MAY-JUNE MEAN TEMPERATURE RECONSTRUCTION OVER THE PAST 300 YEARS BASED ON TREE RINGS IN THE QILIAN MOUNTAINS OF THE NORTHEASTERN TIBETAN PLATEAU

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SUMMARY

A juniper (Juniperus przewalskii Kom.; synonym: Sabina przewalskii) tree-ring width chronology was developed to investigate the regional climate variability for the Qilian Mountains. Statistically, the chronology was appropriate for reconstructing the regional mean temperature of May-June from A.D. 1700 to the present. The phenomenon of synchronous extremely high temperatures and extreme droughts in the 1920s was revealed by comparing our reconstruction with drought events in this region. Multi-taper spectral analysis indicated the existence of significant low- and high-frequency periods (40–46 years, 34, 23–25, 5.6, 2.1, 2.5–2.8 years). Overall, the study not only extended the temperature record, but also provided reliable long-term temperature information to help understand the possible forcing of climate changes in the Qilian Mountains.

Key words: Qilian Mountains, Juniperus przewalskii, tree-ring width, temperature reconstruction.

INTRODUCTION

Understanding the complex paleo-environmental processes associated with rapid global warming and its effect on the global climate is a major issue in paleo-climate research (Barbara et al. 2007). These changes have been documented in terrestrial and marine climate proxies, such as ice cores, tree rings, lake sediments, corals, and historical archives. However, with its unique combination of annual resolution and exact dating, tree rings play an unusually important role in global climate change studies. Tree-ring-based reconstructions can offer extended records from hundreds to thousands of years for a better understanding of the long-term variability of climate parameters.

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Tree-ring reconstructed temperatures over the past millennium for both the northern boreal region and the entire Northern Hemisphere have demonstrated that climate warming over the past 100 years is unprecedented (Jones et al. 1998; Mann et al. 1998; Briffa et al. 2001). Moreover, ice-core data indicate that temperature over the Tibetan Plateau in China has increased significantly in the past 100 years (Yao et al. 2000, 2002; Yang et al. 2006).

The Tibetan Plateau is an ideal area for climate change reconstructions because of its unique geographical position and by the fact that it has been relatively undisturbed by anthropogenic activities (Gou et al. 2006). This is why many scientists have been attracted to investigate the climate history of this high-continental region (e.g., Van Campo & Gasse 1993; Gasse et al. 1996; Wang et al. 2002; Liang et al. 2009; Shao et al. 2009; Zhang et al. 2009). A number of tree-ring studies have been conducted in recent years here, some of which included the reconstruction of temperature, precipitation and the Palmer Drought Severity Index (PDSI) for single sites or regions (Bräuning 1994; Hughes et al. 1994; Shao & Wu 1994; Tian et al. 2007). However, long high-resolution paleo-climatic proxies for this zone or elsewhere in China are still rare. Moreover, most of the previous investigations focused on the events that occurred in the two extreme seasons, summer (June to August) and winter (December to February). Fewer studies were concerned with the spring to summer transition (Liu et al. 2004).

In this study, we report on a 300-year tree-ring width based May-June temperature reconstruction for the Qilian mountains, located at the northeastern margin of the Tibetan Plateau, a data-sparse and environmentally sensitive region. This area is situated at the transition between the Asian summer monsoon and the westerlies. Therefore, ecosystems in this area are expected to respond very sensitively to climatic change.

**STUDY AREA**

The Qilian Mountains, located between 93° 30’ to 103° 00’ E and 36° 30’ to 39° 30’ N, about 850 km long and 200–300 km wide with peaks over 4000 m a.s.l. (Tuanjie Peak, 5826 m), create a strong rain shadow effect for monsoons coming from the southeast (Gou et al. 2005). This region is influenced by both continental climate and local climate of the Tibetan Plateau. It is also characterized by a semi-arid climate, which is strongly influenced by the East Asian monsoon and the westerlies. The mean annual precipitation varies between 150–410 mm and is unevenly distributed in both space and time. The precipitation decreases from east to west and its amount from October to February is only 5–10% of the annual sum. The mean temperature is 0–5 °C between 2000–3000 m a.s.l. Rainfall and temperature show synchronous maxima during the summer season (June-August).

