Dendroclimatic Temperature Record Derived from Tree-Ring Width and Stable Carbon Isotope Chronologies in the Middle Qilian Mountains, China

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Source: Arctic, Antarctic, and Alpine Research, 39(4) : 651-657

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(07-506)[LIU-X]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 39, No. 4, 2007, pp. 651–657

Dendroclimatic Temperature Record Derived from Tree-Ring Width and Stable Carbon Isotope Chronologies in the Middle Qilian Mountains, China

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Abstract

Using long-lived Qilian juniper (*Sabina przewalskii* Kom.) in the middle Qilian Mountains, the temperature variations in the last 1000 yr were reconstructed. We find that the annual growth ring width and $\delta^{13}C$ series mainly reflect variations in regional temperature. Except in May, warmer temperatures indicate greater growth over the period from December to April, and $\delta^{13}C$ values in tree-rings are higher for years with higher temperature. The notable features in the temperature reconstruction are the occurrence of the Little Ice Age from A.D. 1600 to 1880 and the abrupt warming over the end of past millennia. The comparison of our chronology to a Northern Hemispheric temperature proxy shows that our tree-ring data will facilitate intercontinental differentiation of large-scale synoptic climate variability.

Introduction

Tree-ring chronologies provide a unique environmental archive because of their high resolution and the possibility of constructing precisely dated records covering thousands of years. Width and stable carbon isotope ratios of tree rings have been used to reconstruct past climates by correlating with temperature (Wilson and Grinsted, 1977; Sheu et al., 1996; Aucour et al., 2002), relative humidity (Stuiver and Braziunas, 1987; Loader et al., 1995; Liu, et al., 2003) and human activities (Juknys et al., 2002; Jedrysek et al., 2003).

Over the last two decades, the discovery of long-lived juniper (Wang et al., 1982) has demonstrated significant potential for the paleoclimatic reconstruction from Qilian juniper, a tree species found in China (Zhang and Wu., 1997; Kang et al., 2002, Zhang, et al., 2003). Tree-ring widths of Qilian juniper have proven particularly useful as a proxy for water status, such as moisture index and river run-off (Zhang and Wu., 1997; Kang et al., 2002). So far, however, research has been mainly confined to the width index. In the Qilian Mountains, there is a need for complementary investigations at this key region for climatic reconstructions using tree-ring width and isotope techniques in combination. This paper presents 1000-yr temperature-sensitive tree-ring width and stable carbon isotope chronologies derived from living trees of Qilian juniper (*Sabina przewalskii* Kom.) at timberline. The results differ from Kang et al. (2002) in middle Qilian Mountains, China. Climate reconstructions in the region will provide insights into the spatiotemporal patterns of past climate changes.

Materials and Methods

STUDY AREA AND TREE-RING SAMPLES

The Qilian Mountains (37–39°N, ~99–103°E) are located at the northeastern edge of the Tibetan Plateau, at the convergence of the Qinghai-Xizang (Tibet) Plateau, the Inner Mongolia–Xinjiang Plateau, and the Loess Plateau (Fig. 1). High temperature extremes range from 28.5 to 32.4°C and the low temperature extremes from −27.8 to −29.0°C at Sidalong meteorological station (2600 m elevation) near the sampling site. The annual precipitation ranges from 401.9 to 632.3 mm, the annual evaporation varies between 1041.2 and 1234.2 mm, and the relative humidity is about 57% (Fu and Che, 1990).

Following the International Tree-Ring Data Bank (ITRDB) standards (Grissino-Mayer and Fritts, 1997), Qilian juniper samples were collected at Sidalong Forest Center of Sunan County (38°26′N, 99°56′E) in October 2000. Our sampling site was about 15 km away from and on average 300 m higher elevation than the study site of Kang et al. (2002). The sampled trees are generally growing on steep (42°), south-facing slopes near timberline where there is little disturbance due to human activities. Fifty cores were taken from 25 trees at elevations from 3400 to

