Detecting dryness and wetness signals from tree-rings in Shenyang, Northeast China

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A B S T R A C T

For drought and flood forecasting, it is critical that we understand regional rainfall patterns as well as their potential underlying forcings, particularly in urban regions with greater long-term anthropogenic influences compared to rural areas. To achieve this, three Chinese pine (Pinus tabulaeformis) tree-ring width chronologies were developed from the metropolitan, suburban, and rural sites near Shenyang city of Northeast China and used to study regional dryness and wetness variability in the past 232 yr. January–May precipitation (1771–2002) was successfully reconstructed from the tree-rings, although urban factors caused a slightly reduced response of the tree-rings to precipitation. Our reconstruction captures certain local rainfall variability and dryness/wetness signals, such as three unusually dry decades (1920s, 1850s and 1960s), an unusually dry half-century (1850–1899) and some significant cycles (2–8 yr and ~20 yr) associated with them. It also reveals a relatively equal number of dry/wet events (38.79% wet years versus 35.78% dry years) and a recent drying trend. Our study also indicates the feasibility of using urban tree-rings to reconstruct dry/wet patterns in city environments.

1. Introduction

Climate extremes, particularly droughts covering large areas over a prolonged period of time, are a serious concern around the world due to their significant impacts on human beings and ecosystems (Easterling et al., 2000; IPCC, 2002; Shen et al., 2007). Recently this concern was heightened by the increasing intensity of large-scale climate change and unprecedented changes both present and past (Cook et al., 2004; Li et al., 2006; Shen et al., 2007; Li et al., 2009). Northeast China, adjacent to the semiarid region of Northern China and the Mongolian Plateau, is highly vulnerable to anomalous rainfall that results in drought or flood. Agrarian resources of this region are also strongly affected by the changing availability of water (Wen et al., 2005; The Report of Climate Change in Northeast China, 1), 2006). It is thus critical that we better understand dryness or wetness patterns as well as their potential driving forces, in order to establish the fundamentals for drought forecasting.

Reconstructions of long-term dryness/wetness from proxy records, such as tree-rings (Fritts, 1976), are particularly valuable in areas with short instrumental climate records. In China, direct meteorological measurements are often limited in both time and space, and the most reliable records are typically only about 50 yr long (Zhang et al., 2000). The longer records are produced by tree-rings should therefore be useful for regional environmental assessment and planning and for larger-scale climatic analyses (Jacoby et al., 2003).

Dendrochronological resources for climate reconstruction are extremely scarce in or near cities across China due to past detrimental forestry policies and increasing population demands on forest resources. This makes it very difficult to find an adequate number of suitable old trees in many regions for sampling, especially near urban environments. Fortunately, some invaluable old trees have been preserved in temples, mausoleums, and scenic areas in some places, such as in Shenyang, Northeast China. Although anthropogenic activities have resulted in complicated growing conditions and more non-climatic effects on these trees in cities versus natural regions, tree growth responses to climate in urban environments can still be acceptably detected (Chen et al., 2006a,b, 2007, 2008; He et al., 2007). Critically, tree-ring records of past hydroclimatic variability, their association with historical droughts, and the potential impacts of rapid industrialization and urbanization on the sensitivity of trees to climate are particularly important and necessary to assess regional environmental change. Common to all kinds of dryness or wetness is the fact that they all result from the accumulated effect of changing precipitation over some time period (Wilhite and Glantz, 1985). The focus of the present study is to show the feasibility of rainfall reconstruction using tree-rings in an industrial city in Northeast China, and to understand past dryness and wetness variability in the study area.

2. Data and methods

Chinese pine tree-ring samples were taken from three sites in or near Shenyang (41°11′–42°02′N; 122°25′–123°48′E; Population: ~7.8
million in 2009; Area: 12,980 km², Fig. 1) in inland Northeast China, an area that belongs to the East Asian monsoon climate region (Wen et al., 2005). It is in a transition zone between the mountainous area of eastern Liaoning and the Liaohe Plain that connects Northern China and the Mongolian plateau. Its annual average temperature is 7.8 °C and its annual precipitation is 707 mm (1906–2002). The first sampling site in this study is at Zhaoling Mausoleum, located in the metropolitan area of the city. The second site is at Fuling Mausoleum, located in the east suburbs, about 13.6 km in distance from the metropolitan area of the city. Both sites are listed in the World Cultural Heritage List of United Nations Educational, Scientific, and Cultural Organization. The third site is in the Qianshan Mountain scenic area, 50 km south of Shenyang.