Since most investigated localities are located in arid or semi-arid areas, tree growth generally reflects moisture changes rather than temperature variability (Zhang et al. 2003; Sheppard et al. 2004; Shao et al. 2005; Herzschuh et al. 2006). To get a reliable temperature reconstruction, we selected the comparatively wet eastern margin of the Tibetan Plateau for our study area, since the altitudinal vegetation belts there are mainly determined by a temperature gradient.
Our sampling site (38.97° N; 98.8° E) is situated in the Sunan county of the Gansu Province in the eastern part of the Qilian Mountains at 2900–3000 m a.s.l. (Fig. 1). Between 2000–3000 m a.s.l., the annual mean precipitation increases with elevation (from 150 to 500 mm) while the annual mean temperature decreases with elevation (from +6.2 to -9.6 °C). The vegetation distribution closely follows the temperature- and precipitation-determined heat/water combination in the mountains. They are (from low to high elevation): desert steppe, forest steppe, sub-alpine shrubby meadow, alpine cold desert, and ice/snow zone. The forest steppe zone ranges from 2600 to 3500 m a.s.l.

Below 2600 m, a natural temperate steppe with *Achnatherum splendens* and *Stipa* spp. exists only as fragments due to replacement by intensive agriculture (Herzschuh et al. 2005).

The closest meteorological station available for our study is located near our sampling site at Sunan. This station’s record covers the period of 1957–2006. Precipitation is concentrated from May–September (Fig. 2), coincident with the highest temperature.
Figure 2. Monthly precipitation (bars) and mean temperature (line) at the meteorological station of SuNan for 1957–2000.

MATERIAL AND METHODS

In September 2000, 22 increment corers were extracted from 10 living juniper trees and processed using standard dendrochronological techniques at the Lanzhou University Tree-Ring Lab. Firstly, the cores were air dried, mounted, and sanded to smooth the surface; secondly, all samples were cross-dated using skeleton plots (Stokes & Smiley 1968) and their dated ring widths were measured to ±0.001 mm precision; finally, the quality of visual cross-dating was checked by the COFECHA program (Holmes 1983). These methods ensured exact dating for each annual ring-width series.

The tree-ring chronology used for climate reconstruction was developed by the ARSTAN program (Cook 1985), mainly using conservative detrending methods based on negative exponential functions or straight lines of any slope. A cubic smoothing spline with a window width equal to 67% of the series length was also used in a few cases when anomalous growth trends occurred. Since the sample size declines in the early portion of the tree-ring chronology as younger trees drop out, a method must be used to determine at what point the sample size becomes too small for the chronology to be reliable. To determine this point, we applied the Subsample Signal Strength statistics (SSS; Wigley et al. 1984) with a threshold value of 0.85 chosen to determine the most reliable time span of the chronology. The starting year chosen by this procedure was A.D. 1686. On the other hand, running average correlation (RBAR) and Expressed Population Signal (EPS) (Briffa & Jones 1990) statistics indicate that the chronology loses reliability prior to about A.D. 1700. We therefore use the more conservative cut-off of the chronology which extends back to A.D. 1700 (Fig. 3).
Correlations between tree growth and monthly temperature and precipitation were calculated over their common period of both data sets, 1957–2000. This was done for a 13-month dendroclimatic year from prior to current August. As shown in Figure 4,

Figure 3. The reliable time span (1700–2000) of the standardized tree-ring index chronology (top) for the Qilian Mountains and its sample size in number of cores (bottom).

