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Seasonal temperature reconstruction from central China based on tree ring data

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ABSTRACT

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Mean temperature of March and April for the Qinling Mountains has been reconstructed based on *Abies chensiensis* tree-ring width for the last 250 years, with good chronology replication since 1828 to 1991 AD. The explained variance of the reconstruction was 50·8%. Eight relative cold and 8 warm periods for early spring have been found. Power spectrum analysis displays 24, 21·82, 20·00, 18·46, 2·76, 2·73, 2·26, 2·11 and 2·09 yrs cycles. The reconstruction was significantly negatively correlated to dryness/wetness indices, which were derived from historical documents, with $r = -0{\cdot}297$ ($N_3 = 229, p < 0{\cdot}0001$) after 10 years moving average. After 1900, r reached $-0{\cdot}718$ ($N_4 = 75, p < 0{\cdot}0001$). This suggests that lower mean temperature of March-April could be a signal of drought for the year, and *vice versa*.

Key-words—Qinling Mountains, China, Ring width, Temperature reconstruction.

मध्य चीन से प्राप्त वृक्ष-वलय मौसमी तापमान के अभिलेख

यू लिउ, लिमिन मा, मैल्कॉम के. ह्यूजेस, ग्रेग एम. गार्फ़िन-वॉल, किउफ़ांग काई, ज़ीशेंग एन. एवं स्टीवन डब्ल्यू. लीविट

सारांश

विगत सन् 1828 से 1991 ई. के दौरान उत्कृष्ट कालानुक्रम पुनरावृत्ति के साथ 250 वर्षों की *एबीज़ चेन्सिएन्सिस* वृक्ष की वलयी चौड़ाई को आधार मानकर क्विनलांग पर्वतश्रेणी के मार्च एवं अप्रैल माह के औसत तापमान का पुनर्सृजन किया गया। पुनर्सृजित तापमान का विश्लेषित औसत प्रसरण 50·8% था। प्रारंभिक बसन्त ऋतु की क्रमशः 8 शीत तथा 8 उष्ण अवधियाँ पाई गईं। ऊर्जा स्पेक्ट्रमी विश्लेषण 24, 21·82, 20·00, 18·46, 2·76, 2·73, 2·26, 2·11 एवं 2·09 वर्ष के चक्र प्रदर्शित करता है। पुनर्सृजन शुष्क/आर्द्र सूचकांकों से ऋणात्मक रूप से सहसम्बन्धित है, जिन्हें 10 वर्षीय गतिशील औसत के पश्चात आर = -0·297 (एन$_3$ = 229, पी. < 0·0001) के साथ ऐतिहासिक दस्तावेजों से निगमित किया गया था। सन् 1900 ई. के पश्चात आर मान -0·718 तक (एन$_4$ = 75, पी. < 0·0001) पहुँच गया था। इससे प्रस्तावित होता है कि मार्च से अप्रैल माह के मध्य निम्न औसत तापमान वर्ष हेतु अनावृष्टि का संकेतक हो सकता है तथा इसी अनुक्रम से आगे के अनुमान भी किए जा सकते हैं।

संकेत शब्द—क्विनलिंग पर्वतश्रेणी, चीन, वलयी चौड़ाई, तापमान, पुनर्सृजन.

INTRODUCTION

WITH their high resolution and reliability, tree rings play a very important role in global climate change study. The CLIVAR (Climate Variability and Predictability) program of the World Climate Research Program especially emphasizes the study of the variations of the Earth's climate over the last 100 to 1,000 years, which should feed directly into a better understanding of climate variability and predictability (The PAGES/CLIVAR Intersection, 1994). The PAGES (Past Global Changes) Project of the International Geosphere-Biosphere Program stresses the extraction of high resolution climatic proxies on similar time scales (PAGES, 1995). Tree-ring research has been listed as an important technique in both programs.

