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RESEARCH ARTICLE

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Chinese pine tree ring width chronology and its relation to climate conditions in the Qianshan Mountains

Abstract Taking Chinese pine in Qianshan Mountains as a sample, the tree ring width chronology including Standard, Residual, and Arstan chronologies was established. The results show that the tree ring width of Chinese pine is highly correlated with the temperatures from May to July and from September to November. Statistically significant positive correlations were observed between tree ring width and the extreme minimum temperatures in July and mean minimum temperatures in September. The chronology was significantly or very significantly correlated with extreme minimum temperatures in December and the following January, with mean minimum temperatures in January, with annual precipitation and with precipitation in April, May and the following December. The Chinese pine responded strongly to the monthly/yearly water vapor pressure and relative humidity. Annual and largely monthly evaporation in April–July had a negative effect on tree growth, and was particularly striking for evaporation in April–July. The narrow tree rings recorded by the chronology demonstrated the 30 occasions of extreme drought since 1800. The growth of Chinese pine in the Qianshan mountains were also affected by climate changes on a hemispheric and global scale. There were 11-, 23- and 50-year-common periodicities between the chronology and solar activity and 10-, 20- and 45-year-common periodicities between the chronology and geomagnetic activity.

Keywords Qianshan mountains, Chinese pine, tree ring width chronology, climate

1 Introduction

As a perfect environmental proxy, tree ring chronology has been widely recognized and used in many national and international research programs. It has been used to determine many natural past issues and events, such as air temperature anomalies, rainfall variability, frequency of wild fires, volcanic activities, earthquakes, the effect of glaciers and other events. Living and dead trees, fossil wood, pruned limbs etc, are often the material used in this field. Common international standards and methods have been also established (Fritts, 1976; Hughes, 1982; Cook and Kairiukstis, 1990). More recently, many extra-long tree ring studies have been reported (Yang et al., 2000; Yao et al., 2001; Kang et al., 2002; Cook et al., 2004; Helama, 2004; Liu et al., 2004; Shao et al., 2004). Tree ring chronologies for Scots pine in northern Europe have extensions to over 7500 years (Eronen et al., 2002; Grudd et al., 2002). Oak tree ring chronologies in Ireland and England were more than 8000 years long (Leuschner et al., 2002; Spurk et al., 2002). In China, some millennial-scale chronologies have been developed (Kang et al., 2002; Liu et al., 2004; Shao et al., 2004). Attention in the most current Chinese dendrochronological research has mainly concentrated on samples from semi-arid and arid regions in central and western China, including research in the grasslands and Daqingshan mountains of Inner Mongolia, the Huashan, Qinling and Qilian mountains as well as the Tianshan mountains and the West Sichuan and Tibetan plateaus (Wu and Shao, 1993). Much attention has also been drawn to tree ring research in moderately dry-wet and cold-warm regions, e.g. in the Changbai, Tianmu, Yi and Daxing'anling mountains. Compared to these regions, research in tree rings for

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industurial regions in northeastern China are relatively rare.

The Chinese pine (*Pinus tabulaeformis* Carr.), an endemic conifer species in the Qianshan Mountain region, is the most important dendrochronological source for climate and environmental reconstruction in China, for it forms very distinct annual rings, allowing for reliable tree ring analysis and age determination. The species has a long life (about 300–500 years) and large ecological amplitude in northern China (Li, 1988). Therefore, based on samples of Chinese pines grown in scenic areas of the Qianshan mountains in Liaoning, China, the focus of the present work is to describe a case study showing the feasibility of tree ring width chronology development near cities in central China where most of the population resides. We will discuss the relationship between Chinese pine tree ring width chronology and climate variables, indicating the reliability and the necessity of studying Chinese pine tree rings as an environmental proxy and seeking to understand general rules of past local environmental variation in the study area and the effect of the environment on tree growth.

2 Methods

2.1 Sample collection

The sample sites were located in the scenic areas of the Qianshan mountains (41°11′23″N, 123°08′01″E) with a mean annual temperature of 8.7°C and mean annual precipitation of 729.5 mm. The regional vegetation belongs to the plant flora of northern China and lies in the transitional zone of plant distribution for the plant floras of northern China, of the Changbai mountains and of Mongolia. Most cities of central-southern Liaoning Province are located around these scenic areas. Given the sampling standards of the International Tree-Ring Data Bank (ITRDB), 45 cores from 22 trees in four sites and other four disc samples from four dead trees were sampled in April, 2005 (Table 1). These trees had diameters at breast height (DBH) ranging from 34 to 75 cm and heights between 8 m and 17 m. Three sampling sites were on well-drained south facing slopes with gradients between 4% and 10%, At least one sampling site was on a steep north facing slope with a gradient of about 70%. The soil of the sample sites are brown taiga sandy soils with depth exceeding 15 cm. Two or three increment cores were taken from each of the 22 Chinese pine trees and two time series of tree ring widths were obtained in two different directions from each of the four disks.

2.2 Development of chronology

Mounted sample cores and raw discs were fine-sanded with sand paper of decreasing grain size to 600 grit. After adequate polishing, all tree rings were visually cross-dated to their exact year of formation using standard dendrochronological techniques (Fritts, 1976; Hughes, 1982; Cook, 1985; Schweingruber, 1987; Cook and Kairiukstis, 1990; Wu, 1990). In some cases, the surface of the cross-sections was moistened with drops of water, which increased the contrast between early and late wood tissues and improved the distinction between growth zones in general. Ring width was measured to the nearest 0.01 mm by a LINTAB5 tree-ring measurement and analytical system. The data were assessed using the TASP-Win software. The resulting data set for trees at each individual site was tested for dating accuracy using the program COFECHA (Holmes, 1983). Severely rotten or broken up cores that were not significantly correlated with the mean chronology were discarded. In the end, 53 radii from 26 trees were used to develop the tree-ring width chronology. The master dating series from COFECHA contained the following information: The time span of the master series was 235 years (1770–2004 A.D.). The number of dated series was 53. The total number of rings in all series was 7324. The total number of dated rings checked was 7321. The inter-correlation of the series was 0.58 and the average mean sensitivity was 0.32. The mean length of the series was 138.2 years and the number of absent rings accounted for 0.171% of the total number of rings. The autocorrelation of order 1 was 0.78 and the standard deviation 0.42. Prior to the analysis, the ring-width series were standardized with the program ARSTAN (Cook and Holmes, 1986). A detrending procedure was used to remove non-climate variation, such as a hypothesized negative exponential age-related trend, by fitting a curve to each tree-ring series. This removed most of the low frequency variation, provided for dimensionless indices and prevented faster growing trees from dominating the inter-annual variability. We fitted conservative negative exponential and straight-line curves for our study (Fritts, 1976). Based on 26 Chinese pines, three versions of

