A comparison of tree-ring records and glacier variations over the past 700 years, northeastern Tibetan Plateau

Xiaohua GOU,[1,2] Fahu CHEN,[1] Meixue YANG,[3] Gordon JACOBY,[2] Jianfeng PENG,[1] Yongxiang ZHANG[1]

[1]*Center for Arid Environment and Paleoclimate Research, Lanzhou University, 298 Tianshui Road, Lanzhou 730000, China*
E-mail: xhgou@lzu.edu.cn
[2]*Tree-Ring Laboratory, Lamont–Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA*
[3]*Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, 260 Donggang West Road, Lanzhou 730000, China*

ABSTRACT. The ecological environment of the headwater area of the Yellow River, west China, is seriously deteriorating because of the harsh natural environment, weakened ecological systems and intensified human activities as well as regional climate changes. Forests and glaciers coexist in this area. Glaciers in the area have retreated over the last decade because of climate change. Most glaciers on the Tibetan Plateau (TP) tend to retreat during warm intervals and advance during cold intervals. Tree-ring records provide an important index for examining past climate changes. A total of 139 core samples from 97 living cypresses (*Juniperus przewalskii*) in the central region of the Yellow River headwater area, the Animaqin mountains, northeastern TP, were sampled from three sites that are close to each other. The chronologies were developed using the ARSTAN program. Analyses indicate that these tree-ring width records reflect the summer maximum temperature of the study area over the past 700 years. The tree-ring records and the glacier advances recorded by terminal moraines are compared. Inferred summer maximum temperatures suggest three cold periods during the Little Ice Age, around AD 1500, 1700 and 1850. These cold intervals are consistent with the glacier moraine record from the region.

INTRODUCTION

High-resolution climate variations over the past 1000 years derived from ice cores, historical archives, tree-rings, corals and lake sediments have been examined previously (Briffa and others, 1995; Yao and others, 1996a b; Wu and others, 2001). The Tibetan Plateau (TP) is an ideal area for climate-change reconstruction and study because its unique geophysical position allows paleoclimate records to be preserved and because it has been relatively undisturbed by anthropogenic activities. Therefore, the proxy records reliably reflect the natural features of climatic and environmental changes. Ice-core (Yao and others, 1996a, b) and tree-ring (Kang and others, 1997) records were used to reconstruct the general patterns of climate change over the past 1000 years on the TP. Based on comparative analysis of the high-resolution climate records from the Guliya ice core from northwestern Tibet and the Dulan tree-ring history from Qinghai province, west China, Yao and others (2001) reconstructed climate changes over the past 2000 years. They found that temperatures in both regions have increased gradually, with some fluctuations. Rapid warming took place during the 20th century, and the trend appears to be accelerating. Both ice-core and tree-ring archives recorded three very cold periods during the Little Ice Age (LIA) that were virtually simultaneous in the different records. Spectral analysis revealed that periodicity in the ice-core and tree-ring records was mostly related to solar activity, indicating that climate variations on the TP may be driven, at least in part, by solar activity.

The Animaqin mountains, located in the heart of the headwater region of the Yellow River, northeastern TP, are rich in forest resources and relatively undisturbed by anthropogenic activity. The main species in the forest is cypress (*Juniperus przewalskii*), the oldest living tree found in China (Kang and others, 1997). The main peak, Maqingganri (6283 m a.s.l.; Fig. 1), is covered by glaciers and snow and surrounded by mountain ranges.

Modern glaciers developed on the TP. Over the 20th century, its glaciers advanced and retreated in response to climate changes (Pu and others, 2004). Yao and others (2004) noted that under the impact of the current warming trend, glaciers in this part of central Asia have retreated continuously in recent decades. Glacier retreat has intensified in the past 10 years and has had a definite impact on the water resources for arid northwest China.

Recent studies show that the glaciers in the Animaqin mountains are sensitive to global climate warming (Liu and others, 2002a). This raises the question, how have these glaciers responded to climate change over past centuries? To explore this further, three tree-ring width chronologies were developed from the Animaqin region and compared with glacier variations.

