Difference in tree growth responses to climate at the upper treeline: A case study of Qilian Juniper in the Anyemaqen Mountains

PENG Jianfeng1, 2, GOU Xiaohua1, CHEN Fahu1, LI Jinbao3, LIU Puxing4, Zhang Yong1, FANG Keyan1

1. Center for Arid Environment and Paleoclimate Research (CAEP), Key Laboratory of Western China’s Environment Systems MOE., Lanzhou University, Lanzhou 730000, China;
2. College of Environment and Planning, Henan University, Kaifeng, 475004, China;
3. Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Columbia University, NY 10964, USA;
4. College of Geography and Environment Sciences, Northwest Normal University, Lanzhou 730070, China

Abstract:

Three ring-width chronologies were developed from Qilian Juniper (Sabina przewalski kom.) at the upper treeline along a west-east gradient in the Anyemaqen Mountains. Most chronological statistics, except for Mean Sensitivity (MS), decreased from west to east. The first principal component (PC1) loadings indicated that stands in a similar climate condition were most important to the variability of radial growth. PC2 loadings decreased from west to east, suggesting the difference of tree-growth between eastern and western Anyemaqen Mountains. Correlations between standard chronologies and climatic factors revealed different climatic influences on radial growth along a west-east gradient in the study area. Temperature of warm season (July-August) was important to the radial growth at the upper treeline in the whole study area. Precipitation of current May was an important limiting factor of tree growth only in the western (drier) upper treeline, while precipitation of current September limited tree growth in the eastern (wetter) upper treeline. Response function analysis results showed that there were regional differences between tree growth and climatic factors in various sampling sites of the whole study area. Temperature and precipitation were the important factors influencing tree growth in western (drier) upper treeline. However, tree growth was greatly limited by temperature at the upper treeline in the middle area, and was more limited by precipitation than temperature in the eastern (wetter) upper treeline.

Key words: dendrochronology; treeline; climate-growth correlations; Qilian juniper;
With the rapid development of dendrochronology, tree ring records have become one of the most important proxies of climate and have been used to study climate change over much of the globe (Mann et al 1998; Esper et al. 2002; Mann and Jones 2003). High-resolution proxy climate records, such as those derived from tree-ring series, are of great value for understanding natural background variation in environmentally sensitive regions of China (Liu et al. 2005a).

The Tibetan Plateau (TP) is a unique geographical cell on earth with an average elevation above 4000m a.s.l., and climate changes over the plateau play an important role in global change. It is considered that the TP was a sensitive area to global change, and it was also the initial region of climate change of eastern Asia at the decadal scale (Tang et al. 1988). There have been great progresses in using tree-rings to study climate change on the TP since the earliest studies in its southeastern part (Wu and Lin. 1978). Qilian juniper (Sabina przewalskii kom.) is a native tree species growing in the northeastern TP, with cold- and drought-tolerant taxon forming forests. Due to the extreme growth conditions and long potential lifespan of more than 1000 years, tree-ring scientists have developed the longest chronology of China using Qilian juniper tree ring width data (Kang et al.1997, Zhang et al. 2003), and reconstructed and analyzed climate change of past millennium on the TP (Kang et al. 1997; Zhang et al. 2003; Shao et al. 2004; Liu et al. 2005b).

In order to fully understand climate variability, it is necessary to have a good spatial and temporal coverage of climate variables. So there were lots of studies about regional differences of level environmental gradient (Jacoby et al. 1996; Bräuning 2001; Rigling et al. 2002; Rolland 2002; Linderholm et al. 2003; Macias et al. 2004), and most regional studies located near treeline (Esper and Schweingruber 2004; Frank and Esper 2005; Lara et al. 2005; Wilmking and Juday 2005). Of course, northern and high-latitude alpine treelines are generally thought to be limited by temperature. However, the difference in tree growth responses to climatic factors exists at different upper treelines.

To our knowledge, there have been no studies of Qilian juniper growth in relation to regional difference of climatic variability using tree-ring series at the upper treeline on the northeastern TP. One exception is to compare climatic variability at upper and lower treelines in the Dulan area by Liu et al (2006). There was few or none dendrochronological studies in the Anyemaqen Mountains before Gou et al. (2006a, b) and Peng et al. (2007). This paper attempts to use three ring-width chronologies developed from Qilian Juniper at the upper treeline from east to west in the Anyemaqen Mountains to analyze their responses to climatic factors and to detect the difference of climatic variability.
Results

Three ring-width chronologies were developed from Qilian Juniper wood at the upper treeline along a west-east gradient in the Anyemaqen Mountains (Figure 1). The chronological statistics were shown in Table 1. Except that MS (mean sensitivity) increased from west to east (DQH-YYCH-HBSH), other statistics, including SD (standard deviation), AC1 (first order autoregressive coefficient), SNR (signal-to-noise ratio), EPS (expressed population signal), all decreased from west to east (DQH-YYCH-HBSH). Higher SNR and EPS value in Table1 indicated there are more climatic information in these chronologies. The differences could be due to different climate conditions from west to east in the Anyemaqen Mountains.

