A tree-ring record of 500-year dry-wet changes in northern Tibet, China

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Abstract: Drought variability of the Tibetan Plateau is an important component across the Asian monsoon. Long-term information about the history of drought is, however, limited because the instrumental records are short. In this study we developed a tree-ring chronology of Sabina tibetica from northern Tibet and used it to reconstruct the history of drought variation for the region. Response analysis shows that water availability in spring and early summer is the main factor limiting the radial growth of Sabina trees in northern Tibet. A May–June Palmer Drought Severity Index (PDSI) reconstruction for the past 500 years ($r = 0.66$, $P < 0.0001$) shows that the seventeenth century was the driest century, whereas the eighteenth, nineteenth and twentieth centuries were the wettest. The sixteenth century was not significantly different from the long-term mean. The major periods of reconstructed dry conditions include AD 1600–1610, 1617–1624, 1630–1632, 1639–1654, 1665–1681 and 1692–1701. Significant wetter periods were found to be AD 1520–1532, 1702–1705, 1716–1722, 1752–1758, 1839–1857 and 1928–1943. The drought rhythm in northern Tibet has three prominent periodicities: 2–7 and 130–200 years for the whole reconstruction and 16–24 years during the ‘Little Ice Age’ (1520 to 1720). Two points of significant abrupt change in tree rings were found in years of 1530 and 1715, which may indicate the onset of dry and wet conditions during the ‘Little Ice Age’. There is an abrupt change around 1965, which may foreshow the beginning of regional prominent warming.

Key words: Tree ring, northern Tibet, Palmer Drought Severity Index, PDSI, climate reconstruction, ‘Little Ice Age’, China.

Introduction

The Tibetan Plateau, with an average elevation above 4000 m a.s.l., is one of the most prominent topographic features on the Earth’s surface. Along its southern flank are the Himalayas with heights reaching 8844 m a.s.l. into the troposphere. The plateau plays an important role in the Asian monsoon system by acting as an anomalous mid-tropospheric heat source (Zhao and Moore, 2004). Additionally, seven of the world’s largest rivers originate on the plateau, and the climate of this region is thus crucial for water resources of most of the Asian continent. Climate change on the Tibetan Plateau is of great importance (Yanai et al., 1992), as it impacts the livelihood of more than half of the world’s population. High-resolution climate proxy records from the Tibetan Plateau, however, are short and have limited spatial coverage (Zhang et al., 2003).

While there are several dendrochronological studies in eastern and central Tibet (Wu and Lin, 1978; Wu et al., 1988, 1989, 1990; Bräuning, 1994, 1999, 2001; Bräuning and Mantwill, 2004), little work has been done on the Naqchu region in northern Tibet. This region is the most important pasturing area in Tibet. The grassland is greatly influenced by climate, especially drought. Therefore, palaeoclimatic records are needed to examine the full range of past drought variability, including magnitude and duration, to better anticipate future climate change.

In addition, drought is a main factor limiting tree growth at the ecotone between the grassland and the forest at Nachqu region in northern Tibet. Climate change models predict higher temperatures and increased variability in precipitation in the future for the Tibetan Plateau (Zhang et al., 1996), which may increase the frequency and intensity of drought.

The Palmer Drought Severity Index (PDSI) is the most prominent index of meteorological drought to measure departures from...
local mean moisture conditions. It is calculated from monthly temperature and precipitation totals (Palmer, 1965; Dai et al., 2004). The PDSI has been successfully used in many dendroclimatic analyses of the past drought variation (Stahle et al., 1985, 1988; Cook et al., 1999, 2004; Sauchyn et al., 2001; Pohl et al., 2002; Watson and Luckman, 2004; Adams and Kolb, 2005; Copenheaver et al., 2005), in part because it approximates the response of tree growth and the soil moisture reservoir to current and antecedent climatic conditions.

In this study we developed a 500-yr ring-width chronology from trees of *Sabina tibetica* and reconstructed PDSI for the Nakqu region in northern Tibet. We compared the reconstruction with other precipitation and/or temperature records near this region and examined the regional extent of these historical drought anomalies.