Tree rings are being combined with early instrumental records, historical documents, and other natural archives to build a season by season history of Earth's climate for the last millennium. Recent study reveals that the 20th century is a warm period compared to the last several centuries (Jacoby *et al.*, 1996; Mann *et al.*, 1998). During the steep rise of global warming in the past 20 years, annual spring mean temperature has increased significantly more rapidly than any other season in Northern Hemisphere (Groisman *et al.*, 1994). How about it in China?

The Qinling Mountains stretch more than 1500 km from the east to the west in central China. They form an important climatic demarcation line between north and south. Several dendrochronological contributions have been made for this region (Liu *et al.*, 1990; Wu & Shao, 1994; Shao & Wu, 1994; Yin & Wu, 1995). Hughes *et al.* (1994) reconstructed precipitation variation for April- June and May-July by using *Pinus armandii* in the eastern part of the mountains. It has been demonstrated that the 1920's and 1930's are the distinct dry periods in the past 400 years. By combining tree-ring and documentary data quantitatively, Wu *et al.* (1995) reconstructed total precipitation of April-July more precisely for Mt. Huashan in the east of the Qinling Mountains.

In this paper, we report a reconstruction of early spring (March to April) mean temperature using tree-ring data of *Abies chensiensis* from the central Qinling Mountains. The validation tests, statistical methods and historical documents were employed to verify the reconstruction, and provide objective methods for specifying the degree to which the tree-ring reconstruction replicated the actual instrumental record of climate.

TREE RING MATERIAL

The samples were collected from Eagle Peak (33°5'N, 108°5' E, elevation 2200-2500 m) in Zhen'an county (Fig. 1), Shaanxi Province, central Qinling Mountains, in the summer of 1993, during Chinese-United States joint cooperation.

The trees sampled were growing on north-facing aspects with slopes from 30° to 60°. The soil thickness are of about 10-30 cm with greatest depth at the moistest sites. There are a mixture of mountain-brown-earth and yellow-brown-forest soil. The dominant tree species at the site is *Abies chensiensis* and other trees are *Tsuga chinensis*, *Pinus armandii*, *Betula platyphylla* and *Cupressus funebris*. The stand is fairly open, with 5-10 m between trees and a discontinuous canopy. Three cores were taken from each of 25 trees. Two cores from every individual were used to develop tree-ring chronologies, and the third one was used to do X-ray density analysis, which will be reported elsewhere.

The samples were dried, glued and mounted. The cores were sanded to a smooth surface using sandpaper to 500 mesh (Phipps, 1985; Swetnam, 1985). Then, each growth ring for each core was assigned to the correct calendar year through cross-dating method (Stokes & Smiley, 1968). All samples were measured to within 0·01 mm using a Velmex-1 measuring system. Quality control of cross-dating was performed by a cross-correlation procedure COFECHA (Holmes, 1983), and the cores which did not match the master series well were removed. The program ARSTAN (Cook, 1985) was employed to produce tree-ring chronologies from the cross-dated series. In this paper the raw ring-width series were detrended by fitting cubic spline with a 50% variance reduction function (VRF) at 85 years wavelength (Cook & Kairiukstis, 1990). In the processing, the effects of non-synchronous disturbance events and age-related trend were reduced. Three versions of the chronologies, therefore, were obtained: standard (STD), residual (RES) and 'ARSTAN'(ARS). Fig. 2 shows the statistical characteristics of three kinds of chronologies for the Eagle Peak site. The statistical features of the detrended and residual series are listed in Fig. 3.