SAMPLE COLLECTION AND CHRONOLOGY DEVELOPMENT

The study area, the Animaqin mountains, is located in the northeastern TP (Fig. 1). The vertical vegetation distribution is significant in this area, and the dominant vegetation is sub-alpine meadow. Cypress is distributed on both sides of the river valley with an open canopy. The thin soil under the forest is poor and rocky. Most of the plants under the forest are sub-alpine species, such as *Dasiphora fruticosa*, *Potentilla chinen*, *Polygonum viviparum* and *Leontopodium leontopodioides*.

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Tree-ring cores were taken from three sample sites, MQB, MQD and MQF, in the Qiemuqu valley, and tree-ring width chronologies were developed. The distance between each sample site is <20 km and the sites are about 30 km away from Maqingangri, the main peak of the Animaqin mountains. The distances between the sample sites and the meteorological stations range from 70 to 180 km. Information about the sample sites and the tree-ring cores is shown in Table 1. The locations of the sample sites and weather stations as well as Maqinggangri are shown in Figure 1.

All samples were collected from the south slope of Qiemuqu valley, the first major branch of the Yellow River. To ensure that they contain consistent climate signals, the variation of the sample-site elevation was limited to 100 m and the microenvironment of the living trees was carefully selected. Most tree-ring cores were taken from isolated trees or trees in small groves. Because there were many missing rings, samples were taken from young trees or those growing near the riverbank to aid in cross-dating; however, these were not used to develop the final tree-ring width chronologies. A total of 139 tree-ring cores from 97 trees were used to develop the chronologies.

We have sampled trees at many other sites in this region and know first-hand that the development of the climatic signal in these high-elevation, semi-arid regions is complex. The standard concepts that the upper tree-line is limited by temperature while the lower tree-line is limited by moisture are insufficient to define the most useful and significant climate signals. In this study, we use the inverse temperature signal in lower-elevation trees (presumed to reflect reduced evapotranspiration losses) to extract the climate-change signal.

The standard techniques of dendrochronology were used to process the sampled tree-ring cores (Fritts, 1976; Cook and Kairiukstis, 1990). The samples were cross-dated using three methods in three steps: skeleton-plot cross-dating, ring-width curve cross-dating, and testing of cross-dating with the COFECHA program (Stokes and Smiley, 1968; Holmes, 1983). Because there were up to seven missing rings in a century, the plots were essential for correct dating. The cross-dated tree rings were measured on a Velmex tree-ring width measuring system. The ARSTAN program (Cook and Holmes, 1986; Cook and Kairiukstis, 1990) was used to develop the chronologies. Most tree-ring series were detrended using a negative exponential curve; where this was not appropriate, a spline was used. Figure 2 presents the standard STD chronologies for the three sites, with sample size and expressed population signal (EPS). It is necessary to quantify the degree to which the chronology signal is expressed when the series are averaged. The chronology signal, expressed as a fraction of the total chronology variance, then quantifies the degree to which this particular sample chronology portrays the hypothetically perfect chronology. This has been termed EPS (Cook and Kairiukstis, 1990). The mean of the three chronologies was calculated and calibrated using the observed meteorological data.

For the common period 1960–2001, the three sites correlate negatively with the observed average temperature records from Xinhai, Tongde, Maqin and Maduo located around the sample sites (Table 2). Table 2 shows that the three chronologies and the mean chronology are negatively correlated to April, May, June and September temperatures. The highest correlation is between the chronologies and the mean temperature from April to September. The correlation coefficient is –0.60 ($p < 0.001$). The statistical correlation between the chronologies and the maximum temperature (Table 2) is similar, but slightly stronger, $R = -0.67$, ($p < 0.001$). These correlations indicate that the negative tree-ring indices reflect the maximum summer temperatures in the research area. This is probably because higher maximum temperatures result in higher evapotranspiration which leads to less moisture in the soil. The latter would inhibit or slow tree growth.