Conventional dendrochronological techniques (Fritts, 1976; Holmes, 1983; Cook, 1985) were used in developing the tree-ring width chronologies for the three sites (Chen et al., 2006a, 2007, 2008; He et al., 2007): The samples were mounted, air dried, and sanded to a high polish (Stokes and Smiley, 1968). Rings were measured to the nearest 0.001 mm, and were checked by the program COFECHA for quality control of crossdating (Holmes, 1983). The crossdated raw ring widths were conservatively detrended using negative exponential or linear curves. The resulting tree-ring indices, calculated as ratios of the ring widths to their respective growth curve values, were bi-weighted averaged together to generate a standard chronology using the program ARSTAN (Cook, 1985). The statistic of expressed population signal (EPS) (Briffa and Jones, 1990) was used with a threshold value of 0.85 to determine the period for which the chronology is sufficiently replicated to be deemed reliable. Three versions of a master chronology were developed, each with its own inherent characteristics: a Standard chronology (STD), a Residual chronology (RES) and an ARSTAN chronology (ARS). The STD and ARS chronologies are usually very similar in both high and low frequencies, but the latter relies on the use of autoregressive modeling to reduce the possible effects of competition in closed canopy forests (Cook and Holmes, 1986). In contrast, the RES chronology emphasizes high-frequency variations through the use of autoregressive pre-whitening that removes autocorrelation from the series. Based on acceptable statistic quality control criteria (Chen et al., 2006a, 2007, 2008; He et al., 2007) (Table 1; Fig. 2), we consider our ring-width chronologies to be valid for dendroclimatic study.

Local instrumental precipitation records (1906–2002) were obtained from the Regional Meteorological Observatory of Shenyang (Fig. 1). Although the local meteorological station was moved twice (April 1908 and January 1916), no significant abrupt changes in these precipitation records were detected (Sun et al., 2006). Even so, there appears to have been a change in the correlations between tree growth and climate that may reflect some level of inhomogeneity in the meteorological data (see below).

Considering the close locations of three sites and their homogeneous macro-scale climatologies, the chronologies were used together
to detect regional climate signals. Morlet wavelet analysis (Torrence and Compo, 1998) and Multi-Taper Method (MTM) spectrum analysis (Mann and Lee, 1996) were employed to examine the spectral properties of these time series. An index of dryness and wetness was defined according to the standard of Editorial Committee of Academy of Meteorological Science, China Central Meteorological Administration (AMSCCMA) (1981) (Table 2).