Table 1 Information of sampling site and samples

sampling site	elevation/m	number of trees	number of cores	time span/year	total number of years
Wuliangguan Temple	326	1	2	1830–2003	174
Cixiangguan Temple	300	3	6	1844–2004	161
Muyuan Nunnery	318	14	28	1780–2004	225
southern Muyuan Nunnery	307	4	9	1770–2004	235
unknown location (disc)	–	4	8	1921–2003	83

a master chronology were developed: a standard chronology (STD), a residual chronology (RES) and an Arstan chronology (ARS) (Fig. 1). Statistical indices and measures of quality control of the chronologies are presented in Tables 2 and 3.

2.3 Environmental data

It is important to evaluate the environmental representation of these Chinese pine tree ring width chronologies by analyzing their relationship with past environmental factors, particularly climate variables, after they have been developed. Thus, the choice of environmental materials was as follows: meteorological variables for Anshan city from 1961 to 1995, including annual/monthly mean temperature and annual/monthly precipitation; meteorological variables for Shenyang city (a distance of about 72 km away from sample sites), including yearly/monthly mean temperature and yearly/monthly precipitation from 1906 to 2003, extreme monthly minimum and maximum temperatures, mean monthly minimum and maximum temperatures, yearly/monthly water vapor pressure, yearly/monthly evaporation and yearly/monthly relative humidity from 1951 to 2003. The time series of the number of sunspots (SSN, 1700–2004) was obtained from the National Geophysical Data Center, USA (http://www.ngdc.noaa.gov/stp/SOLAR/); the geomagnetic sudden commencement time series (GSC, 1868–2004) was obtained from the

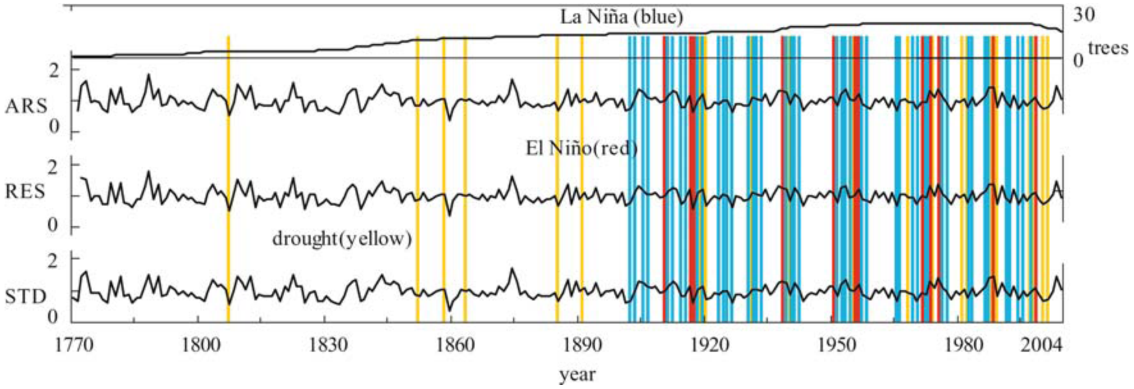

Fig. 1 ARS, RES and STD chronology for the Qianshan mountains. Vertical solid lines show El Niño (red)/La Niña (blue) years during the last hundred years and extreme regional drought years (yellow).

Table 2 STD, RES and ARS chronology statistics for the Qianshan mountains*

chronology	mean	median	mean sensitivity	standard deviation	skewness	kurtosis	autocorrelation order 1
STD	0.9828	0.9718	0.2181	0.2215	0.4870	0.2385	0.2511
RES	0.9949	0.9946	0.2406	0.2119	0.4506	0.7436	0.0165
ARS	0.9943	0.9816	0.2180	0.2232	0.6292	0.7996	0.2317

Note: *Common interval time span 1858 to 1999; 15 trees; 28 radii

Table 3 Detrended series and residual series statistics for the Qianshan mountains

item	detrended series	residuals (white noise)
mean correlations		
among all radii	0.295	0.349
between trees (Y variance)	0.275	0.332
within trees	0.857	0.814
radii vs mean	0.552	0.593
signal-to-noise ratio	5.678	7.457
agreement with population chronology	0.850	0.882
variance of first eigenvector	32.66%	37.74%
chron common interval mean	0.978	0.991
chron common interval standard deviation	0.195	0.188
subsample signal strength (SSS)		
SSS > 0.75	1836(8 trees)*	1830(7 trees)*
SSS > 0.80	1844(11 trees)*	1837(9 trees)*
SSS > 0.85	1857(15 trees)*	1848(12 trees)*
SSS > 0.90	1940(24 trees)*	1897(19 trees)*

Note: * means continuous (Wigley et al., 1984).

Russian Academy of Sciences, Geophysical Center, World Data Center for Solar-Terrestrial Physics, Moscow: (http://www.wdcb.ru/stp/data/sudden.com/). Significant El Niño events (1900–2000) were obtained from website: http://ww2010.atmos.uiuc.edu/(Gh)/wwhlpr/el_nino.rxml?hret=/guides/mtr/eln/pred.rxml and significant La Niña events (1900–2000) were obtained from website: http://www.bom.gov.au/climate/enso/ninacomp.shtml. Global surface air temperature anomaly (GSATA, 1880–2004), global land-ocean temperature index (GLOTI, 1880–2004) and north hemisphere temperature anomaly (NHTA, 1880–2004) were obtained from the National Aeronautics and Space Administration, USA: (http://data.giss.nasa.gov/gistemp/graphs/). Pacific Decadal Oscillation (PDO, 1900–2004) were obtained from NOAA and the University of Washington, USA: (http://tao.atmos.washington.edu/pdo/) and extreme drought records were obtained from local archives and organized by Wen et al. (2005).