RESULTS

Correlations between tree growth and monthly temperature and precipitation were calculated over their common period of both data sets, 1957–2000. This was done for a 13-month dendroclimatic year from prior to current August. As shown in Figure 4,

Figure 4. Correlation between tree-ring data and monthly temperature (black bars) and precipitation (grey bars) records for the biological year (previous August – current August) as well as seasonally summarized climatic values; asterisks indicate correlations of 95% confidence levels.
the current year precipitation correlated positively with the tree-ring width index, but not very strongly in May (0.21) and June (0.28). The temperature in the current growth season, however, was significantly negatively correlated with tree growth. Strong negative ($p < 0.05$) correlations were found in May (-0.56) and June (-0.37). Likewise, prior August (-0.46) also significantly correlated with tree growth, which indicates a carry-over effect of climate on tree growth into the following year (Fritts 1976). After combining the months with high correlations between temperature and tree growth, the highest significant correlation (-0.603) occurred for the season May/June.

From a physiological perspective, the cambium of Qilian juniper is likely to become active in May (Shao et al. 2005). Therefore, by the end of June or early July, the early-wood should be largely formed. During the period of cambial activity, enough soil moisture must be available for tree growth when evaporation and evapotranspiration are high and the trees are in full vigor (Shao et al. 2005). Soil moisture loss will be mainly controlled by evapotranspiration, which is determined largely by temperature. If the temperature is too high, soil moisture loss will be rapid and lead to physiological drought stress in the trees. Under this condition, the available moisture cannot meet the needs of tree growth. Therefore, the resulting annual ring will be narrow, which leads to the modeled negative correlation between tree growth and temperature. Thus, temperature is an appropriate climate parameter to be reconstructed from our juniper tree-ring width chronology. Based on these results and considerations, we reconstructed the current May/June temperature from our Qilian Mountains juniper chronology by means of a linear regression model (Cook & Kairiukstis 1990):

$$T_{5.6} = 15.576 - 3.128 \text{STD}_t$$

Leave-one-out test (Mosteller & Tukey 1977) was used to explore the stability of the model, since the observation period is short, covering only 44 years. This involves the calculation of the correlation of the time series after removing the values for one year progressively throughout the whole time period (Fig. 5).
The model was statistically stable, however, the year 1981 was unusual. The explain-
ed variance rose from 36 to 38.4% ($r = 0.620, p < 0.00001$) if we omitted 1981 from the
model. The climate records indicate that the temperature in 1981 was close to the long-
term mean, but total precipitation in May and June was only 46.3 mm, which is 64% of
the 44-year mean (76.99 mm). Moreover, there was scarcely any precipitation (3 mm) in
May, about 11% of the 44-year mean (28.14 mm), a crucial month for tree-ring growth.
We inferred that the extreme drought directly controlled soil moisture in 1981. This
condition was different from normal years, in which temperature mainly controlled tree
growth. Finally, in order to discount the possible interference to the temperature recon-
struction, we removed the year 1981 from the model. The new regression model is:

$$T_{5-6} = 15.821 - 3.413 \text{STD}_t$$

The statistical fidelity of this model was examined by cross-validation tests. As
shown in Table 1, the results of the calibration indicated that our regression model was
valid. The positive RE test result ($RE = 0.33$) also indicated that the model has more

Table 1. Calibration and verification test for the period 1957–2000.

<table>
<thead>
<tr>
<th>R</th>
<th>$R^2$</th>
<th>F</th>
<th>S1</th>
<th>S2</th>
<th>t</th>
<th>RE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.62</td>
<td>0.384</td>
<td>25.58</td>
<td>31 (31**, 28*)</td>
<td>31 (30**, 28*)</td>
<td>3.1</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Note: R, correlation between observed and estimated series; $R^2$, explained variance; F, F-statistics
(Fritts 1991); the sign test counts the agreements and disagreements (S1, S2) between the ob-
served and estimated departures from the mean; S1 is the general sign test between observation
and reconstruction that measures the association at all frequencies; S2 is a similar test, but made
for the first differences thus reflecting the high-frequency climatic variation; ** and * indicate
significance at the 0.01 and 0.05 level, respectively; t, product mean; RE, reduction of error.
skill than the mean climatology of the temperature data. Our reconstruction accounted for 38.4% of the recorded instrumental temperature data variance over 1957–2000, which was not very strong but still highly significant. A comparison of the actual and reconstructed temperature in common period was shown in Figure 6.