### Table 1

<table>
<thead>
<tr>
<th>Quality control/Sample site and chronology type</th>
<th>Zhaoling</th>
<th>Fuling</th>
<th>Qianshan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.9865</td>
<td>0.9931</td>
<td>0.9960</td>
</tr>
<tr>
<td>Median</td>
<td>0.9822</td>
<td>1.0024</td>
<td>0.9864</td>
</tr>
<tr>
<td>Mean sensitivity</td>
<td>0.1775</td>
<td>0.1958</td>
<td>0.1791</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.0204</td>
<td>0.1811</td>
<td>0.2184</td>
</tr>
<tr>
<td>Skewness</td>
<td>−0.2044</td>
<td>−0.3868</td>
<td>−0.1960</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>0.0453</td>
<td>0.0431</td>
<td>0.4898</td>
</tr>
<tr>
<td>Autocorrelation order 1</td>
<td>0.4535</td>
<td>0.0842</td>
<td>0.5094</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Index value</th>
<th>Moisture condition</th>
<th>Definition for dryness and wetness</th>
<th>Standard of dryness and wetness in this study</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wetness</td>
<td>( R_s \geq (R_{mean} + 1.175) )</td>
<td>( R_s \geq 155.27 \text{ mm} )</td>
</tr>
<tr>
<td>2</td>
<td>Weak wetness</td>
<td>( (R_{mean} + 0.335) &lt; R_s &lt; (R_{mean} + 1.175) )</td>
<td>( 135.18 \text{ mm} &lt; R_s &lt; 155.27 \text{ mm} )</td>
</tr>
<tr>
<td>3</td>
<td>Normal status</td>
<td>( (R_{mean} - 0.335) &lt; R_s &lt; (R_{mean} + 0.335) )</td>
<td>( 119.62 \text{ mm} &lt; R_s &lt; 135.18 \text{ mm} )</td>
</tr>
<tr>
<td>4</td>
<td>Weak dryness</td>
<td>( (R_{mean} - 1.175) &lt; R_s &lt; (R_{mean} - 0.335) )</td>
<td>( 99.82 \text{ mm} &lt; R_s &lt; 119.62 \text{ mm} )</td>
</tr>
<tr>
<td>5</td>
<td>Dryness</td>
<td>( R_s &lt; (R_{mean} - 1.175) )</td>
<td>( R_s &lt; 99.82 \text{ mm} )</td>
</tr>
</tbody>
</table>

\( R_s \) is the precipitation of the year \( i \), \( R_{mean} \) is the mean precipitation of the overall period, and \( S \) is the standard deviation (SD) of the precipitation during the overall period.

\( ^a \) The standard of Editorial Committee of Academy of Meteorological Science, China Central Meteorological Administration (AMSCCMA) (1981).

### 3. Results

Analyses were performed for monthly mean temperature and monthly total precipitation over the previous and current years when both meteorological records and tree-ring data are available (1906–2002). Very similar relations between local precipitation and the three kinds of chronologies (STD, RES, ARS) were detected, so the correlations for one version of chronology were illustrated only (Fig. 3). This was done over the whole period (1906–2002) and for a number of discrete decades. The latter was done to test for changes due to the April 1908 and January 1916 station moves and the likelihood of frequent anthropogenic disturbances on tree growth at the urban sites in the latter part of the 20th century (Yu and Huang, 1994; Shang et al., 1997). These factors may have contributed to the lower correlations between urban tree growth and January–May precipitation (JMP) prior to 1916 and after 1985 (Fig. 3B). Thus, the period 1916–1985 was chosen to build the regression model to reconstruct JMP for Shenyang from 1771 to 2002. Based on the above analysis of potential urban effects to the trees of different sites, simple averaging or using the first principal component of the three chronologies was considered unsuitable because both methods would result in contamination of the rural area chronology (Qianshan) by the urban chronologies (Zhaoling and Fuling). Therefore, stepwise multiple regressions based on the correlations between precipitation and chronologies from the different sites were used for the reconstruction. The RES based reconstruction explained the highest JMP variance and overall regression F-test among the three versions of chronologies (Table 3; Fig. 4). Therefore, the remaining discussions in this paper will be mainly based on the RES reconstruction (Fig. 5A).

The statistical fidelity of the RES based model was examined by split sample calibration–verification tests (Meko and Graybill, 1995) (Table 4). The reduction of error (RE) and the coefficient of efficiency (CE) tests are both positive, indicating some level of model skill. The results of sign test for the 1916–1950 model are slightly weak. In spite of that, the overall split calibration–verification tests indicate a reasonable level of validity for our regression model. In addition, there is a highly significant relationship between actual and estimated precipitation over the full 1916–1985 period \((r = 0.579, p < 0.001)\) (Fig. 4). Based on this final reconstruction of JMP, we developed the January–May dryness/wetness index (JMDWI) of Shenyang from 1771 to 2002 (Table 2; Fig. 5B).