3 Results and discussion

3.1 Relationship between tree ring width and local temperature

The correlations between Chinese pine tree ring width chronologies for the Qianshan mountains and local meteorological records from 1961 to 1974 and their correlations from 1976 to1990 were inconsistent, no doubt partly due to the fact that the local Anshan meteorological station had been relocated in 1975 (relocated from 41°07′N, 122°55′E, elevation 216 m to 41°05′N, 123°00′E, elevation 773 m) (Fig. 2). Therefore, we also used meteorological records of Shenyang, along with the meteorological records of Anshan to analyze the relationships of these chronologies and climate variables (Fig. 2, Table 4).

First, correlations between chronologies and temperatures were analyzed. We found that low temperatures in winter to early spring (December–April) and in summer–autumn were positively correlated with Chinese pine tree ring widths. Significant correlations ($p < 0.05$) exist between the three versions of chronologies and extreme minimum temperatures in December–January and in July and mean minimum temperatures in January and September. Even though the temperature variables were not significantly correlated with the chronologies during most of the growing season, Chinese pine tree ring widths were negatively correlated with high temperatures and positively correlated with low temperatures in pre-and post growing seasons and in pre-and post dormancy seasons. The mean minimum temperatures in May–June (the chronologies were significantly correlated ($p < 0.05$) with mean temperatures and extreme maximum temperatures in May and had extremely significant correlations ($p < 0.01$) with mean temperatures in June for Shenyang) and in September were closely correlated with Chinese pine tree ring widths.

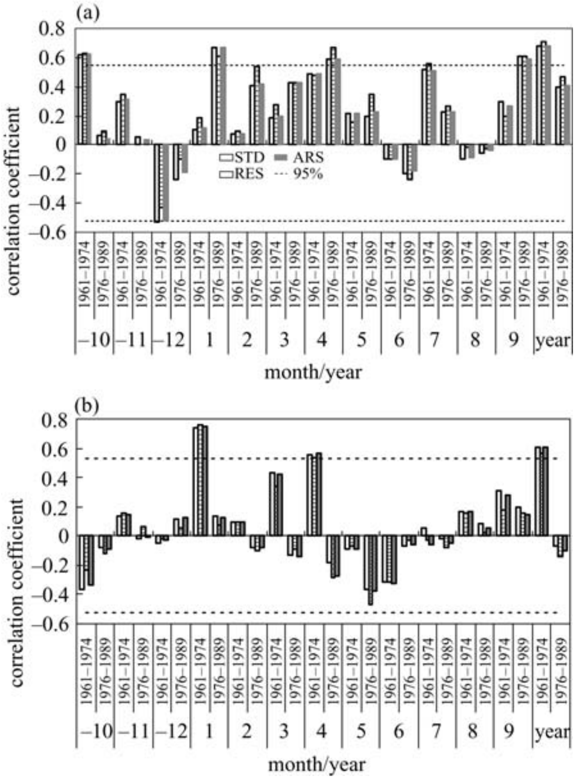

Fig. 2 Correlation between precipitation, mean air temperature (Oct–Sep) and tree ring width in Anshan
(a) Correlation between tree-ring width and precipitation before (1961–1974)/after (1976–1989) weather station was moved; (b) Correlation between tree-ring width and mean air temperature before (1961–1974)/after (1976–1989) weather station was moved.

Similar to the research on other conifers, not only Chinese pine on the Qianshan mountains but also at the Fuling Mausoleum and the Zhaoling Mausoleum in Shenyang (Chen, 2006) show clear responses to low temperatures in winter (Colenutt, 2000; Liang, 2001; Splechtna, 2002; Shao et al., 2004). Generally, December–January is the coldest period of the year in this region. Lower air temperature in the winter could lead to deep frozen soils and lower ground temperatures, thus, the relatively slow ground temperature recovery time and the relatively late period for root system growth shorten the annual growth period of the trees and are most likely the reasons for narrow tree rings (Yuan and Li, 1999; Shao et al., 2004). Other research indicated that low temperatures could lead to frost injury in tree cells, increasing cell mortality. Moreover, low temperatures also damage the shallow roots of trees (Yuan and Li, 1999) and therefore affect subsequent tree growth during the growing season. Other investigators considered that low temperatures could increase the mortality of hibernaculum and annotinous branches and leaves (Wu et al.,

Table 4 Correlation coefficients between Qianshan tree ring-width chronologies and Shengyang climate parameters