**Materials and methods**

**Study area**

The study areas are located near Nu River (Salween) between Nyainqen Tanggula Shan and Tanggula Shan, and the conterminous zone of the Northern Tibetan Plateau and the Eastern Tibetan Canyon, southwest of China. Two tree-ring sites, Sogxian and Lhari counties, were sampled in northeastern and southeastern Tibet Nakqu Region (Figure 1). The study areas are characterized by subhumid plateau monsoon. Mean annual precipitation is about 645 mm while mean annual temperature is 0.56ºC (average temperature of January and July is −10.7ºC and 10.1ºC from 1957 to 2002, respectively). July is the hottest month (average temperature 21.3ºC) while June is the wettest month (mean precipitation 137mm) (Figure 2). The mean annual frost-free period is 59 days while the mean relative humidity is 50–55% (climate data were provided by Sogxian and Lhari meteorologic stations). Forest and shrub ecotone cuts across the study area from east to west. Dominant tree species are *Sabina tibetica*, *Picea likiangensis var. balfouriana*, *Abies georgei var. smithii*, *Larix griffithiana*, and *Pinus armandi*. The study sites are pure juniper (*Sabina tibetica*) forests growing on hillside besides valleys. Soils are mainly acid umber and podzolic soil (Scientific Survey Group of the Qinghai-Tibet Plateau, Chinese Academy of Sciences, 1985).

**Chronology development**

One core per tree was collected from relatively old trees in the field. In total 66 increment cores were collected at two sites in Sogxian and Lhari counties. To minimize non-climatic influences on ring growth, only trees with no obvious injury or disease were sampled. Increment cores were dried and mounted on wooden holders, and were sanded with progressively finer grit sand paper. The tree rings were visually cross-dated using skeleton plots. Tree-ring widths were measured to the nearest 0.001 mm with a...
TA Unislide Measurement System (Velmex Inc., Bloomfield, New York). The cross-dated tree-ring sequences were quality checked by the COFECHA program (Holmes, 1983), and errors were corrected following microscopic examination of the tree-ring characteristics. Cores that did not cross-date were not included in this analysis.

We used the computer program ARSTAN to detrend the ring-width sequences using a negative exponential curve or a straight line with negative slope (a horizontal line) and to average the standardized ring-width sequences into a master chronology for Lhari and Sogxian (Cook and Holmes, 1986; Cook and Kairiukstis, 1990). All series of the two sites were then applied to develop a new synthetic chronology for regional climate analysis (Figure 3). Sample depth within the chronology typically decreases back in time and may result in time-dependent variance changes in the earlier part of the chronology. The variance in chronologies was stabilized in the chronology compilation process with the Briffa RBAR-weighted method, which uses average correlations between series in combination with sample size each year to make adjustments in the variance for changes in sample size (Osborn et al., 1997).

**Statistical analysis**

To reconstruct past climate variation, correlation analysis was used to identify the influence of climate on ring-width growth. Climate data used for this analysis included monthly mean temperature, monthly minimum temperature, monthly maximum temperature, total monthly precipitation, monthly mean humidity and monthly mean PDSI over a span of 14 months (from September of the previous year to October of the current year). Instrumental climate records of Sogxian and Lhari were obtained from the China National Climatic Data Center. The climate records of mean temperature and precipitation over a common period at the two sites were averaged into a single climate record for regional climate analysis, respectively. PDSI data (1951 to 2003) at a site (31.25°N, 93.75°E) between Sogxian and Lhari was obtained from the NOAA-CIRES ESRL/PSD Climate Diagnostics branch, Boulder, Colorado, USA, through their web site: http://www.cdc.noaa.gov/
**Results and discussion**

