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Climatic implications of a 3585-year tree-ring width chronology from the northeastern Qinghai-Tibetan Plateau

X. Shao [a,*], Y. Xu [a], Z.-Y. Yin [b], E. Liang [c], H. Zhu [a], S. Wang [d]

[a] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, PR China
[b] Department of Marine Science and Environmental Studies, University of San Diego, San Diego, CA 92110, USA
[c] Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100085, PR China
[d] Institute of Archaeology, Chinese Academy of Social Sciences, Beijing 100710, PR China

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ABSTRACT

In this study we develop a tree-ring width chronology of Qilian juniper (*Sabina przewalskii* Kom.) in the northeastern Qaidam Basin (northeastern Qinghai-Tibetan Plateau), China, which extends from 1580 BC to AD 2005 lasting 3585 years. This is by far the longest ring-width chronology in China. It is composed of archaeological wood samples from 13 sites, samples of living trees growing at a site with relatively good moisture condition and other long living trees from multiple sites approximately 100 m below the local upper treeline. Our results suggest that the archaeological wood and long living tree-ring width series belong to the same statistical population, which allows the construction of a single, regional composite chronology. We find that ring-width variations of the archaeological wood have statistical characteristics that are more similar to those trees from the lower part of the forest belt, where the moisture regime during the months at the onset of the growing season is the primary control on tree growth. Only after these analyses it becomes certain that the ring-width variations of the archaeological wood represent the variation of moisture conditions in the past. Therefore, the entire composite chronology is moisture-sensitive and suitable for reconstruction of the drought history and the related climate forcing over the past three millennia in the study region. The composite chronology shows considerable variations at inter-decadal to centennial timescales, with ten major multi-decadal low-growth periods corresponding to severe drought events in the past 2850 years, especially for two prominent events centered on AD 1480s and AD 1710s. On the other hand, significant high-growth periods were found centered on AD 590s and AD 1570s, and also in the past 30 years.

1. Introduction

The Qinghai-Tibetan Plateau, the highest and largest plateau on Earth, plays a very important role in modulating regional and continental scale climates by its thermodynamic and kinetic processes (Ye and Gao, 1979; Bansod et al., 2003; Wu et al., 2007). Several studies indicated that the Plateau is also a region sensitive to recent global climate change (Liu and Chen, 2000; Yao et al., 2002; Duan et al., 2006; Tian et al., 2006). Therefore, this region is of paramount importance in climatic change studies. However, instrumental records over the Plateau seldom exceed 50 years in lengths and, thus, cannot provide the information required for evaluation of the present conditions in the context of long-term changes of the past and for projecting possible future climate changes (Bradley, 2000a,b). High-resolution proxy records of past environmental changes, such as tree rings, can preserve information on subannual to centennial timescales and present a comprehensive picture of natural climate variability (Hughes et al., 1994; Briffa, 2000; Esper et al., 2002; Briffa et al., 2004; Cook et al., 2004a). Furthermore, proxy records of climate spanning multiple millennia are critical in understanding the causes of climate change, particularly the climate forcing in the 20th century (Mann et al., 1998; Hughes et al., 1999; Crowley, 2000; Fye et al., 2003; Moberg et al., 2005; Cook et al., 2006; Jones et al., 2009).

Numerous studies have proven tree-ring data as an effective proxy in reconstruction of past climate (D'Arrigo and Jacoby, 1993; Mann et al., 1998; Esper et al., 2002; Mann and Jones, 2003; Briffa et al., 2004; Cook et al., 2004b). Tree-ring data obtained from semi-arid regions and highlands are used widely due to the fact that harsh growth environments make tree growth very sensitive to climatic fluctuations (Yadav et al., 1999; Esper et al., 2002; Cook et al., 2003, 2004b; Bräuning and Mantwill, 2004; Treydte et al.,

* Corresponding author.
E-mail address: shaoxm@igsnrr.ac.cn (X. Shao).

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2006). By far, the longest ring-width chronology for climatic reconstruction with precipitation signals is 7979 years long, using samples of bristlecone pine from the White Mountains of the western United States (Hughes and Graumlich, 1996). Other examples of long chronologies can be found in northern Finland (7500 years), northern Sweden (7400 years), and Tasmania (4136 years) and all of them were used in reconstructions of warm-season temperature (Grudd et al., 2002; Helama et al., 2002; Cook et al., 2006). These long proxy records with annual resolution have offered insight to patterns of climate change of interannual to centennial timescales and made important contributions to improve our understanding of the mechanisms of climate change (IPCC, 2007).

In this study we used an endemic species of China, Qilian juniper (*Sabina przewalskii* Kom.) growing in the northeastern part of the Qinghai-Tibetan Plateau. Previous studies have demonstrated that this species can provide millennium long tree-ring chronologies (Zhang et al., 2003, 2009; Sheppard et al., 2004; Liu et al., 2005, 2006a; Shao et al., 2005; Gou et al., 2006; Yin et al., 2008; Liu et al., 2009). Particularly in the mountains encompassing the eastern part of the Qaidam Basin (Fig. 1), living Qilian junipers commonly reach an age of over 800 years, and on some rare occasions grow for more than 1500 years (Zhang et al., 2003; Sheppard et al., 2004; Shao et al., 2009). Due to the high quality of juniper wood, it is often used to construct tomb chambers and coffins. Since the Silk Road had passed through this region in the past 2000 years, many ancient tombs up to the Tang Dynasty (prior to AD 850) (Cheng, 2001; Xu, 2001, 2002) are preserved. In the Dulan area of the eastern Qaidam Basin (Fig. 1), living Qilian junipers in conjunction with the archaeological wood samples preserved in the ancient tombs had been employed to develop two approximately 2500-year long ring-width chronologies (Zhang et al., 2003; Sheppard et al., 2004). Recently Liu et al. (2009) combined the samples of archaeological wood also from Dulan with samples of the living trees from the Wulan and Dulan areas (Fig. 1) and developed a 2485-years ring-width chronology. These studies show the great potential of using archaeological wood in developing tree-ring chronologies spanning multiple millennia in the region.

One question of debate associated with these chronologies, however, is which climatic factor is mainly reflected by the ring-width variations of the archaeological wood. In two of the

