistency across reconstructions. The periods that are inconsistent with our

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reconstruction are highlighted in green.

A significant positive correlation was found between our reconstruction and the February-April mean temperature (CB, Zhu et al. (2009)) and April-July minimum temperature (LB, Lyu et al. (2016)) in the Changbai Mountains at low and high frequencies (Fig. 6c-d). Although the three records display highly synchronous variations, there are several notable differences. The most obvious differences occur in the years of 1800-1850 and 1870-1950, especially at low frequencies (Fig. 6a-d). These differences may be due to the reconstruction bias of using a single species. The two temperature records (CB and LB in Fig. 6) in Changbai Mountains were both based on tree-ring widths of *P. koraiensis* (Zhu et al., 2009;Lyu et al., 2016), which is known to have an unstable growth-climate relationship (Zhu et al., 2015b). There are two temperature records based on the ring widths of *F. mandshurica* for the Changbai Mountains (Yu, 2019;Wang et al., 2012), but we were unable to access these records. Nevertheless, a visual comparison of our reconstruction and the two temperature sequences indicates some differences (Yu, 2019;Wang et al., 2012).

In general, our mixed-species temperature reconstruction shows absolute advantages, with higher accuracy and reliability than previous temperature reconstructions that use only one species (*P. koraiensis* or *F. mandshurica*). This ingenious tree species mixing method significantly improves the model stability and reliability. It provides a valuable reference for tree-ring-based paleoclimate reconstructions in areas with unstable growth-climate relationships.

4.3 Linkages to the Atlantic Multidecadal Oscillation

The Atlantic Multidecadal Oscillation (AMO) has been shown to play a key role in influencing global climate (Knight et al., 2006), especially in North America (Nigam et al., 2011;Oglesby et al., 2012;Gan et al., 2019) and Europe (Vicente-Serrano and López-Moreno, 2008;Brgel et al., 2020). In this study, we found that the AMO has a strong effect on the growing-season minimum temperature in the northern Changbai Mountains, which is in line with previous tree-ring-based temperature reconstructions in northeastern China (Zhu et al., 2015a;Zhu et al., 2017;Li and Wang, 2013;Lyu et al., 2016). Temperature in the northern Changbai Mountains fluctuates on 59.6- and 78.4-year cycles, which is consistent with the 60-80-year cycle (AMO) of the North Atlantic SST anomalies (Gray, 2004) (Fig. 7). We found strong and significant spatial correlations between our reconstructed temperature and the SST anomalies over the Atlantic Ocean (Fig. 7a), and between the actual AMO index and the April-September land surface CRU TS4.04 minimum temperature in the Changbai Mountains (Fig. 7b). These correlations reveal a potential linkage between the AMO and the temperature in the northern Changbai Mountains. Similar significant (p<0.01) and positive correlations exist between the temperature reconstruction for the northern Changbai Mountains and the actual (annual: R=0.378, decadal: R=0.7) (Enfield et al., 2001) and reconstructed (Gray: annual: R=0.285, decadal: R=0.494; Mann: decadal: R=0.643) (Mann et al., 2009;Gray, 2004) AMO

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indices at both annual and decadal scales (Fig. 8), further confirming the effect of the AMO on temperature in the Changbai Mountains.

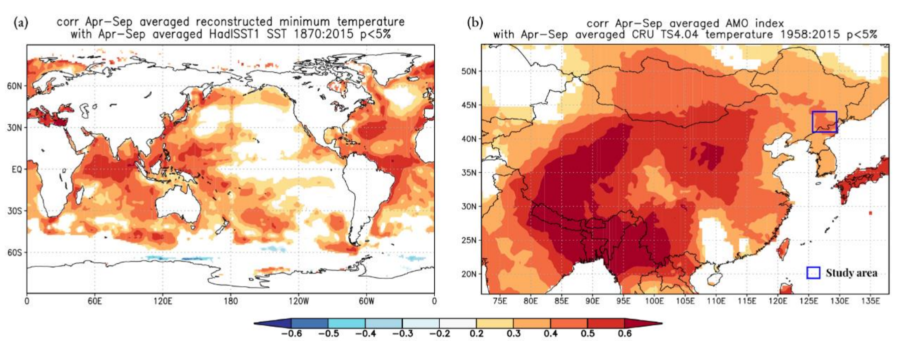

Figure 7. The influence of the AMO on the growing-season minimum temperature in the northern Changbai Mountains. (a) Spatial correlation between reconstructed April-September averaged minimum temperatures with Sea Surface Temperatures at a global scale. The spatial correlation was calculated for April-September and covers the period from 1870 to 2015. (b) Spatial correlation of the actual AMO (Enfield et al., 2001) with April-September land surface minimum temperature from the CRU TS4.04 for the period 1958-2015. Maps with filled p-values > 5% were masked out.

