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Drought Reconstruction in the Qilian Mountains over the Last Two Centuries and Its Implications for Large-Scale Moisture Patterns

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ABSTRACT

We present a composite tree-ring chronology from two sites of Qilian Juniper (*Sabina przewalskii*) in the northwestern Qilian Mountains (QM), Northwestern China. Precipitation in June was found to be the main limiting factor for tree-growth. The tree rings are also significantly and positively correlated with June precipitation over large areas of the northern Tibetan Plateau (TP). The authors thus consider that the tree-ring based drought reconstruction from 1803–2006 is representative of a large area drought history. During the reconstruction period, persistent and severe dry epochs occurred in the 1820s–1830s, 1870s–1880s, 1920s, and 1950s–1960s, and persistent wet periods were found from 1803–1810s, 1890s–1920s, and 1970s–1980s. The severe dry and wet periods are similar to those found over the northeastern TP, indicating the potential linkages of the drought regimes between them. Comparison with global SST indicates that the drought variability is closely related to the tropical Pacific and Arctic Ocean SSTs, suggesting the connection of regional moisture variations to the Asian monsoon and westerly belt circulations, respectively.

Key words: drought variability, tree rings, SST, Qilian Mountains

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1. Introduction

The Tibetan Plateau (TP) is a unique geographical region with an average elevation greater than 4000 m above mean sea level. Climate over the plateau is influenced by the mid-latitude westerly winds and Asian monsoon (Wang et al., 2005; Lu et al., 2007). In order to better understand climate variations, it is necessary to have good spatial and temporal coverage of climate variables (Knapp et al., 2002; Peng et al., 2008). However, meteorological stations over the TP are sparse and short (e.g., few records extend before 1950s), which limit the scope of historical climate study which is possible in this area. This situation may be improved by employing tree-ring data, which provides a climate archive with precise dating, extensive spatial availability, and high climatological sensitivity (Fritts, 1976).

Tree rings have been widely used to study the climatic variability of the past centries or millennium over the TP (Kang et al., 2002; Zhang et al., 2003; Sheppard et al., 2004; Shao et al., 2005, 2006; Liu et al., 2006; Gou et al., 2006, 2007a,b; Huang and Zhang, 2007; Tian et al., 2007; Zhang and Qiu, 2007; Li et al.,

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2008a; Fang et al., 2009). A few of these studies have investigated large-scale climate variability over the TP, and found that low-frequency precipitation variation in Delingha(DLH), Dulan(DUL), Ulan(WUL), and the headwater area of the Yellow River show a similar pattern (Shao et al., 2005, 2006; Zhang and Qiu, 2007; Li et al., 2008a). However, none of these studies have focused on the northern Qilian Mountains (QM). To our knowledge, there have been no studies using tree-ring data to investigate the relationship between the drought variability of the northern QM and the northeastern TP, which hinders our ability to understand in detail the climatic variability over the northeastern TP.

In this paper, a new tree-ring width chronology was developed from two sites of Qilian Juniper (*Sabina przewalskii*) in the northwestern QM. As shown below, this chronology represents June precipitation variability over a large area of the northeastern TP, which helps provide information about the drought history over the entire northeastern TP. Because a large portion of China is influenced by the Asian monsoon, the moisture variability of many areas in China is impacted by SST (Chang et al., 2000; Lau and Weng, 2001; Li et al., 2008a). Thus, we have explored the linkages of the regional precipitation and reconstructed drought to the global SST. The purposes of this study are: (1) to reconstruct regional drought variability for the northwestern QM during the last two centuries; (2) to compare with other chronologies developed from the northeastern TP to gain insights into the regional climate variability; (3) to investigate the linkages of the actual and reconstructed precipitation to the global SST variability.