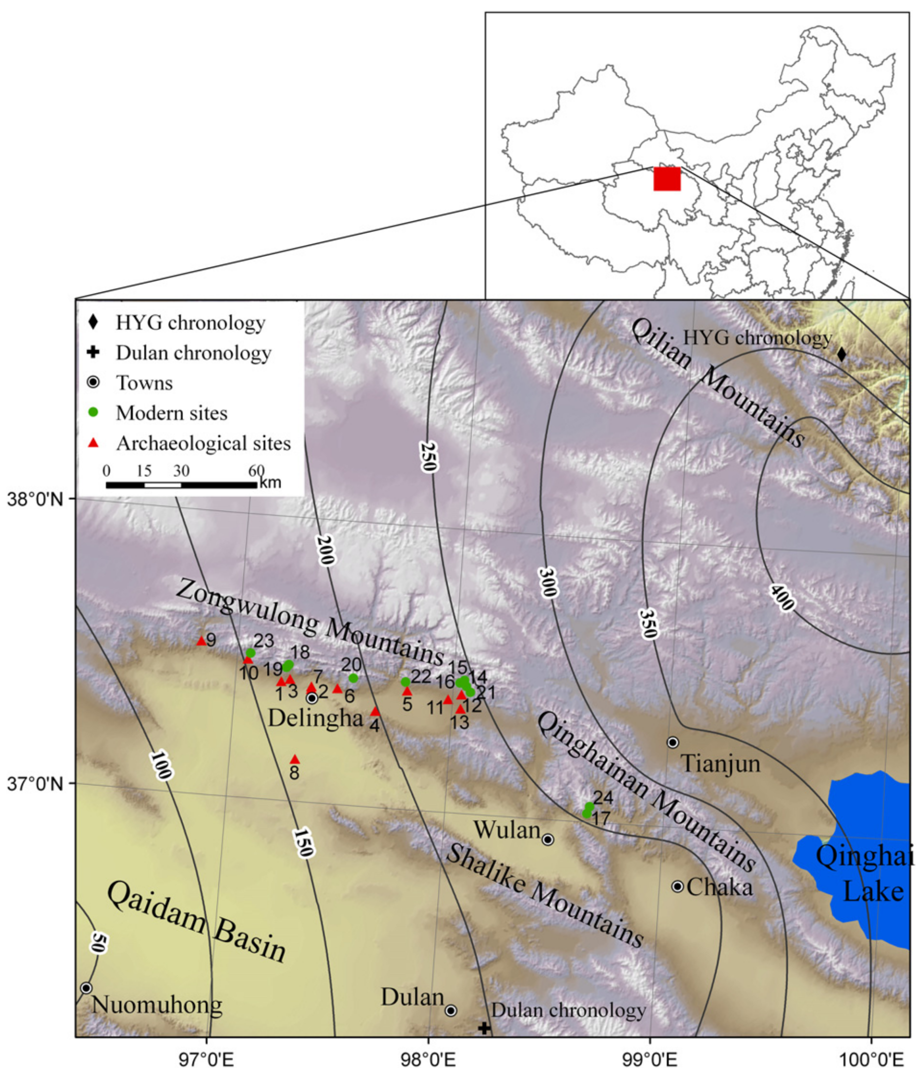

Fig. 1. Locations of the tree-ring sampling sites and the isohyets of mean annual precipitation in mm (1971–2000) in the study area. Also presented are sites of the Dulan Chronology (Zhang et al., 2003) and HYG chronology in the Qilian Mountains (Zhang et al., 2009). Site numbers are identified in Table 1. Precipitation data are from the National Meteorological Information Center of China.

aforementioned studies the archaeological samples were used to represent past precipitation variations i.e. Zhang et al., 2003; Sheppard et al., 2004), while in the other study by Liu et al. (2009) the archaeological samples from the same area were used to reconstruct temperature variations. These inconsistencies stem from the fact that it is impossible to establish direct relationships between the archaeological chronologies and climatic variables since observed climatic data do not overlap in time with the archaeological samples. Previous studies have found that the growth of the living junipers is sensitive to local moisture variability (Zhang et al., 2003; Sheppard et al., 2004; Shao et al., 2005; Yin et al., 2008). On the other hand, juniper ring widths at the upper treeline in the Wulan and Dulan areas (Fig. 1) are found to be significantly correlated with the winter-half year temperature and July temperature (Zhu et al., 2008; Liu et al., 2006b). If the archaeological samples are combined with those moisture-sensitive samples from living trees, it would imply that the combined long chronology is moisture-sensitive. In contrast, if the archaeological specimens are grouped with the temperature-sensitive samples of living trees to form a long chronology, this chronology would be regarded as temperature-sensitive. Therefore, it is necessary to determine the climatic implications of the archaeological wood before developing a long chronology for the purpose of reconstruction of past climate.

Recently we constructed a master ring-width dating chronology using archaeological samples of Qilian juniper in combination with samples from both living and dead trees in the eastern Qaidam Basin (Shao et al., 2009). This chronology covers the past 3585 years, which is by far the longest tree-ring chronology in China. As a dating chronology, however, its climate implications are uncertain and, therefore, cannot be used directly to reconstruct past climate. The purpose of this study is to develop an updated ring-width chronology of Qilian juniper from the Delingha area in the northeastern Qaidam Basin, where very old living trees have been found together with archaeological wood (Fig. 1). All samples used in this updated ring-width chronology are entirely independent of those used in the published Dulan chronologies by Zhang et al. (2003), Sheppard et al. (2004) and Liu et al. (2009). More importantly, we want to make certain that the long chronology has definitive climatic signals and, therefore, is suitable for the reconstruction of past climate.

Grissino-Mayer (1996) pointed out several problems in using archaeological wood in dendroclimatic studies. First, it is necessary to establish whether the archaeological specimens come from the same statistical population of the living trees. In addition, one needs to resolve the problem that the means and variances of the living and archaeological samples coming from the same site may not be stationary as the sample size changes over time (Dean, 1988). As archaeological samples may have shorter lengths than the living samples, the capability of using the resulted chronologies to evaluate long-term climate trends can be seriously limited (Fritts, 1976; Dean, 1988). In our study, we used various procedures in sample screening and chronology construction to address these issues. Before the long chronology was composed, a chronology made entirely of archaeological samples was compared with chronologies from different growth environments in the same general area. This step is essential since trees at different elevations may be affected by different climate factors with variable intensities (LaMarche, 1974; Fritts, 1976; Hughes and Funkhouser, 2003). We also examined the relationships between climate factors and tree growth in different microenvironments. By doing so, we can decipher the climatic signals embedded in the archaeological chronology, so that the composite long chronology contains consistent climate signals over the past three millennia.

2. Data and methods

2.1. Study area and tree-ring materials

The study area is located in the northeastern part of the Qinghai-Tibetan Plateau, China. More specifically, it is in the northeastern Qaidam Basin, Qinghai Province (Fig. 1). Due to its interior location within the Eurasia continent, little moisture can be brought here from the oceans. Therefore, the climate of the study area is dry and of continental nature. It is influenced by both the westerlies (Dai, 1990) and the Asian monsoons that during the rainy season of May to September bring moisture to here (Li et al., 2006). The mean annual precipitation is only 177.4 mm for the period 1971–2000 at the Delingha station (data from the National Meteorological Information Center of China, Fig. 1). The city of Delingha is located at elevations higher than 2900 m above mean sea level (a.m.s.l.) with a long-term mean temperature of $-10.9\,^{\circ}$C in January and $16.5\,^{\circ}$C in July (Fig. 2). The vegetation in the study area is described as a desert steppe by Zheng (1996), with various desert and grassland plants as the dominant species. The mountains to the north and east of Delingha are covered by Qilian junipers in an elevation zone between 3500 m and 4100 m a.m.s.l., which receives orographic precipitation. The junipers here typically grow to 3–5 m tall and 30–40 cm in diameter at the breast height. Since the forest is very sparse, individual trees are minimally interfered by any neighboring canopies. Besides Qilian junipers, stands of Qinghai spruce (*Picea crassifolia*) also appear in the zone of orographic precipitation in the Qinghainan Mountains (Fig. 1). The nearest meteorological station to the Qinghai spruce forest, Chaka (36°47′N, 99°05′E, 3087.6 m), records similar temperatures as those at Delingha but with a higher mean annual precipitation of 208.3 mm for the same period. Tianjun (37°18′N, 99°02′E), approximately 140 km east of Delingha with an elevation of 3417 m a.m.s.l., has a mean annual precipitation of 344.7 mm for the same period. Clearly, annual precipitation increases with elevation in the study area. West of Delingha, annual precipitation decreases to less than 100 mm (Fig. 1), indicating that annual precipitation decreases from east to west in the study area. The published Dulan chronologies (Zhang et al., 2003; Sheppard et al., 2004; Liu et al., 2009) were constructed using archaeological samples from sites approximately 150 km south of the study area.

