April–June precipitation reconstruction for Xi’an and drought assessment for the Guanzhong Plain from tree rings of Chinese pine

Feng Chen, Yujiang Yuan, Wenshou Wei, Ziang Fan, Ruibo Zhang and Shulong Yu

ABSTRACT

Variations in earlywood width (EWW) of Chinese pine in the Nanwutai Mountain were used to develop high-resolution climate proxy data to extend existing climate records in Guanzhong Plain, Shaanxi Province, China. Growth–climate response analyses showed the EWW series in Nanwutai Mountain are mainly influenced by spring and early summer precipitation. Based on the EWW series derived from the Nanwutai Mountain, we developed an April–June precipitation reconstruction for Xi’an for the period 1800–2009. The climate/tree-growth model accounts for 36.4% of the instrumental precipitation variance during the period 1951–2009. Spatial climate correlation analyses with the gridded precipitation data revealed that our precipitation reconstruction contains a strong regional precipitation signal for the Guanzhong Plain. Our reconstruction successfully captured recent climatic changes and agreed, in general, with other tree-ring-based precipitation reconstructions from nearby regions on a decadal timescale. The rainfall/drought series in northern China also showed highly synchronous decreasing trends since the 1970s, suggesting that precipitation related to the East Asian summer monsoon has decreased by large spatial and temporal (decadal) scales. In addition, wavelet analysis revealed the existence of some decadal (13.3-year) and interannual (9.1-, 5.4-, 3.1-, and 2.1-year) cycles, which may potentially be the fingerprints of some proposed climate change forcings, such as El Niño-Southern Oscillation and solar activities.

Key words | Chinese pine, drought event, earlywood width, precipitation, reconstruction, Xi’an

INTRODUCTION

As the largest city in northwest China, Xi’an is the capital of Shaanxi Province, and is also one of the oldest cities in China with a history of more than 3,000 years. Although annual precipitation is more than 500 mm, the frequency and severity of hydrologic droughts and other hydroclimatic events are of critical importance in the economic development of Xi’an and to the rapidly growing urban population. In addition, as a major winter wheat cultivation zone, the hydroclimate conditions of the Guanzhong Plain during spring and early summer play a vital role for winter wheat production (Simelton et al. 2008). Water resource management and agricultural planning require detailed and reliable knowledge of hydroclimate conditions on annual to centennial timescales. However, climate stations were not installed on most areas of the Guanzhong Plain before 1950. Therefore, we need to develop the hydroclimate reconstructions to provide us with the knowledge of the past frequency and severity of climatic anomalies such as drought and wet periods for coping with climate change.

As one of the best sources of paleoclimate information, tree-ring series have been used to reconstruct past climate factors to understand climate change over time in China (Wang et al. 2010; Chen et al. 2012a; Liang et al. 2012; Liu et al. 2013; Gou et al. 2013; Yang et al. 2014). The selection...
of reconstructed factors and the quality of the reconstruction are dependent on the physiological characteristics of tree and specific site conditions. Tree-ring width and maximum density data from the high elevation sites are used to reconstruct the past temperature variations, but reconstructions of precipitation and drought that are mainly based on tree-ring width from the low-elevation sites have also been identified as being valuable when addressing regional climate change (Wang et al. 2010; Liu et al. 2013; Chen et al. 2013a, 2013b). Chen et al. (2013c) have recently reconstructed precipitation variations over the past 380 years using earlywood width (EWW) data from a low-elevation site in east Gansu in the Guanzhong–Tianshui economic zone. However, to date, there still remains a lack of long-term dendrohydroclimatic data in the drought-prone Guanzhong Plain, Shaanxi Province.

Here, we present a tree-ring-based precipitation reconstruction for Xi’an spanning the period 1800–2009. As shown below, this precipitation reconstruction is representative of precipitation conditions in a large area to the south and east of the Guanzhong Plain, which increases our understanding of the overall drought history over the Guanzhong Plain. We use this long record to detect extreme dry events (droughts) in the Guanzhong Plain. Furthermore, we also employ wavelet analysis and related methods to investigate potential periodicities and forcing factors of precipitation of Xi’an.