No seasonal rainfall (January–May) was found below 50 mm and only the JMP in 1874 exceeded 200 mm in our reconstruction over the latest two centuries (1771–2002) (Fig. 5A). There are 23 yr below
100 mm, 172 yr between 100–150 mm and 36 yr between 150–200 mm of the rainfall. The five driest rainfall years were 1859, 1920, 1813, 1838 and 1807, respectively, and the five wettest rainfall years were 1874, 1788, 1809, 1822 and 1843. The 1920s, 1950s and 1960s were the three driest decades, the 1840s, 1930s and 1770s were the three wettest decades, and the period of 1850–1899 was the driest half-century. The 19th century was also drier than the 20th century. Specifically, there were 90 wet years (38.79% of the total), 83 dry years (35.78% of the total) and 59 normal years (25.43% of the total) over the whole period. The mean JMP of our reconstruction is 127.40 mm, which is in the range of the de

variability (Fig. 6). Wavelet power is found between 2 and 8 yr and near 20 yr in both JMP and JMDWI from 1771 to 2002 (Fig. 7A, B). The 2–8 yr periodicity band is most significant during the whole period (Figs. 6 and 7A, B).

4. Discussion

4.1. Significant seasonal response of radial growth to climatic change

In this region, Chinese pine tree-rings have correlated significantly with local and regional temperature variations, particularly to temperatures in winter and spring (Chen et al., 2006a, 2007, 2008; He et al., 2007). In this study, the positive correlations ($r_{\text{mean}} = 0.463, n = 70, p < 0.01$) between the three RES and JMP (Fig. 3) suggest that previous winter–spring precipitation is also crucial for tree growth in the growing season. Winter precipitation enriches soil moisture storage and reduces the impacts of heavy water loss through evaporation, whereas spring precipitation directly increases the soil moisture availability and thus compensates the soil water loss due to evapotranspiration (Shi et al., 2008). On the other hand, the relatively weak correlations between June–October precipitation (78.43% of the annual total) and the three RES chronologies suggest that trees are less sensitive to moisture deficiency in the growing season (Fig. 3A).

A slightly decreasing correlation (negative linear trend of 10 yr correlations) between the precipitation and tree growth in the metropolitan center (ZMres) and the outskirts (FMres) of the city from 1950s to 1960s suggests that urban development and anthropogenic factors have affected the response of Chinese pine to climatic variables (Fig. 3B). This is the period when the People's Republic of China was just founded, Shenyang City served as a heavy industrial base of the country, and the center of Northeast China began to
expand at its fastest rate. This trend is clearer in the former (ZMres) than the latter (FMres). However, trees growing in the more remote rural area (QMres) did not show this trend. This result supports the finding that urban factors had strong effects on Chinese pine’s growth in this area (Huang et al., 1993; Yu and Huang, 1994; Shang et al., 1997). Specifically, the metropolitan mean annual temperature was 1.2–1.4 °C higher than that of the suburbs (Editorial Committee of Shenyang Local Histories, 1989) and there was about a 20–30 air quality index difference in daily airborne particulate matter (PM10) (Daily Air Quality Report of Shenyang, 2006) between the suburbs and the metropolitan areas of Shenyang during summer and autumn. The concentration of atmospheric pollutants in Shenyang is higher than those in other natural sites, and these pollutants have very strong

Table 4

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>r²</td>
<td>0.314</td>
<td>0.319</td>
<td>0.266</td>
<td>0.378</td>
<td>0.335</td>
</tr>
<tr>
<td>Adjusted r²</td>
<td>0.305</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>0.56</td>
<td>0.564</td>
<td>0.516</td>
<td>0.615</td>
<td>0.579</td>
</tr>
<tr>
<td>RE</td>
<td>0.352</td>
<td>0.385</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CE</td>
<td>0.342</td>
<td>0.378</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sign test</td>
<td>20+ / 15−</td>
<td>28+ / 7− ***</td>
<td>25+ / 10− ***</td>
<td>18+ / 17−</td>
<td></td>
</tr>
</tbody>
</table>

RE is reduction of error statistic and CE is coefficient of efficiency statistic.

** Significant at p < 0.01.
corrosion effect on the exposed objects (Wang et al., 2004). The previous investigation also showed that the concentrations of the trace elements Cu, Cd, and Pb in the soil are higher than the background concentration of local soil (Shang et al., 1997). With the impact of human activities, soil phosphate activation and soil nutrient (organic matters, total nitrogen, available nitrogen, total phosphorus Table 5 Comparison of dominative dry/wet periods between the estimation for Shenyang and some other tree-ring-based precipitation or dryness/wetness reconstruction before 1906 (no instrumental records period of Shenyang).