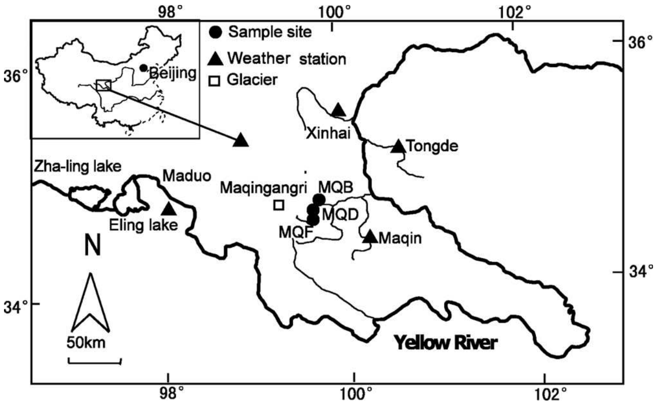

Fig. 1. Map of the sample sites and nearby weather stations (Xinhai, Tongde, Maqin and Maduo). The three sample sites, MQB, MQD and MQF, are <30 km apart and are located in the headwater area of the Yellow River in the northeastern TP. All three sample sites are within 30 km of the main peak in this area, Maqingangri (6282 a.s.l.).

Table 1. Sample sites and tree-ring cores. All tree-ring cores were taken from living trees growing at the lower forest line in this area. The average correlation coefficient is the mean of the correlation coefficients between each width series and the master series. Mean sensitivity shows the variation of the tree-ring width series, and the high mean sensitivity shows the good quality of the tree-ring cores

Sample site	Location	Elevation m a.s.l.	Sample size	Average correlation coefficient	Mean sensitivity	Rings missing %	Time interval AD
MQB	34°47′08″ N, 99°47′21″ E	3550–3650	53/38	0.741	0.543	2.597	470–2002
MQD	34°43′25″ N, 99°40′01″ E	3600–3700	34/22	0.645	0.400	1.074	1163–2001
MQF	34°45′15″ N, 99′41′29″ E	3650–3700	52/37	0.662	0.365	1.068	1230–2002

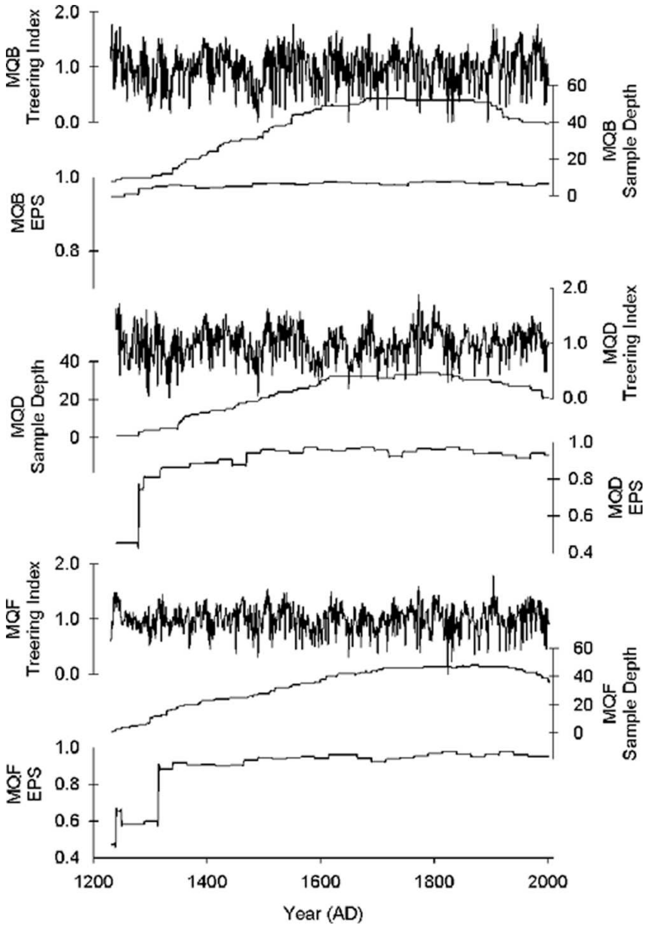

Fig. 2. STD chronologies with sample depth and EPS curve of the three sample sites. The three chronologies are similar, and for the last 700 years they all have an EPS of >0.85.