As mentioned earlier, ancient tombs have been found on the alluvial fans of the Zongwulong Mountains with elevations between 3000 m and 3600 m a.m.s.l in the study area (Fig. 1). During the past decade, tomb robbers had destroyed many of these tombs and thrown out unwanted content in the field, including juniper logs

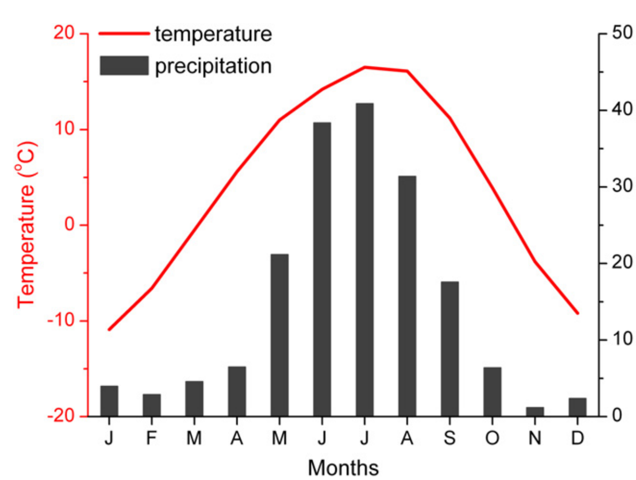

Fig. 2. The long-term mean climate characteristics at the Delingha station, based on data for the period 1971–2000.

that were collected later. According to the archaeologists, most of the tombs were dated to the period of Tubo Kingdom (AD 633–842), the Tibetan Kingdom coexisted with the Chinese Tang Dynasty, based on the formation and construction style of the tombs, the accompanying burial materials, and the paintings on the coffins (Cheng, 2001; Xu, 2001, 2002, 2005). Our recent 3585-year master dating chronology (Shao et al., 2009) was based on archaeological wood from a total of 22 sites in Delingha and Dulan in conjunction with living and relict trees from a total of 29 sites from Delingha, Tianjun, Wulan, and Dulan areas. In the current study, we used the archaeological samples from 13 sites in the Delingha area, a subset of the available archaeological sites. These samples included wooden discs and increment cores (two cores from each log) collected during 2003–2005 (Table 1). Except for one site (BLE in Fig. 1 and Table 1) located on the bottom of Qaidam Basin, all the sites are located on the alluvial fans in the foothills of the Zongwulong Mountains. Some of the sites included specimens from several tombs of close proximity. For example, at MHG we collected cores from 5 different tombs. The rationale of limiting our study in the Delingha area is to make the task of comparing the archaeological and modern samples more feasible. Additionally this is the area that has rendered very old living trees (up to over 1500 years) (Shao et al., 2009), which offer long common periods with the archaeological samples for the purpose of comparison.

Table 1
Information of the sampling sites used in this study. All archaeological sites are located around Delingha, Qinghai Province, northwestern China.

No	Site code	Latitude N (°)	Longitude E (°)	Altitude (m)	Site type	Specimen type	No. samples tree/core
1	BGT	37.42	97.21	3380	Tomb	Block	8
2	BGX	37.40	97.35	3060	Tomb	Block	11
3	NHT	37.43	97.25	3360	Tomb	Block	4
4	XTT	37.34	97.65	3190	Tomb	Block & core	46/77
5	MHG	37.42	97.79	3290	Tomb	Core	55/110
6	AZG	37.41	97.47	3245	Tomb	Block	2
7	SNC	37.41	97.35	3080	Tomb	Block	11
8	BLE	37.15	97.30	2877	Tomb	Block	5
9	AQTG	37.54	96.83	3336	Tomb	Block	3
10	ZHG	37.49	97.05	3544	Tomb	Block	9
11	BRT	37.40	97.98	3390	Tomb	Block	8
12	GARG	37.42	98.04	3556	Tomb	Block	15
13	ALST	37.37	98.04	3445	Tomb	Block	5
14	DLH4W	37.45	98.05	3720	Hillslope hollow	Core	23/46
15	DLH4S	37.46	98.05	4060	Dead trees at upper limit	Core	20/40
16	DLH4U	37.46	98.04	4060	Living trees at upper limit	Core	20/39
17	WL2U	37.03	98.65	3960	Living and dead trees at upper limit	Core	75/138
18	DLH1	37.48	97.24	3730	Living trees below upper limit	Core	31/61
19	DLH2	37.47	97.23	3780	Living trees below upper limit	Core	34/73
20	DLH3	37.45	97.54	3920	Living trees below upper limit	Core	79/168
21	DLH4	37.44	98.06	3800	Living trees below upper limit	Core	67/144
22	DLH5	37.45	97.78	3700	Living trees below upper limit	Core	67/146
23	DLH6	37.51	97.06	3780	Living trees below upper limit	Core	29/67
24	WL2	37.04	98.66	3700	Living trees below upper limit	Core	44/91

Since most of the juniper logs used for constructing the tomb chambers and the blocks for coffins are generally large and thick, we can assume that those trees must have grown in niches with relatively good growth conditions and good accessibility for harvesting. In 2005 and 2006 we sampled additional sites in the Delingha area, including trees in a hillslope hollow at the site DLH4 (DLH4W, Fig. 1, Table 1). This site represents an environment of good moisture condition as the convergent flows from the top slope and surrounding ridgelines tend to accumulate here. To represent the full range of the living conditions of the junipers found in the study area, we also collected cores at and near the upper limit of tree growth at site DLH4 (DLH4U), including some relic trees or standing snags nearby (DLH4S, Fig. 1, Table 1). From our experience, the sample depth prior to AD 1000 tends to be low and we hope that sampling the standing snags would help address this issue. For the purpose of comparison, two sites from the Wulan area were also included in this study (Fig. 1). One is an upper treeline site named WL2U. At this site, we added samples from standing snags in combination to those samples from living trees used in an earlier study (Zhu et al., 2008). The other is from the lower portion of the forest belt and named WL2 which has also been used in an earlier study (Yin et al., 2008). The rest of the samples are from sites DLH1–DLH6 (Fig. 1) as described in Shao et al. (2005), where living trees were sampled on hillslopes up to approximately 100 m below the upper tree limit.

The samples were cross-dated using the method described by Stokes and Smiley (1968) and Fritts (1976). The details of sample processing and measurement can be found in Shao et al. (2009). In the following, the name of a given site (e.g., WL2U) with a letter “C” at the end would denote the name of the ring-width chronology for that site (e.g., WL2UC).

2.2. Chronology development

In order to reduce statistical noise and to enhance the climate signals, specimens with the percentage of missing rings higher than 5% and those of poor correlations with the master series in COFECHA (Holmes, 1983) were excluded when chronologies were developed. Archaeological specimens with time spans shorter than 100 years were also excluded because they could limit the capability for the chronology to capture century-scale variability (Cook et al., 1995). This process increased the mean segment lengths of the archaeological chronology and made the sample lengths more comparable among the archaeological and living tree samples. Samples from the 13 archaeological sites in Delingha were grouped together to develop an archaeological chronology (DLHAC). Living tree specimens used to construct the chronologies DLH1–DLH6 in the Delingha area (Shao et al., 2005) were grouped together to develop a composite living-tree chronology (DLHLC). Samples from the hillslope hollow at DLH4 were used to develop a chronology (DLH4WC) for representing sites of relatively good moisture conditions. Specimens of both relic and living trees from the upper tree limits from the sites of DLH4 and WL2 were grouped together to compose the upper treeline chronologies, namely DLH4UC and WL2UC, respectively.