month	climate parameters	chronology			month	climate parameters	chronology		
		STD	RES	ARS			STD	RES	ARS
−10	E.Mi.	−0.110	−0.128	−0.106	−10	M.Pr.	0.206*	0.193	0.196
	E.Ma.	0.047	0.062	0.056		W.V.P.	0.105	0.065	0.103
	M.	−0.064	−0.092	−0.177		Ev.	−0.347*	−0.307*	−0.334*
	M.Mi.	0.023	−0.025	0.020		R.H.	0.245	0.224	0.241
	M.Ma.	−0.150	−0.167	−0.139					
−11	E.Mi.	0.054	0.011	0.036	−11	M.Pr.	−0.075	−0.046	−0.084
	E.Ma.	−0.197	−0.159	−0.177		W.V.P.	0.013	0.028	0.007
	M.	−0.054	−0.060	−0.061		Ev.	−0.111	−0.077	−0.108
	M.Mi.	0.025	0.010	0.012		R.H.	0.070	0.076	0.061
	M.Ma.	−0.098	−0.069	−0.196					
−12	E.Mi.	0.310*	0.272	0.302*	−12	M.Pr.	−0.234*	−0.195	−0.224*
	E.Ma.	0.228	0.231	0.234		W.V.P.	−0.074	−0.028	−0.065
	M.	0.044	0.032	0.037		Ev.	0.140	0.133	0.144
	M.Mi.	0.130	0.130	0.130		R.H.	−0.263	−0.217	−0.258
	M.Ma.	0.005	0.018	0.010					
1	E.Mi.	0.270	0.230	0.264	1	M.Pr.	−0.001	0.050	0.007
	E.Ma.	0.224	0.214	0.200		W.V.P.	0.189	0.161	0.182
	M.	0.168	0.138	0.158		Ev.	0.114	0.121	0.121
	M.Mi.	0.296*	0.261	0.288*		R.H.	−0.135	−0.127	−0.136
	M.Ma.	0.237	0.213	0.232					
2	E.Mi.	0.059	0.017	0.259	2	M.Pr.	0.137	0.118	0.122
	E.Ma.	0.007	−0.024	0.004		W.V.P.	0.158	0.212	0.160
	M.	0.047	0.068	0.058		Ev.	−0.060	−0.039	−0.043
	M.Mi.	0.094	0.118	0.102		R.H.	0.062	0.092	0.054
	M.Ma.	0.015	0.023	0.021					
3	E.Mi.	0.212	0.227	0.217	3	M.Pr.	0.139	0.159	0.133
	E.Ma.	−0.134	−0.091	−0.133		W.V.P.	0.224	0.303*	0.228
	M.	0.070	0.029	0.017		Ev.	−0.195	−0.156	−0.182
	M.Mi.	0.212	0.281*	0.223		R.H.	0.155	0.189	0.152
	M.Ma.	0.110	0.153	0.117					
4	E.Mi.	0.155	0.123	0.142	4	M.Pr.	0.325**	0.339**	0.334**
	E.Ma.	0.073	0.098	0.085		W.V.P.	0.344*	0.318*	0.336*
	M.	−0.015	−0.029	−0.009		Ev.	−0.459**	−0.452**	−0.456**
	M.Mi.	0.160	0.167	0.159		R.H.	0.357**	0.330*	0.349*
	M.Ma.	−0.038	−0.059	−0.045					
5	E.Mi.	0.040	0.075	0.037	5	M.Pr.	0.238*	0.242*	0.234*
	E.Ma.	−0.280*	−0.228	−0.263		W.V.P.	0.126	0.165	0.127
	M.	−0.197	−0.196	−0.201*		Ev.	−0.390**	−0.374**	−0.383**
	M.Mi.	0.064	0.116	0.068		R.H.	0.207	0.203	0.196
	M.Ma.	−0.224	−0.155	−0.206					
6	E.Mi.	0.113	0.137	0.113	6	M.Pr.	0.079	0.096	0.079
	E.Ma.	−0.256	−0.209	−0.243		W.V.P.	0.332*	0.359**	0.339*
	M.	−.280*	−0.245*	−0.272**		Ev.	−0.518**	−0.513**	−0.519**
	M.Mi.	0.018	0.066	0.027		R.H.	0.450**	0.437**	0.450**
	M.Ma.	−0.315*	−0.272	−0.306*					
7	E.Mi.	0.259	0.261	0.274*	7	M.Pr.	0.034	0.026	0.031
	E.Ma.	−0.182	−0.159	−0.174		W.V.P.	0.060	0.054	0.062
	M.	−0.137	−0.134	−0.128		Ev.	−0.425**	−0.396**	−0.415**
	M.Mi.	0.099	0.125	0.113		R.H.	0.184	0.138	0.173
	M.Ma.	−0.191	−0.163	−0.181					
8	E.Mi.	0.090	0.050	0.022	8	M.Pr.	0.129	0.158	0.145
	E.Ma.	0.001	0.015	0.001		W.V.P.	0.070	0.079	0.073
	M.	0.010	0.023	0.004		Ev.	−0.341*	−0.376**	−0.349*
	M.Mi.	0.016	0.000	0.015		R.H.	−0.069	−0.061	−0.063
	M.Ma.	−0.039	−0.060	−0.054					
9	E.Mi.	0.169	0.188	0.175	9	M.Pr.	0.041	−0.013	0.007
	E.Ma.	−0.068	−0.026	−0.056		W.V.P.	0.326*	0.293*	0.312*
	M.	0.108	0.131	0.111		Ev.	−0.436**	−0.429**	−0.435**
	M.Mi.	0.294*	0.284*	0.287*		R.H.	0.253	0.196	0.239
	M.Ma.	0.100	0.150	0.106					

(*Continued*)

month	climate parameters	chronology			month	climate parameters	chronology		
		STD	RES	ARS			STD	RES	ARS
1–12	M.	0.022	0.022	0.027	1–12	M.Pr.	0.238*	0.236*	0.234*
	SSN	−0.075	−0.055	−0.064		W.V.P.	0.323*	0.332*	0.320*
	GSC	−0.08	−0.075	−0.068		Ev.	−0.510**	−0.495**	−0.504**
						R.H.	0.205	0.197	0.195
−1–12	M.	0.006	0.013	0.007	−1–12	M.Pr.	0.128	0.076	0.127
	SSN	−0.010	−0.015	−0.001		W.V.P.	0.004	−0.071	−0.003
	GSC	−0.014	−0.009	−0.006		Ev.	−0.295*	−0.193	−0.276*
						R.H.	−0.029	−0.077	−0.033

*$p < 0.05$; **$p < 0.01$. –: prior year parameters. E.Mi.: Extreme minimum temperature; E.Ma.: Extreme maximum temperature; M.: Mean temperature;M.Mi.: Mean minimum temperature; M.Ma.: Mean maximum temperature; M.Pr.: Precipitation; W.V.P.: Water vapor pressure; Ev.: Evaporation; R.H.: Relative humidity; SSN: Number of sunspots; GSC: Sudden geomagnetic commencement.