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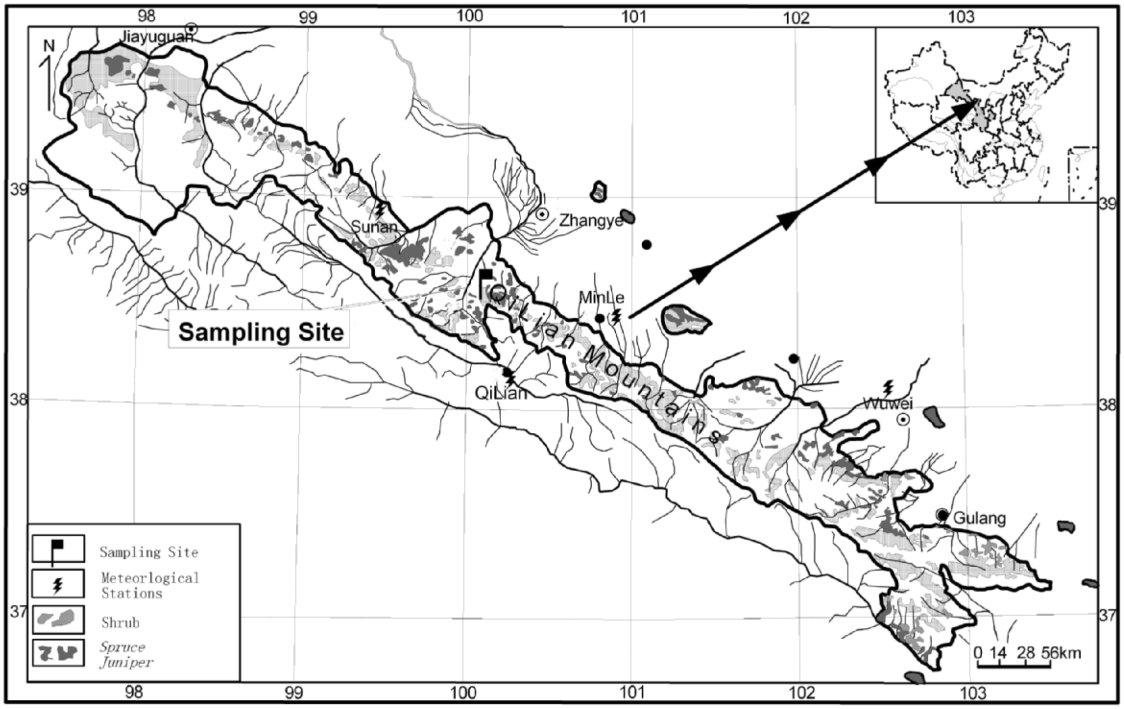

FIGURE 1. Location of tree-ring sampling site and meteorological stations used in this study.

3550 m in a relatively open stand. An increment borer was used to enable cross dating and to establish tree-ring width chronology. Samples included four discs for isotope analysis.

TREE-RING WIDTH CHRONOLOGY

Using basic procedures of tree-ring analysis (Fritts, 1976) and of tree-ring research in arid zone (Shao et al., 2003), the skeleton-plot technique was used for the primary dating, and the cross-dating was further checked with the computer program COFECHA (Holmes, 1983).

In order to retain low-frequency information, we used conservative detrending methods to remove age-related growth trends (Fritts, 1976). Each tree-ring series was fitted with a negative exponential curve, while preserving variations of all frequencies that may be related to climate (Cook and Kairiukstis, 1990). Using the ARSTAN function (Cook and Holmes, 1986), we synthesized a standard tree-ring width chronology using double-weighted average methods for detrending series as shown in Figure 2.

The mean sensitivity of width chronology is 0.18 with mean variance 0.21, and first order autocorrelation coefficient is 0.49, which suggests that there is a 24.0% lag between previous and current years. The S/N ratio of standard chronology is 8.9 and the explained variance of first principal component is 40.84% (Liu, et al., 2005).