In previous studies, a regional growth curve for Qilian juniper was estimated using samples mainly from archaeological wood with piths from the Delingha and Dulan areas (Xu and Shao, 2007). In the present study, we employed this regional growth curve to describe the age-related growth trend when developing the archaeological chronology. The growth curves for other chronologies were estimated by either a negative exponential function or linear regression with a negative slope. For samples with piths and showing a clear ascending trend in the first 50 years of growth, a general negative exponential curve or Hugershoff growth curve was used (Warren, 1980). To remove the growth trend, the measured ring width of a given year was divided by the corresponding growth trend value of that year for all the chronologies except for WL2UC. Since there were a few samples with inflation bias near the ends of the data intervals when division was applied on the samples from the site WL2U, we used the difference between the measured ring width and the corresponding growth trend value to remove the growth trend and the variance was stabilized by power transformation (Cook and Peters, 1997). Then the detrended indices for a given site or a given type of chronology were processed by the biweight robust mean estimation in the ARSTAN program (Cook, 1985) to construct the standard chronology.

In order to show the strength of common signals in the chronologies, a within-chronology common interval analysis for each chronology was performed using the detrended index series. This included the calculations of 1) the Pearson correlation coefficients among all the series, and 2) the expressed population signal (EPS) (Wigley et al., 1984), which is a metric indicating the level of chronology confidence (Briffa and Jones, 1990). Because the number of cores per tree was not the same in the common period, the effective chronology signal (ECS) (Briffa and Jones, 1990) was also calculated in the within-chronology common period analysis, which is similar to the correlation coefficients among all series, but with consideration of the different sample sizes.

In developing the final composite long chronology, all detrended indices selected from the sites used were averaged by the biweight robust mean estimation in ARSTAN program (Cook, 1985), and a within-chronology common interval analysis was also performed on the resulted chronology.

2.3. Chronologies comparison

Strong cross-dating between the archaeological, standing snags and living trees specimens in the study region (Shao et al., 2009) suggests that it is appropriate to combine them into a regional composite chronology. This would provide a continuous ring-width record from 1580 BC to AD 2005, lasting 3585 years in length. However, before we can combine the archaeological specimens with the relic and living tree specimens to form the composite chronology, it is necessary to show whether the archaeological samples come from different statistical populations as the other samples. We used the 2-sample Kolmogorov–Smirnov (K–S) test (Hollander and Wolfe, 1999) to validate the agreement of the statistical distributions of the samples. The between-chronology common interval AD 551–750 was selected for the test, which was common among DLHAC, DLHLC and WL2UC. The first year of this period was selected based on the number of cores of DLHLC to meet the criterion of robust replication based on the value of EPS (Wigley et al., 1984) and the last year was selected based on the number of cores of DLHAC for the same reason. Before the 2-sample K–S test was performed, the ring-width index values of the chronologies were normalized by their common interval means and standard deviations.

The other task before we can construct a chronology with definitive climatic signals was to ascertain the environments where the archaeological samples came from because trees growing at different elevations of their distribution may respond differently to climate (LaMarche, 1974; Fritts, 1976; Hughes and Funkhouser, 2003). In our case, the growth of trees at the upper treeline may be more limited by temperature than by precipitation, while those at the lower part of the forest distribution in the semi-arid areas may be more influenced by precipitation (Liu et al., 2006b; Zhu et al., 2008; Zheng et al., 2009). Since it is not possible to establish direct relationships between the archaeological chronology and observed climatic variables, the only feasible way is to examine the similarities between the archaeological chronology and the other chronologies representing a variety of growth environments. To achieve this we used correlation analysis for the common intervals. Two between-chronology common intervals were involved. One is the common period AD 551–750 as selected above; the other one used was AD 1200–1995, common among all modern chronologies (DLHLC, DLH4WC, DLH4UC, WL2UC, and WL2C). The first year of this period was selected because at that year the shortest chronology DLH4WC had robust replication according to its EPS value.

To distinguish the variation patterns in different frequency domains, we performed high-pass and low-pass filtering on the original chronologies. The weights of the filters are based on the reciprocal filters as described by Fritts (1976). Then correlation analysis was performed on three sets of data, i.e., the original unfiltered data, the high-pass filtered data, and the low-pass filtered data. Since there were strong autocorrelations in the low-pass filtered data, the degree of freedom (DF) for significance testing was adjusted as follows (Bretherton et al., 1999):

$$DF = N\frac{1 - r_1 \times r_2}{1 + r_1 \times r_2},$$

where N is the number of observations and r_1 and r_2 are the first-order autocorrelations of the two series, respectively.

2.4. Relationship between tree growth and climate

The climate-tree growth relationship was identified starting with correlation analysis between ring-width chronologies and climate variables. Monthly climate records extending continuously from 1956 to 2005 from the nearby meteorological station of Delingha (37°22′N, 97°22′E, 2982 m a.m.s.l.) were obtained from the National Meteorological Information Center of China, including mean air temperature and total precipitation. Since the width of an annual ring can be the result of climatic conditions integrated over a long period (Fritts, 1976), monthly mean temperature and total precipitation from July of the year prior to the ring formation to August of the current year of the ring growth were included in the analysis. We also included the annual total precipitation and annual mean temperature calculated from the prior July to current June in the correlation analyses to examine the accumulative effects of climate variables on tree growth.

To verify the results of correlation analysis, response function analysis (Fritts, 1976) was performed using the program PRECON (version 5.17B) with 500 bootstrap iterations (Fritts, 1991). In the response function analysis, the independent climate variables are transformed to principal components so that the co-linearities between the climate variables are resolved. After the number of principal components was selected with the PVP-criterion (Guiot, 1990), the regression coefficients corresponding to the principal components were transformed back to the corresponding original climate variables. The bootstrap method was used to provide robust significance testing, which uses the Monte Carlo simulation technique to estimate the standard errors of the response function weights (Fritts, 1991). The months included in the response function analysis were the same as those in the correlation analysis except for the annual data.

3. Results and discussion

3.1. The general characteristics of the chronologies

As stated earlier, the chronologies DLH4UC and WL2UC represent the upper treeline environment. DLH4WC represents a location with relatively good moisture condition and WL2C also represents a site with good moisture condition as indicated by the co-existence of both spruce and juniper stands. DLHLC integrates samples from 6 different sites in the Delingha area (DLH1-6, Fig. 1 and Table 1), which are relatively dry in general.

The overlaps between the archaeological chronology and the living-tree chronologies varied in length (Fig. 3). Table 2 shows the general characteristics of the individual chronologies. The within-chronology common period of DLHAC is shorter than those of the other chronologies because the sample lengths of the archaeological wood are generally shorter as indicated by the median segment lengths (Table 2). The median segment length of a chronology is a useful diagnostic for determining the maximum resolvable low-frequency variance due to climate in a tree-ring chronology after its individual ring-width series have been detrended (Cook et al., 1995, 2003). In our case, climatic variability at timescales at least of 400 years might be usefully resolved if the chronologies are used to perform climate reconstructions.

The characteristics of the archaeological chronology are within the ranges of the metrics of the other chronologies. The mean correlation of DLHAC is 0.31, as compared to 0.27 of WL2UC and 0.45 of DLH4W. The mean sensitivity of DLHAC is 0.24, as compared to 0.19 of WL2UC and 0.35 of WL2C. Similar patterns are also found for the ECS and EPS. WL2UC renders the lowest all-series correlation and the lowest ECS among all the chronologies. The above results suggest that the archaeological chronology is similar to the other chronologies representing different growth environments in those commonly used evaluation metrics of ring-width chronologies. According to Wigley et al. (1984), all chronologies presented in Table 2 are suitable for dendroclimatology since EPS exceeds the recommended threshold of 0.85 in all cases.