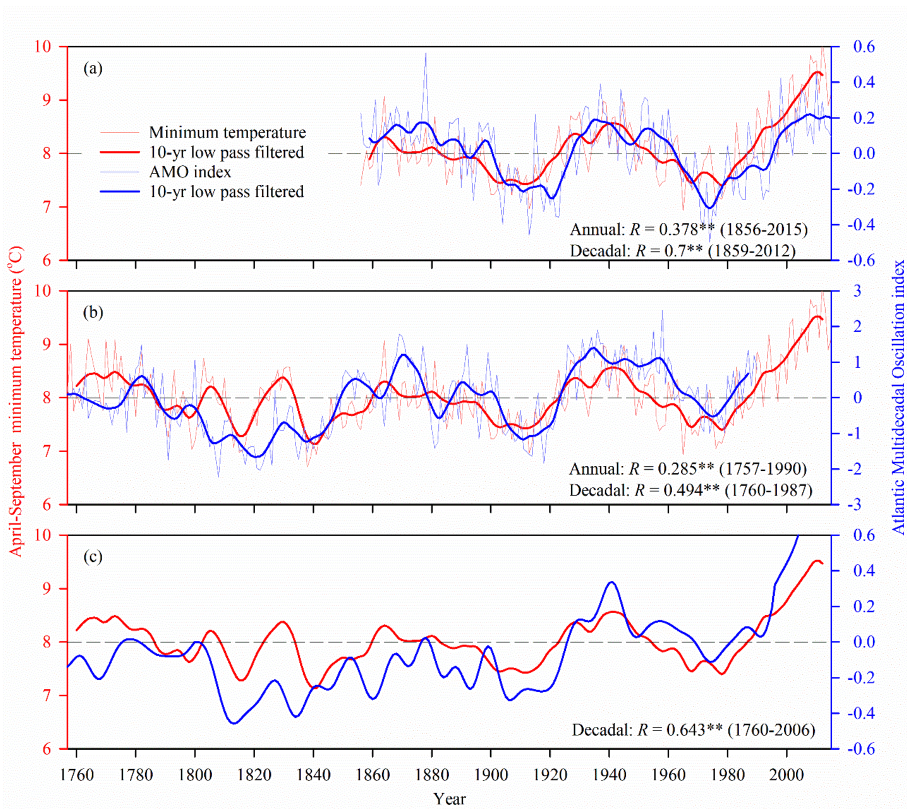

Figure 8. The influence of the Atlantic Multidecadal Oscillation (AMO) on the growing-season minimum temperature in the northern Changbai Mountains. (a) The reconstructed temperature and the actual AMO index from Enfield et al., (2001). (b) The reconstructed

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temperature and the reconstructed annual Sea Surface Temperature anomalies for the North Atlantic (AMO index) from Gray (2001). (c) The reconstructed temperature and the reconstructed AMO index from Mann et al., (2009). The red line in (a)-(c) denotes the reconstructed growing-season minimum temperature from this study (thin line) and its 10-year low-pass loess filter (bold line). The blue line in (a)-(c) denotes the AMO index from this study (thin line) and its 10-year low-pass loess filter (bold line). Correlations are shown in each panel. Double asterisks denote correlation significance at the 99% confidence level.

Previous studies have also confirmed that the AMO can strongly influence China's climate (Li et al., 2015;Wang et al., 2013), with impacts on temperature and drought in the southwest (Fang et al., 2019;Shi et al., 2017;Zeng et al., 2019), northwest (Chen et al., 2013), and northeast (Liu et al., 2019;Zhu et al., 2018b;Zhu et al., 2020a). The SST anomalies in the North Atlantic or AMO can change oceanic-atmospheric-land surface interactions and directly affect the local climate in eastern Asia (Wang et al., 2013;Wang et al., 2009). Temperature in the northern Changbai Mountains is significantly ($p<0.01$) positively correlated with the actual AMO indices from prior April to current September (Table S3). The composite April-September air temperature anomaly for the three AMO extreme periods during the past 100 years also confirms our results (Fig. 9). Temperature over our study area had a positive temperature anomaly during the two warm periods from 1935 to 1955 and 2000 to 2020. However, it has a negative anomaly during the cold periods from 1970 to 1990 (Fig. 9b-d). The 500-mb vector wind data confirm that a strong atmospheric circulation originating in the North Atlantic traverses all of Eurasia before dropping over northeast Asia (Fig. 9a). This circulation brings warm/cold air masses from the Atlantic Ocean and Eurasia to northeastern China (Fig. 9a). The AMO may also affect temperature in the Changbai Mountains by modulating other large-scale circulation patterns. For example, large-scale circulation related to Pacific Ocean-atmospheric coupling processes, such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, could affect local temperatures in northeastern China (Zhang and Thomas, 2007;Dong et al., 2006;Zhu et al., 2017).