**Chronologies and their relationship with climatic variables**

Statistical characteristics of the site chronologies showed that *S. tibetica* in this region is a promising species for dendroclimatic studies. The strength of signals expressed by the tree-ring indices increased with the increase in the number of sample replications (Table 1). Consequently, the chronology intervals used in the analysis were 1494–2004 and 1542–2004 for the two site chronologies, and 1573–2004 for the combined chronology, which contained at least five sample replications for each year (Figure 3). All three chronologies had high SNR (signal-to-noise ratio), SD (standard deviation) and EPS (expressed population signal), indicating that the radial growth of different trees was responding to common factors. First-order autocorrelation (AC1) for the three chronologies ranged from 0.48 to 0.52, which showed some consistency within sites and regions. Variance in first eigenvector (VFE) accounted for 22–35% of the variance in the site chronologies. The value of mean sensitivity (MS) of the three chronologies was rather small, nevertheless it was enough to obtain accurate results with response function methods (Rolland, 1993).

The two chronologies of Sogxian and Lhari showed a common signal though with an altitude difference of 379 m. The strength of the common signal can be assessed using the mean interseries and chronologies correlations, which displayed a stronger common signal in tree growth in Lhari than Sogxian. The synthesis chronology correlated better with Lhari than Sogxian because the segment of SCSL chronology (1494–1753) consisted mainly of Lhari samples. Although the correlation coefficient between Sogxian and Lhari chronologies was not high, it reached the significant level of *P* < 0.001 (Table 2). These reflected the common responses to climatic influences. Consequently we combined the two chronologies into a synthesis chronology.

The climate–growth response patterns were similar in the two site chronologies (Figure 4). The chronology of Sogxian was positively correlated with May precipitation, June humidity and January minimum temperature of the growth year and November maximum temperature of the previous year, and was negatively correlated with May and June mean temperature and June maximum temperature of the growth year. The Lhari chronology was positively correlated with May and June precipitation and July and August mean temperature of the growth year and November mean and maximum temperature of the previous year, and was negatively correlated with May mean and maximum temperature of the growth year. Thus, the monthly mean temperatures and monthly total precipitation at these sites were negatively correlated. The chronologies at two sites were negatively correlated with May and June temperature of the growth year, and were positively correlated with November temperature of the previous year.

The response function analysis between the synthetic chronology and the averaged climate records of the two sites were applied to determine monthly regional weather variables significantly affecting tree growth. The results of the response function were similar to those at the two sites (Figure 4). The synthetic chronology was negatively correlated with May and June mean temperature of the growth year and November precipitation of the previous year, and was positively correlated with May precipitation of the growth year and November temperature of the previous year. The correlation relationship between the synthetic chronology and averaged climate records was stronger than those at the two sites, which indicated that tree growth in this region exhibited common characteristics of climatic limited factors.

At high elevation sites, abundant precipitation was generally combined with enhanced cloudiness and reduced radiation input and temperature (Bräuning and Mantwill, 2004). Ring width of high-elevation conifers is often reduced by low winter temperatures

### Table 1  Chronology statistics for the standardized tree-ring width chronologies used in the study

<table>
<thead>
<tr>
<th>Site</th>
<th>Long.(E)</th>
<th>Lat.(N)</th>
<th>Elevation (m a.s.l.)</th>
<th>N</th>
<th>Length of chronology</th>
<th>MS</th>
<th>SD</th>
<th>AC1</th>
<th>SNR</th>
<th>VFE</th>
<th>EPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sogxian</td>
<td>94.29</td>
<td>31.63</td>
<td>3854</td>
<td>27</td>
<td>1494–2004</td>
<td>0.17</td>
<td>0.22</td>
<td>0.51</td>
<td>3.80</td>
<td>21.93%</td>
<td>0.85</td>
</tr>
<tr>
<td>Lhari</td>
<td>93.46</td>
<td>30.60</td>
<td>4233</td>
<td>31</td>
<td>1542–2004</td>
<td>0.17</td>
<td>0.20</td>
<td>0.48</td>
<td>11.25</td>
<td>34.95%</td>
<td>0.92</td>
</tr>
<tr>
<td>SCSL</td>
<td></td>
<td></td>
<td></td>
<td>58</td>
<td>1512–2004</td>
<td>0.14</td>
<td>0.17</td>
<td>0.52</td>
<td>21.92</td>
<td>21.62%</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Note: *N* is the number of trees; MS is the mean sensitivity; SD is the standard deviation; AC1 is the AutoCorrelation order 1; SNR is the signal-to-noise ratio; VVF is the variance in first eigenvector; EPS is the expressed population signal; SCSL is the synthetic chronology of Sogxian and Lhari.

