A 2,326-year tree-ring record of climate variability on the northeastern Qinghai-Tibetan Plateau

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[1] High-resolution climate proxy records covering the last two millennia on the Qinghai-Tibetan Plateau are scarce yet essential to evaluation of the patterns, synchroneity and spatial extent of past climatic changes including those in the Medieval Warm Period (MWP) and the Little Ice Age (LIA). Here we present a 2326-year tree-ring chronology of *Sabina przewalskii* Kom. for Dulan area of northeastern Qinghai-Tibetan Plateau. We find that the annual growth rings mainly reflect variations in regional spring precipitation. The greatest change in spring precipitation during the last two millennia seems to occur in the second half of the 4th century. The North Atlantic MWP was accompanied by notable wet springs in the study region during A.D. 929–1031 with the peak occurring around A.D. 974. Three intervals of dry springs occurred in the period of LIA. Our tree-ring data will facilitate intercontinental comparisons of large-scale synoptic climate variability for the last two millennia. *INDEX TERMS:* 4211 Oceanography: General: Benthic boundary layers; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 1620 Global Change: Climate dynamics (3309); 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 9320 Information Related to Geographic Region: Asia. **Citation:** Zhang, Q.-B., G. Cheng, T. Yao, X. Kang, and J. Huang, A 2,326-year tree-ring record of climate variability on the northeastern Qinghai-Tibetan Plateau, *Geophys. Res. Lett.*, *30*(14), 1739, doi:10.1029/2003GL017425, 2003.

1. Introduction

[2] Palaeoclimate studies generally recognize that Earth's climate has undergone continuous changes during the last two millennia. However, there has been considerable uncertainty as to the amplitude, synchroneity and spatial extent of many climate fluctuations such as the Medieval Warm Period (MWP, from about the 9th to 14th centuries) and the Little Ice Age (LIA, from about the 16th to 19th centuries) [*Bradley and Jones*, 1993; *Hughes and Diaz*, 1994]. Long tree-ring records from different areas of the globe have been used to examine the nature of climate variability covering these periods on continental or hemispheric scales [*Briffa*, 2000; *Mann et al.*, 1998; *Briffa and Matthews*, 2002]. To better understand the late Holocene climate requires expansion of tree-ring sample collection covering extensive and diverse areas of the world [*Briffa and Osborn*, 1999], but there have been few long tree-ring records available in the vast areas of the Qinghai-Tibetan Plateau [*Zhang*, 2003], which acts as an elevated heat or cold source for the atmosphere and plays an important role in modifying the Asian monsoon circulation [*Murakami*, 1987]. The lack of data is a major impediment to our effort in increasing spatial resolution of climate reconstruction for this remote yet climatically sensitive region.

[3] In this paper we report a 2326-year ring-width chronology derived from archaeological wood and living trees of *Sabina przewalskii* Kom. in Dulan area of northeastern Qinghai-Tibetan Plateau, China. The long tree-ring chronology allows us to examine a wider range of past climate variation, and to identify whether the North Atlantic MWP and the LIA were accompanied by climate changes on the Qinghai-Tibetan Plateau. Comparisons of the tree-ring data with climate proxy records in other areas will provide insights into the spatiotemperal patterns of past climate changes.

2. Materials and Methods

2.1. Study Area and Tree-Ring Samples

[4] Our study area is located in Dulan ($35°50' \sim 36°30'$N, $97°40' \sim 98°20'$E) of northeastern Qinghai-Tibetan Plateau (Figure 1). Mean annual total precipitation in this area is 240 mm, with most of the rainfall occurring in May to September. Mean monthly air temperatures are $-10.3°$C in January to $15.0°$C in July. *Sabina przewalskii* Kom. is the most important single tree species on south-facing mountain slopes, and usually grows scatterly in open stands at an elevation between 3100 m and 3800 m. The growth of sabina trees is under stress as indicated by the stripbark morphology and partial dieback of some upper limbs.

[5] Tree-ring samples of archaeological wood were collected from well-preserved sabina tree trunks from several ancient tombs in Dulan during a field investigation in the autumn of 2001. These tombs were constructed about 1200 years ago, but were damaged by grave robbers in different time thereafter [*Xu*, 2002]. We collected 10 disc samples from the tree trunks (used as building blocks) taken out from different tombs. We further investigated a wood-lined tomb in the field and collected 10 increment core samples from the tree trunks inside the cabins. Increment cores from living sabina trees were also collected in the same area in order to establish the climate-growth relationship and crossdate the annual growth rings of the ancient tree trunks. We chose the sampled trees selectively, with consideration of obtaining long tree-ring series (generally from large-diameter trees) and high sensitivity to climatic variations (generally from a slope and coarse soil habitat and distant from neighbouring trees).