Principal Component Analysis (PCA) was performed on three standard chronologies for the common time period 1850-2002. PC1 has the largest loading of the chronologies and represents the greatest common variance (63.097%) in all chronologies (Table 2). The PC1 loadings were positive for all chronologies (Figure 2) and reflect the tendency for growth patterns to be correlated over the whole sampling area, which are consistent with the macroclimate environment. PC2 and PC3 account for 25.563% and 11.034% of the total variance (Table 2), respectively, and PC2 weighting coefficient (Figure 2) decreased (0.778— -0.067— -0.624) from west to east (DQH-YYCH-HBSH). Therefore, PC2 indicated the difference of tree-growth from west to east in the Anyemaqen Mountains. Because, temperature and precipitation of the eastern Anyemaqen are higher than those of the western Anyemaqen, which is about 4° in temperature and 18% in relative humidity. Also, Table 3 showed that precipitation decreased from east to west (HN-MQ-MD or HN-TD-XH) along the Anyemaqen Mountains.

Correlations among standard chronologies (1850-2002) were low. The highest correlation was 0.501 between DQH and YYCH chronology, and the lowest (0.286) was between DQH and HBSH, and only 0.453 between YYCH and HBSH.

Correlations between standard chronologies at the upper treeline and climatic factors revealed differences in radial growth along west-east gradient in the study area. Temperature of warm season (July-August) was important to radial growth in the whole study area. Precipitation of current May was only an important limiting factor to tree growth at the west (drier) sampling site, while precipitation of current September limited tree growth at the east (wetter) site (Figure 3). Response function analysis results showed that there were regional differences between tree growth at the upper treeline and climatic factors in various
sampling site of the whole study area. Temperature and precipitation were the important factors influencing tree growth at the west (drier) treeline. However, tree ring widths were greatly limited by temperature at treeline in the middle area and more limited by precipitation than temperature in the eastern region (Figure 4).

Discussion

In the PCA, the first PC accounted for the greatest proportion of the total variance in the three chronologies, the second PC accounted for the largest fraction of the remaining total variance, and so on. Each PC was orthogonal (unrelated) to the others and involved a linear combination of the three chronologies. The series of PC scores over the chronology length represented the growth variation common to the three sites. The weight associated with each chronology indicated information about the characteristic growth relationship between a specific site and the PC: the higher the weight, the closer the relationship (Legendre and Legendre 1998; Zhang and Hebda, 2004).

Similar results of correlations among standard chronologies about level gradient study were described by Macias et al (2004) in previous studies across northern Fennoscandia. Macias thought that the lower correlation could be due to the youngest and the least replicated chronologies. But in this study, lower correlation could be attributed to more young trees in eastern HBSH chronology and different climate conditions at different level sampling sites.

As shown in Figure 3, we found that correlations between temperature and tree growth at upper treelines were similar at different sampling sites. Tree growth has positive and significant correlations (above 95% significant level) with temperatures in current warm period, but varies with August/July/July-August for DQH, YYCH, and HBSH sampling site, respectively. Significant (above 95% significant level) and negative correlations with temperature of previous July/August/October and current September were only found at the DQH sampling site. All tree growth has negative correlation with current April-May temperature. However, complex correlations occurred between precipitation and tree-growth at upper treelines from west to east Aynemaqen. Significant correlations (above 95% significant level) with current May (positive) and September (negative) were found for DQH sampling site, while previous July (negative) and current September (negative) were found for HBSH sampling site, but no significant correlations were found for YYCH sampling site.