<table>
<thead>
<tr>
<th>Year</th>
<th>Shenyang</th>
<th>Baiyinaobao</th>
<th>Tengger</th>
<th>Mid-North</th>
<th>Baotou</th>
<th>Central Qilian</th>
<th>East Qilian</th>
<th>North Helan</th>
<th>Mongolia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-May</td>
<td>Apr-Jul</td>
<td>Sep-Aug</td>
<td>May-Jun</td>
<td>Feb-Jul</td>
<td>Jul-Jun</td>
<td>Mar-Apr</td>
<td>May-Jul</td>
<td>Aug-Jul</td>
<td></td>
</tr>
</tbody>
</table>

A Dominative wet periods or single years
1771–1774 1767–1781 1766–1776
1789–1793 1783–1816 1775–1789
1805–1809 1802–1814 1800–1807
1837–1852 1839–1859 1826–1849 1820–1830
1865–1874 1869–1875 1868–1876

B Dominative dry periods or single years
1775–1788 1782–1888 1777–1782 1771–1775
1794–1804 1789–1801 1790–1799 1791–1795; 1801–1805
1875–1888 1876–1885 1877–1894 1877–1878 1865–1884

Dry periods 1915–1931, 1956–1970 and 1992–2002, and wet periods 1932–1955 and 1970–1991 of Shenyang are not in the table. Baiyinaobao, west of Northeast China (Liu et al., 2003); South edge of the Tengger Desert, Northwest China (Gao et al., 2005); Mid-North region, China (Liu et al., 2002); Baotou, North China (Liu et al., 2001); Central Qilian mountains, Northwest China (Yang et al., 2005); East Qilian Mountains Northwest China (Gou et al., 2001); North Helan Mountains, Northwest China (Liu et al., 2004); Northeast Mongolia (top ten dry and wet periods in the whole period) (Pederson et al., 2001).

Fig. 6. The MTM spectrum for (A) actual January–May precipitation (JMP) from 1906 to 2002; (B) RES based JMP, (C) STD based JMP, and (D) ARS based JMP from 1771 to 2002. The smooth curves represent confidence level at 95% and 99%.
and available phosphorus) are significantly related to the growth of pine roots in both lateral and longitudinal directions in the sample sites (Han et al, 2006).

4.2. Characteristics of local and regional moisture change

Consistent with local (Shenyang) and regional (Northeast China) precipitation records, our reconstructions do not indicate any apparent long-term decreasing or increasing trend during the latest 100 yr. Instead, a weak decreasing trend over the most recent 50 yr is indicated that may be part of the overall interdecadal variability in the reconstruction (Fig. 8). Although our reconstructions are based on the high-frequency RES chronology, which has little variability greater than 30 yr (Figs. 6 and 7), the century-scale correspondence between our estimates and the instrumental record suggests that relatively moderate change might be one of the notable precipitation characteristics in this region during the latest two centuries (Fig. 8).

Relatively dry conditions are indicated for 1810–1836, and wet conditions are indicated for 1889–1914, 1932–1955, and 1970–1991. Shorter duration wet and dry periods ranged from 4 to 15 yr and 10 to 16 yr, respectively. Wavelet analysis also indicates periods of dryness or wetness having occurred with a mean periodicity of about 20 yr in the past. In addition, more than 70% of the droughts in Shenyang happen in spring time (Wen et al., 2005). Thus, February–May precipitation is not the key factor of yearly wetness as it seldom turns into flood. Nearly 90% (50 yr) of the documented spring droughts (Feb–May) correspond with our estimated dryness, whereas only 23.53% (4 yr) spring flood (Feb–May) correspond with our estimated wetness (Wen et al., 2005) (Fig. 5B).