2.2. Tree-Ring Chronology and its Relationships With Climatic Variables

[6] Ring-widths of the discs and increment core samples were measured to the nearest 0.001 mm using a Lintab tree-

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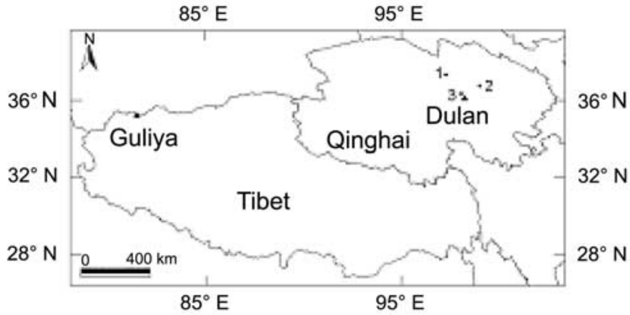

Figure 1. Map of Qinghai and Tibet in China showing the locations of Dulan for tree-ring chronology, Guliya for ice core data comparison, and the meteorological stations (1, Delingha; 2, Chaka; and 3, Dulan).

ring measurement system. Each tree ring was assigned a calendar year of its formation by means of crossdating [*Fritts*, 1976], a technique that is based on the recognition that trees growing in the same period and under the same controlling factors exhibit similar variation in the year-to-year sequences. The crossdated ring-width series were standardized using a conservative curve-fitting method and then averaged to minimize the random signals due to fluctuation in micro-site conditions [*Cook et al.*, 1990]. The resulting yearly values, called "tree-ring indices", reflect the growth variations caused by large-scale environmental forcing, most likely the climate.

[7] Relationships between tree-ring indices and climatic variables are identified using the software PRECON [*Fritts*, 1996] and the techniques of response function and correlation analysis. The response function [*Fritts et al.*, 1971] is a linear multiple regression technique that uses the principal components of monthly climatic variables to estimate tree-ring growth. This method overcomes the inter-correlation problems among climatic variables. The correlation analysis helps understand the climate-growth relationships by directly calculating the simple correlation coefficients [*Blasing et al.*, 1984]. The climatic data are regional averages from three nearby meteorological stations in Dulan, Chaka (36°47′N, 99°05′E) and Delingha (37°22′N, 97°22′E) for the period from 1953 to 2000 (Figure 1). Since the climatic conditions in the previous year usually have effects on tree-ring growth of the current year [*Fritts*, 1976], the monthly climatic variables over a 13-month period, from September 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 growth.

3. Results and Discussion

3.1. Tree-Ring Chronology and Growth Response to Climatic Variables

[8] Twenty samples from the ancient tombs and 68 samples from Dulan living trees, among which 55 samples were collected and examined previously in a separate study [*Kang et al.*, 1997], were successfully crossdated. The longest common growth interval for ancient and living trees was 621 years. The mean inter-series correlation coefficient was 0.68, suggesting that the tree rings of different samples contain common climatic signals. The chronology is capable of preserving much of the climate variance on time-scales from interannual to a few hundred years, since the average length of the 88 samples is 574 years (six samples are more than 1000 years long) [*Cook et al.*, 1995]. The strength of climatic signals expressed by tree-ring indices is a function of the number of sample replications. The chronology interval 326 B.C.–A.D. 2000 contains usually at least four sample replications for each year except for a short period A.D. 780–881 in which only three or two samples are available.

[9] The results of the response function analysis show that tree-ring growth is correlated positively with temperature in October of the prior growth year and in March of the growth year and, during May and June, it is correlated positively with precipitation and negatively with temperature (Figure 2). The simple correlation analysis show that the tree-ring indices are most strongly correlated with the spring precipitation (May–June) ($r = 0.58$, $p < 0.001$), and not well-correlated with the temperature in previous year's October and current year's March at the significance level $p < 0.1$. This climate-growth relationship indicates that moisture stress in growing season is a major limiting factor to tree-ring growth. This result is in general agreement with that observed in dendro-climatological studies of the same species in other areas of the Qinghai-Tibetan Plateau [*Zhang and Wu*, 1999; *Brauning*, 2001; *Huang et al.*, 2002], suggesting that the annual growth rings mainly reflect variations in regional spring precipitation.