TREE-RING CARBON STABLE ISOTOPE CHRONOLOGY

Leavitt and Long (1984) suggested that four trees are adequate to assess $\delta^{13}C$ within a site. The rings in this study were very narrow, and even under a binocular lens, it was not feasible to attempt to separate annual rings without risking contamination from the previous and following years in the wood sample. So increment cores from four discs and cores from five other different

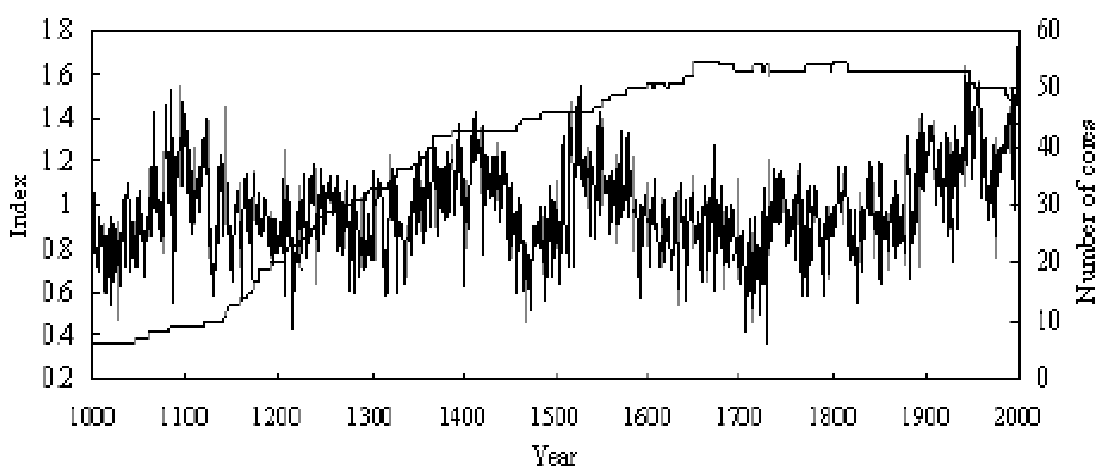

FIGURE 2. Ring-width chronology developed for Qilian juniper in middle Qilian Mountains, along with the sample depth plot.

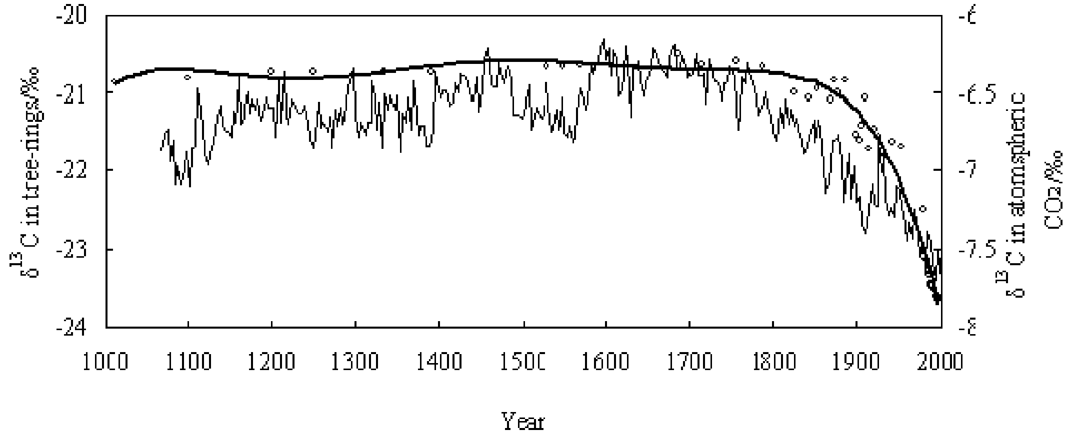

FIGURE 3. Raw averaged 3-yr groups δ^{13}C-records of tree-ring cellulose from Qilian juniper and δ^{13}C in atmospheric CO_2 covering the period from 1060 to 2000. Open points show the δ^{13}C data in atmospheric CO_2 from ice-core (Francey et al., 1999; Trudinger et al., 1999).