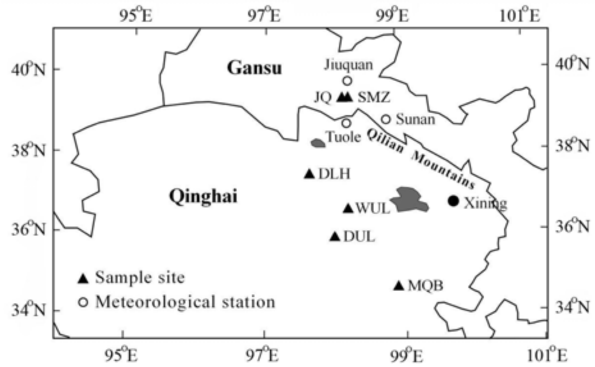

Fig. 1. Map of the sampling sites (JQ, SMZ, DLH, WUL, DUL, and MQB), and the meteorological stations (Jiuquan, Tuole, and Sunan).

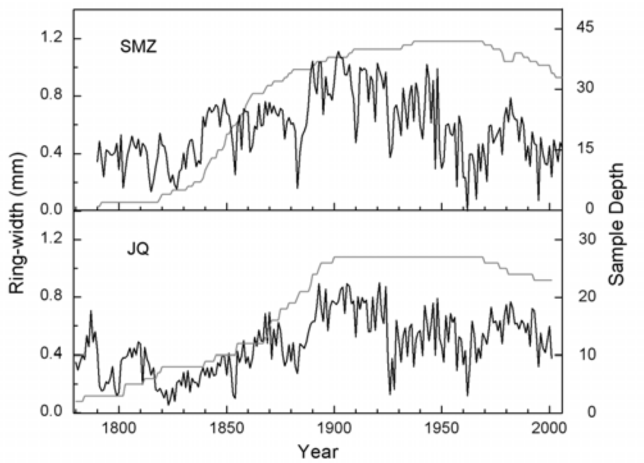

Fig. 2. The mean ring-width measurements of samples at sites SMZ and JQ (black lines) and their corresponding sample depths (grey lines).

2. Data and methods

2.1 *Tree-ring data*

Tree-ring samples used in this study were collected from two sites in the northwestern QM of the northeastern TP (denoted as JQ and SMZ, see Fig. 1 and Table 1). Qilian Juniper (*Sabina przewalskii*) is the dominant tree species in this area, which is sparsely distributed on the mountain slope at an elevation between 2700–3400 m a.s.l. Increment cores were taken from living trees of Qilian Juniper at both sites. All sampled trees appeared healthy and relatively isolated, representing optimal conditions for maximizing climate signals contained in the growth rings. Our two sampling sites are close to each other, and the JQ chronology was developed by Tian et al. (2007).

In the laboratory, standard techniques of dendrochronology were used to process the sampled tree cores. After air drying, mounting and sanding in the laboratory, all the samples were carefully cross dated with skeleton plots (Stokes and Smiley, 1968), and each ring-width was subsequently measured to 0.001 mm precision. The COFECHA program (Holmes, 1983) was further employed to check the quality of visual cross dating. These methods ensure exact dating for each of growth ring series with annual resolution. The average correlation coefficients between raw series and the mean series of the sample sites are 0.755 (SMZ) and 0.693 (JQ), respectively, reflecting reliable dating of these samples.

As the two sample sites were not far from each other and their mean ring-width series agreed well with each other (Fig. 2), all the raw series were standardized to develop one ring-width chronology (denoted as WQL) to better represent the regional climate signal. The computer program ARSTAN (Cook, 1985) was then used to develop the chronology. In order to re-

Table 1. General information about the sample sites and the meteorological stations.