Table 2. The correlation coefficients between the standard chronology index (MQB, MQD, MQF and their averaged chronology) and the mean temperature as well as the mean maximum temperature of four weather stations (Xinhai, Tongde, Maqin and Maduo). The tree-ring index for four chronologies is significantly and negatively correlated to the mean temperature and mean maximum temperature (April–September)

	MQB	MQD	MQF	Mean
Mean temperature				
January	0.10	0.16	0.06	0.11
February	–0.02	0.02	–0.08	–0.03
March	0.03	–0.01	–0.08	–0.01
April	–0.36*	–0.38*	–0.43†	–0.41†
May	–0.50†	–0.56†	–0.54†	–0.56†
June	–0.29	–0.38*	–0.43†	–0.38*
July	–0.33*	–0.06	–0.13	–0.20
August	–0.20	0.03	–0.10	–0.11
September	–0.32*	–0.35*	–0.33*	–0.35*
April–September	–0.59†	–0.50†	–0.58†	–0.60†
Mean max. temperature				
January	0.10	0.18	0.13	0.14
February	–0.20	–0.10	–0.18	–0.17
March	–0.17	–0.05	–0.08	–0.12
April	–0.30	–0.32*	–0.34	–0.34*
May	–0.53†	–0.59†	–0.58†	–0.60†
June	–0.55†	–0.49†	–0.62†	–0.59†
July	–0.38*	–0.11	–0.19	–0.27
August	–0.10	0.17	0.09	0.03
September	–0.28	–0.33*	–0.24	–0.30
April–September	–0.68†	–0.55†	–0.61†	–0.67†

*Correlation coefficient is above 95% significance.
†Correlation coefficient is above 99% significance.

GLACIER ADVANCES IN NORTHEASTERN TIBETAN PLATEAU AND THE TREE-RING WIDTH CHRONOLOGY

Glacier retreat/advance on the TP during the LIA or even earlier was examined using the terminal moraines left by the glaciers (Pu and others, 2001, 2002; Liu and others, 2002a, b; Wang and Ding, 2002), while glacier variations in the last 100 years have been monitored and compared with the historical archives. Glacier variation is a sensitive proxy index for the alpine climate changes. The comparison of the glacier advance/retreat, the ice-core records and the temperature fluctuations on the TP shows that glacier retreat in the past 100 years on the TP has coincided with climate warming.

During global warming, especially the rapid warming since the 1980s, the glacier termini on the TP have retreated quickly (Ren and others, 2003; Pu and others, 2004). Glaciers on the edge of the eastern and southern TP have varied dramatically, while those in the middle and northern regions of the TP have been more stable. This indicates that glaciers on the margins of mountain regions are more sensitive to climate change than those in the interior.

The advance of Dongkemadi glacier in the 1980s and Qiangyong glacier in the late 1970s, the slowed retreat of Rongbu glacier in Qomologma in the 1980s and Hailuogou glacier in the 1970s and early 1980s, and the stable condition of glaciers in the middle and west Qilian Shan in the late 1970s and 1980s all reflect lower temperatures on the TP in the 1970s. Conversely, the dramatic retreat of all the above-mentioned glaciers in the 1990s is related to continuous warming on the TP since the 1980s. For the periods of lower temperatures (early 1900s to 1920–30s) and higher temperatures (around 1940s), some glaciers fit the pattern. Wang and Zhang (1992) and Wang and Ding (2002) analyzed the relationship between observed global glacier variations and climate changes and found that changes of alpine glacier termini lag behind the climate change by roughly one decade. Taking this lag effect into account, the temperature variations are consistent with the glacier fluctuations: the temperature increases during the 1930s–40s and 1980s are consistent with the dramatic retreat of most glaciers on the TP during the 1940s–60s and 1990s.

Figure 3a compares the Animaqin tree-ring chronology and the regional temperature series and shows that the Tianjun and Dulan tree-ring data vary similarly with the Dunde ice cap's $\delta^{18}O$ curve (Yang, 2003). The cold period AD 1400–1850 reflects the LIA in this region. A warm, dry interval during the period AD 1200–1370 (Liu and others, 1998) is reflected in the Dunde ice-core pollen record and is also evident in the regional temperature curve. Three significant cold events appeared around AD 1500, 1700 and 1850 and were interrupted by two warm events around AD 1550 and 1750. It was found that the advance of the glaciers (Fig. 3b) (Zheng and others, 1990; Wang, 1991) coincided with the cold periods in this region.