trees were cut into 3-yr ring groups and the samples in the same period were combined covering the period from A.D. 1060 to 2000. All samples were ground in a mill to 60-mesh size. Then the α-cellulose was extracted using the method modified by Mullane et al. (1988) from Green (1963) with three steps: (1) Removal of the extractives with a 1:1 toluene-ethanol mixture, (2) removal of the lignin with a $NaClO_2$-acetic acid solution, and (3) removal of the hemicellulose with NaOH. The cellulose samples were dried and about 6 to 7 mg were weighed and vacuum-sealed in Pyrex tubes with an excess (about 1.5 g) copper oxide (CuO) wire as oxide and some platinum wire as catalyst. Each of the cellulose samples was then combusted at 550°C for 4 h to produced CO_2 (Li et al., 1994). Other studies have used a shorter combustion at higher temperature, but the procedure described here obviates the need for quartz-glass tube, which are more expensive and difficult to prepare. Purified CO_2 was analyzed on a Delta-plus mass spectrometer (Finnigan MAT) in the State Key Laboratory of Cryospheric Sciences, Chinese Academy of Sciences. The standard deviation during combustion and analysis is below ±0.1‰. The results were corrected and expressed as deviations from the PeeDee Belemnite (PDB) standard: $\delta^{13}C = (R_{(sample)}/R_{(standard)} - 1) \times 10^3$ per mil, where $R = {}^{13}C/{}^{12}C$.

Figure 3 illustrates a 940-yr δ^{13}C record from AD 1060 to 2000 with 3-yr resolution. The δ^{13}C series varies by about 3.03‰ in the 940 yr. Linear regression of δ^{13}C with time yields a slope of 0.01‰ yr^{-1} from 1800 to 2000. The long-term decrease from 1750 to 2000, however, is smaller than the results from Mt. Helan and Huangling (Liu et al., 2004). The first-order correlation coefficient of autoregression is 0.65, which implies that there is a significant 42.2% isotope lag effect between the each 3-yr sample. It is noted that this results not removed the effects of averaging 3 yr to one value.

Since the beginning of the 19th century, the atmospheric carbon dioxide concentration has increased and its carbon stable isotope ratio ($\delta^{13}C_{atm}$) has decreased (Stuiver and Braziunas, 1987). Both affect the δ^{13}C ratio of plants because the carbon isotope composition of photosynthetically produced organic matter is determined by the δ^{13}C value of the atmospheric CO_2 and the leaf intercellular to atmospheric CO_2 concentration (Farquhar et al., 1982). These effects will mask the natural climatic signal to a greater or lesser degree. When considering the relationships between cellulose isotopic composition and meteorological parameters, this long-term effect has to be corrected. In this study, values of $\delta^{13}C_{atm}$ were taken from ice-core (Trudinger et al., 1999; Francey et al., 1999), as shown in Figure 3, and a correction can be applied for the past 1000 yr as follows (Farquhar et al., 1982):

$$\Delta^{13}C = \left(\delta^{13}C_{atm} - \delta^{13}C_{plant}\right)/\left(1 + \delta^{13}C_{plant}/1000\right) \qquad (1)$$

where $\delta^{13}C_{plant}$ and $\delta^{13}C_{atm}$ are stable carbon stable isotope ratios in tree-rings and in atmospheric CO_2, respectively. Then using equation (1), we obtain the isotope shift Δ^{13}C series shown in Figure 4, in which the effects of atmospheric CO_2 have been removed, for further climatic analyses.

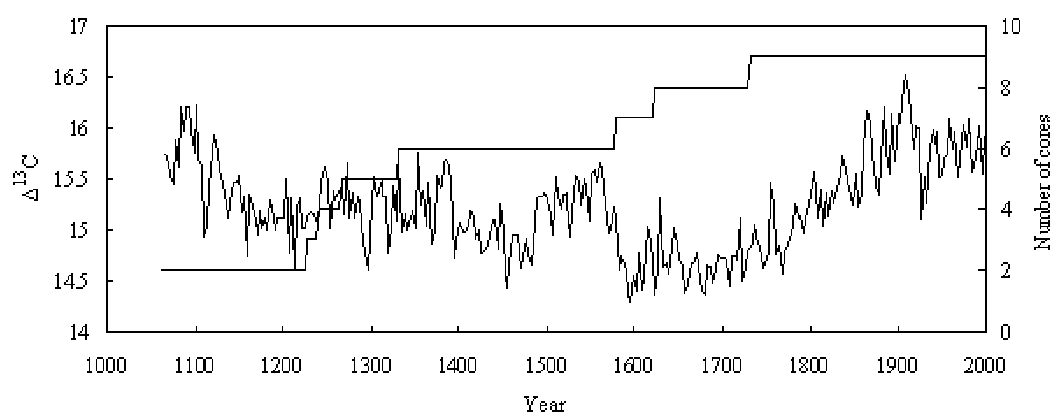

FIGURE 4. Carbon isotope discrimination (Δ^{13}C) series using equation (1) to eliminate the effects of declining atmospheric $\delta^{13}CO_2$, along with the number of tree cores used for isotope analysis (right axis).