DLHLC, DLH4WC, DLH4UC, and WL2C have the same level of mean sensitivity values and all-series correlation coefficients, while WL2UC displays the lowest values of these measures. A comparison of the statistics between WL2UC and WL2C indicates that the upper treeline chronology is quite different from its lower-elevation counterpart. These differences in the chronology characteristics are probably caused by the difference in environmental parameters changing with elevation.

3.2. Comparison among chronologies

Table 3 presents the results of the 2-sample K–S test on sample populations for the period AD 551–750, the common interval for DLHAC, DLHLC, and WL2UC. The null hypothesis that the two samples come from the same statistical distribution cannot be rejected for any of the comparisons. Therefore, it is likely that the archaeological samples come from the same statistical population as the relic and living trees. This further validates the similarities in the characteristics among the chronologies discussed in the previous section.

Table 4 lists the results of correlation analysis for the interval AD 551–750. All three chronologies are positively and significantly correlated to each other ($p < 0.01$) for the unfiltered data, as well as for the high-pass filtered data. For the low-pass filtered data, however, the correlations among these chronologies are not statistically significant at the 0.05 level. The lowest correlations are found between DLHLC and WL2UC for each of the three data sets (original unfiltered, high-pass filtered, and low-pass filtered), which implies that WL2UC and DLHLC share the least common signals between them. It is also noted that the correlations between DLHAC and DLHLC are always the highest among all three data sets, indicating stronger common variation signals between these two chronologies than those of the other chronologies. As the samples of DLHLC are obtained from the lower portion of the forest belt, the logs and wood used in the tombs were likely harvested from similar environments. We could reason that people would not harvest the stands at high elevations or locations with poor accessibility if large trees that could be easily accessed were available.

The high-pass filtered data produce the strongest correlations, while the low-pass filtered data produce the poorest ones among the chronologies. The discrepancies between DLHAC and DLHLC are

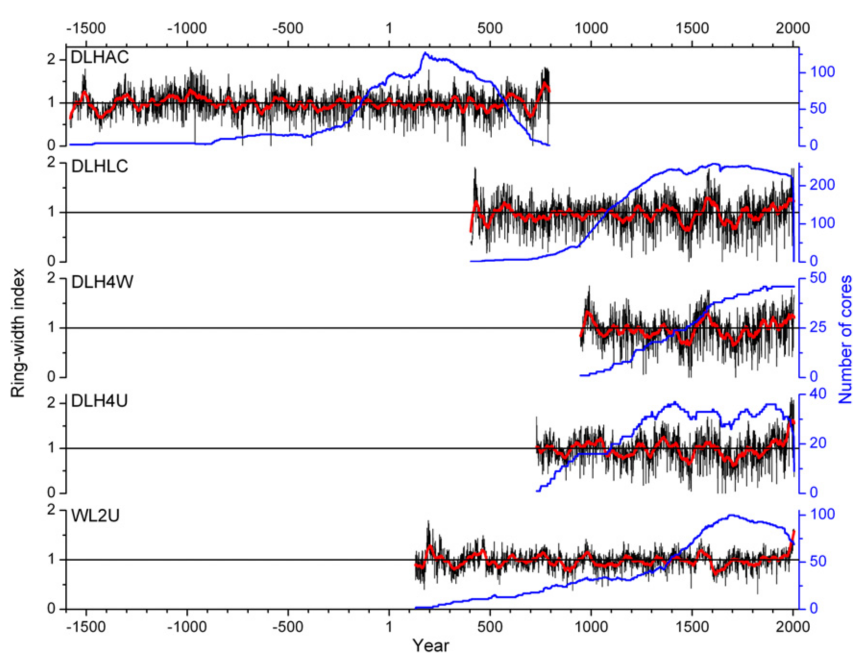

Fig. 3. Ring-width index series of the archaeological (DLHAC) and modern (DLHLC, DLW4W, DLH4U, and WL2U) chronologies and the numbers of cores used in chronology development. Red lines represent the 31-year moving averages.

Table 2
Standard chronology statistics and results of common period analysis.

	DLHAC[a]	DLHLC[b]	DLH4WC	DLH4UC[c]	WL2UC[c]	WL2C
First year	1580 BC	AD 404	AD 947	AD 729	AD 130	AD 845
Last year	AD 793	AD 2004	AD 2005	AD 2005	AD 2005	AD 2001
Chronology length	2373	1601	1059	1277	1876	1157
Median segment length	401	657	516	483	528	690
Tree/core	115/201	169/306	23/46	28/54	75/138	24/44
Mean correlation[d]	0.31	0.39	0.45	0.40	0.27	0.37
Percentage of missing rings	1.602%	1.958%	1.653%	1.593%	0.372%	2.08%
Mean Sensitivity	0.24	0.32	0.33	0.31	0.19	0.35
First-order autocorrelation	0.37	0.35	0.37	0.40	0.43	0.40
Common period (AD)	201–500	1601–2000	1601–2000	1601–2000	1601–2000	1601–2000
Tree/core	39/59	116/185	21/35	10/11	41/61	15/23
All-series correlation	0.37	0.43	0.46	0.43	0.30	0.37
Effective chronology signal	0.43	0.49	0.52	0.44	0.37	0.42
Expressed population signal	0.97	0.99	0.97	0.89	0.96	0.93

[a] Using samples from archaeological sites.
[b] Using samples from chronologies DLH1 to DLH6.
[c] Using samples from dead trees and those from the upper tree limit.
[d] Mean correlation is based on all detrended series with 20 or more years of overlap.

obvious in the low-frequency domain (Fig. 3). This feature may be partially related to the replication of the chronologies and the age-related growth trends. The period AD 551–750 is in the later part of DLHAC with the number of samples changing from 68 down to 6, but it is in the earlier part of DLHLC with the number of samples changing from 5 to 13. Such dramatic changes in the sample depth may have influenced the fluctuation patterns in the low-frequency domain. On the other hand, the procedure of removing growth trends probably has affected the variation pattern in the low-frequency domain of DLHLC during this period. In contrast, the correlation of WL2UC to DLHAC does not show such changes in different frequency domains, while its correlation to DLHLC shows similar changes as that between DLHAC and DLHLC. This may also result from the influence of detrending on the low-frequency domain in the earlier part of DLHLC.

We further compared the non-archaeological chronologies for the interval AD 1200–1995. The correlations between the chronologies are all positive and statistically significant ($p < 0.05$) except for that between WL2UC and DLHLC in the low-frequency domain (Table 5). The highest correlations are found between DLHLC and DLH4WC in all three data sets. Additionally, the correlations do not change much in different frequency domains. These results indicate that DLHLC and DLH4WC carried much similar variation signals in all frequency domains, although the samples came from sites of different topographic characteristics. Even though we cannot compare DLHAC and DLH4W directly due to the absence of a common interval, the strong correlations between DLHAC and DLHLC and those between DLHLC and DLH4W link the archaeological wood in the tombs to locations with relatively good growth conditions, similar to the hillslope hollow site sampled in our study.

In general, WL2UC produces low correlations with the other chronologies, but its correlations with DLH4UC are all positive and statistically significant (Table 5). This suggests that the similarity between the two locations (upper treeline sites) leads to similar variation patterns in the ring-width indices. The lowest correlation is found between WL2UC and DLHLC, especially in the low-pass filtered data. Therefore, it seems unsuitable to include WL2UC and DLH4UC in developing the long composite chronology together with the archaeological specimens.