### Table 2  Correlations between chronologies and mean tree to tree correlation (RABR) for the three chronologies

<table>
<thead>
<tr>
<th>Chronology</th>
<th>SCSL</th>
<th>Lhari</th>
<th>Sogxian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCSL</td>
<td>1.00</td>
<td>0.94*</td>
<td>0.39*</td>
</tr>
<tr>
<td>Lhari</td>
<td>0.94*</td>
<td>1.00</td>
<td>0.17*</td>
</tr>
<tr>
<td>Sogxian</td>
<td>0.39*</td>
<td>0.17*</td>
<td>1.00</td>
</tr>
<tr>
<td>Mean tree to tree correlation</td>
<td>0.15</td>
<td>0.30</td>
<td>0.17</td>
</tr>
</tbody>
</table>

* Significant at *P* < 0.001.
as a consequence of bud damage, frost desiccation and reduced root activity because of low soil temperature (Körner, 1998; Bräuning and Mantwill, 2004). The increase in winter temperature may reduce these damages. An increasing trend of winter precipitation over the past century at high elevations and in many subarctic regions led to delayed snowmelt in these permafrost environments. As a result, the initiation of cambial activity (necessary for the formation of wood cells) has been delayed (Vaganov et al., 1999). Consequently, it may reduce the tree radial growth in the next year. For all that, why heavy snow in winter had negative effects on tree growth at high elevations is still unknown (Takahashi et al., 2005).

The positive correlation with summer temperature was reasonable, which suggested that significant high temperatures and suitable precipitation in summer of the growth year could increase the radial growth of *S. tibetica* in northern Tibet. The results of response functions analysis showed that the precipitation and temperature of May and June of the growth year and November of the previous year were important climatic factors for radial growth. However, when controlling for precipitation in May and June of the growth year and November of the previous year, the partial correlation coefficient between the chronologies and temperature did not reach the 5% significance level. When controlling for temperature, the precipitation had the same results. The partial correlation indicated that the *S. tibetica* radial growth in this region is not solely controlled by temperature or precipitation. Therefore we checked the influence of combined climatic factors on *S. tibetica* radial growth. Positive correlation with precipitation and negative correlation with temperature during the growing season relate to the input (rainfall) and output (evapotranspiration) processes that determine soil water availability. As PDSI combines the influence of temperature and precipitation, we investigated the radial growth response to PDSI.

Response function analysis indicated that the synthetic chronology was only positively correlated with May and June PDSI of the growth year (Figure 4). Correlations between tree-ring widths and May–June PDSI were as high or higher than for precipitation or temperature alone, suggesting that tree rings integrate a set of climate incorporated in the PDSI.

The tree growth of northern Tibet focused on May to September. This holds especially for spring, when early wood cells, which account for about 90% of the total ring-width, are formed (Bräuning and Mantwill, 2004). Consequently, the climatic conditions of May–June are important to radial width. Furthermore, the generalized negative association between May temperature and radial

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**Figure 4** Response functions analyses of standard chronologies with local monthly weather variables at Sogxian (A, B) and Lhari (C, D) and the synthetic chronology with averaged weather variables of the two sites (E) and PDSI (F), respectively. MT, monthly mean temperature; P, monthly total precipitation; HT, monthly maximum temperature; LT, monthly minimum temperature; HM, monthly mean humidity. The asterisks above columns represent a significant ($P < 0.05$) effect of temperature, precipitation or PDSI on tree-ring index.
The model obtained was:

$$Y = -6.47 + 7.33X$$  \hspace{1cm} (1)$$

where $Y$ is mean May–June PDSI and $X$ is the tree-ring index.