TABLE 1

Correlation matrix of temperature and precipitation among neighboring stations covering the common period.

	Zhangye	Minle	Wuwei	Sunan	Qilian
(a) Temperature					
Zhangye	1				
Minle	0.940	1			
Wuwei	0.915	0.860	1		
Sunan	0.844	0.864	0.761	1	
Qilian	0.820	0.834	0.756	0.787	1
(b) Precipitation					
Zhangye	1				
Minle	0.729	1			
Wuwei	0.268	0.270	1		
Sunan	0.760	0.759	0.187	1	
Qilian	0.430	0.416	0.183	0.542	1

Tree-Ring Width and Stable Carbon Isotope/Climate Relationships

Climate data from the Zhangye observation station (38°56′N, 100°26′E, 1483 m elevation, period of record 1951–2000), and the Minle observation station (38°27′N, 100°49′E, 2271 m elevation, period of record 1958–2000) are used for climate response analysis. Before the data were used, tests of homogeneity and randomness against the trend were performed used the Mann-Kendall statistic and double-mass analysis. It should be noted that the record from the Zhangye station has missing values in 1951–1953. The reference stations used in these tests (see Fig. 1 for locations) were Wuwei (38°56′N, 100°2′E, 1532 m elevation, period of record of 1951–2000), Sunan (38°50′N, 99°37′E, 2312 m, period of record of 1957–2000), and Qilian (38°11′N, 100°15′E, 2787 m elevation, period of record of 1957–2000).

The statistical tests show that temperature data among the six stations has no significant inhomogeneity and also precipitation trends are concurrent (Table 1), except data from Wuwei station due to its greater distance from Qilian Mountains. We noted that the distance between Sidalong station and our sampling site is small, but the climatic data of this station were not chosen for response analysis because they are incomplete and the record period is short.

We calculated simple linear correlation coefficients between width and stable carbon isotope ratios, and monthly temperature and precipitation of the current and previous biological years of all nearby stations; the results show the closer relationships between the two proxies (width and stable carbon isotope ratios) and climate data from Zhangye (1954–2000) and Minle (1958–2000). So we combined records of the two stations from 1958 to 2000 to represent regional climatic variability.

Relationships between tree-ring width index and stable carbon isotope to climatic variables are identified using the correlation analysis by calculating the simple correlation coefficients (Blasing et al., 1984). Since the climatic conditions in the previous year usually have an effect on tree-ring growth of the current year (Fritts, 1976), the monthly climatic variables over a 12-mo period, from October of the prior growth year to September of the current growth year, are used as predictor variables to determine their significance in affecting the concurrent ring width and carbon stable isotope ratio.

The results of correlation analysis show that radial growth is positively correlated with temperature from previous October to September of the current year, except in May (Fig. 5a), with higher growth indicating warmer temperatures and lower growth cooler conditions. The most important periods of temperature influence on tree growth can be divided into two stages: December