Date Type	Site code	Location	Elevation (m)	Samples (Cores/Trees)	Time span
Tree-ring	SMZ	39°25′N; 98°27′E	3050–3090	45/23	1790–2006
	JQ	39°46′N; 98°29′E	2800–2900	27/12	1780–2001
Meteorological data	Jiuquan	39°46′N; 98°29′E	1477	–	1951–2005
	Sunan	38°50′N; 99°37′E	2312	–	1957–2005
	Tuole	38°48′N; 98°25′E	3367	–	1957–2000

move the growth trends, all the tree ring series were conservatively detrended by the most appropriate functions. Finally, a cubic spline with a 50% frequency-response cutoff equal to 67% of the series length was used to treat most series (54 series). The other series were conservatively detrended by fitted negative exponential curves (6 series) and linear regression (12 series). As generally the sample size declines in the early part of the tree-ring chronologies, we used the expressed population signal (EPS) (Cook and Kairiukstis, 1990) with a threshold value of 0.85 to evaluate the most reliable time span of the chronologies. Based on this procedure, we consider the ring-width chronology to be valid for dendroclimatic study. Therefore, the starting year of the chronology is 1803.

In order to identify whether the WQL chronology represents features that are coherent over large areas of the northeastern TP, the chronology is compared with others on the northeastern TP (i.e., DLH, DUL, WUL, and MQB; see Fig. 1). DUL and MQB were developed by Zhang et al. (2003) and Gou et al. (2007a), respectively. WUL is a chronology from Shao et al. (2005, 2006; denoted WL4). DLH is the mean value of three chronologies, i.e. two chronologies from Shao et al. (2005, 2006; denoted DLH1 and DLH2) and the chronology from Zhang and Qiu (2007). All of the chronologies are sensitive to moisture variability, and demonstrate very strong coherence with other moisture-sensitive chronologies for the same area (Shao et al., 2005, 2006; Gou et al., 2007a; Zhang and Qiu, 2007).

2.2 *Climate data*

In order to investigate climate-tree growth relationships in the study region, the WQL chronology was correlated with monthly temperature and precipitation records from three nearby meteorological stations (Jiuquan, Sunan, and Tuole; see Fig. 1 and Table 1). As shown in Fig. 3, precipitation and temperature records of the three stations in the common period 1957–2000 show sharp increases in May, peaks in July, and diminishment in August and thereafter. May–September rainfall at the Jiuquan (84.78 mm), Sunan (255.39 mm), and Tuole (284.08 mm) stations accounts for 80.2%, 86.3%, and 91.9% of the annual rainfall, respectively. The annual mean (May–September) temperatures at the Jiuquan, Sunan, and Tuole stations are 7.35°C (18.52°C), 3.75°C (13.44°C), and −2.84°C (7.28°C), respectively. Therefore, the seasonality for both the precipitation and temperature at those stations indicates that the study area may be affected by the monsoon climate (Zhang and Crowley, 1989; Wang, 2006). It is clear that precipitation at Tuole is much higher than Jiuquan and marginally higher than Sunan, while temperature shows an opposite trend. This pattern is at least partially due to the discrepancy in their site elevations (Table 1). The average values of the temperature and precipitation of the three stations were used as the regional mean climate data during the common period 1957–2000.

Two other climate datasets were used in this study. To demonstrate that both the tree-ring chronology and the precipitation records reflect large-scale rainfall variability, we correlated the data with the regional monthly gridded precipitation dataset developed by the Global Precipitation Climatology Centre (GPCC, at 1° × 1° resolution; Schneider et al., 2008). To conduct spatial analysis of local precipitation and recon-

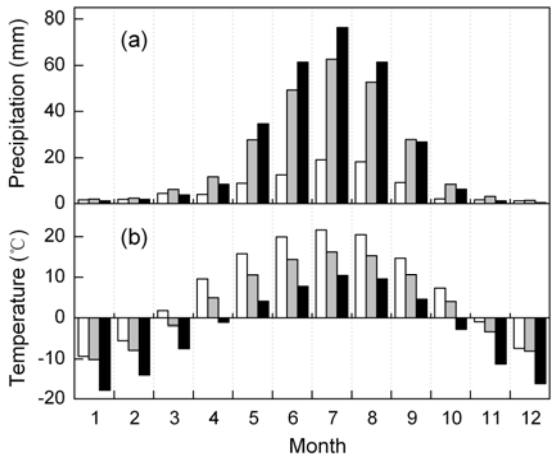

Fig. 3. (a) Monthly total precipitation and (b) monthly mean temperature records for the meteorological stations at Jiuquan (white bars), Sunan (grey bars), and Tuole (black bars) during 1957–2000.

structed drought with global SST, we employed the extended reconstructed SST dataset (ERSST.v2) developed by Smith and Reynolds (2004). The above analyses were performed using the KNMI Climate Explorer (available at http://www.knmi.nl).