3.3. Relationships between tree-ring chronologies and climate

Previous studies (Shao et al., 2005; Yin et al., 2008) found that the ring widths of Qilian junipers at the sites DLH1-DLH6 and WL2 in the study area were positively correlated with May and June moisture conditions that were regulated mainly via concurrent precipitation and temperature (evapotranspiration). Correlation analysis (Fig. 4) and response function results (Fig. 5) in the current study show that DLHLC and DLH4WC (from the stand with relatively good moisture condition) have similar relations to climatic factors as those of the site chronologies of DLH1–DLH6 (Shao et al., 2005). Both DLHLC and DLH4WC are significantly and positively correlated to May and June precipitation and negatively correlated to June temperature (Figs. 4a,b and 5a,b). High precipitation in May and June replenishes the soil moisture after the dry autumn, winter, and earlier spring, which helps producing wide annual rings. In contrast, high temperature in June causes high evaporation and transpiration, which deplete soil moisture and result in water stress for tree growth and narrow annual rings. Correlation analysis also indicates that annual precipitation summed from the prior July to current June has the highest coefficient with DLHLC and DLH4WC. These results indicate that trees from the lower part of forest belt are moisture-sensitive. The moisture regime during the months at the onset of the growing season is important for tree growth at these sites, which is true even for locations with relatively good moisture conditions in the study area (e.g., DLH4W and WL2). These results are consistent with previous ring-width dendroclimatic studies from the nearby areas (Zhang et al., 2003;

Table 3
Statistical significance of the 2-sample Kolmogorov–Smirnov (K–S) test on statistical populations of the samples for the common interval AD 551–750.

	DLHAC	DLHLC
DLHLC	0.465	
WL2UC	0.792	0.465

Table 4
Correlation coefficients and the degrees of freedom or the adjusted degrees of freedom among DLHAC, DLHLC and WL2UC for the common interval AD 551–750.

Site	High-pass filtered data		Unfiltered data		Low-pass filtered data	
	DLHAC	DLHLC	DLHAC	DLHLC	DLHAC	DLHLC
DLHLC	0.77**/198		0.62**/198		0.44/8.5	
WL2UC	0.45**/198	0.32**/198	0.43**/198	0.26**/198	0.41/9.6	0.13/11.8

**Significant at 0.01 level.

Table 5
Correlation coefficients and the degrees of freedom or the adjusted degrees of freedom among the modern chronologies in the common interval AD 1200–1995.

Site	High-pass filtered data				Unfiltered data				Low-pass filtered data			
	DLH4W	DLHLC	DLH4UC	WL2UC	DLH4W	DLHLC	DLH4UC	WL2UC	DLH4W	DLHLC	DLH4UC	WL2UC
DLHLC	0.88**/794				0.88**/794				0.87**/26.5			
DLH4UC	0.86**/794	0.86**/794			0.80**/794	0.83**/794			0.75**/24.8	0.81**/25.9		
WL2UC	0.64**/794	0.62**/794	0.67**/794		0.55**/794	0.50**/794	0.58**/794		0.44*/26.1	0.35/27.2	0.48*/25.5	
WL2C	0.82**/794	0.82**/794	0.74**/794	0.70**/794	0.79**/794	0.80**/794	0.66**/794	0.57**/794	0.76**/26.1	0.78**/27.1	0.57**/25.5	0.44*/26.7

*Significant at 0.05 level.
**Significant at 0.01 level.

Sheppard et al., 2004; Shao et al., 2005; Liu et al., 2006a; Yin et al., 2008).

As shown above, DLHAC displayed variation patterns more similar to that of DLHLC in both low and high frequency domains than to the other chronologies during the interval AD 551–750. Additionally, DLHLC was also more strongly correlated with DLH4WC in the interval AD 1200–1995. Therefore, the climatic responses of the archaeological chronology, DLHAC, can be extrapolated from those of DLHLC and DLH4WC. DLHLC represented relatively dry environments and had a wide spatial coverage (over 70 km across), while DLH4WC represented a relatively moist environment in the study region. Since both DLHLC and DLH4WC are moisture-sensitive, we can conclude that DLHAC is also moisture-sensitive and that the variation of ring widths in the archaeological wood can be used to infer the variation of moisture conditions in the past. Our results here should clear the confusion present in previous studies, in which archaeological samples were combined with either moisture-sensitive (Zhang et al., 2003; Sheppard et al., 2004) or temperature-sensitive (Liu et al., 2009) modern samples.

The next question is whether the samples from the upper treeline should be used to construct a regional moisture-sensitive chronology for the study area. For DLH4UC at the upper treeline, strong positive relationships are found between the ring widths and previous July and current June precipitation, and strong negative relationship to June temperature in both correlation analysis and response functions (Figs. 4c and 5c), indicating that the tree rings at the upper treeline at this site still contain signals of moisture conditions. However, we also find significant positive correlations between temperature and tree growth for the months from October of the previous year to February of the current year (Fig. 4c) and a strong positive relation for November of the previous year in the response functions (Fig. 5c) at this site. It is clear that at DLH4U, temperature in the winter-half year is also a limiting factor of tree growth. The effect of temperature is even more obvious at the site WL2U. Here temperatures of 8 consecutive months from the previous September to current April are positively correlated with tree growth with statistical significance (Fig. 4d). In the response functions, temperatures of previous October and that of current April have significant influence on tree growth (Fig. 5d). In addition, the positive correlation of tree growth with May and June precipitation and negative correlation with June temperature as seen at the other sites are absent and the annual mean temperature calculated using data from prior July to current June produces the highest correlation at WL2U (Fig. 4d). It can be concluded that at WL2U, a site of the upper treeline, temperature is the main limiting factor of tree growth, which is different from all other sites examined in this study. The moisture condition at site WL2U is among the best in the study area, as indicated by the appearance of Qinghai spruce at this site in the lower elevations. It is the good moisture condition that reduces the influence of precipitation on tree growth, although the elevation of the site is lower than that of the DLH4U by about 100 m.

Generally speaking, temperature is the major limiting factor for trees growing along the upper treeline (Fritts, 1976). Positive correlations between winter temperature and tree growth have been found in numerous studies (Pederson et al., 2004; Liu et al., 2006b, 2007, 2009; Zhang and Qiu, 2007; Zhu et al., 2008). However, profound positive growth–precipitation association at upper treeline sites has also been found in semi-arid areas, such as the Snake Range of east-central Nevada (LaMarche, 1974; LaMarche and Stockton, 1974). Earlier studies using samples from the upper treeline in Wulan (Zhu et al., 2008) and Dulan (Liu et al., 2006b) found positive correlations between ring width and July

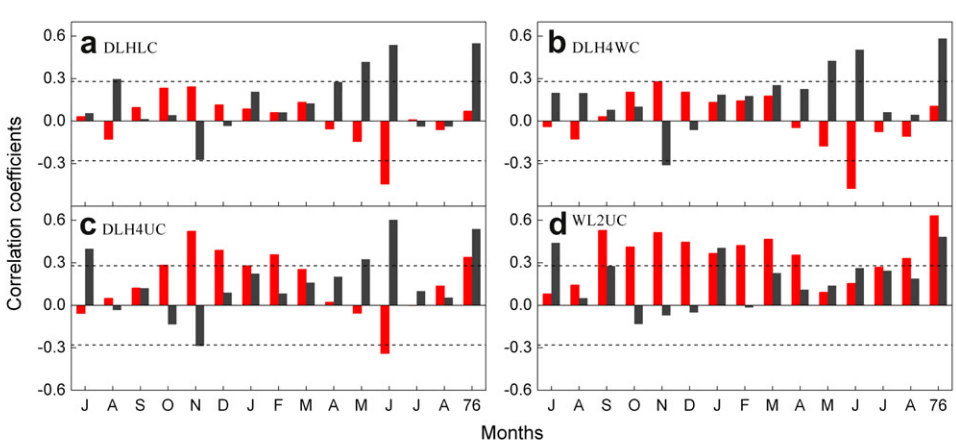

Fig. 4. Correlation coefficients between climate variables at the Delingha station and ring-width chronologies for months from July of the previous year to August of the current year of ring formation, using data for the period 1956–2004. The notion "76" represents that the values are calculated from July of the previous year to June of the current year. Red bars are for temperature, and black bars are for precipitation. The horizontal lines indicate the 95% confidence intervals for correlation coefficients.