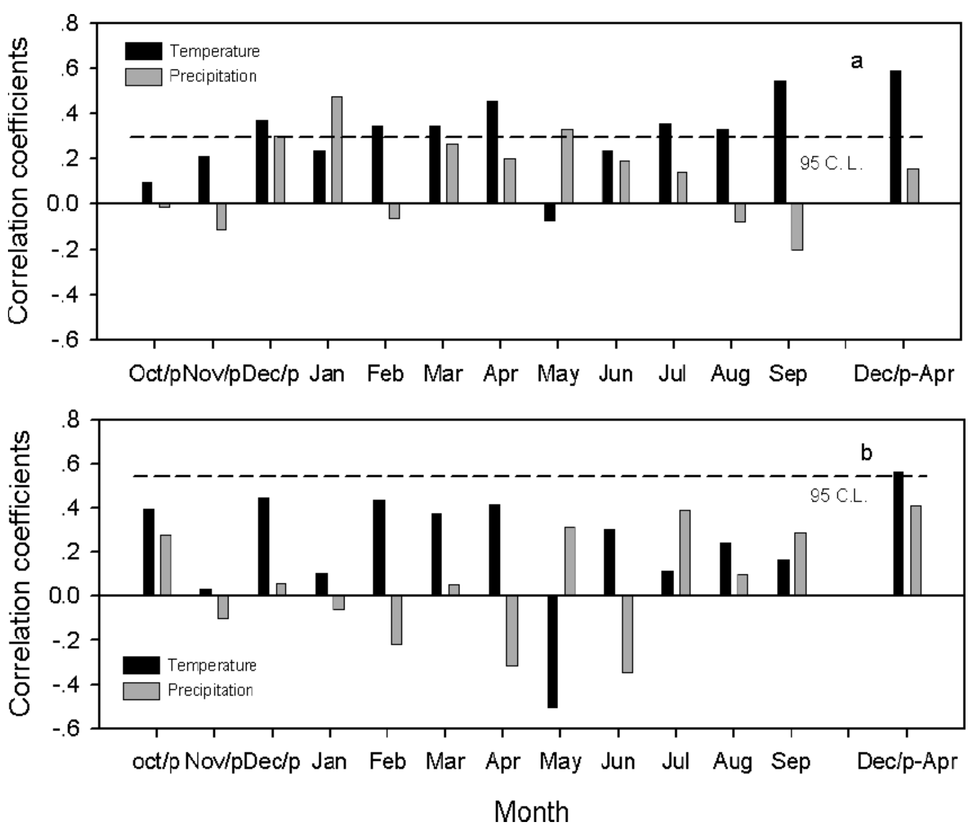

FIGURE 5. Monthly correlation coefficients of tree-ring width chronology and stable carbon isotope series to combined instrumental data from Zhangye and Minle meteorological station from 1958 to 2000. (a) Correlation coefficients for ring width (1 yr) to climate data. (b) Correlation coefficients for stable carbon isotope (3 yr) to climate data. Dashed lines show the 95% confidence limits. p: the climate data of previous growth year.