**DISCUSSION**

The reconstruction shows May–June temperature fluctuations over the period 1700–2000 A.D. (Fig. 7a). The mean temperature is 12.43 °C, with a standard deviation (SD) of 0.784 °C. A quantitative interval analysis of our reconstruction was given based on a 5-year FFT (Fast Fourier Transform) smoothed running average. This analysis divided the record into three categories based upon the proximity to the mean. The mean of this smoothed series was 12.44 °C with SD = 0.52 °C. Here, we defined a “high temperature period” as the mean plus one SD and a “low temperature period” as the mean minus SD (high temperature period > 12.83 °C; normal, 12.83~12.04 °C; low temperature period < 12.04 °C). Warm phases with a duration of more than 4 years occurred during the periods 1747~1756 (10 years), 1788~1799 (12 years) and 1924~1934 (11 years). Cold

![Figure 7](image_url)

Figure 7. (a) Reconstructed temperature of May–June (thin line) for AD 1700–2000 and its 5-year FFT (Fast Fourier Transform) smoothed running average (bold line); (b) average air temperature from May to June in China for the last 100-year period (Lin et al. 1995); (c) reconstructed PDSI of March–September (thin line) for AD 1855–2001 and its 5-year FFT smoothed running average (bold line) (Tian et al. 2007); (d) drought and famine classification in Northwestern China for AD 1700–1974 (bar) from documentary records, the droughts are quantified from 6 (severe) to 1 (weak).
phases with a duration of more than 4 years occurred during 1723–1738 (16 years) and during 1805–1808 (4 years). Most of these cold years were also found in other temperature reconstructions for the Tibetan-Eastern Himalayan area and reflected large-scale climate anomalies (Wu & Shao 1995; Cook et al. 2003; Bräuning & Mantwill 2004). Normal climatic phases include the periods 1700–1722 (23 years), 1739–1746 (8 years), 1757–1787 (31 years), 1800–1804 (5 years), 1809–1923 (115 years) and 1935–2000 (66 years). Cool and warm spells are of similar length. It is worth to note that those years, in which the values of the smoothed series were below the mean (12.44 °C), accounted for 69.6% (80 years) from 1809–1923. This period is characterized by slightly cool years rather than by slightly warm years. In addition, from 1880 to 2000, May–June temperature shows an increasing linear trend of about 0.87 °C, which agrees well with the global warming trend in the late 20th century.

Our reconstruction extends the temperature history for the Qilian Mountains for the season May to June back to 1700 A.D., providing a long background to evaluate local temperature variability. This offers the possibility to compare this record with the series of average air temperature for the past century based on the analysis of monthly mean temperatures of 711 stations in China from 1873–1990 (Lin et al. 1995) (Fig. 7b). Both curves show a high similarity of temperature variations during the 20th century (Fig. 7a, b): the temperature rose in the early 20th century and reached a maximum centered around 1930 (Fig. 7, shaded area). During that period, the mean value of the decadal temperatures rose by more than 1.3 °C according to the 1700–2000 mean. Then, temperature began to decline and increased again from the beginning of the 1980s.