For the calibration period (1951–2000) of the final reconstruction, the adjusted $r^2$ is 0.436 (Table 3). As the difference between RMSE (root mean squared error of validation) and $s_e$ (the standard error of the estimate) is small (0.30), the RE (reduction of error) statistic (0.39) is larger than 0.30 over the verification period (1951–2000) using leave-one-out method validation, which indicates the reconstructed equation is reliable. For additional verification, the sign test (5.78) and product means test statistics (3.14) were both found to be significant at the 0.001 level. The product means test measures the level of agreement between the actual and estimated values and takes into account the sign and magnitude of departures from the average (Fritts, 1976). Tree-ring indices explained 44% of the variance in PDSI (Figure 5). These results indicated that the model used here passed the critical tests for verification and was optimized by achieving the greatest predictive capability for the fewest independent variables.

As the model proved to be reliable, the fitted linear model was used to reconstruct May–June PDSI back to 1494. Reconstructed PDSI generally matches both the interannual patterns and decadal-scale trends in the actual PDSI time series (1951–2000) (Figure 6). The largest outlier (the difference between values observed and predicted by the model) was 2.87 in 2000, with the actual PDSI being much higher than that reconstructed. Trees do not often capture extreme wet periods (Fritts, 1976). The plots of the actual and reconstructed PDSI showed the general tendency for the reconstructed values to have smaller amplitude than the actual values, which is a predictable feature given that only a percentage of the actual variation has been modelled. The reconstructed climates can, therefore, be considered conservative estimates of actual climate.
sharp increase in moisture at the beginning of the sixteenth and eighteenth centuries. The 1840s was the wettest of the last 500 years. Most of these periods are found in other temperature and precipitation reconstructions from the Tibetan Plateau (Wu and Lin, 1978, 1988; Bräuning, 1994; Qin et al., 2003; Wang et al., 2004; Linderholm and Bräuning, 2006).

The variance in SCSL chronologies was stabilized in the chronology compilation process with the Briffa RBAR-weighted method (Osborn et al., 1997). The relative reduction was greater for the early period, and when applied to adjust the regional mean time series it reduced the early enhanced variance a little further. The extreme years of drought or wetness did not basically change in the whole series especially after 1810 because of the constant sample size. This adjustment also had little effect on the period of wetness and drought change, while mainly influencing the magnitude of high and low growth events in the earliest centuries. The 1510s–1540s was the wettest period before adjustment. The water availability in this period, however, became near normal after adjustment. The value of the whole series fell slightly after adjusting the variance, ie, the climate became a little drier. Consequently, changes in the frequency of extremes and the period of wetness–drought switch over the five centuries is unlikely owing to changes in sample depths as the chronology variance resulting from sample size was stabilized and sample size was determined to be adequate for the full period, as evaluated by the EPS, while the magnitude of wetness and drought events may largely change.

Wavelet analysis indicates that the drought variability has not remained constant during the last 500 years (Figure 7). The most prominent periodicities on the whole reconstruction are 130–300 years. There is, however, a very strong peak at 250 years. The 250-yr periodicity could be linked with longer-term changes in variability of large-scale modes of solar activity, which forced a recurrent pattern of drought with a dominant periodicity of 206 years (Hodell et al., 2001). In addition, the low frequency signal may be the direct response of tree growth to the variations in the solar cycle because of the strong irradiation in the Tibetan Plateau. This is questionable because the series only contains roughly two cycles. Other significant periodicities on most of the reconstructions are found between 2 and 7 years, which characterizes the variability of ENSO-related time series (Schöngart et al., 2004), whereas the periods are distributed over time of 1530–1555, 1580–1620, 1830–1855 and 1920–1980. The period of 1920–1950 was known as a relatively quiescent period of ENSO (Webster et al., 1998; Wang et al., 2004), therefore the other time segments could also be weak ENSO periods. Many of the more extreme anomalies, such as severe droughts and flooding have strong teleconnections to ENSO events (McCabe and Dettinger, 1999; Cook et al., 1999). In spring, high temperatures and lack of rainfall during ENSO events could bring drought to the region (Shaman and Tziperman, 2005).