Generally, May-September is a warmth-humid season on the Tibetan Plateau (Qinghai Forest Editorial Committee, 1993). Figure 5 also showed that May-September mean
temperature was almost above 5° and precipitation over 40 mm at some nearby weather stations. Positive correlation between tree-growth at upper treelines and temperature of July-August could be due to higher temperature in this period could be sufficient to tree-growth at upper treelines. Similar result that high-latitude alpine treeline is generally thought to be limited by available warmth was reported by Wilmking and Juday (2005). Increase in air temperature and evaporation in April-May resulted in shortage of water in the start of tree growing period, so high temperature in April-May limited tree growth at treeline. Generally, the upper treeline is the area with high precipitation in the high mountains; therefore there are few significant correlations with precipitation at the three sampling sites. However, May was the start of tree growing period on the Tibetan Plateau, with increasing in air temperature and evaporation. High precipitation in May had a positive effect on tree growth in DQH, which not only provides moisture for photosynthesis but also benefits to capture nutriment from the environment. Similar results were reported in the south Qinghai plateau (Qin et al, 2003) and the Delingha (Shao et al. 2004) and Dulan (Liu et al. 2006) in Qinghai province. This was apparently related to their level sites, because these level sites are to the west of DQH sampling site with a much drier climate than DQH sampling site. To east and wetter HBSH site, September was the last tree growing period; here plentiful precipitation was suited lower temperature sequentially limiting tree-growth.

Similarly, response function analysis results of tree-growth to climatic factors were different for different regions (Figure 4). Explained variances of growth to climate factors (including temperature and precipitation together, temperature and precipitation) almost had a decreasing trend from west to east. However, only growth variances in YYCH to precipitation were the lowest in the three regions. Figure 6 showed that temperature was the main limiting factor to tree growth in the western DQH and middle YYCH sampling sites, similar results was reported by Kang et al (1997) in the Dulan area of Qinghai, and Wang et al (1982) and Liu et al (2005b) in the Qilian Mountains. This could be due to its location in west part of the study area that is far from monsoon. At this point, it was reasonable that precipitation was an important limiting factor of tree growth in the western DQH sampling site. Growth variance to temperature is less than that of precipitation in the east regions (HBSH) (Figure 4), it was obvious that precipitation was a more important factor on tree-growth; this could be due to a large change of monthly precipitation resulting from summer monsoon.

Materials and methods
Study Area

The Anyemaqen Mountains are located on the fold-zone margin of the northeastern Tibetan Plateau, a transition zone of monsoon to non-monsoon, semi-wetness to semi-aridity, and warm zone to sub-frigid zone. It is also the core area of Yellow River headwaters natural reserve. This is a climate-sensitive and complex area, and is characterized by a short and mild summer period and a relatively long and cold winter period. In this area, the mean annual temperature is 0.5-3.9°C, the warmest month mean temperature is 11.0-14.2°C, accumulate temperature above 0°C is 1402.4-2006.0°C. The mean annual precipitation is about 450-620 mm, 56%—62% of the annual precipitation falls in summer due to the monsoonal regime, while the winters are cold and dry because of the prevalence of continental air masses from central Asia (Wang 1988). Qilian Juniper is almost exclusively found on the southern slopes (including southeast-facing and southwest-facing) of 3400-3800 meter above sea level, and mainly distributes in the Hebei, Yangyu, and Zhongtie forestry centre (Figure 6), with simple structure within forest and monolayer pure forest. This area is the most southern boundary and the highest boundary of Qilian Junipers (Qinghai Forest Editorial Committee, 1993). Therefore it is important to study this sensitive region to climate change.

Field sampling

Fieldworks were carried out in June and July of 2003 and 2005. Three sampling sites near treeline along west-east transect were found in DQH (Zhongtie forestry centre) and YYCH (Yangyu forestry centre) and HBSH (Hebei forestry centre), respectively (Figure 6). Each sampling site was adopted in sampling-zone with interior high-gap of about 15 meters, 20-30 of the biggest and presumably oldest trees were selected for increment core sampling. Trees were selected subjectively, with the view of obtaining climatic signals from sensitive trees and reducing non-climatic signals from local disturbances. 1-2 cores were extracted at a height of about 1.3m (at breast height) from each tree (Table 4).

Chronology development

In the laboratory, all cores were mounted in slotted wooden boards and polished with different sandpaper of progressively fine grit, until annual ring boundaries could be easily distinguished, and then were dated following the procedures of Stokes and Smiley (1968). The ring widths were measured using a Velmex measure system, with 0.001 mm precision. All measured tree-ring sequences were quality-checked with the computer program
COFECHA (Holmes 1983), the cores with poor quality (e.g., fragmented, or rotten) were excluded to improve the common signals in tree-ring width sequences. Standard and residual chronologies were developed with ARSTAN program (Cook and Holmes 1986) by combining standardized tree ring series with biweighted robust estimation. The resulted individual core index series are averaged to produce a ring-width chronology with biological growth trends removed while preserving variations that are likely related to climate (Cook and Kairiukstis 1990). Our data were detrended by fitting a negative exponential curve to the raw ring-width data. In some cases a cubic spline equal to 67% of the series length was also used (Cook and Kairiukstis 1990). In general, the sample size declines in the early portion of a tree-ring chronology; therefore we used the sub-sample signal strength [SSS] (Wigley et al. 1984) with a threshold value of 0.80 to evaluate the reliable time span of the final chronologies. In so doing three standard chronologies were developed from tree ring width at upper treelines from west to east in Aynemaqen Mountains (Figure 1).