2002) and affected tree growth in any current year and thus, positive correlations between Chinese pine tree ring widths and temperature variability existed. According to the research by Tao et al. (Jin et al., 1988; Tao et al., 1988), this phenomenon is rather related to the inhibition of photosynthesis, since the relatively low temperature in winters, particularly long with temperatures below 0°C could lead to long time inhibition of photosynthesis and less photosynthate. Furthermore, photosynthesis requires convalescence after being inhibited for long periods in the winter at temperatures below 0°C, corresponding to long convalescence. That is to say, cold winters indicate late photosynthetic recovery in the spring. Generally, photosynthesis in the spring is stronger than that in the summer and its contribution is also greater than in the summer, partly due to the support by photosynthate in the summer for growth in the following year. The reason that the growth of Chinese pine is positively correlated with minimum temperatures and negatively with maximum temperatures in pre-and post grown season and in pre-and post dormancy season, is that high temperatures in spring or in summer can cause increases in transpiration, evaporation, moisture loss and internal nutrient consumption of the trees. This leads to narrow rings, whereas low temperatures in these seasons can promote Chinese pine growth. On the other hand spring temperatures are related to bud germination and the length of the growing season. Temperatures in the autumn are related to the time span of the growing period and the growth increment of the current year. All of our information indicated that monthly temperature variation in the spring and autumn have higher correlations with Chinese pine tree ring width than that of any other period in this study.

3.2 Relationship between tree ring width and local dry/wet variability

The chronologies were significantly correlated ($p < 0.05$) with annual, previous December and May precipitation for Shenyang and January and April precipitation for Anshan. Highly significant correlations ($p < 0.01$) between the chronologies and precipitation in April for Shenyang were also found (Fig. 2, Table 4). The correlation between chronology and precipitation in April–May for Shenyang was $r_{\text{Shenyang}} = 0.389$ ($p < 0.01$, $n = 98$) and for Anshan $r_{\text{Anshan}} = 0.343$ ($p < 0.05$, $n = 35$). Even though the correlations between chronologies and precipitation in February and in March were insignificant, the correlation coefficients indicated some close relationships. Table 4 shows that the Chinese pine responded significantly to annual water vapor pressure ($p < 0.05$) and was highly significant ($p < 0.01$) in June. The responses in March, April and September were also significant ($p < 0.05$). Similar to water vapor pressure, annual relative humidity was closely correlated with the Chinese pines and show highly significant correlations ($p < 0.01$) in May and in July. On the other hand, negative correlations between the Chinese pine tree rings and relative humidity were found in January and August. The annual and mostly monthly evaporation had a negative effect on pine growth and were significant for evaporation in April–July. However, the evaporation in December–January was positively correlated with the growth of the Chinese pine.

Our investigation also shows that rainfall has a great effect on Chinese pine growth in the period of bud germination in early spring (April and May) in this region. In addition, Chinese pine was at the edge of its dormancy stage and the ground did not freeze during the period from the end of November to the beginning of December in the region of Shenyang city and the Qianshan mountains. Heavier rainfall indicated colder climate (precipitation was negatively correlated with air temperature in Shenyang from 1905 to 2003 ($r = -0.185$, $n = 99$, $p = 0.067$), as well as in Anshan) leading to the end of the growing season for the pines and the start of the deep dormancy stage. The direct explanation of this is that rainfall enhanced the cold in winter and the cold climate affected tree growth, as mentioned earlier. The same response of the Chinese pine to the rainfall was also detected at the Fuling Mausoleum and the Zhaoling Mausoleum in Shenyang (Chen, 2006).

The response mechanism of Chinese pine growth to rainfall is not quite clear. It is possibly related to soil moisture during the pre-and post thawing stage in earlier spring, or to heavy precipitation leading to lower temperatures and affected air temperature recovery, or it continued the low temperature since January and intensified frost damage. The research of Tao et al. (1988) indicated precipitation in this period could affect the mortality rate of shallow roots caused by the cold and thus, affected tree growth. The variation in air humidity such as water vapor pressure and relative humidity had a stronger effect on Chinese pines than that of a single rainfall variables, i.e., the available moisture content in the air contributed more to Chinese pine growth than precipitation and suggests that the aerial part of the Chinese pine is more sensitive to water supply. Negative effects existed between evaporation and Chinese pine growth, particularly in April–September, the early growing stage in the spring and the growing stage in the summer, since this period is the most sensitive stage of pines to rainfall deficiency and drought and evaporation in this period indicated regional water surplus and deficiency, thus, some positive or negative effects to the Chinese pine growth can be contributed by evaporation. However, the evaporation in December–January was positively correlated with the growth of Chinese pines and indicated evaporation is closely related to temperature ($r = 0.582$, $p < 0.01$, $n = 52$). High evaporation in the coldest months suggests high regional air temperatures which could reduce the cold causing mortality of tender leaves, shorten the period of hibernaculum, shallow roots and other functions and tissues and thus, promoted the pine growth.

Compared with the archives (Wen et al., 2005), the narrow tree rings recorded demonstrated the occurrence of 30 extreme droughts since 1800. Half of these (15 incidences or years) droughts corresponded to negative anomalies of tree ring width indices. Furthermore, when we add narrowing mutations of positive anomalies of tree ring widths, at least seventy per cent of drought records (21 incidents or years) were recorded by the chronologies, particularly the spring droughts (Fig. 1). There were 27 dry years of the total number of 49 dry years (55.1%), mentioned in records of the Academy of Meteorological Science, China Central Meteorological Administration, 1981 (the time period covered in the records was from 1770 to 1979). Based on the same method, the data, supplied from 1980 to 2003, corresponded to negative anomalies of tree ring width indices and most of the remaining records of dry years corresponded to narrow rings and narrowing mutations of Chinese pine tree rings. There were only 16 drought years (53.3%) among the 30 drought records of Wen et al. (2005) corresponding with the records of dry years in the archives of the Academy of Meteorological Science, Chinese Central Meteorological Administration, 1981 and lower than 70%, the drought representation level of the Chinese pine rings. The Chinese pine tree ring chronologies were not significantly correlated with annual and 3-, 5-, 11-year running mean data of dryness/wetness. However, after seven grade decompositions by a discrete approximation of Meyer wavelets (DMEY) (considering the decomposition limitation of Meyer wavelets, the continuous level of dryness/wetness records and accurate degree of actual records dates from 1774 to 2004), most signals at the different grades were closely correlated and, except for grades 1 (D_1) and 2 (D_2), show consistent fluctuation in the high frequency band (Fig. 3).