MATERIALS AND METHODS

Study area

The study area is located in the Nanwutai Mountain only a 30-km distance to Xi’an (Figure 1). The region is influenced by the temperate semi-humid continental monsoon climate. This zone is also closely associated with the East Asian summer monsoon variations (Chen et al. 2013c). The annual sum of precipitation in this area is 569.5 mm and the annual mean temperature is 13.8°C (average temperature of January and July is –0.4°C and 26.7°C from 1951 to 2009, respectively). July is the hottest month and is also the wettest month (mean precipitation 99.1 mm). The dominant tree species of the Nanwutai Mountain include Chinese pine (Pinus tabuliformis) and Chinese cork oak (Quercus variabilis). The sampled site is Chinese pine forests growing on hillsides. The soil beneath the forest is mainly brown pine mountain soil.

Sampling and tree-ring chronology development

In the 2010 summer season, we sampled trees at a site (Nanwutai, 33°59′35″ N, 108°58′13″ E) in the Nanwutai Mountain. In general, one 10 mm core and one 5 mm core were sampled with the increment borers from each tree at breast height for ring-width measurement, but for trees believed to be of old age (about 1/3 of the sampled trees), two 10 mm core and one 5 mm core were collected, where the 10 mm cores will be used for tree-ring density analyses. In total, 25 cores of 5 mm and 33 cores of 10 mm from 25 trees were collected. The sampling site was at 1,380–1,450 m elevation a.s.l.; on north slopes, it was with an inclination of 10–30°.

Tree-ring cores were air-dried, mounted on wooden holders, and sanded using progressively finer sandpaper (200–600 grit). First, annual ring widths of all cores were
measured to the nearest 0.001 mm using a Velmex measuring system. Second, extraction of volatiles of the 10 mm cores was performed by hot water and alcohol solution. The 10 mm cores were cut transversely into strips of 1.00 ± 0.02 mm thickness with a twin-bladed saw. The strips were subjected to X-ray analysis. The densitometric analysis of these X-ray films was carried out on DENDRO 2003 tree-ring workstation at the Key Laboratory of Tree-ring Physical Chemical Research of China Meteorological Administration, China. To obtain good measurements, the steps described by Schweingruber et al. (1978) were adopted. The boundary between earlywood and latewood was identified as the midpoint between the maximum and minimum density measurements of each ring. Finally, the EWW data of the 10 mm cores were obtained.

The program COFECHA (Holmes 1983) was used to test the accuracy of our cross-dating and measurement of annual ring widths, and then EWW data were compared to the annual ring width cross-matching results. To remove non-climatic, age-related growth trends from the raw ring width and density measurement series, we used the program ARSTAN to detrend the EWW sequences using the negative exponential function and to average the standardized sequences into the master chronology (Fritts 1976; Cook & Kairiukstis 1990). The variance in chronologies was stabilized in the chronology compilation process with the Briffa Rbar-weighted method (Osborn et al. 1997). The ARSTAN program produces three versions of standardized chronologies: Residual, Standard, and Arstan. The residual EWW chronology was used in further analyses.

Climate data and statistical analysis

Instrumental climate records (Xi’an, 34 18’ N, 108 56’ E, altitude 398 m a.s.l., 1951–2009) were obtained from the China National Climatic Data Center (Figure 2). The meteorological data of Xi’an was screened for inhomogeneities using the Potter’s T-test (Potter 1981). The relationship between tree-ring chronology and the climatic data was analyzed using the DENDROCLIM 2002 (Biondi & Waikul 2004). All statistical procedures were evaluated at $P < 0.05$ level of significance. In the correlation analysis, the climate data along with EWW series were examined from the previous July to the current September.

A linear regression equation between the predictors (EWW index) and the predictand (precipitation) was computed for the calibration period. Because the climate record is not long enough to be divided into the calibration and verification sections, the leave-one-out cross-validation was used to evaluate the goodness-of-fit of the model (Blasing et al. 1981). Verification statistics used included the reduction of error (RE) and coefficient of efficiency (CE) statistics, the sign test, first-order sign test, and the Pearson’s correlation coefficient. To indicate our record’s geographical representation, the precipitation reconstruction was correlated with gridded precipitation dataset of CRU TS3.21 (Mitchell & Jones 2004) for the period 1951–2009. The analyses were conducted using the KNMI climate explorer (http://climexp.knmi.nl). Wavelet analysis was employed to analyze potential periodicities of the precipitation reconstruction (Torrence & Compo 1998).