3. Results and discussion

3.1 *Climate-tree growth relationships*

Correlation analyses between tree ring chronology and monthly precipitation and temperature data from previous July to current September were conducted in the common period 1957–2000. As shown in Fig. 4, precipitation in the previous August (correlation coefficient r=0.477) and current June (r=0.665) were significantly and positively correlated with tree growth. Temperature in previous August (r=−0.342) and current June (r = −0.387) were significantly and negatively correlated with tree growth. The relationships between tree growth and precipitation were much more significant than for tree growth and temperature, and negative correlations with temperature are accompanied by positive correlations with precipitation. Obviously, precipitation played a more important role than temperature in modulating tree growth, implying that tree-ring indices largely represent signals of rainfall rather than temperature. Therefore, the study will primarily discuss the precipitation variability.

The correlation coefficients between tree-ring indices and different periods of precipitation were also calculated. The highest correlation between tree-ring indices and the seasonal precipitation was found in May–June (0.658). This relationship is in good agreement with previous dendroclimatic studies of the same species at other moisture-sensitive sites on the neighboring northeastern TP (Qin et al., 2003; Zhang et al., 2003; Sheppard et al., 2004; Shao et al., 2005; Huang and Zhang, 2007; Zhang and Qiu, 2007; Li et al., 2008a). In order to further test whether tree-ring

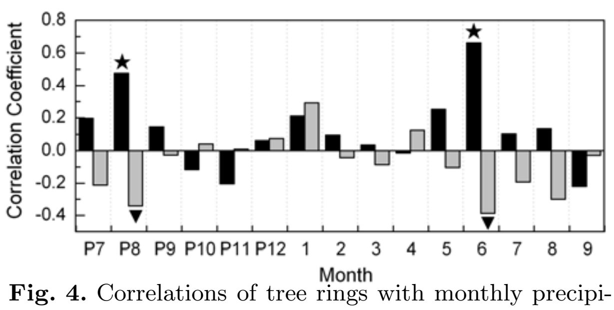

Fig. 4. Correlations of tree rings with monthly precipitation (black bars) and temperature (grey bars) records during 1957–2000. The asterisk and the triangle indicate correlations at the 99% and 95% confidence levels, respectively.

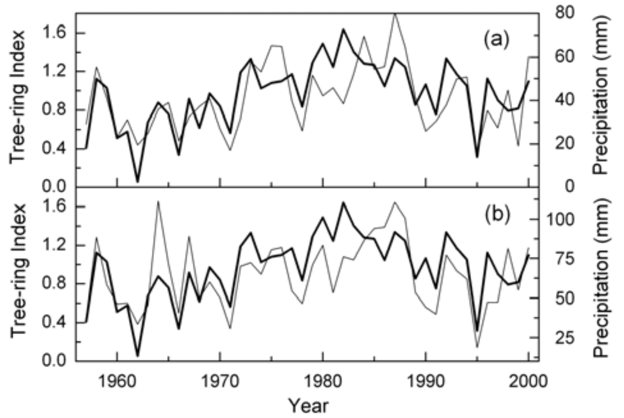

Fig. 5. Temporal changes of tree-ring series (thick lines), and precipitation (thin lines) for (a) June and (b) May–June during 1957–2000.

indices were really better at capturing May–June precipitation than June precipitation, we compared the temporal changes of tree-ring indices and the precipitation during the period 1957–2000. As shown in Fig. 5a, June precipitation was well estimated by tree-ring indices, even for the low-frequency variability. May-June precipitation was also well estimated by tree-ring indices, but the low-frequency variations tended to be underestimated, especially during the 1960s (Fig. 5b). This phenomenon may be attributed to the lack of strong low-frequency variations of May precipitation (not shown). However, tree-ring index was seemingly better at tracking May–June precipitation than June precipitation for the high-frequency variations. Our analysis thus suggests that tree-ring indices explain more information about June precipitation in the study area, although tree-ring indices also record May precipitation information.