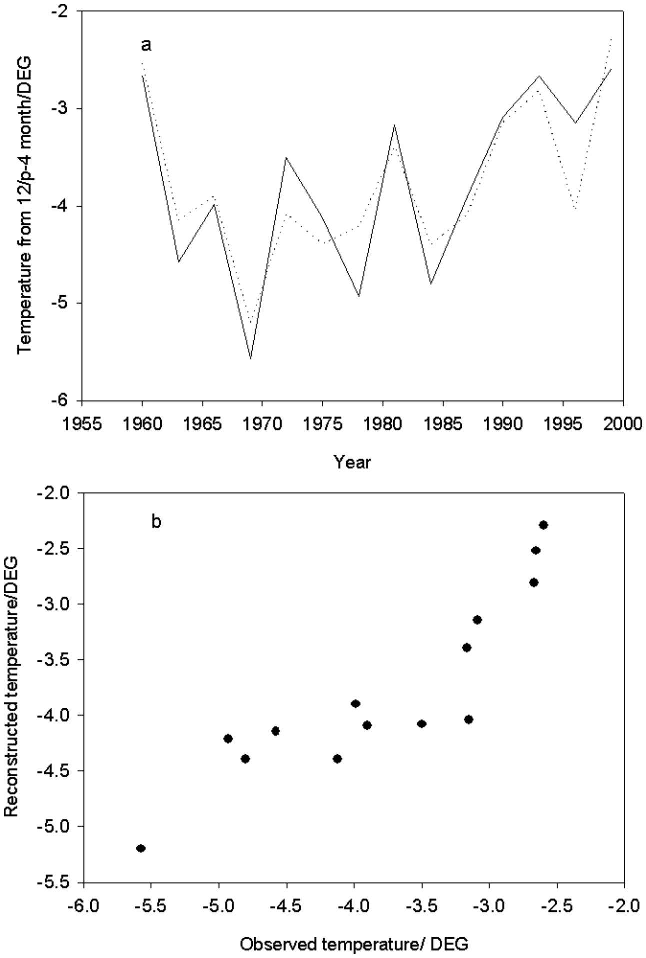

FIGURE 6. Comparison of observed and reconstructed temperature from previous December (12p) to current April (4). (a) Time series plot. Solid line indicates observed value and dash line indicates reconstructed value. (b) Scatter plot.

of previous year to April, and July to September. In addition, during the December of prior year to January and from March to July, tree growth is correlated positively with precipitation. The relationships between carbon stable isotopes and temperature shows similar relationships to width and temperature: in May the $\Delta^{13}C$ is related negatively to temperature, but in other periods, the relationship is positive, namely high temperature corresponds to higher $\delta^{13}C$ values. The climate variables and stable carbon isotope relationships are relatively complex at various periods, and in April, May, and June, the effects of temperature and precipitation on $\Delta^{13}C$ are reversed, but in period from July to September, there were concurrent effects on $\delta^{13}C$ variables. In addition, the simple linear correlation coefficient between ring width and $\Delta^{13}C$ spanning the period from 1065 to 2000 at a 3-yr time resolution shows a significant positive trend ($r = 0.419$, $P < 0.001$), suggesting that the two series contain similar information. As shown in Figure 5, the relationship of ring width (yearly values) and carbon stable isotope (3-yr mean) to temperature from December of the previous year to April were significant with correlation coefficients of 0.599 ($P < 0.001$) and 0.577 ($P < 0.05$), respectively. The results indicate that temperature is a major factor limiting tree growth and carbon metabolism; we interpret the tree-growth rate and stable carbon isotope variations in tree-rings at this tree-line site to be primarily controlled by temperature.

Regional Variability in Reconstructed Temperature

Having established good relationships between ring width, $\delta^{13}C$ and December–April temperature, we now reconstruct the past 1000 yr temperature changes with 3-yr resolution. The reconstruction equation is

$$Y = -48.783 + 4.223 \times WD + 2.537 \times SCIR \qquad (2)$$

where Y is average temperature, WD is tree-ring width index, and SCIR is stable carbon isotope ratio value, $\Delta^{13}C$. Figure 6 shows the comparison of the observed mean temperature from previous December to current April with the reconstructed temperature in the calibration period. It can be seen that there is a very good association between them (Fig. 6a). The reconstruction captures 75.6% (adjusted for loss of degrees of freedom, $R^2_{adj} = 71.2\%$, $F = 17.039$, $P < 0.0001$) of temperature variance over the calibration period 1960–2000 ($n = 14$) with 3-yr resolution. These statistics suggested that the reconstruction formula was reliable, and it could be used to reconstruct past temperature variations.

The temperature standard deviation anomalies are shown in Figure 7 after reconstruction obtained from equation (2). The reconstruction of temperature in middle Qilian Mountains (Fig. 7a) shows that the temperature was relatively high above the mean during the first century of the record, corresponding to the Medieval Warm Period (Zhang, 1994; Shi and Zhang, 1996; Hughes and Diaz, 1994). From 1200 to 1600, the temperature shows greater amplitude fluctuations. After 1600, the record turns to a state of lower temperatures until the later part of 19th century, namely the Little Ice Age (Yao et al., 1991). This is followed by a period of temperature increase to the present time. The $\delta^{18}O$ data (indicating temperature fluctuation) in ice-core drilled from Mt. Qilian (Yao et al., 1991), the nearby long- and high-resolution proxy data currently available in this region, show good agreement with our reconstruction except for the period of around 1690. This agreement between such widely separated sites further suggests a common climatic signature.