RESULTS

Precipitation reconstruction

The EWW series were positively correlated with May–June precipitation and negatively correlated with May–June temperature (Figure 3). The results showed that precipitation in spring and early summer was the main factor limiting the radial growth of Chinese pine trees in the Nanwutai Mountain. At the same time, evaporation increased with
the rise in temperatures of May–June, which accelerated the drought stress.

The experience of tree-ring research indicates that as seasonal combinations of climate data are more representative than just one single month, we used the seasonal combinations of precipitation and temperature for further analysis. In addition, partial correlation analyses between the EWW series and climate data were also employed to avoid the inter-correlation among climatic variables. After combining the months that have high correlation between precipitation and the EWW series, we found that the correlation \( r = 0.604, P < 0.001 \) between the EWW series and total April–June precipitation was highest and significant. The partial correlation coefficient between the EWW series and May–June temperature is \( r = -0.04, P > 0.05 \). When temperature signal was removed by the partial correlation, the total April–June precipitation still has relatively high correlation \( r = 0.518, P < 0.01 \) with the EWW series. Although the EWW series was significantly negatively correlated with monthly temperatures, partial correlation results demonstrated that the coincident variation of EWW was controlled by precipitation.

Based on the results and the above theory, total April–June precipitation is the most appropriate seasonal predictor for climate reconstruction. A linear regression model between the EWW series and total April–June precipitation for the calibration period was significant \( (F = 32.661, P < 0.001, \text{adjusted } r^2 = 0.353) \).

The model obtained was

\[
Y = 29.828 + 136.595X \tag{1}
\]

where \( Y \) is the total April–June precipitation and \( X \) is the EWW series.

The resulting statistics of leave-one-out cross-validation are shown in Table 1 (Fritts 1976; Cook & Kairiukstis 1990). Both the RE and CE are strongly positive for the verification period, indicating considerable validity in the reconstruction model. The results of the sign test and the first-order sign test, which describes how well the predicted value tracks the direction of actual data, exceed the 99% confidence level. These results indicate that the model used here passed the critical tests. Precipitation data for the full 1951–2009 period was then used to calibrate the final reconstruction (Figure 4). The final precipitation reconstruction which explains 36.4% of the variance was truncated prior to the year 1800 based on a threshold value (0.8) of the expressed population signal (Wigley et al. 1984).

<table>
<thead>
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<th>Table 1</th>
<th>The leave-one-out cross-validation statistics for total April–June precipitation reconstruction for Xi’an</th>
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<tr>
<td>( R )</td>
<td>( F )</td>
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<td>0.604</td>
<td>32.661</td>
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\( R \) is Pearson’s correlation coefficient; \( F \) is \( F \)-value; \( \text{RE} \) is reduction of error; \( \text{ST} \) is sign test; \( \text{FST} \) is the first-order sign test; and \( \text{CE} \) is coefficient of efficiency.
The characteristics of precipitation reconstruction

The reconstructed and low-pass filtered precipitation is presented in Figure 5. According to the precipitation reconstruction, dry periods with below-average precipitation (164.9 mm) occurred in the periods 1800–1801, 1807–1813, 1822–1826, 1832–1840, 1859–1868, 1873–1878, 1898–1902, 1921–1930, 1958–1968, and 1976–2009. Extremely dry years (≤2 SD) occurred in the years 1900, 1901, 1926, 1929, and 2007. In contrast, the periods 1802–1806, 1814–1821, 1827–1831, 1841–1858, 1869–1872, 1879–1897, 1903–1920, 1931–1957, and 1969–1975 were relatively wet. Extremely wet years (≥2 SD) occurred in the years 1887, 1946, 1953, 1956, and 1974. The dry years (≤1 SD) accounted for 17.0% (36 years) of the years during the whole precipitation period.
reconstruction, while the wet years (≥1 SD) accounted for 14.3% (30 years) of the years. The years 1926 (75.5 mm) and 1956 (257.3 mm) are reconstructed as the most extreme years. As indicated by our precipitation reconstruction, the drought epoch in 1921–1930 is the most severe and long-lasting drought in the study area since the year 1800.