In order to identify whether the above relationship between tree growth and regional precipitation variability exists over a large spatial domain, we correlated the WQL chronology with the regional GPCC gridded precipitation data of the growing season (i.e., May–September). As shown in Fig. 6b, the chronology is significantly and positively correlated with June precipitation over large areas of the northern TP, while there is no significant correlation with regional precipitation in other months (not shown), suggesting that June moisture variability over the northern TP can be reflected by tree-ring indices from the northwestern QM. This finding is similar to that of a previous tree-ring study on the northeastern TP (Li et al., 2008a).

Correlations of meteorological records with the regional GPCC gridded precipitation were also calculated to investigate if the precipitation records in the northwestern QM are capable of representing regional

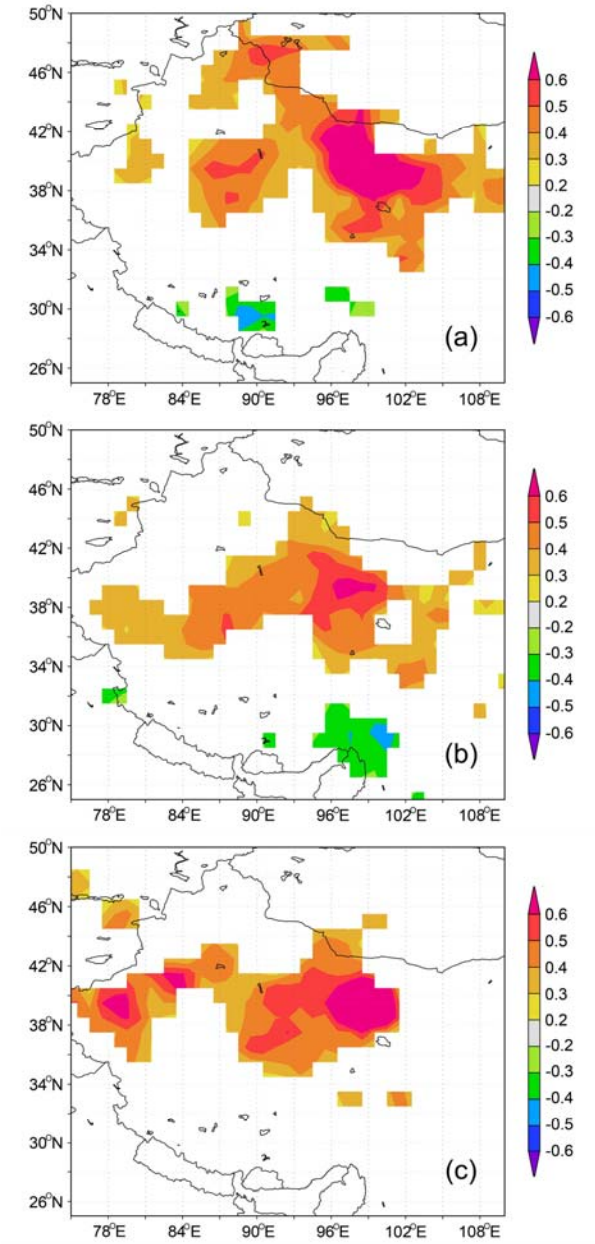

Fig. 6. Correlation patterns of (a) local June precipitation with concurrent regional GPCC precipitation; (b) tree rings with regional GPCC June precipitation; and (c) local July–September precipitation with concurrent regional GPCC precipitation. All the correlations were calculated for the period of 1957–2000 and the insignificant correlations (i.e., $\alpha > 10\%$) were masked out.