Above all, the accuracy of Chinese pine tree ring chronology as a proxy and measure of sensitivity of the pines to water distribution, is corroborative evidence.

3.3 Response of tree ring width to large-scale climate change

Figure 1 indicated some information of large-scale climate fluctuation was recorded by tree rings, e.g., twenty-nine El Niño events (63.0%) among 46 significant El Niño events and eight La Niña events (66.7%) among the 12 significant El Niño events, which corresponded to the anomaly mutations of the chronologies. After removal of the low frequency effect of global warming, Chinese pines on the Qianshan mountains show strong responses to the high frequency fluctuations of large-scale climate changes (GSATA, GLOTI, NHTA) during the period of early winter (November), early spring (February–March) and the transition of summer to autumn (August–September). The pines clearly responded to PDO during the growing seasons (Table 5). Clear responses were also found in the warm period of PDO (Fig. 4). After the 11- and 15-year running means, the tree ring width index, developed via a COFECHA routine, was closely correlated with the annual GSATA ($n = 120$, $r = 0.219$, $p < 0.05$) and annual PDO ($n = 98$, $r = 0.266$, $p < 0.01$). More information of the clear responses of pines to large-scale climate factors was found by DMEY wavelet analysis. The chronologies efficiently proved the strong wave signals of PDO in the 26-year periodicity and GSATA in the 20.8-year periodicity at the 20–30 year scale via discrete Fourier transformation spectrum and cross Morlet wavelet analyses. Chinese pines on the Qianshan mountains clearly responded to large scale temperature variation (GSATA, GLOTI and NHTA) in early winter (November). A possible reason might be that this period was the beginning of the winter in this region. Large-scale air temperature variation affected regional climate change during the following season (December–January) and thus, affected the Chinese pine growth as well as the effects of global temperature fluctuations in the earlier spring and the transition season of summer and autumn.

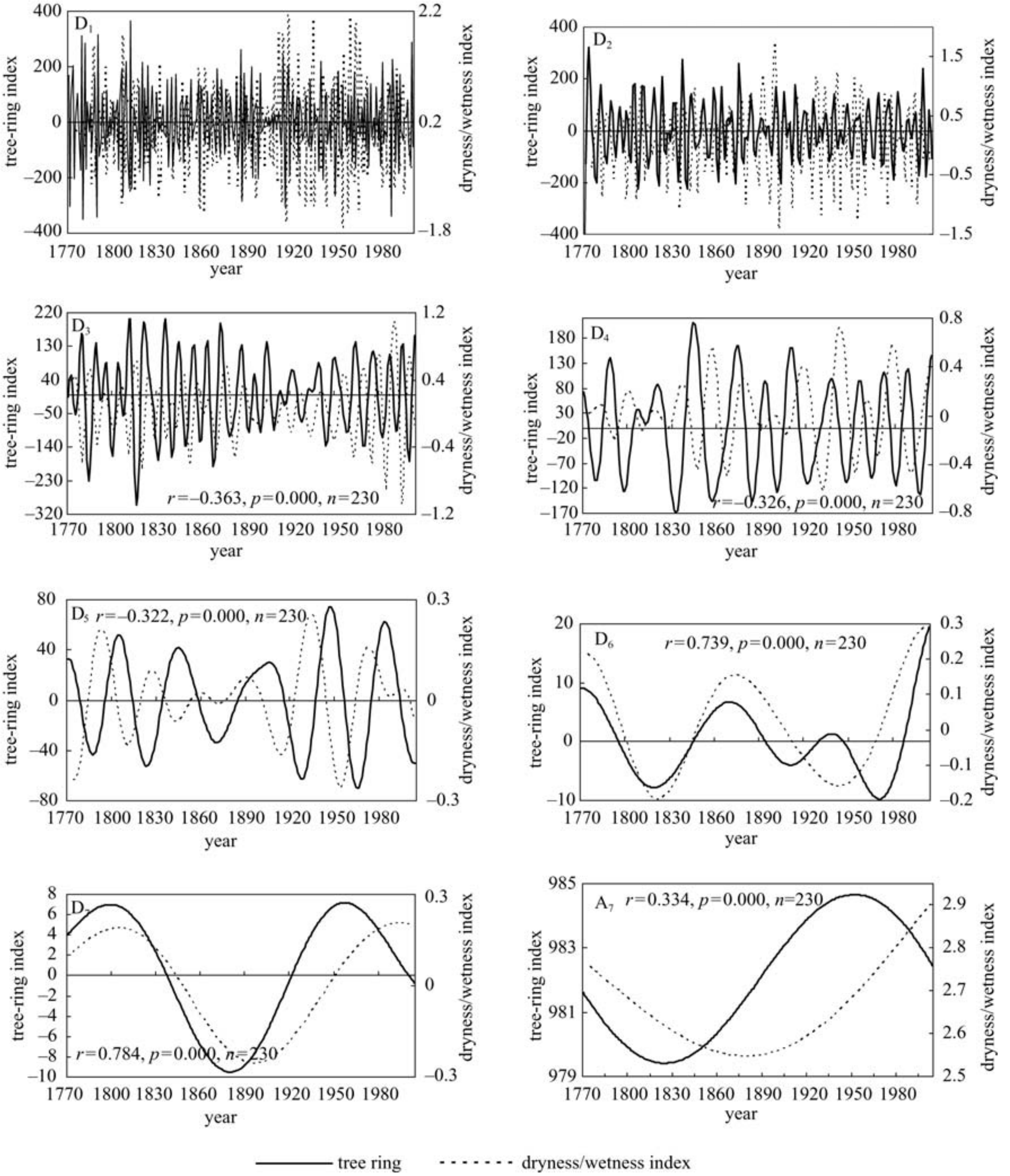

Fig. 3 Analysis of DMEY wavelet for STD chronology and dryness/wetness index time series in Shenyang
Original signal OR = $A_7 + D_7 + D_6 + D_5 + D_4 + D_3 + D_2 + D_1$; A: low frequency signal; D: high frequency signal; Suffix number is grade of decomposition.