Climate data

Five meteorological stations (Maduo, Maqin, He’nan, Tongde and Xinghai) in the study area are selected (Table 3 and Figure6). The mean annual temperature and precipitation (1960-2001) are shown in Figure 4. All stations have the most precipitation and the highest temperature in July; and each station holds mean monthly temperature above 5°C and monthly precipitation above 40 mm (except Maduo in May) during May-September. Correlation analysis results of climatic records between 5 meteorological stations showed that correlation coefficients between mean monthly temperature and between total monthly precipitation were above 98%, with remarkable consistency. After calculating and comparing, we found that the tree-ring chronologies are better correlated with the climatic data from Maqin and He’nan, which are the nearest meteorological station to YYC and HBS, respectively. The nearest meteorological station to DQH is Tongde, which is unfortunately situated in a deep valley and featuring a different climate regime and weaker correlated with tree-ring chronology from DQH. Thus we used the second nearest station (Xinghai) with better correlation to tree-ring chronology instead. Accordingly, we used climatic records from Xinghai, Maqin and He’nan meteorological stations for DQH, YYCH and HBSH sampling sites in the previous calibration, respectively.

Tree growth-climate relationships
In order to describe tree growth variations, PCA (principal component analysis) (LaMarche and Fritts 1971; Brubaker 1980) was used to examine the structure of the relationships between the standard tree-ring series and evaluate the shared variance among standard chronologies. PC analysis was conducted by using the software PCA (Grissino-Mayer et al. 1996) for the common interval 1850–2002 in this study.

To identify the influence of climatic factors on tree growth, standard chronologies were compared to temperature and precipitation by correlation functions (Blasing et al. 1984) with DENDRO2002 software program (Biondi 2000), and response function analysis with PRECON software program version 5.17 (Fritts 1998). In the two analyses, the relationships between ring width and monthly climate data were examined for a sequence of 18 months starting with May of the previous year and ending in October of the current year in which the ring formed. The significance of the response coefficients was tested with a bootstrap method, which assesses the variability of the coefficients based on a large number of sub-samples randomly extracted, with replacement from the initial data set (Guiot 1991). Such random sampling and the subsequent calibration and verification of the climate-growth model were iterated 500 times with the program PRECON (Fritts 1998).

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References:


**Figure Captions:**

Figure 1. The three standard chronologies developed at treeline in Aynemaqen Mountains.

Figure 2. Scatterplots of the loadings derived from each standard series of the PC1 and PC2.

Figure 3. Correlation of 3 standard chronologies with mean monthly temperature and total monthly precipitation in Xinghai/Maqin/He’nan meteorological stations, respectively.

Figure 4. Mean monthly temperature (0.1°C) and total monthly precipitation (mm) averaged for AD 1960-2001 using records from each meteorological station in the Anyemaqen Mountains.

Figure 5. Response results of tree-growth at treeline from west to east in Anyemaqen Mountains to climatic factors

Figure 6. Summary map of sampling sites and meteorological stations.
Table Captions:
Table 1. Standard chronological characteristics: sub-sample signal strength (SSS), mean sensitivity (MS), standard deviation (SD), first order autocorrelation (AC), signal-to-noise ratio (SNR), and expressed population signal (EPS).
Table 2. Principal component analysis derived from 3 tree-ring standard chronologies
Table 3. Locations and mean annual temperature and annual precipitation (1960-2001) of each meteorological station close to sampling sites.
Table 4. Locations of the sampling sites and the number of cores of each chronology and the temporal span of the chronologies are included.
Figure 1. The three standard chronologies developed at the upper treeline in the Aynemaqen Mountains.