Local dry/wet changes may have a regional significance that contributes to complex environmental and ecological events at a large spatial-temporal scale, such as dust storms and locust plagues during certain periods (Fig. 5; Table 6). For instance, including 1858 and 1859, the lowest two years of precipitation in our reconstruction, documented severe droughts (Wen et al., 2005) correspond well with our estimated dryness (90%) from 1771 to 2002. Past occurrences of strong spring dust storms in northern China (Deng and Jiang, 2006) also showed significant correlation with our estimated JMP \((p < 0.01)\) and JMDWI \((p < 0.05)\) after applying a 3-year moving average to the data. The relationship of actual precipitation and the daily airborne particulate matter variables between some places in Northeast and North China also support this finding, such as in Shenyang and in Beijing (39°28′–41°05′N, 115°20′–...
117°30'E (precipitation (1951–2002) = 0.438, p < 0.01; PC1 explains 71.877% of their total variance; PM10, obtained from daily air quality reports of the two cities; r = 0.251, p < 0.001). In addition, our estimates of dry and wet variations also correlate with radial growth changes of other tree species growing in the same region, e.g. Betula ermanii tree-ring width variation (Yu, 2004) and Pinus koraiensis stable isotope δ13C (1789–1988) and dust storms occurrence extent (1954–2002) with Shenyang.

Table 6

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time span</th>
<th>Season</th>
<th>Location</th>
<th>JMP correlation</th>
<th>JMDWI correlation</th>
<th>Years of moving average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryness/wetness index[1]</td>
<td>1771–2002</td>
<td>May–Sep</td>
<td>Shenyang and vicinity</td>
<td>−0.174**</td>
<td>0.215**</td>
<td>3</td>
</tr>
<tr>
<td>Betula ermanii tree-ring width[2]</td>
<td>1819–2002</td>
<td>Yearly</td>
<td>Northeast China</td>
<td>−0.182</td>
<td>0.207**</td>
<td>3</td>
</tr>
<tr>
<td>Locusta migratoria manilensis occurrence[4]</td>
<td>1949–1999</td>
<td>Yearly</td>
<td>China</td>
<td>−0.263**</td>
<td>0.306</td>
<td>3</td>
</tr>
<tr>
<td>Dust storms frequencies[5]</td>
<td>1771–2013</td>
<td>Yearly</td>
<td>North China</td>
<td>−0.227**</td>
<td>0.180</td>
<td>3</td>
</tr>
<tr>
<td>Yearly typhoon numbers which hit China[9]</td>
<td>1880–2002</td>
<td>Yearly</td>
<td>China</td>
<td>0.292**</td>
<td>−0.301**</td>
<td>3</td>
</tr>
<tr>
<td>East Asian winter monsoon index[10]</td>
<td>1873–1996</td>
<td>Dec–Feb</td>
<td>East Asia</td>
<td>−0.290**</td>
<td>0.251</td>
<td>3</td>
</tr>
<tr>
<td>East Asian summer monsoon index[11]</td>
<td>1873–1996</td>
<td>Jun–Aug</td>
<td>East Asia</td>
<td>0.153</td>
<td>−0.194</td>
<td>4</td>
</tr>
<tr>
<td>Global Hadley circulation index[12]</td>
<td>1948–2002</td>
<td>Jan–May</td>
<td>Global</td>
<td>−0.289</td>
<td>0.316**</td>
<td>3</td>
</tr>
<tr>
<td>ENSO index[13]</td>
<td>1871–2002</td>
<td>Jan–May</td>
<td>China</td>
<td>−0.167</td>
<td>0.202</td>
<td>5</td>
</tr>
</tbody>
</table>

[1]: Discontinuous data from Editorial Committee of Academy of Meteorological Science, China Central Meteorological Administration (1981); [2]: Yu (2004); [3]: Xu et al. (2002); [4]: Wu et al. (2006); [5]: Deng and Jiang (2006); [6]: Zhou and Zhang (2003); [7]: Hughes et al. (1994); [8]: Pederson et al. (2001). One to three estimated dryness/wetness years in Shenyang can be found in every top ten tree-ring based dry/wet period (5-year-average) for northeast Mongolia; [9] Wang et al. (1999), records from 1998 to 2002 were obtained from the Yearly Report on the State of Environment in China; [10] and [11]: Shi and Zhu (2000); [12]: Zhang et al. (2007); and [13]: Refer to Fig. 7.