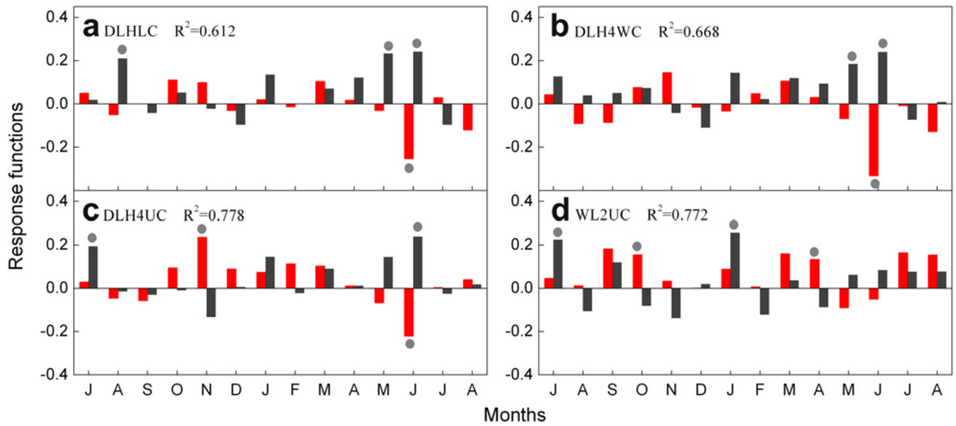

Fig. 5. Response functions between the ring-width chronologies and climate variables at the Delingha station, using data for the period 1956–2004. The months used and graphic symbols are the same as in Fig. 4. The circles represent the months with statistically significant ($p < 0.05$) response functions. R^2 is the variance explained by the reponse function.

temperature, but such correlations are not statistically significant in our data (Figs. 4 and 5). Nevertheless, the relationships of tree growth at DLH4U and WL2U with temperature in the winter-half year suggest that DLH4UC and WL2UC are different from the other chronologies evaluated in this study as the major limiting factors of tree growth are different at these sites.

3.4. The composite chronology and its comparison with other chronologies

Based on the above results, a composite moisture-sensitive chronology (DLHCC) is developed using the samples from the 13 archaeological sites and those from locations below the upper treeline in the Delingha area, including a total of 553 cores from 307 trees (Fig. 6). The samples from the site DLH4W are included because they are indirectly linked to the archaeological specimens through the strong relationship with DLHLC. Samples from the upper treelines are excluded since they may introduce unwanted signals of temperature variations. The composite chronology covers 3585 years starting from 1580 BC to AD 2005. The median segment length is 521 years, which is adequate to preserve multi-centennial scale variations in the chronology.

In the common period analysis, the period AD 551–700 is selected using the data from 15 cores of 11 trees, in which 10 cores from 8 trees are from the archaeological wood. The mean correlation among all the samples is 0.29 and the ECS is 0.31. These values are relatively low compared to those presented in Table 2, mostly resulted from integrating samples from multiple locations or sites.

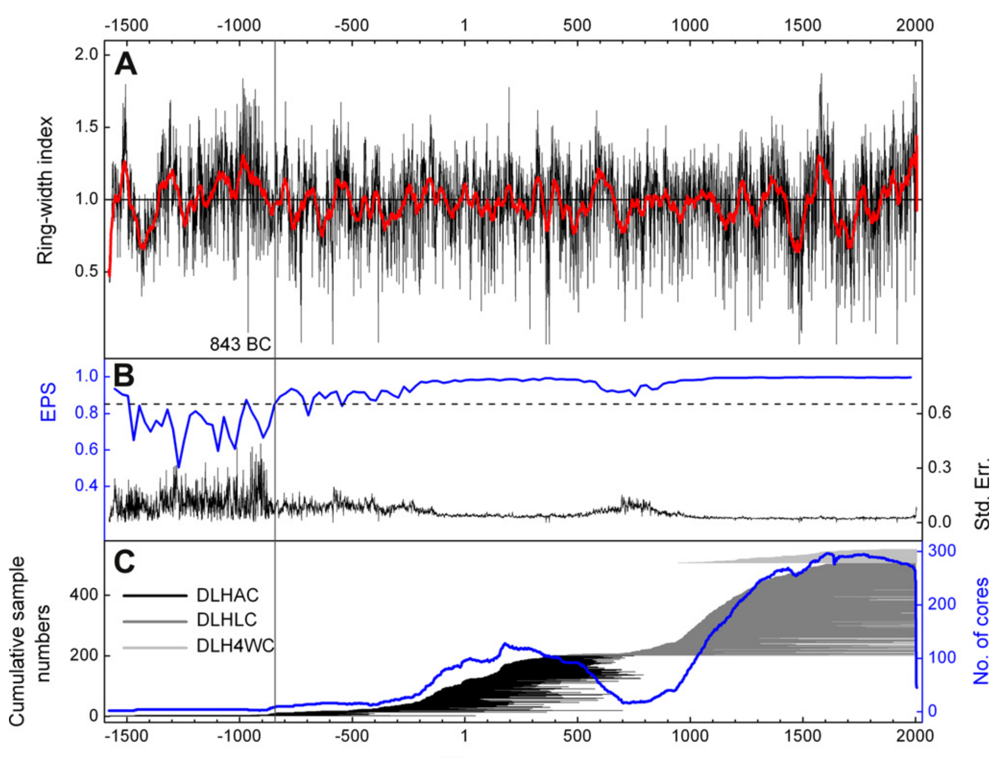

Fig. 6. The composite chronology DLHCC (A) with 31-year moving averages (red line), the 50-year moving EPS (upper part of B), the standard errors of the composite chronology (lower part of B), and the sample depth (number of cores) of the composite chronology and the age profile of the tree-ring series used (C), indicating samples from different sources.