Figure 2. Scatterplots of the loadings derived from each standard series of the PC1 and PC2.
Figure 3. Correlations of three standard chronologies with mean monthly temperature and total monthly precipitation in Xinghai/Maqin/He’nan meteorological stations, respectively. (Vertical dot line is a dividing line between precious year and current year, and the left is precious year. Ellipse indicates correlations above 95% significant level.)
Figure 4. Response results of tree-growth at the upper treeline from west to east in the Anyemaqen Mountains to climatic factors (T+P: temperature and precipitation together; T: temperature; P: precipitation)

Figure 5. Mean monthly temperature (0.1°C) and total monthly precipitation (0.1mm) averaged for AD 1960-2001 using records from the meteorological stations in the Anyemaqen Mountains.
Figure 6. Map showing the location of the sampling sites and meteorological stations.
Table 1 Standard chronological characteristics: sub-sample signal strength (SSS), mean sensitivity (MS), standard deviation (SD), first order autocorrelation (AC1), signal-to-noise ratio (SNR), and expressed population signal (EPS). The common interval was set as 1850-2000.

<table>
<thead>
<tr>
<th>Study sites</th>
<th>SSS&gt;0.8 Since (core)</th>
<th>Standard chronology</th>
<th>Common interval 1850-2000</th>
<th>Detrended series</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQH</td>
<td>1550(11)</td>
<td>0.214</td>
<td>0.399</td>
<td>0.693</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.328</td>
</tr>
<tr>
<td>YYCH</td>
<td>1745(9)</td>
<td>0.216</td>
<td>0.343</td>
<td>0.671</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.956</td>
</tr>
<tr>
<td>HBSH</td>
<td>1819(4)</td>
<td>0.223</td>
<td>0.338</td>
<td>0.614</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.218</td>
</tr>
</tbody>
</table>

Table 2. Principal component analysis derived from 3 tree–ring standard chronologies (the common time period 1850-2002).

<table>
<thead>
<tr>
<th>Principal component</th>
<th>Eigenvalue</th>
<th>% total variance</th>
<th>Cumulative % variance explained</th>
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<tbody>
<tr>
<td>PC1</td>
<td>1.8929</td>
<td>63.097</td>
<td>63.097</td>
</tr>
<tr>
<td>PC2</td>
<td>0.7669</td>
<td>25.563</td>
<td>88.660</td>
</tr>
<tr>
<td>PC3</td>
<td>0.3402</td>
<td>11.340</td>
<td>100.000</td>
</tr>
</tbody>
</table>

Table 3 Locations and mean annual temperature and annual precipitation (1960-2001) of each meteorological station close to the sampling sites.

<table>
<thead>
<tr>
<th>Meteorological station</th>
<th>longitude</th>
<th>latitude</th>
<th>Altitude (m a.s.l.)</th>
<th>T(℃)</th>
<th>P(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maduo (MD)</td>
<td>98°13′E</td>
<td>34°55′N</td>
<td>4273.3</td>
<td>-3.88</td>
<td>312.2</td>
</tr>
<tr>
<td>Maqin (MQ)</td>
<td>100°15′E</td>
<td>34°28′N</td>
<td>3720.0</td>
<td>-0.53</td>
<td>506.4</td>
</tr>
<tr>
<td>Henan (HN)</td>
<td>101°36′E</td>
<td>34°44′N</td>
<td>3500.0</td>
<td>0.25</td>
<td>583.4</td>
</tr>
<tr>
<td>Tongde (TD)</td>
<td>100°39′E</td>
<td>35°16′N</td>
<td>3290.4</td>
<td>0.46</td>
<td>422.0</td>
</tr>
<tr>
<td>Xinghai (XH)</td>
<td>99°59′E</td>
<td>35°35′N</td>
<td>3324.3</td>
<td>1.23</td>
<td>350.6</td>
</tr>
</tbody>
</table>

Table 4. Locations of the sampling sites and the number of cores of each chronology and the temporal spans of the chronologies.

<table>
<thead>
<tr>
<th>Site &amp; I.D.</th>
<th>Long.</th>
<th>Lat.</th>
<th>Elev.(m)</th>
<th>Years</th>
<th>Length (yrs)</th>
<th>Mean ring-width (±SD)</th>
<th>Number of cores/trees</th>
</tr>
</thead>
<tbody>
<tr>
<td>DQH</td>
<td>100°04′05″E</td>
<td>35°00′05″N</td>
<td>3755</td>
<td>1433-2004</td>
<td>572</td>
<td>0.49±0.213</td>
<td>50/33</td>
</tr>
<tr>
<td>YYCH</td>
<td>100°20′10″E</td>
<td>34°48′01″N</td>
<td>3800</td>
<td>1615-2002</td>
<td>388</td>
<td>0.80±0.347</td>
<td>45/40</td>
</tr>
<tr>
<td>HBSH</td>
<td>100°43′33″E</td>
<td>34°43′32″N</td>
<td>3730</td>
<td>1807-2004</td>
<td>198</td>
<td>0.92±0.42</td>
<td>29/21</td>
</tr>
</tbody>
</table>