The comparison between the tree-ring index (high index indicates low summer maximum temperatures) and the glacier variations indicates that several glacier advances coincided with periods of low summer maximum temperature, around AD 1500 and 1700 (Fig. 3c). These data suggest that the tree-ring record is in general agreement with the advance and retreat of the glaciers in the region. Unfortunately, the glacier observation record is less than a century long, and in most cases just a few decades long, so it is difficult to compare the tree-ring records and the glacier variations. Both the advance and retreat of glaciers and the growth of the trees are dependent on temperature and precipitation variations, although growth of the trees at different elevations can be conditioned by other factors.

CONCLUSIONS

The history of glacier variations over the past 100 years on the TP has been discerned by both direct observation and paleoclimate analysis, although only a few glaciers have been observed continuously and the observation period is short. The results presented here show that the warming in the most recent three decades is reflected by a general retreat of glacier termini. Different paleoclimate indices showed that glacier advance on the eastern TP coincides with climate-cooling periods, especially the three very cold periods during the LIA around AD 1500, 1700 and 1850.

Tree-ring records are an important tool for paleoclimate change research. Three tree-ring width chronologies were developed from 139 cypress (*Juniperus przewalskii*) tree-ring cores sampled from 97 living trees from three sites in the central headwater region of the Yellow River. The analyses showed that the mean chronology indices correlate negatively with the mean maximum temperature in the research area.

A comparison of the tree-ring and glacier variation records indicates that the trees in the area recorded glacier variations on the northeastern TP. Here glacier advances were shown to be contemporaneous with periods of reduced summer maximum temperatures. These data suggest that carefully collected tree-ring histories have the potential to serve as proxies for reconstructing glacier variations in the same region, as both are affected by temperature and precipitation changes. Such an approach can be advantageous in regions like the Animaqin mountains where forests and glaciers coexist. However, problems of interpretation remain. For example, it is important to quantify the lagged response of the glaciers to climate changes if their variations are to be better reconstructed using tree-ring histories.

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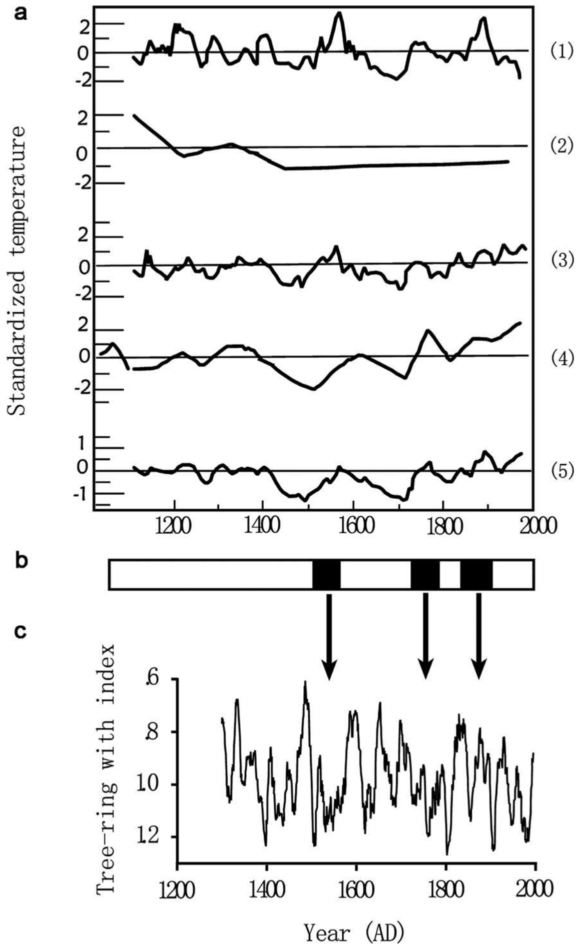

Fig. 3. Temperature series and glacier advances in the northeastern TP. (a) Standardized decadal-scale proxy records reflecting surface air temperature for sites in the northeastern TP and 50 year means of regionally averaged temperature anomalies (after Yang, 2003): (1) tree-ring width chronology from Tianjun, Qilian Shan; (2) water temperature in Qinghai lake; (3) tree-ring widths from Dulan Qinghai; (4) $\delta^{18}O$ of Dunde ice core; (5) regionally averaged temperature. (b) Glacier advances (black bars) in northeastern Tibet (after Zheng and others, 1990; Wang, 1991). (c) Tree-ring width index reconstructed from the Animaqin mountains, which is negatively correlated with summer maximum temperatures. The *y* axis of the tree-ring width index has been reversed.

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