large-scale rainfall processes. Similar to tree-ring indices, June precipitation at the stations is significantly and positively correlated with GPCC June precipitation over large areas of the northern TP (Fig. 6a), and this phenomenon is also seen for other months. For example, Figure 6c shows significant correlation with July–September precipitation, although the region of correspondence becomes smaller but more significant. These results suggest that precipitation records in the northwestern QM are capable of representing the regional rainfall patterns.

3.2 *Long-term drought variability*

The above climate-growth relationship analysis demonstrates that the correlations between tree rings and June precipitation are strong enough for conducting reconstructions. Therefore, a simple linear regression model was used to reconstruct precipitation for the northwestern QM. During the common period between tree-ring data and precipitation (1957–2000), the reconstruction accounted for 44.2% of the actual precipitation variance. As shown in Fig. 5a, we can infer that the reconstruction estimates the observed changes of June precipitation very well, because precipitation was reconstructed by a simple linear regression model.

Split-sample calibration-verification tests (Meko and Graybill, 1995) were employed to evaluate the statistical fidelity of our reconstruction model. The resulting statistics are shown in Table 2. There are 44 years of observational data; 29 years of data were used for calibration, and 15 years data were used for verification. The values of the two most rigorous tests of model validation, the reduction of error (RE) and the coefficient of efficiency (CE) are both positive, which indicates significant skill in the tree ring estimates. The results of a sign test for 1957–1985, 1986–2000, and 1957–1971 are all above the 99% confidence level, while for 1972–2000 the results are weak, which is possibly due to the higher precipitation during 1972–1990 (Fig. 5a). At any rate, these test results demonstrate the validity of our regression model. Therefore, the precipitation was reconstructed over the period A.D. 1803–2006 (Fig. 7).

As shown in Fig. 7, the mean June precipitation is only 41.8 mm, suggesting an arid growing environment

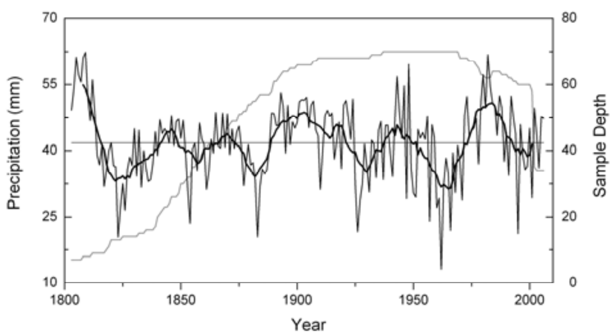

Fig. 7. Reconstruction of June precipitation (thin line) for 1803–2006 and its 11-year running average (thick line), and the corresponding sample depth (grey line).

Table 2. Statistics for calibration and verification test results for the common period of 1957–2000.

	Calibration (1957–1985)	Verification (1986–2000)	Calibration (1972–2000)	Verification (1957–1971)	Full Calibration (1957–2000)
R	0.689	0.678	0.503	0.776	0.665
R^2	0.475	0.460	0.253	0.603	0.442
Reduction of error	/	0.386	/	0.864	/
Coefficient of efficiency	/	0.374	/	0.577	/
Sign test	26+/3−*	12+/3−*	16+/13−	12+/3−*	/

*Significant at α <0.01.

in the northwestern QM. The June precipitation has a slight moistening trend since the 1810s, while the variability also has a gradual increase, especially since the 1920s. Over the length of the precipitation reconstruction from 1803–2006, extreme dry years are found in 1823, 1854, 1883, 1926, 1957, 1962, 1966, and 1995, when June precipitation was less than 25 mm, 40% lower than the mean. Interestingly, these extreme dry years occurred about every 35 years, which may be attributed to the Bruckner cycle of solar activity (Tian et al., 2007).

