ORIGINAL PAPER

# Anomalous temperature–growth response of *Abies faxoniana* to sustained freezing stress along elevational gradients in China's Western Sichuan Province

Zong Shan Li · Guo Hua Liu · Bo Jie Fu · Chan Juan Hu · Shu Zheng Luo · Xing Liang Liu · Fei He

Received: 19 January 2011/Revised: 8 March 2012/Accepted: 12 March 2012 © Springer-Verlag 2012

Abstract A network of ten Faxon fir tree-ring width chronologies was constructed from sites ranging in elevation from 3,000 to 3,450 m in the Wolong Natural Reserve in Western Sichuan Province, China. The site chronologies display significant inter-site correlations (mean R = 0.647, p < 0.001) and the first principal component (PC1) accounts for 68.32 % of the total variation of the chronologies, implying a high degree of similarity in growth variation among the elevation gradients. Correlation analysis using monthly climate data indicates that the radial growth response of Faxon fir along the elevation gradients is markedly similar to common climatic signals, such as sunshine duration (positive) and cloud cover (negative), from January to March. Thus, it appears that winter freezing stress, which is caused by low solar radiation and high cloudiness, is the major environmental factor regulating the growth of trees across the elevational gradients. In addition, the site chronologies have no elevationdependent growth responses to temperature or precipitation. Irrespective of the elevational differences of the sample sites, an anomalous reduction in radial growth occurred consistently since the 1960s, diverging from the instrumental temperature records since the 1990s. The

X. L. Liu · F. He Institute of Ecology, Sichuan Forestry Research Academy, Chengdu 610081, China cause of this divergence may be ascribed to the recent accelerated winter freezing stress and its role in controlling radial growth.

**Keywords** Abies faxoniana · Tree-ring · Dendroclimatology · Elevation gradient · Western Sichuan

# Introduction

There is compelling evidence that the exceptional warmth of the late 20th century far exceeded natural climate variability within a historical context (Crowley 2000; Intergovernmental Panel on Climate Change (IPCC) 2007; Kerr 2007). Recent warming has induced biological and ecological responses from biotic communities throughout the world (Walther et al. 2002; Root et al. 2003; Bertrand et al. 2011; Maclean and Wilson 2011). Subalpine forests are particularly sensitive to temperature variability (Hoch and Körner 2003), and a significant upward shift along elevational gradients has been detected among tree species in mountainous regions (Colwell et al. 2008; Lenoir et al. 2008). The prediction of forest dynamics in the context of future climate change mandates a need to understand treegrowth changes as related to elevational gradients (Zhang and Hebda 2004).

With respect to forest ecosystems, dendrochronological techniques can contribute to bioclimatic studies by providing insight on tree growth response to elevational gradients (Filippo et al. 2007). Tree growth at high-elevation timberline is traditionally associated with air temperature, while a positive correlation with precipitation predominates at low elevations (Fritts et al. 1965; LaMarche 1974; Wilson and Hopfmueller 2001). In contrast to this generalized idea, several studies have observed similar growth

Communicated by S. Leavitt.

Z. S. Li  $\cdot$  G. H. Liu ( $\boxtimes$ )  $\cdot$  B. J. Fu  $\cdot$  C. J. Hu  $\cdot$  S. Z. Luo State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Science, Chinese Academy of Sciences, 18 Shuangqing Road, Haidian District, Beijing 100085, China e-mail: ghliu@rcees.ac.cn

variation patterns along the elevation ranges, and some common limiting climatic factors might synchronize tree growth at different elevations. For example, in the subtropical mountains of northwestern Argentina, the radial growth of four species growing at different elevational zones was strongly regulated by water availability (Morales et al. 2004). Esper et al. (2007) showed that low and high elevational subsets of central Asian juniper trees (Juniperus semiglobosa, J. seravchanica, and J. turkestanica) revealed significant coherence over the common period, and this uniform growth behavior was hypothesized to be forced by solar radiation variations controlled by cloud cover changes. Liang et al. (2010) demonstrated that the initiation of tree-ring growth in Smith firs (Abies georgei var. smithii) is controlled by common climatic signals such as July minimum temperature across a broad elevational range in the Sygera Mountains of the southeastern Tibetan Plateau.