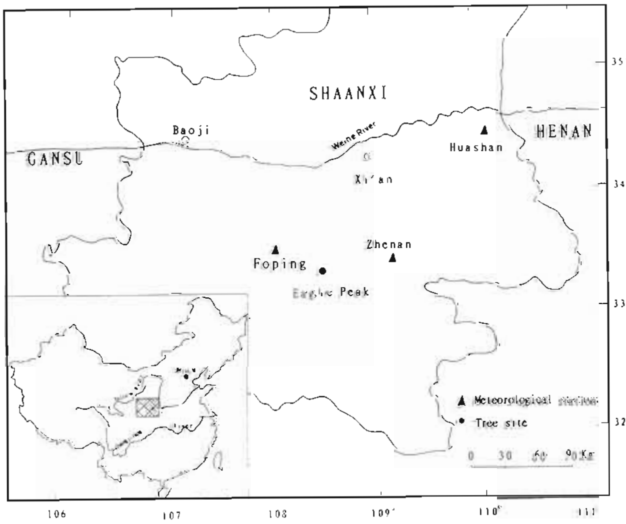

Fig. 1—The location of sampling site and nearby observation stations

	STD[1]	RES[2]	ARS[3]
Mean sensitivity	0·156	0·158	0·150
Standard deviation	0·201	0·147	0·204
First order autocorrelation	0·509	0·052	0·552
Skewness	0·056	0·214	0·208
Kurtosis	1·363	1·212	3·205

[1] Standard chronology
[2] Residual chronology
[3] Arstan chronology

Fig. 2—The statistical characteristics of STD, RES and ARS chronologies.

	Detrended	Residual
Mean correlation between all series	0·238	0·296
Mean correlation between trees	0·230	0·289
Mean correlation within a tree	0·302	0·355
Signal/noise ratio	3·280	4·470
Expressed population signal (EPS)	0·766	0·817
% Variance in 1^{st} PC	28·1%	32·9%

Fig. 3—The statistical features of detrended and residual series.

TRANSFER FUNCTION

Meteorological data were taken from Zhen'an, the nearest observation station (1958-1992, 35°26'N, 109°56'E, elevation 625 m). There were no missing data. These data were used to analyze the relationship between ring-width indices and climate. Homogeneity was tested by both double-mass analysis (Kohler, 1949) and the Mann-Kendall (Mann, 1945) statistical method. Foping (33°32'N, 107°59'E, elevation 1191·8 m), Xian (34°18'N, 108°56'E, elevation 397 m) and Huashan (34°29'N, 110°05'E, elevation 2064 m) stations were used as references. The results show that the Zhen'an data have no inhomogeneity.

Both correlation analysis and response function (Fritts & Wu, 1986) indicated that tree growth is positively influenced by mean temperature of March and April, with r=0·697 (p<0·0001) (Fig. 4). Ring-width at this site had a weak response to precipitation.

Previous work based on various tree-ring variables of *Pinus armandi*, such as ring width (Wu & Shao, 1994), ring width and density variables (Hughes *et al.*, 1994) and tree-ring climate modelling (Yin & Wu, 1995) in the eastern Qinling Mountains revealed that April temperature is a significant factor in limiting tree growth of this region. Our results are quite similar to those studies.

Generally speaking, early spring temperature is a crucial factor for the commencement of tree growth, formation of new needles, and the effective length of the growing season.

Since the STD chronology has the highest correlation with the climatic data, it has been used to do further analysis. Considering that auto-correlation in the STD chronology was more than 0·5, a transfer function between tree-ring-width (predictors) and mean temperature of March to April (predictand) is designed as follows:

$$\hat{T}_{34} = 4{\cdot}919\,W_{(t)} - 0{\cdot}962\,W_{(t+1)} + 6{\cdot}655 \qquad (1)$$

$$(r = 0{\cdot}713,\ F = 16{\cdot}018,\ P < 0{\cdot}0001)$$

Where $\hat{T}_{34}$ is mean temperature of March to April. $W_{(t)}$ and $W_{(t+1)}$ are the indices of the $STD_{(t)}$ and $STD_{(t+1)}$ chronologies, separately. For the calibration period of 1958-1991 (N_1=34), the equation is highly significant. The predictor variables account for 50.8% (and 47.6% when adjusted for loss of degrees of freedom) of the variance in the temperature. Fig. 5 shows the comparison of actual and estimated March to April mean temperature for the interval of 1958-1991.

CLIMATIC RECONSTRUCTION

In terms of the transfer function, we reconstructed the March-April mean temperature for 1741-1991 AD (Fig. 6). However, the chronology is not strongly replicated until 1828 AD, the first year in which the Subsample Signal Strength (SSS) reaches 0·85 (Wigley *et al.*, 1984). The curve displays obvious cold and warm spring variation alternately.