As shown in Figure 6, significant positive correlations are found with the northern side of Qinling Mountains in Shaanxi Province, with highest correlations occurring in the middle and eastern Guanzhong Plain, especially in Xi’an. The results confirm that our precipitation reconstruction captures broad-scale regional precipitation variations. As shown in Figure 7, significant ($P < 0.05$) spectral peaks are found at 2.1, 3.1, 5.4, and 9.1 years, and significant multi-decadal cycles ($P < 0.05$) are found at 13.3 years.

**DISCUSSION**

Although our precipitation reconstruction was based on the residual EWW chronology, considerable decadal scale precipitation variability was retained in our reconstruction. The dry periods in 1807–1813, 1822–1826, 1859–1868, 1873–1878, 1898–1902, and 1921–1930 were also detected as dry periods in neighboring Tianshui by Chen et al. (2015b). The dry periods in 1807–1815 and 1822–1826 were synchronous with dry conditions in northwestern China (Chen et al. 2015a, 2015b, 2015c). The intervals in the late 19th century and early 20th century were relative wet, especially the period 1903–1920. The most severe and long-lasting drought over the past 210 years occurred during the late 1920s. This long-lasting drought event has also been recorded in tree rings from northern China (Liang et al. 2006). Yuan (1994) combined the historical records (documentary, meteorological, and hydrological evidence) and reported that the 1920s drought was the most severe and long-lasting drought in the 20th century, and covered Shaanxi, Gansu, Ningxia, Qinghai, Gansu, eastern Xinjiang, and Inner Mongolia in China. The climate was relatively wet from the 1930s to 1950s, which was also reported from the Hengduan Mountains by Fan et al. (2008). The period 1976–2009 was relatively dry, especially 1990–2000, which coincides with a drying trend in the east part of northwestern China since the 1980s (Li et al. 2007; Shi et al. 2007; Chen et al. 2015c). This drying trend would raise the risk of depleting water resources and vulnerability of the regional...
ecological systems for the Guanzhong Plain. Although the strengthening East Asia summer monsoon since the early 1990s had promoted the growth of trees in our study area (Liu et al. 2012), no fundamental shift occurred.

Wavelet analysis indicates that the precipitation cycles have not remained constant during the last 210 years (Figure 7). The significant spectral peaks at 9.1 and 13.3 years were identified in our precipitation reconstruction ($P < 0.05$), which resembles other findings from northern China and suggests the influence of solar activities on the regional climate change (Li et al. 2011; Liu et al. 2015). Most of the interannual cycles (5.4, 3.1, and 2.1 years) fall within the range of variability of the El Niño-Southern Oscillation (ENSO). The ENSO has been found to have strong influences on the strength of the East Asian summer monsoon (Zhun & Chen 2002; Lu 2005). Thus, similar to other annually resolved precipitation/drought reconstructions from northern China (Li et al. 2007; Liu et al. 2013; Chen et al. 2013c), ENSO signals might be reflected in the tree-ring series of moisture-sensitive trees. However, the mechanism of how the climate and tree growth interacts at various timescales awaits further investigation.

**CONCLUSIONS**

To improve the understanding of long-term precipitation changes of Xi’an, we present a 210-year total April–June precipitation reconstruction based on the tree-ring EWW series from the Nanwutai Mountain area. The precipitation reconstruction reveals that dry episodes occurred during the periods 1800–1801, 1807–1813, 1822–1826, 1832–1840, 1859–1868, 1873–1878, 1898–1902, 1921–1930, 1958–1968, and 1976–2009. Wet intervals occurred in 1802–1806, 1814–1821, 1827–1831, 1841–1858, 1869–1872, 1879–1897, 1903–1920, 1931–1957, and 1969–1975. At the same time, spatial correlations with the gridded precipitation dataset reveal that our reconstruction represents a high degree of regional precipitation variability over the Guanzhong Plain. During the past 30 years, a clear drying trend of the Guanzhong Plain has occurred. Comparison with other records from nearby regions confirmed the reliability of our precipitation reconstruction. The wavelet analysis results indicate the existence of some important cycles for the precipitation variability, possible climatic mechanisms, and relationships with solar activity and ENSO. Extension of dendroclimatological studies to other regions of eastern China will be necessary to develop an integrated understanding of the large-scale climate features and teleconnections that have occurred over the past centuries in and around northern China.

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