3.2. Regional Variability in Spring Precipitation

[10] The Dulan chronology (Figure 3) shows that the spring precipitation was in a relatively low level of variability around the mean during the earliest interval, between 326 B.C. and the end of the 3rd century. It varied rather strongly above and below the mean during the 4th to mid-7th centuries. After a 160-year period of dry condition in spring in the mid-7th to early 9th centuries, it turned into a state of wet condition till the late 11th century. The spring precipitation was then characterized by fluctuations at

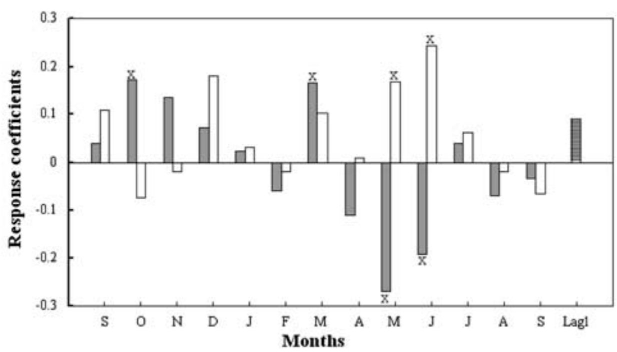

Figure 2. Response function coefficients showing the relationships between radial growth of *Sabina przewalskii* Kom. and monthly mean air temperature and total monthly precipitation for the regional climatic data set for the period 1953–2000. Lag 1 represents the tree-ring growth in the previous year. Black bars stand for temperature, white bars for precipitation, and x for significance at the 0.05 level as tested by bootstrap method.

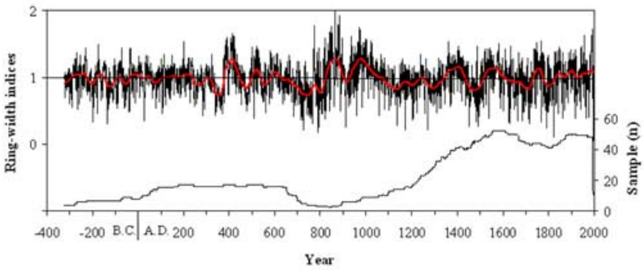

Figure 3. The 2326-year ring-width chronology of *Sabina przewalskii* Kom. and the number of samples for each year in Dulan area of eastern Qinghai-Tibetan Plateau. The smoothed curve superimposed on the chronology is derived after filtering to emphasize long-term fluctuations (the filter is a cubic spline passing 50% of the variance in a sine function with a wavelength of 64 years).

multidecadal to century timescales till the mid-19th century, followed by a period of moist condition to the present.

[11] The greatest change in spring precipitation during the last two millennia seems to occur in the second half of the 4th century (Figure 3). The tree-ring indices increased from a low value 0.46 in A.D. 369 to a high value 1.60 in A.D. 392, suggesting that the climatic shift can be completed within about two decades. The tree-ring samples covering this interval of abrupt shift are well replicated (Figure 3); therefore we suggest that the climatic shift reflects a real aspect of the climate dynamics and is worth further research.

[12] In order to obtain a detailed picture of the regional climate variability for the last two millennia, we compared the Dulan chronology with the δO^{18} data (indicating temperature fluctuation) in ice core from Guliya (Figure 1) of western Qinghai-Tibetan Plateau, which is the only long and high-resolution proxy data currently available in this region [*Yao et al.*, 1996]. Despite the distance between the study areas of the tree rings and ice core, comparison of the two independent records on the same plateau helps examine climate variability over a larger spatial scale.