The mountains oriented north to south in Western Sichuan, which are located along the eastern flanks of the Qinghai-Tibetan plateau, contain three major tributaries of the Yangtze River-the Yalong, Dadu, and Min Riversconverging within a 150-km corridor. The resulting landscape patterns include extreme topographic gradients between deeply incised parallel gorges of approximately 1,000 m in elevation and glaciated peaks (7,556 m a.s.l.) within a distance of less than 30 km (He et al. 2003). The pronounced elevation climatic gradients lead to a differentiation of the mountain forests into several elevation belts (Shen et al. 2004). Western Sichuan is an ideal area for dendroclimatological studies along elevation gradients due to its unique geography, ecology, and topography. Many tree-ring studies in Western Sichuan have focused on climate-growth responses (Li et al. 2010a) and climatic reconstructions (Shao and Fan 1999; Wu et al. 2005; Qin et al. 2008; Li et al. 2010b). However, analyses focusing specifically on climate-growth relationships along vertical

transects have received less attention. In this study, we established ten tree-ring chronologies of Faxon fir (*Abies faxoniana* Rehd. et Wild) from two elevational gradients in Western Sichuan Province, China. The main objectives of the study were to: (1) investigate variability in the radial growth patterns of the site chronologies along the elevational gradients, and (2) identify the climatic factors most responsible for such growth patterns. These investigations provide some insight into the role of regional forest dynamics and their relationships with climatic change.

# Materials and methods

#### Study area

The research was conducted at Mt. Balang in the core area of the Wolong Natural Reserve (Western Sichuan Province, China), which is one core habitat for the giant panda (Ailuropoda melanoluca David), a well-known endangered species (Fig. 1). The mountain forests of Mt. Balang, at an elevation of 5,040 m, are differentiated into elevational belts (Guan et al. 1984; Liu 2002). The southern side of the mountain is usually covered by mixed forests of broadleaved and sclerophyllous oak species, while Faxon fir commonly dominates the canopy of the cold-temperate coniferous forests on the northern side of the mountain. Faxon fir can grow from ca. 2,750 m up to ca. 3,500 m (the upper treeline), whereas isolated trees reach even higher than 3,800 m. Faxon fir is considered as one of the climax species of the sub-alpine coniferous forests in Western Sichuan Province (Liu 2002). Soils that support subalpine forest are classified (Chinese system) as mountain brown coniferous forest soils. Soils vary in depth from shallow (<30 cm) to deep (>100 cm), and limestone is the main parent material in our study area (Zhang 1983; Taylor et al. 2006).

Fig. 1 a Location map of the tree-ring sample site, meteorological station and CRU gridded climate data points in Wolong Natural Reserve (Western Sichuan Province, China). b Autumn view of a northeastern slope of Balang Mountain in Wolong Natural Reserve, where *Abeis faxoniana* forest was targeted for sampling. Photograph by Zongshan Li



Lying in the East Asian Monsoon Region, the climate variability of Wolong Natural Reserve is significantly affected by warm-wet monsoon masses in summer and continental air masses in winter, both of which strongly influence the precipitation and temperature patterns of this region (Böhner and Lehmkuhl 2005), resulting in an alternation between rainy (from May to October) and dry (from November to April) seasons. The spring and autumn seasons are not well defined and last one month or less (Zheng et al. 2006). According to climate data from the Desheng Meteorological Station in this reserve (2,730 m, 102°58'E, 30°51'N; Zheng et al. 2006), mean annual precipitation is about 846 mm, 80 % of which falls during the summer monsoon season from May to October. The mean annual temperature and relative humidity are 8.4 °C (January -1.7 °C and July 17.0 °C) and 80 %, respectively.

# Sampling and chronology development

The field work was carried out at Mt. Balang in September 2009 and September to October 2010. Tree-ring cores were collected along two elevational gradients from 3,000 to 3,450 m (hereafter referred to as A and B), representing the typical forest type of Faxon fir. The two gradients were separated horizontally by about 50 m (Fig. 1). Five single-species sites were selected at each gradient: one treeline site at 3,450 m (hereafter A1 and B1), one timberline site at 3,400 m (hereafter A2, B2), and three mid-elevation interior forest sites at 3,000 to 3,300 m (hereafter A3 to A5 and B3 to B5; Table 1). Because previous anthropogenic disturbance has resulted in extensive degradation of conifer forests (which are dominated by young hardwoods such as

*Betula*) below 3,000 m, we did not collect samples from sites lower than 3,000 m. At each site, a minimum of 30 trees were selected for sampling and one increment core was extracted from each tree. To minimize non-climatic influences on tree-ring growth and maximize the ages of the sampled trees, only the largest diameter trees with no obvious injury or disease were sampled. Cores were taken on the sides of the tree perpendicular to the ground slope as close as possible to the base of the tree. Cores were placed in plastic straws, and labels were placed on each straw. In total, increment cores from 400 trees were extracted with an increment borer.