The correlation (r), sign test (S_1, S_2), F value, reduction of error (RE) and product mean (t) (Fritts, 1991) are all significant (Fig. 7), and indicate that the reconstructed data track the independent early spring mean temperature data quite well from 1958 to 1991. S_1 is the general sign test between observation and reconstruction (N_1=34) that measures the associations at all frequencies. S_2, which reflects the high-frequency climatic variations, is a similar test to above (n=33), and it is made for the first differences (Fritts, 1991).

As the possibilities for independent verification are severely limited by the shortness of the instrumental record,

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Mar.-Apr.
STD	0·173	0·166	0·325*	0·687*	0·117	0·123	0·217	0·236	0·264	-0·135	0·697*
RES	0·1	0·062	0·263	0·497*	0·096	0·01	0·186	0·19	0·108	-0·203	0·528*
ARS	0·188	0·139	0·319*	0·648*	0·033	0·096	0·172	0·26	0·21	-0·149	0·668*

Fig. 4—The correlation between observed temperature and ring width.

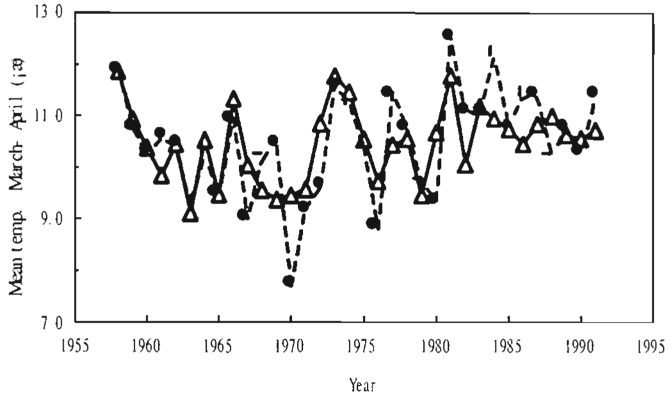

Fig. 5—Comparison of observed (dashed line) and estimated (solid line) March-April mean temperature for the interval 1958-1991.

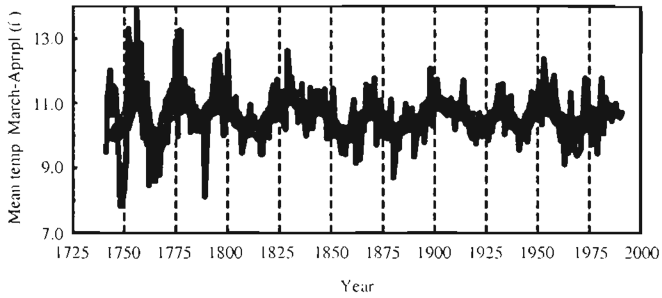

Fig. 6—Reconstructed March-April mean temperature for the period 1741-1991 AD. Smoothed line is the 10 years moving average.

the reliability of the reconstruction is also confirmed by comparison between observation data from meteorological stations nearby, not used in the calibration (Fig. 8).

The other unique independent paleoclimate proxy record, dryness/wetness indices that were generated from abundant Chinese historical documents (Academy of Meteorological Science, 1982), can provide much information to verify our reconstruction. In enormous Chinese historical writings there are abundant climatic descriptions, which are of great value for studying climatic fluctuations. During 1970's, hundreds of climatologists processed these materials from more than 2200 local annals and many other historical writings nationalwide, and abstracted from them more than two million and two hundred thousand characters. The dryness/wetness of each year in the recent 510-years period are classified into 5 grades: grade 1 – wettest, grade 2 – wet, grade 3 – normal, grade 4 – dry, and grade 5 – drought (Academy of Meteorological Science, 1982).