3.4 Relationship between tree ring width, solar activity and geomagnetic activity

The number of sunspots (SSN) was closely correlated with the tree ring index after 11-year running mean (Table 6) and the chronologies show consistent fluctuation with the number of sunspots and significant common periodicities near 11, 23 and 50 years (Fig. 6). In addition, the sudden geomagnetic commencement index (GSC) was also clearly correlated with the tree ring index. The relationships between SSN, GSC and tree rings are more clearly shown by DMEY wavelet analysis (Fig. 5). After the 11-year running mean, the correlation coefficient between the Chinese pine tree ring index and SSN was 0.198 ($p < 0.05$) from 1868 to 2004 and 0.176 ($p < 0.05$) with GSC. The chronologies also had consistent fluctuations and significant common periodicities near 10, 20 and 40 years with GSC.

Life at the surface of the Earth only exists because of the energy flux that our planet receives from the sun.

Table 5 Correlation coefficients of tree ring-width chronologies for Qianshan with large scale climate factors after 11-year running means (prior October to September)

large scale climate factors	chronology ($n = 119$)	month										
		−10	−11	1	2	3	4	6	7	8	9	10
GSATA	STD		−0.353**		−0.205*	−0.198*					−0.188*	
	RES	−0.187*	−0.376**	−0.19*	−0.262**	−0.236**		−0.218*		−0.235**	−0.248**	
	ARS		−0.357**		−0.222*	−0.215*				−0.199*	−0.206*	
GLOTI	STD		−0.270**		−0.181*	−0.259**				−0.193*		
	RES		−0.299**	−0.183*	−0.233*	−0.304**	−0.199*	−0.227*	−0.198*	−0.241**	−0.223*	
	ARS		−0.274**		−0.196*	−0.279**		−0.194*		−0.209*	−0.186*	
NHTA	STD		−0.250**			−0.263**			−0.187*	−0.219*		
	RES		−0.250**			−0.287**			−0.225*	−0.243**		
	ARS		−0.236**			−0.269**			−0.200*	−0.219*		
PDO△	STD								0.217*	0.269**	0.250*	0.232*
	RES									0.242*	0.216*	0.244*
	ARS								0.198*	0.261**	0.238*	0.231*

$*p < 0.05$; $**p < 0.01$; △ from January to December; 5-year running mean value.

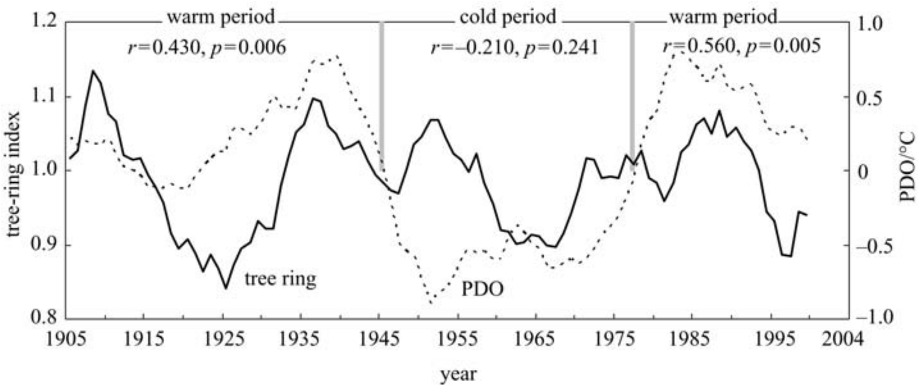

Fig. 4 Correlation between STD chronology and PDO time series

Table 6 Correlation coefficients of tree ring-width chronologies for Qianshan with yearly/monthly SSN (after 11-year running means, $n = 228$)

chronology	month												
	1	2	3	4	5	6	7	8	9	10	11	12	1–12
STD	0.123	0.133*	0.077	0.136*	0.111	0.066	0.114	0.130*	0.123	0.118	0.127	0.133*	0.132*
RES	0.161*	0.173**	0.119	0.178**	0.159*	0.113	0.165*	0.166*	0.164*	0.158*	0.172**	0.179**	0.199**
ARS	0.176**	0.182**	0.125	0.191**	0.176**	0.124	0.175**	0.179**	0.178**	0.169*	0.187**	0.188**	0.212**
RES[a]	0.215**	0.179**	0.240**	0.217**	0.236**	0.209**	0.188**	0.193**	0.236**	0.219**	0.223**	0.231**	0.307**

$*p < 0.05$; $**p < 0.01$; [a]Yu, 2004.

Solar radiation affects atmospheric and oceanic circulations, which also affect the biosphere (IPCC, 2001). One of the most important characteristics of solar variability is the sunspot variation in the visible half of the sun, quantified by the number of sunspots (Stuiver and Quay, 1980). Tree ring data have been used to study climate in the past in relation to solar activity (Hughes, 1982; Murphy, 1990; Dutilleul and Till, 1992; Kurths et al., 1993; Cook et al., 1997). Generally, the variation of SSN is clearly related with Chinese pine tree rings on the Qianshan mountains. The RES chronology of *Picea jezoensis* for the dark coniferous forests on the upper part of the Changbai mountains (Yu, 2004) responded similarly. Although the mechanism of the Chinese pine response to GSC is not entirely clear, its effects on the pines of the Qianshan mountains might be attributed to the effect of GSC on regional climate change (Bochniček and Hejda, 2005) and it therefore affected the growth of the pines. On the other hand, the activities of GSC and SSN had different effects on the growth of the pines due to a slight inconsistency in the activities of GSC and SSN (Le and Ye, 2003). This mechanism is still unclear and is a subject for future research.