** Significant at p < 0.01.
* Significant at p < 0.05.
isotope fractionation on Changbai Mountains, Northeast China (Xu et al., 2002) (Table 6).

4.3. Verification of regional and global characteristics

Our reconstruction has been verified by data from local archives and from other studies at large temporal–spatial scales (Fig. 5; Tables 5 and 6). The 19th century was a relatively dry period in the region of Northwest China, Mongolia and Northeast China (Editorial Committee of AMSCMA, 1981; Pederson et al., 2001; Li et al., 2006). This low-frequency fluctuation of dryness was even found in some places in Europe (Wilson et al., 2005) and North America (Cook et al., 2004; Gray et al., 2004). The estimated low-frequency drying trend during the most recent 50 yr also coincides with data from most places in Eastern China (Shen et al., 2007), Northern China (Wang and Zhai, 2003) and Northeastern China (He et al., 2006; The Report of Climate Change in Northeast China (1), 2006), but does not agree with some reconstructions in Central China (Hughes et al., 1994), Northwestern China (Li et al., 2006) and Mongolia (Pederson et al., 2001).

At inter-annual and decadal time scales, some severe dry decades, like the 1920s, were widely recorded in many tree-ring series in China (Liang et al., 2006; Li et al., 2007), and are also clearly indicated in our work (Fig. 5; Table 5). Most dominant dry periods in these tree-ring-based precipitation records likewise correspond well to our dry periods. However, the dominant wet periods in those records do not correspond well with our results (Table 5). This suggests a more diverse regional wetness in this season as compared to periods of dryness in northern China.

4.4. Effects of Pacific Ocean climate regimes

As a region located near the west Pacific Rim, regional climate variability in Northeast China is greatly influenced by the Pacific Ocean (The Report of Climate Change in Northeast China (1), 2006; Li et al., 2009). Furthermore, our previous results show that the Chinese pine in Shenyang has been influenced by solar activity, geomagnetic activity, and larger-scale global climatic variability (Chen et al., 2006a, 2007, 2008; He et al., 2007). Specifically, the East Asian monsoon correlates well with regional moisture change in Shenyang (from p < 0.05 to p < 0.01), especially in winter (December–February) (p < 0.01) (Table 6). Correlations were also found between our reconstruction and annual numbers of typhoons that hit China, the January–May El Niño-Southern Oscillation (ENSO), and January–May atmospheric circulation, particularly after applying a 3–5 yr moving average of the data (from p < 0.05 to p < 0.01) (Table 6). Based on the Morlet wavelet analysis (Torrence and Compo, 1998) and MTM spectrum analysis (Mann and Lee, 1996), certain periodic characteristics of tropical Pacific climatic regimes like ENSO (Allan et al., 1996) and tropical biennial oscillation (TBO) variability (its dominant peaks at 2–3 yr) (Meehl, 1987) were found in our reconstruction, e.g. a 2.4-yr periodicity (p < 0.05), a 2.4–yr periodicity band (p < 0.05) and spectral peak near 6 yr (p < 0.05). In addition, the cross-wavelet analysis results in Fig. 7C and D indicate the presence of common 2–4 yr and 6–8 yr periods of variability between ENSO and our reconstruction.

5. Conclusions

Spring precipitation in Shenyang is crucial for sustaining the regional ecosystem there. Our tree-ring based reconstructions of precipitation and a dryness/wetness index quantitatively extends the dry/wet history of Shenyang back to 1771 A.D., thus providing a longer record for evaluating local drought variability and its causes. This reconstruction is the easternmost one in China based on tree-ring widths and is in a city where the water regimes are not normally limiting to plant growth. This dryness and wetness reconstruction does not indicate any obvious long-term trend in recent years, but shows distinctive interdecadal variations. Moreover, the recent drying and warming tendency and the influence of the Pacific Ocean climate system on local dryness/wetness at different scales deserve further attention.

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