[13] The tree-ring chronology shows that, corresponding to the North Atlantic MWP, the ring widths were increased apparently during A.D. 929–1031 with the peak occurring around A.D. 974. The anomalous period of high growth in the mid-9th century was obtained from only two or three sample replications and, therefore, cautions should be taken when interpreting the tree-ring data for this period. The δO^{18} data in ice core show relatively high values around 970s [*Yao et al.*, 1996]. This observation suggests that the climate in this period was relatively moist in spring, and probably warm in non-growing season. Studies of historical documents in eastern China [*Chen and Shi*, 2002] showed that an apparent warm and relatively dry climate occurred in A.D. 960–1099, which falls within the MWP. *Esper et al.* [2002] studied the MWP climate from long tree-ring chronologies in the Northern Hemisphere extratropics, and indicated that the warmest period covers the interval A.D. 950–1045, with the peak occurring around A.D. 990. These results indicate that the spring precipitation regime on the northeastern Qinghai-Tibetan Plateau experienced a notable change during the North Atlantic MWP. It is interesting to note that the interval of increased precipitation on the plateau was shorter than the interval of the MWP in the North Atlantic, and the occurrence of climatic change on the plateau leads to eastern China [*Chen and Shi*, 2002] and regions studied by *Esper et al.* [2002] by a few decades. Although it is not clear if the MWP-associated climate occurred on the northeastern Qinghai-Tibetan plateau, our tree-ring record suggests that the North Atlantic MWP was accompanied by a notable wet condition in our study region during A.D. 929–1031.

[14] A notable phenomenon in the Dulan chronology is that a short interval of rapid growth reduction, A.D. 906–920, occurred between two states of above-average growth (Figure 3). The δO^{18} data in Guliya ice core also show a trough in the A.D. 910s [*Yao et al.*, 1996]. This phenomenon indicates that the northeastern Qinghai-Tibetan Plateau might have experienced a sudden and severe drought and, perhaps, also coldness in this interval. This event implies that the climate system during a warm state may fail and recover very rapidly within about 15 years.

[15] Climatic change studies have documented the occurrence of LIA on the Qinghai-Tibetan plateau [*Yang*, 2001], but it has been unclear whether the climatic events in the LIA were synchronous over space and accompanied with changes in other climatic parameters, such as seasonal precipitation. Our tree-ring chronology in Dulan does not indicate evidence of sustained below average growth, but rather it shows climate fluctuation with three episodes of reduced tree-ring growth occurring in about A.D. 1450s–1510s, 1640s–1720s, and 1790s–1820s. These three episodes correspond very well with that of the sabina tree ring-width chronology in Wulan (37°02′N, 98°41′E) [*Huang et al.*, 2002], which is about 90 km northeast of Dulan, suggesting that these features reflect regional climate variations. The three episodes also coincide with periods of low δO^{18} values in ice cores from nearby areas on the Plateau [*Yao et al.*, 1997], although some differences exist in the timing of trough conditions. These observations suggest that the LIA climate on northeastern Qinghai-Tibetan Plateau might be characterized by the occurrence of three episodes of cold condition in non-growing season and dry condition in growing season. Since the climate on the plateau is under the influence of monsoon circulation, a cold and snowy winter might result in a weak summer monsoon, thus bringing less precipitation to the region [*Tang et al.*, 1979]. The extremely cold condition in autumn of the prior growth year and March of the growth year may also play a role in reducing tree-ring growth as indicated by the growth response function (Figure 2).

4. Conclusions

[16] The 2326-year tree-ring chronology is currently the longest and annually-resolved climate proxy record on the Qinghai-Tibetan Plateau and in China. Our results show that climate on the plateau has undergone oscillations and, sometimes, very rapid swings during the last two millennia. The greatest change in spring precipitation during the last two millennia occurred in the second half of the 4th century. The climate proxy data reveal that the North Atlantic MWP and the LIA were accompanied by climate changes on the

northeastern Qinghai-Tibetan Plateau. The climatic event in the early 10th century should receive more attention in studies of large-scale synoptic climate variability because it may yield insight into the climatic instability during a warm state. Our results highlight the need to better understand the Asian monsoon subsystems operating over Qinghai-Tibetan Plateau and their linkages with North Atlantic as well as tropical climate. In addition, the establishment of the chronology utilizing materials from ancient tombs provides a precise dating for archaeological perspectives and will help us better understand the role of climate in shaping local societies with a long history, a question of great interest with looming climate change.

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References

Blasing, T. J., A. M. Solomon, and D. N. Duvick, Response function revisited, *Tree-Ring Bull.*, *44*, 1–15, 1984.

Bradley, R. S., and P. D. Jones, 'Little Ice Age' summer temperature variations: Their nature and relevance to recent global warming trends, *Holocene*, *3*, 367–376, 1993.

Brauning, A., Climate history of the Tibetan Plateau during the last 1000 years derived from a network of Juniper chronologies, *Dendrochronologia*, *19*, 127–137, 2001.

Briffa, K. R., Annual climate variability in the Holocene: Interpreting the message of ancient trees, *Quat. Sci. Rev.*, *19*, 87–105, 2000.