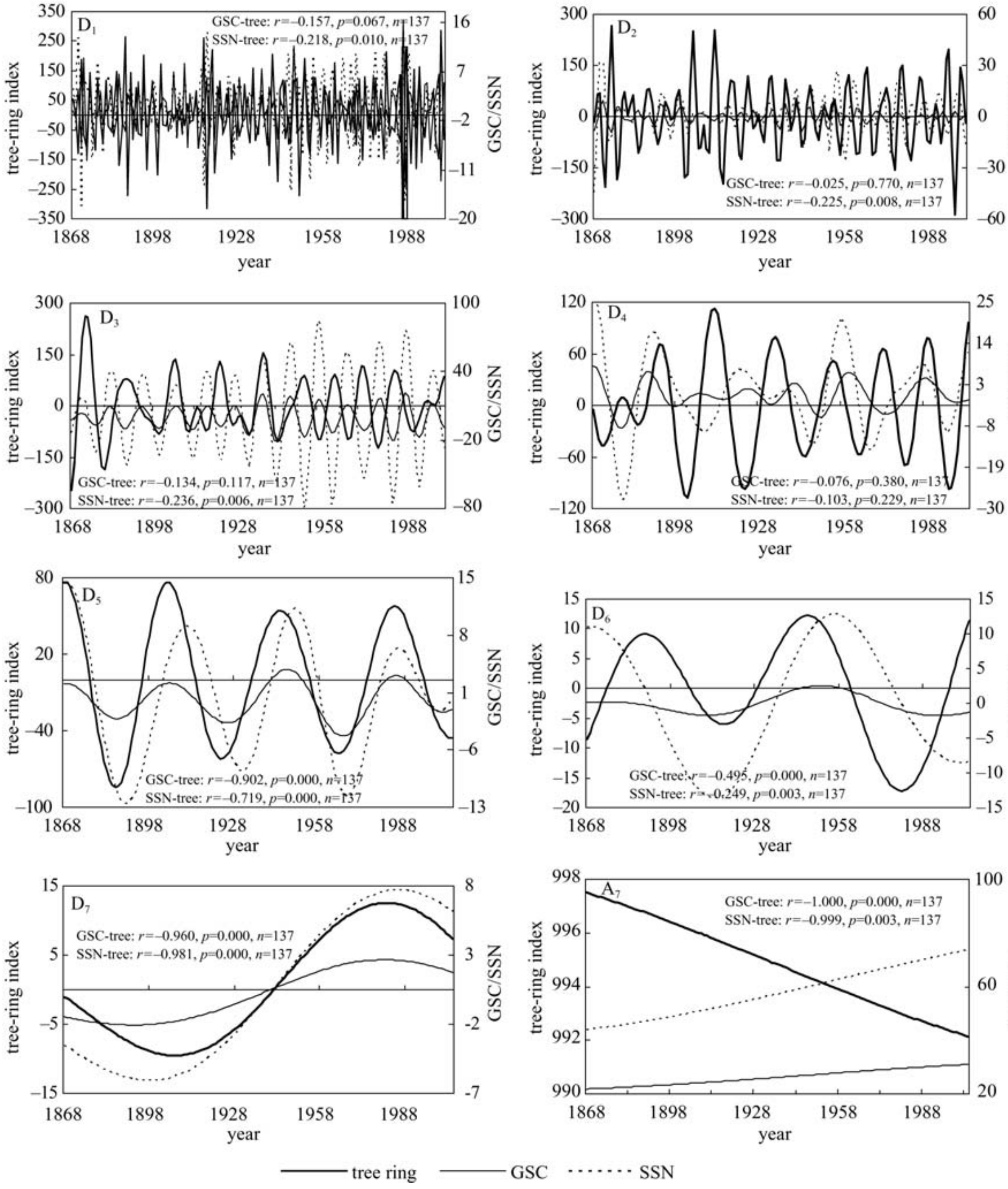

Fig. 5 Analysis of DMEY wavelet for STD chronology and SSN, GSC time series

Original signal OR = $A_7 + D_7 + D_6 + D_5 + D_4 + D_3 + D_2 + D_1$; A: low frequency signal; D: high frequency signal; suffix numbers are decomposed grades.

4 Conclusions

The Chinese pines on the Qianshan mountains in the south of northeast China responded significantly to both precipitation and temperature variability, particularly during spring. Minimum winter temperatures were another factor dominant in the growth of these pines. Significant responses of the Chinese pines to hemispheric and global temperature variation show up during spring and winter. PDO also affected the Chinese pines on the Qianshan mountains seasonally (dominantly during the growing season in this region), with clear effect in the warm period of PDO. Furthermore, the Chinese pines in this region clearly responded to solar and geomagnetic activities. It is obvious that, as a proxy, Chinese pine tree ring width chronology for the Qianshan mountains has its specific applied values which can be used in further research.

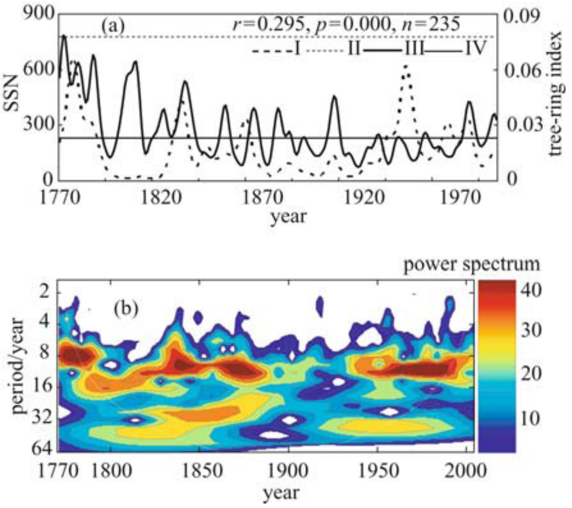

Fig. 6 Analysis of Morlet wavelet for time series of number of sunspots and ring-width STD chronology
A: the scale-averaged wavelet power over the 2–8 years band for the sunspot number; B: the time series of the cross-wavelet spectrum between number of sunspots and ring-width STD chronology. The smooth curve is the significance level at 0.05 level. I) SSN; II) 95% confidence level of SSN; III) tree ring; IV) confidence level of tree ring.

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