The anomaly of the East Asian monsoon seems to coincide with ENSO events in many cases, which also exhibit 2–6 years oscillation (Shi et al., 1998). Rainfall decreases with weakened monsoon intensity. The monsoon also influences temperature at high elevation. Bräuning and Mantwill (2004) showed evidence of increased summer monsoon rainfall as a consequence of global warming.
after 1980. Our reconstruction, however, did not change after 1980, presumably because of the negative interaction of temperature and precipitation. The 2–7 year periodicity could also be related to the climatological, physiological or external rough two year cycle in this region.

Decadal-scale periodicities of 16–24 years appeared during the ‘Little Ice Age’, which suggested that there existed drought variation even occurring at lower temperatures. The cause of the ‘Little Ice Age’ is unknown, but many people have pointed to the similarity of reduced solar activity and the timing of the ‘Little Ice Age’. The approximate bidecadal drought rhythm in northern Tibet could be modulated by the years of Hale solar cycle minima and 18.6-yr lunar tidal maxima (Currie, 1984; Cook et al., 1997). These results do not eliminate, however, the possibility that drought change rhythm is forced by coupled ocean–atmosphere processes. Recent modelling results suggest that unstable ocean–atmosphere interactions in the North Pacific could also be responsible for the rhythm (Cook et al., 1997).

Wavelet analysis establishes different periods, but does not specify the character of the reconstructed trend in PDSI changes. Thus, the next step was to detect abrupt changes. The Mann–Kendall test was the most appropriate for detecting abrupt changes in climatological series (Esteban-Parra et al., 1995). The application of this test (Figure 8) showed that there were four points of intersection between two trend lines. Only two abrupt points, 1530 and 1715, were significant, because the graphs of the sequential onward version of the statistical trend test (solid line) and the sequential backward curve (dashed line) intersected at the 95% significance level. These points indicate the beginning of drier and wetter conditions during the ‘Little Ice Age’. An increasing drier trend appeared around 1520 and reached its maximum around 1650; in reverse, an increasing wetter trend at the beginning of the sixteenth and the eighteenth centuries, afterwards lost its significance. The moving t-test had similar results to the drought periods detected with the MK-test method, adding robustness to our results. Tang et al. (1998) indicated abrupt climate changes occurred in the early 1920s, 1960s and early 1980s in Qinghai-Tibetan Plateau, which coincided with the abrupt climate change in the Northern Hemisphere. In the recent century, our reconstruction only detected an abrupt change around 1965, which may indicate the beginning of prominent warming.

**Conclusions**

*Sabina tibetica* has been successfully cross-dated and dendrochronologically analysed in northern Tibet. The water availability in spring or early summer (May and June) is the main limitation to radial growth. The chronology is strongly correlated with PDSI records and provides accurate estimates of drought variability. A 500-yr drought record is reconstructed based on this correlation. The reconstruction clearly indicates the time range of the latest ‘Little Ice Age’ (1520–1720) in northern Tibet, which is characterized as cold and dry. The PDSI reconstruction shows the seventeenth century to be the driest century, while the eighteenth, nineteenth and twentieth centuries were the wettest during the past 500 years and there is a trend to wetter conditions between 1720 and 1965. The major periods of dry conditions occurred from 1600 to 1610, 1617 to 1624, 1630 to 1632, 1639 to 1654, 1665 to 1681 and 1692 to 1701. Significant intervals of wetter conditions are found in the periods 1520–1532, 1702–1705, 1716–1722, 1752–1758, 1839–1857 and 1928–1943. The drought rhythm in northern Tibet has three prominent periods: 2–7 and 130–200 years on the whole reconstruction and 16–24 years during the ‘Little Ice Age’ (1520–1720). The 2–7 year periodicity could be driven by ENSO, solar activity or the Asian monsoon. We find two significant points of abrupt change (1530 and 1715) during the ‘Little Ice Age’. The almost significant abrupt event around 1965 may indicate the beginning of regional prominent warming.

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