The June precipitation reconstruction contains considerable low-frequency variability during the past two centuries (Fig. 7). Persistent and severe dry epochs occurred in the 1820s–1830s, 1870s–1880s, 1920s, and 1950s–1960s, and persistent wet periods were found from 1803–1810s, in the 1890s–1920s, and in the 1970s–1980s. Most of these dry and wet periods are consistent with tree-ring studies on the neighboring northeastern TP, where tree rings have been shown to be very sensitive to May–June precipitation (Qin et al., 2003; Zhang et al., 2003; Sheppard et al., 2004; Shao et al., 2005; Huang and Zhang, 2007; Zhang and Qiu, 2007; Li et al., 2008a). As shown in Fig. 8, we calculate the 21-year running average of the WQL chronology along with that of four other chronologies developed from the northeastern TP (i.e., DLH, DUL, WUL, and MQB; Zhang et al., 2003; Shao et al., 2005, 2006; Gou et al., 2007a; Zhang and Qiu, 2007) during the past two centuries. Obviously, the low-frequency variability of our chronology has very strong coherence with the other four chronologies (Fig. 8). This coherency shows that tree growth anomalies in the northwestern QM are capable of representing the regional drought variability over the northeastern TP, at least during the past two centuries.

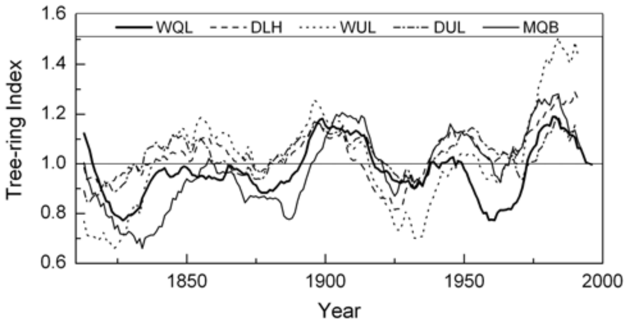

Fig. 8. Comparisons of 21-year running averages between our chronology (WQL) and the four tree-ring chronologies (DLH, WUL, DUL, and MQB) developed for the northeastern TP.

3.3 *Linkages to global SST*

The above climate data analysis suggested that the study area may be affected by monsoon climate (Fig. 2). Prior climate studies based on tree rings have identified high-frequency peaks at 2–3 year time scales in the northwestern QM and vicinity (Kang et al., 2002; Tian et al., 2007), which also existed in this study (not shown). These 2–3 year peak cycles fall within the overall bandwidth of ENSO (Diaz and Markgraf, 2000), suggesting a possible connection of droughts in this region to tropical SST (Chang et al., 2000; Lau and Weng, 2001). Prior studies have shown that climate in the QM is also influenced by the westerly belt (Zhang et al., 2008). Therefore, the actual and reconstructed precipitation were used to clarify the influence of global SST on regional moisture variability in the common period 1957–2000 (Fig. 9).

As shown in Figs. 9a and 9b, the most significant correlations of the actual and reconstructed precipitation with global June SST were all found for the western tropical Pacific Ocean, with a secondary teleconnection region of less significant correlation in the Greenland Sea. This result suggests that these ocean domains may serve as the major moisture sources of June precipitation for our study region. Generally, the western tropical Pacific Ocean and Greenland Sea fall into the Asian-Australian monsoon (Li and Zeng, 2002) and westerly belt (Cui, 1994; Li et al., 2008b) circulation domains, respectively, suggesting possible teleconnections of local droughts to these climate systems. The significant negative correlation patterns with SST for the western tropical Pacific Ocean are also seen for the headwater area of the Yellow River