The reconstruction is significantly negatively correlated to the dryness/wetness index at 95% confidence level for the period 1741 to 1980 AD (N_2=239). For the region there are in total 58 level 4 or 5 drought years. Among them 35 years (60·35%) correspond to the mean temperature from March to April lower than the 250 years mean values (10·6°), and 23 years (39·65%) higher than mean. On the other hand, in 86 level 1 or 2 wettest to wetter years of the records, there are 49 years (57%) corresponding to higher temperature than mean, and 37 years (43%) to lower than mean.

It seems that March-April mean temperature provides information on precipitation in forthcoming seasons. Lower spring temperature could hint the drought, and warm springs at warmer seasons.

Drought years are recorded in documents (Shaanxi Meteorological Station, 1976). For example: **1813** severe drought in Zhen'an, reduced harvest (reconstructed temperature 10.0°); **1900** Zhen'an severe drought (10.5°); **1939** drought in Zhen'an (10.2°); **1944** spring drought for a quite long time in Zhen'an (9.9°), etc.

Some spring cold events also appeared in the reconstruction, such as: **1748** black frost in March (8.1°) in Zhen'an; **1884** heavy frost in April in Zhen'an, and 47 hectares wheat frost-bitten (10.6°); **1923** snow disaster in April in Zhen'an, and large-scale crops injured (10.2°), etc.

In order to emphasize decadal fluctuations, the series were filtered with 10 years moving average and the correlation rises

	r	F	$S_1(a, b)$	$S_2(a, b)$	t	RE	R^2	R^2_{adj}
$\hat{T}_{34}$	0·713	16·018	22(24, 26)	26(24, 26)	3·41	0·406	0·508	0·476

Fig. 7—The statistical characteristics of reconstruction (For definitions of symbols please see text. *a*—exceeds the 95% significant confidence level; *b*—99% level).

Station	Period	Observed *vs* observed	Reconstruction *vs* observed
Zhen'an *vs* Huashan	1958-1989	0.616 (<0.0001)	0.391 (<0.027)
Zhen'an *vs* Xian	1958-1990	0.771 (<0.0001)	0.619 (<0.0001)
Zhen'an *vs* Foping	1958-1990	0.694 (<0.0001)	0.576 (<0.001)

Fig. 8—Correlation between reconstructed and observed data from nearby meteorological stations (*r*, *p*).

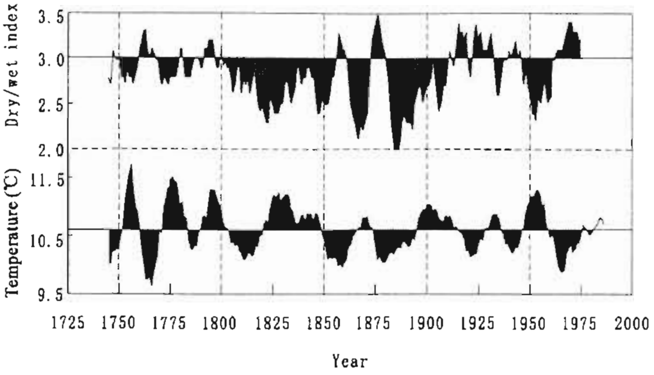

Fig. 9—The comparison between reconstruction and dryness/wetness (D/W) indices derived from historical documents The shading represents dry periods. Two curves were smoothed by 10 years moving average. The dryness/wetness indices were defined as: 1 wettest, 2 wet, 3 normal, 4 dry and 5 drought.

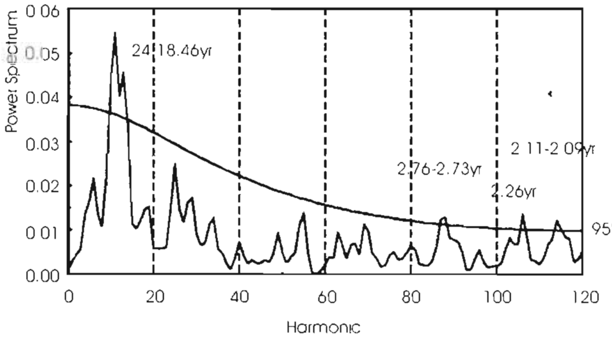

Fig. 10—Power spectrum analysis for reconstruction of early spring temperature (lag years=120, the smoothed line is 95% confidence limit line).