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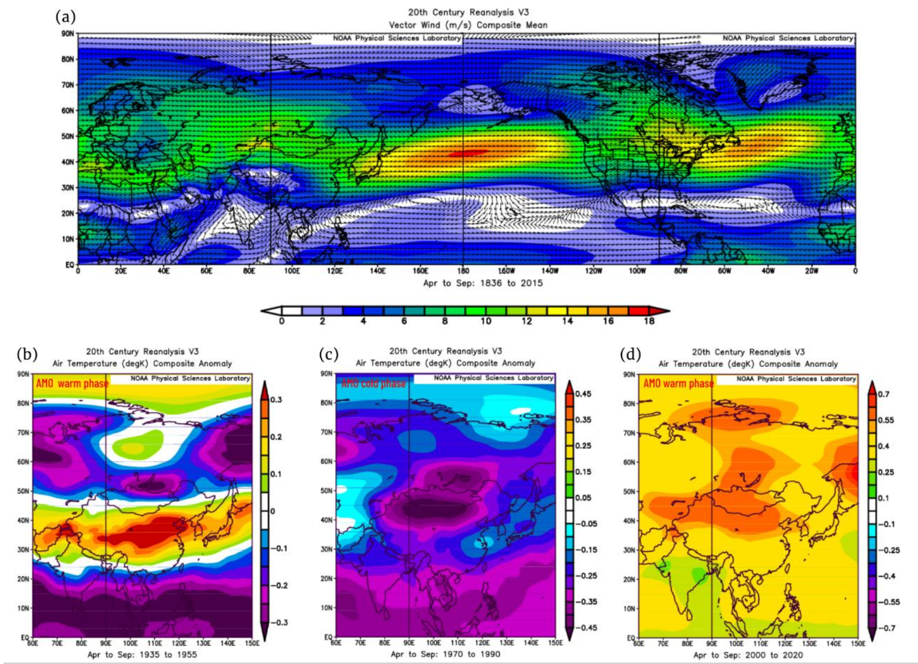

Figure 9. The (a) averaged April to September 500-mb vector wind in the Northern Hemisphere and the (b-d) 20[th] century reanalysis V3 air temperature composite anomaly for three different AMO phase periods during the growing-season (April-September). (b) Warm phase from 1935 to 1955, (c) cold phase from 1970 to 1990, and (d) warm phase from 2000 to 2020.

5 Conclusion

We propose a novel tree-species mixing method to improve the accuracy of tree-ring-based reconstructions in areas with unstable growth-climate relationships. This method significantly improves the model stability and reliability of a temperature reconstruction for the northern Changbai Mountains. During the calibration period from 1958 to 2015, the model explains 68% of the growing-season minimum temperature variation. During the past 259 years (AD 1757-2015), five warm periods (1762-1776, 1828-1831, 1927-1930, 1936-1947, and 1991-2012) and five cold periods occurred (1797-1800, 1811-1820, 1836-1856, 1898-1918 and 1956-1982). Our reconstruction shows good consistency and high accuracy with nearby tree-ring-based reconstructions and historical records. This reconstruction successfully captures the warming observed in the instrumental record since the 1980s. Within the 259-year record, we find significant (p <0.01) annual cycle peaks at 2.7, 3, and 3.5 years, and decadal cycle peaks at 59.6 and 78.4 years. The AMO plays a key role in modulating temperature in the northern Changbai Mountains.

Data availability. The temperature reconstruction in the Changbai Mountains will be uploaded to NOAA, and all the data published in this study will be available for non-commercial scientific purposes.

Author contributions. For this article, LZ and XW conceived the study; LZ, HZ, DY and XZ collected the data; LZ, DC, DY, YZ, HL and XW elaborated the methodology; LZ, SL, ZL, YZ and DY analysed the data; LZ, SL and XW led the writing of the manuscript; LZ, DC, WS, ZL, YZ and XW revised the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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