Briffa, K. R., and T. J. Osborn, Seeing the wood from the trees, *Science*, *284*, 926–927, 1999.

Briffa, K. R., and J. A. Matthews, ADVANCE-10K: A European contribution towards a hemispheric dendroclimatology for the Holocene, *Holocene*, *12*, 639–642, 2002.

Chen, J. Q., and Y. F. Shi, Comparison of the winter temperature in the Yangtze Delta in the last 1000a with the record in Guliya ice core, *J. Glaciol. Geocryol.*, *24*, 32–39, 2002.

Cook, E. R., K. R. Briffa, S. G. Shiyatov, and V. S. Mazepa, Tree-ring standardization and growth-trend estimation, in *Methods of Dendrochronology*, edited by E. R. Cook and L. A. Kairiukstis, Kluwer Press, Dordrecht, pp. 104–123, 1990.

Cook, E. R., K. R. Briffa, D. M. Meko, D. A. Graybill, and G. Funkhouser, The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies, *Holocene*, *5*, 229–237, 1995.

Esper, J., E. R. Cook, and F. H. Schweingruber, Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability, *Science*, *295*, 2250–2253, 2002.

Fritts, H. C., *Tree Rings and Climate*, Academic, pp. 39–94, London, 1976.

Fritts, H. C., *Quick Help for PRECON now called PRECONK Version 5. 11.*, Univ. of Arizona, Tucson, 1996.

Fritts, H. C., T. J. Blasing, B. P. Hayden, and J. E. Kutzbach, Multivariate techniques for specifying tree-growth and climate relationships ad for reconstructing anomalies in paleoclimate, *J. Appl. Meteorol.*, *10*, 845–864, 1971.

Huang, J. G., Q. B. Zhang, and X. C. Kang, A 680-year ring-width chronology of *Sabina przewalskii* and its relationships with climatic variables in the Wulan area of northwestern China, in *Proc. 6th Int. Conf. Dendrochronology*, Laval Univ., Quebec, pp. 151–152, 2002.

Hughes, M. K., and H. F. Diaz, Was there a 'Medieval Warm Period', and if so, where and when?, *Clim. Change*, *26*, 109–142, 1994.

Kang, X. C., L. J. Graumlich, and P. R. Sheppard, The last 1835 years climate changes inferred from tree ring records in Dulan region, Qinghai, China, *Quat. Sci.*, *17*, 70–75, 1997 (in Chinese).

Mann, M. E., R. S. Bradley, and M. K. Hughes, Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, *392*, 779–787, 1998.

Murakami, T., Orography and monsoons, in *Monsoons*, edited by J. S. Fein and P. L. Stephens, pp. 331–364, John Wiley and Sons, New York, 1987.

Tang, M. C., Z. B. Shen, and Y. Y. Chen, On climatic characteristics of the Xizang plateau monsoon, *Acta. Geogr. Sinica*, *34*, 33–42, 1979 (in Chinese).

Xu, X. G., The expedition and research of Tupan tombs in Dulan of Qinghai province, China, in *Studies of the Silk Road in Qinghai Province, China*, Nara International Foundation, Nara, Japan, pp. 212–225, 2002 (in Chinese).

Yang, B., Preliminary study on the temporal and spatial distribution of climatic variations in a decadal resolution since the Little Ice Age, *Arid Land Geogr.*, *24*, 67–73, 2001 (in Chinese).

Yao, T. D., D. H. Qin, L. D. Tian, K. Q. Jiao, Z. H. Yang, and C. Xie, Variations in temperature and precipitation in the past 2000a on the Xizang (Tibet) Plateau: Guliya ice core record, *Sci. China (D)*, *39*, 426–433, 1996.

Yao, T. D., Y. F. Shi, and L. G. Thompson, High resolution record of paleoclimate since the Little Ice Age from the Tibetan ice cores, *Quat. Int.*, *37*, 19–23, 1997.

Zhang, Q.-B., Dendrochronology in western China: progress and prospect, in *Proc. Int. Congress Archaeol. Sci.*, Nara National Research Institute for Cultural Properties, Nara, Japan, pp. 79–84, 2003.

Zhang, Z., and X. Wu, The change and rapid shifts of moisture index and its annual variability since A. D. 1310 in Qilianshan area, *Quat. Sci.*, *16*, 368–378, 1999 (in Chinese).

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