It is noteworthy that there was a significant growth decline in the late 1920s and early 1930s throughout a wide area of northern China. This growth depression was indicative of a severe and sustained drought epoch in the late 1920s and early 1930s (Liang et al. 2006), which was also revealed by the PDSI reconstruction in the Qilian Mountains (Tian et al. 2007) (Fig. 7c). However, our temperature reconstruction (Fig. 7a) and the average air temperature over China (Fig. 7b) show a synchronous occurrence of elevated temperatures, which reflects broad-scale climate anomalies. Thus, we infer that the period of low tree-ring growth arose from simultaneous occurrence of high temperature and severe drought in the late 1920s and early 1930s. Xu (1997) analyzed the possible social and natural factors leading to the great famine in the late 1920s and early 1930s in Northwest China. The drought and famine classification in the affected area has been reconstructed from historical documents (Yuan 1994). The famine classification was quantified from 6 (severe) to 1 (small), as shown in the histograms in Fig. 7d. It confirms the severe conditions that occurred during the late 1920s and early 1930s.

The multi-taper method (MTM) of spectral analysis (Mann & Lees 1996) was employed to examine the frequency domains of our temperature reconstruction. The analysis over the full range of our reconstruction revealed low- and high-frequency cycles for the May to June temperature variability (Fig. 8). Both high frequency (2–3 yrs) and low frequency cycles (34 and 40–46 yrs) exceeded the 99% confidence level based on a red noise null continuum. Other significant periodicities were found at 23–25 and 5.6 years (95%).
The high-amplitude inter-annual cycles (2–3 and 5.6 yrs) are ubiquitous in climate research. These short-term periodicities of 2–7 years are most likely associated with ENSO variability, although some of them might be caused by random natural variations or other geophysical phenomena (QBO) (Li et al. 2007; Rigozo et al. 2007). The same periods have also been found in tree rings in Alaska (Wiles et al. 1998), Southern Brazil (Rigozo et al. 2003) and Chile (Nordemann et al. 2005). El Niño events originating from atmosphere/ocean interactions over the tropical Pacific Ocean (Enfield 1989; Neelin & Latif 1998) are felt in the Eastern Asian continent. This phenomenon is associated with changes in sea-surface temperature caused in part by the incidence of solar radiation. Thus, variations in the incidence of solar radiation can in a certain form intensify or weaken these phenomena (Rigozo et al. 2007).

A peak at about every 34 years in our reconstruction resembles the Bruckner cycle (about 35 years), which was related to variations in the length of sunspot cycles (Wang et al. 2000). This suggests a possible connection of local climate variability and solar activity, which may indicate solar forcing of climate in the Qilian Mountains. The significant peak at 40–46 years was also found in the reconstructed PDSI series on the Qilian Mountains (Tian et al. 2007). It showed the strong association between temperature and drought variability. The similar period indicates a common climatic forcing to temperature and drought change. These cycles around 32–33 years, close to our period (34 yr), have also been found in temperature reconstructions in northern Fennoscandia (Briffa et al. 1992). However, these agreements may be fortuitous, and the physical meanings of the spectral peaks in our reconstruction require further investigation.

Figure 8. MTM spectral analysis of May to June temperature; solid, dashed and dotted lines indicate the 99, 95 and 90% significance levels, respectively; the dash-dotted line indicates the null hypothesis.
CONCLUSIONS

Using climatically sensitive juniper ring-width data, temperature from May to June for the Qilian Mountains, on the northeastern Tibetan Plateau, was reconstructed. Many warm and cool spells in our temperature reconstruction exhibited similarity with average air temperature over China for the past century, which confirmed the reliability of our reconstruction.

In contrast to what has been reported by many studies over the surrounding regions (Liu et al. 2003; Liang et al. 2006; Li et al. 2007), the driest epoch of the last 200 years, from the late 1920s to the early 1930s, was found to be synchronous with a high temperature period in our tree-ring derived reconstruction. Trees showed an abnormal growth decline in the late 1920s and early 1930s, which sensitively corresponded to the extreme climate event.

Similar cyclic variations found with other palaeoclimate records provide insights into the common climate forcing of temperature and drought in the Qilian Mountains. In addition, this condition provides an important clue for understanding how temperature and precipitation may have interactively influenced the climate in the past and possibly will do so in the future in Northwest China. However, this interpretation remains controversial. Thus, it is still very important to explore more methods and develop more evidence to identify the climate forcing of the local environment change.

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