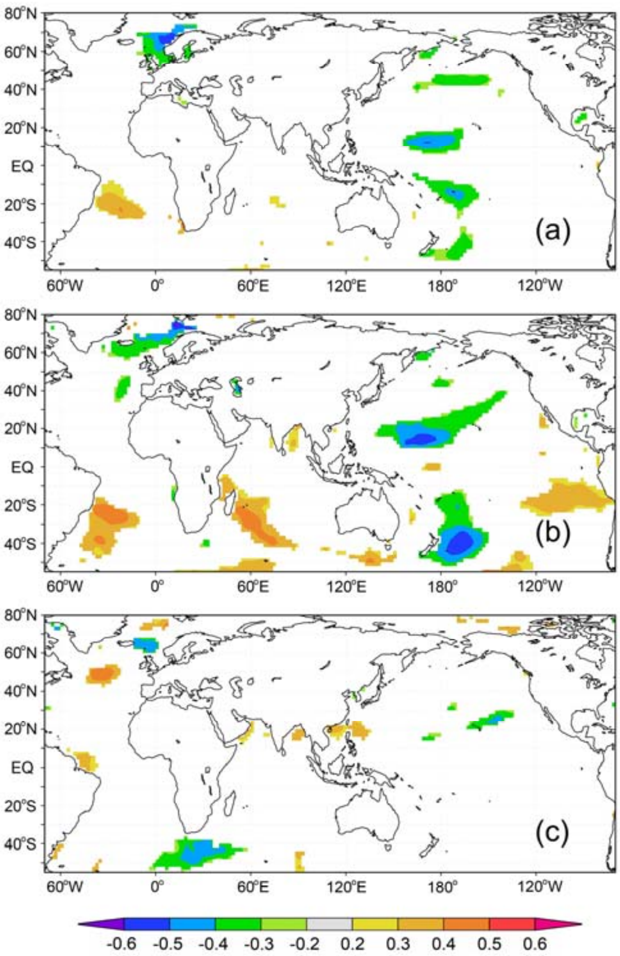

Fig. 9. Correlation patterns of (a) local June precipitation with concurrent global SST; (b) the reconstructed June precipitation with June global SST; and (c) local July–September precipitation with concurrent global SST. All the correlations were calculated for the period of 1957–2000 and the insignificant correlations (i.e., $\alpha > 10\%$) were masked out.

on the northeastern TP (Li et al., 2008a), suggesting similar moisture influences for both regions in June.

In July–September, precipitation in our study area was weakly correlated with global SST (Fig. 9c). This correlation pattern seemed to suggest that the ocean is not the main moisture contributor for the study area. Given the lack of simple explanations for these patterns, future studies are needed to further clarify regional forcing mechanisms.

4. Conclusions

A new ring-width chronology spanning 1803–2006 was developed by merging tree-ring data from two sites of Qilian Juniper (*Sabina przewalskii*) in the northwestern QM. Following standard dendroclimatological methods, June precipitation was reconstructed during the past two centuries. The reconstruction explained 44.2% of the actual June precipitation variability for the common period 1957–2000. During the reconstruction period, extreme dry years are found in 1823, 1854, 1883, 1926, 1957, 1962, 1966, and 1995. Persistent and severe dry epochs occurred in the 1820s–1830s, 1870s–1880s, 1920s, and 1950s–1960s, and persistent wet periods were found from the beginning of the record to the 1810s, in the 1890s–1920s, and in the 1970s–1980s. These results are consistent with dry and wet periods which occurred in the neighboring regions over the northeastern TP. The June precipitation shows a slight moistening trend since the 1810s, while the variability has also gradually increased, especially since the 1920s.

Comparison of our chronology with others developed for the northeastern TP indicates a strong coherency in low-frequency tree growth anomalies during the past two centuries. It is further shown that the chronology is significantly and positively correlated with June precipitation over large areas of the northern TP. This coherency shows that tree growth anomalies in the northwestern QM indicate large-scale drought variability over the northeastern TP, at least during the past two centuries. Comparison with global SST indicates the drought variability is closely related to the tropical Pacific and Greenland Sea SSTs, suggesting possible connection of regional moisture variations to the Asian monsoon and westerly belt circulations, respectively.

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