to –0·297 at the 99% significance level (after smoothing, the sample length N_3=229, p<0·0001). It is clear that early spring low mean temperature corresponds to drought (shaded in the Fig. 9), and warm to wet on decadal-scale, especially after 1900. As calculated after 1900, the two curves were highly correlated with r= -0·718 (N_4=75, p<0·0001). For instance, 1920-1930 in north China is one of the periods of greatest reduction in precipitation of the last 400 years, a consequence of reduced strength of the east Asian summer monsoon (Hughes *et al.*, 1994; Liu *et al.*, 1997; Liu & Ma, 1999). Our reconstruction shows a low temperature interval with 10.1°C, (about 5·2% lower than mean) for 1925-1930, including an extreme low value of 9·7°C of 1929, the driest year in 20th century. But during 1950-1960 south Shaanxi Province suffered flooding to the fullest extent, with reconstructed temperature of 11·6°C, 9·3% higher than the long-term mean.

Both the precision and resolution of series derived from historical documents is likely to be higher after 1900, due to many more records being available than in earlier times (Zhang, 1995). The tree ring based reconstruction does not suffer from this problem, and this difference should be borne in mind when comparing the two kinds of records.

Warm			Cold		
	Period	*TEM(°C)*		*Period*	*TEM(°C)*
1	1773-1784	11·6	1	1961-1973	9·8
2	1947-1960	11·5	2	1939-1946	10·0
3	1792-1806	11·3	3	1785-1791	10·1
4	1829-1848	11·3	4	1849-1860	10·1
5	1931-1938	11·1	5	1807-1828	10·2
6	1898-1915	11·0	6	1916-1930	10·2
7	1974-1992	10·9	7	1746-1772	10·2
8	1861-1872	10·8	8	1873-1897	10·3

Fig. 11—Eight warm and eight cold intervals of early spring for the last 250 years in Zhen'an (250 years mean is 10·6°, TEM—Temperature).

The reconstruction was tested for periodicities in the power spectrum analysis. The result displays remarkable 24, 21·82, 20·00, 18·46, 2·76, 2·73, 2·26, 2·11 and 2·09 yrs cycles for the past 250 years (Fig. 10). The major periodicity is 24 years. Besides this, 2·76 to 2·09 yrs are quite similar to the quasi-biennial oscillation (QBO). The effects of the QBO exist on the large-scale, and it may indicate sea-land coupling (Qian *et al.*, 1998).

Analysis of the 250 years reconstruction indicates that 16 periods were significantly warmer or colder than the mean (Fig. 11), but greatest confidence should be given to those after 1828, because of the poor replication of the chronology before this date.

Three stages (6, 5 & 7) in the warm intervals (Fig. 11) corresponded separately to abrupt warming in the Northern Hemisphere and globally during the last hundred years: end of 19th century, 1920-1930 and 1970's (Bradley *et al.*, 1987; Zeng *et al.*, 1995; Wang & Ye, 1995; Lin *et al.*, 1995). It indicates that the trend variation of the early spring temperature in the Qinling Mountains is quite synchronous with global variations on these time scales.

CONCLUSIONS

The preliminary work reported here confirms that tree-ring data has great potential to extend modern instrumental data in the Qinling Mountains in north-central China.

Based on well cross-dated ring-width series, mean temperature of March to April for Zhen'an China, was reconstructed. The explained variance of the reconstruction reaches to 50·8%. The data illustrations along with the statistics indicate that the tree-ring reconstruction is valid in reproducing the timing and duration of temperature anomalies. Eight relative cold and eight warm periods for early spring have been identified. Power spectrum analysis displays 24, 21·82, 20·00, 18·46, 2·76, 2·73, 2·26, 2·11 and 2·09 years cycles. The reconstruction can be well verified by historical documents at both high and low frequency. The lower mean temperature of March-April could be a signal of drought for the year and *vice versa*.

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