Climatic change studies (Mann et al., 1999; Esper et al., 2002) have documented the occurrence of the Medieval Warm Period and Little Ice Age in the Northern Hemisphere over the last 1000 yr. Figure 7 compares the detailed variations in temperature series from Esper et al. (2002) and our reconstruction. The two chronologies are very similar over the past ~1000 yr, although some differences in the timing of peak conditions are evident. Esper et al.'s (2002) chronology shows evidence for above average temperatures during the Medieval Warm Period (900–1300), while our reconstruction indicated a warmer period covering the interval 1065–1150. After the year 1200, the two chronologies lock together remarkably well at multidecadal and centennial time scales. There is strong evidence for inferred below-average temperature over the much of the 1580–1880 interval, which may be regarded as an expression of the Little Ice Age. Temperature fluctuation in our series shows lower values with episodes of 1160s–1330s, 1440s–1500s, and 1580s–1880s. These three episodes correspond well with that of by Esper et al. (2002) (Fig. 7b), suggesting that temperature change was synchronous to some extent over a large scale. Our analysis also indicated that two warmest periods cover the intervals 1060–1150 and 1900–2000, with the peak occurring around the 1100 and 1999. The comparison suggests our reconstructed temperature has not included all of the Medieval Warm Period and, perhaps, not even its warmest period.

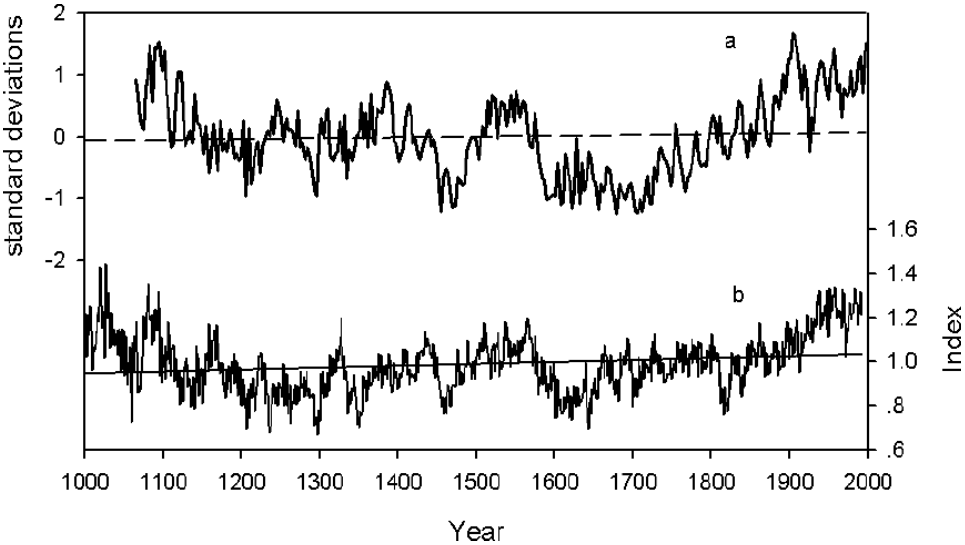

FIGURE 7. Comparison of (a) temperature variations (standard deviations) around mean obtained from tree-ring width and carbon stable isotope in tree-rings in middle Qilian Mountains, and (b) temperature proxy "North Hemispheric regional curve standardization chronology" from Esper et al. (2002). The dashed lines show the trends over the entire periods of the series.

Conclusion

Additional paleorecords are essential for evaluation of climate change, including detection of possible recent anthropogenic influences. Our 1000-yr tree-ring width and carbon stable isotope chronologies are currently the longest temperature-sensitive tree-ring record on Mt. Qilian. This record shows that climate in this region has undergone oscillations, sometimes of large amplitude during the last millennia. The greatest fluctuation in the temperature during the past 1000 yr occurred in 1390 to 1600. The reconstructed climate data reveal that the Medieval Warm Period and Little Ice Age were synchronous in China and the Northern Hemisphere, and they help us better understand the longer climate change history over space and time.

Tree-ring width and stable carbon isotope studies for Mt. Qilian along east to west transects are in progress, and we believe that they will provide longer detailed climatic information.

Acknowledgments

This research was support by the Knowledge Innovation Project of Chinese Academy of Sciences (KZCX2-XB2-04-03), the National Natural Science Foundations of China (40501076), and the Foundation of the State Key Laboratory of Cryosphere and Environment (058143).

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