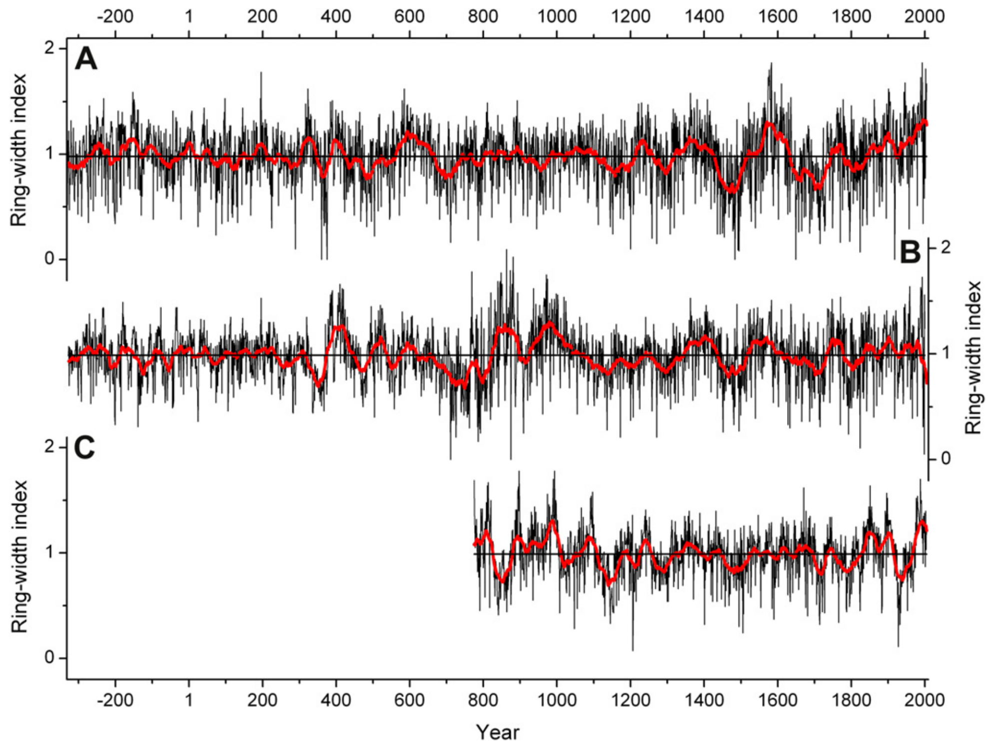

Fig. 7. Comparison among the Delingha composite chronology DLHCC (A), the Dulan chronology (B, Zhang et al., 2003), and the HYG chronology from the Qilian Mountains (C, Zhang et al., 2009). Red lines represent the 31-year moving averages and the horizontal lines represent their long-term means.

Since the common period between the archaeological wood and living tree specimens was relatively short compared to the total length of the chronology, EPS, in stead of subsample signal strength, was used to determine the minimum number of cores required to provide an acceptable estimate of the composite chronology mean value function. Using an EPS value of 0.85 as the criterion (Wigley et al., 1984), we determined that a minimum of nine samples from 6 trees is required to maintain an acceptable level of statistical quality in the chronology signals. Therefore, the composite chronology can be reliably used in dendroclimatic study from 843 BC onward. This is also demonstrated by the standard errors of the chronology shown in the lower part of Fig. 6b, in which years with large standard errors are mostly related to small sample depths.

Besides interannual fluctuations, the composite chronology shows considerable variations on inter-decadal to centennial timescales. During the past 2850 years the multi-decadal to centennial low-growth periods are centered on 740s BC, 630s BC, 480s BC, AD 360s, AD 490s, AD 690s, AD 1150s, AD1290s, AD 1480s, and AD 1710s. The two low-growth periods centered on AD 1480s and AD 1710s are very prominent in terms of duration and amplitude. Two prominent high-growth periods are centered on AD 590s and AD 1570s, and the past 30 years are also characterized by high growth.

Two long moisture-sensitive ring-width chronologies were developed in the Dulan area by Zhang et al. (2003) and Sheppard et al. (2004), respectively. After two missing rings (Shao et al., 2009) were added to the Dulan chronology by Zhang et al. (2003), we compared it with our composite long chronology DLHCC. In addition, a 1232-year chronology of Qilian juniper (HYG) was recently developed in the semi-arid Qilian Mountain area (Zhang et al., 2009), approximately 250 km to the northeast of Delingha (Fig. 1). Fig. 7 displays the chronology DLHCC together with the Dulan chronology and the HYG chronology, while Table 6 lists the correlation coefficients among the three chronologies, which are all positive and statistically significant at the 0.01 level. DLHCC and the Dulan chronology have the strongest correlation due to close spatial proximity. In the low-frequency domain (the thick lines in Fig. 7), most of the low-growth periods in DLHCC are also present in the other two chronologies. However, during AD 700–1050, there are prominent discrepancies among the three chronologies. DLHCC displays more gentle variations around the overall mean condition, while the Dulan chronology and HYG display variations with enhanced amplitudes. This might be due to the weak sample depth in the Dulan chronology (2–9 cores available) and in HYG (5–16 cores available) as compared to 16–116 cores in DLHCC during the same period. On the other hand, the consistency of the low- and high-growth periods of the three chronologies before and after AD 700–1050 should indicate major droughts and wet events with large spatial coverages.

Table 6
Correlation coefficients among the composite chronology, the Dulan chronology (Zhang et al., 2003), and HYG chronology (Zhang et al., 2009).

	DLHCC	DL	HYG
DLHCC	/	328 BC–AD 2000[a]	AD 540–2005[a]
DL	0.66**	/	AD 540–2000[a]
HYG	0.40**	0.33**	/

**Significant at 0.01 level.
[a] The common period for calculating the correlation coefficients.

4. Conclusion

In this study we analyzed archaeological tree-ring samples of Qilian juniper from ancient tombs dated prior to AD 800, and samples of relic and living trees from Delingha in the northeastern Qinghai-Tibetan Plateau in order to construct a moisture-sensitive ring-width chronology. The final composite chronology extends from 1580 BC to AD 2005, covering 3585 years, and is by far the longest ring-width chronology in China.

In most dendroclimatic studies, the selection of sampling sites helps to restrict the major limiting factor of tree growth to be either temperature or precipitation (Fritts, 1976). In addition, the statistical relation of ring widths to climatic variables can reveal the climatic signals of the chronologies. However, this strategy could not be applied directly to the archaeological samples in our study because the archaeological sites might be far from where the trees grew and there was no historical document to record the sites of wood harvest. Additionally, there was no overlap between the archaeological chronology and the instrumental climate records. To decipher the climatic signals of the archaeological specimens, we developed ring-width chronologies from multiple sites covering a wide variety of growth environments. After clearly-defined sample screening procedures, the archaeological samples used in this study were found to be comparable to the relic and living tree samples in terms of sample lengths and common signal strength. Chronology statistics and the results of statistical analyses suggest that the archaeological specimens represented the same statistical population as that of the relic and living trees. The correlation analysis for the common period AD 551–750 showed that there were stronger common variation signals between the archaeological chronology (DLHAC) and the chronology developed using samples from the lower portion of the forest belt (DLHLC) than with the chronology from the upper treeline (WL2UC). The examination of the relationships between the tree-ring chronologies and climate variables indicated that the chronologies from the lower portion of the forest belt (DLHLC and DLH4WC) were exclusively moisture-sensitive, while the chronologies from the upper portion of the forest belt (DLH4UC and WL2UC) also contained strong temperature signals. Considering the accessibility for wood harvesting when the tombs were constructed, it is reasonable to conclude that the archaeological samples did not originate from the upper treeline, but from sites at lower elevations where moisture was the major limiting factor for tree growth.

In construction of the composite chronology, we used the archaeological wood samples from 13 sites and living tree samples from 7 sites in the lower portion of the forest belt in the Delingha area of the northeastern Qaidam Basin. The resulted long composite moisture-sensitive chronology was based on a total of 553 specimens from 307 trees, which can be reliably used for dendroclimatological purposes from 843 BC onward. Ten major multi-decadal low-growth periods, associated with major drought events, were identified during the past 2850 years. Comparing with the Dulan chronology (Zhang et al., 2003) and HYG chronology (Zhang et al., 2009) from the Qilian Mountains, we found that most major low-growth periods in our composite chronology are also found in the other two chronologies, while the greater sample depths of our chronology offered more reliable estimates of past moisture conditions, especially during the period AD 700–1050 when the sample depths of the other two chronologies were low. With its long duration and definitive climatic signals, this composite chronology can be used for quantitative reconstructions of drought history in this region for the past 2850 years, which also sets the foundation for future studies of climate changes at inter-decadal to centennial timescales.

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