In the laboratory, tree-ring cores were prepared according to the methods described by Stokes and Smiley (1968). Cores were glued to standard wooden core mounts and allowed to dry overnight. Cores were then sanded using progressively finer grades of sandpaper (from 140 to 600 grit) to produce flat surfaces on which ring boundaries were clearly visible under magnification (Orvis and Grissino-Mayer 2002). Rings were crossdated through pattern matching with skeleton plotting (Stokes and Smiley 1968) and measured using a LINTAB measuring system with a resolution of 0.001 mm. Crossdating of the measured tree-ring series was verified using the COFECHA program (Holmes 1983). Trees showing low correlation values with the master chronology were excluded from the site chronologies (Grissino-Mayer 2001). A total of 332 increment cores were successfully crossdated and selected for further analysis, while 68 cores were excluded.

Standard chronologies were developed from the crossdated ring-width series using the ARSTAN program (Cook and Kairiukstis 1990). In order to prevent any potential

**Table 1** Summary statistics for tree-ring width chronologies of Abies faxoniana along two elevational gradients in the Wolong Natural Reserve,western Sichuan of China

Chronology code	Elevation (m)	Chronology length	Number of cores	SD	MS	AR1	Rbt <sup>a</sup>	<b>SNR</b> <sup>a</sup>	EPS <sup>a</sup>	VFE <sup>a</sup>
A1	3,450	1,847-2,008	33	0.354	0.157	0.592	0.408	3.636	0.784	26.31
A2	3,400	1,856-2,008	31	0.362	0.176	0.827	0.353	2.708	0.73	20.27
A3	3,300	1,827-2,008	29	0.365	0.178	0.694	0.541	4.065	0.803	33.05
A4	3,200	1,842-2,008	34	0.375	0.187	0.734	0.503	8.107	0.89	32.41
A5	3,000	1,875-2,008	43	0.576	0.199	0.664	0.309	2.408	0.707	21.95
B1	3,450	1,847-2,008	30	0.274	0.168	0.682	0.451	6.144	0.86	26.83
B2	3,400	1,856-2,008	25	0.394	0.176	0.715	0.569	5.037	0.834	37.75
B3	3,300	1,856-2,008	33	0.393	0.177	0.682	0.474	3.773	0.79	27.79
B4	3,200	1,916-2,008	34	0.402	0.21	0.635	0.427	5.471	0.845	26.55
B5	3,000	1,880–2,008	40	0.468	0.238	0.741	0.42	5.704	0.851	25.46

A1, A2, A3, A4 and A5 are the tree-ring chronologies at the elevation gradient A; B1, B2, B3, B4 and B5 are the tree-ring chronologies at the elevational gradient B

SD standard deviation, MS mean sensitivity, AR1 first-order autocorrelation, Rbar mean inter-series correlations, SNR signal-to-noise ratio, EPS expressed population signal, VFE variance in first eigenvector

<sup>a</sup> Calculation for the common interval (1952–1999) of the chronologies

influence of standardized methods on the results of the climate-growth relationships, all tree-ring series were detrended with a fixed cubic smoothing spline with a 50 % frequency-response cutoff of 60 years. This detrending method maximizes the common signal among individual tree-ring series while removing low-frequency trends caused by tree aging and stand dynamics. Deviations of the individual measurement series from the detrending curves were calculated as residuals. All detrended series were averaged to chronologies by computing the biweight robust mean to reduce the influence of outliers (Cook and Kairiukstis 1990). To reduce the potential influence of poorly replicated portions with increasing age, the variance of the chronology was stabilized (Osborn et al. 1997) and the records of the chronology were truncated at a minimum replication of five series.

The chronologies were characterized using the standard deviation (SD), mean sensitivity (MS), mean correlation between trees (Rbt), first-order autocorrelation (AR1), signal-to-noise ratio (SNR), variance in first eigenvector (VFE), and expressed population signal (EPS). These descriptive statistics were calculated for the chronologies in the common period (1952-1999) in order to make an impartial comparison among the chronologies. SD represents the variability of the measurements at all wavelengths and MS quantifies the inter-annual variation in growth between two adjacent rings (Fritts 1976). SNR serves as an expression of the strength of the observed common signal among trees and AR1 indicates the persistence of the site chronologies. Rbt and VFE estimate the amount of year-toyear growth variations common among trees at the same site. EPS defines the reliable part of the chronologies, with a threshold of 0.85 usually accepted as sufficient according to Wigley et al. (1984).

#### Multivariate analysis

The 1925–2008 period, which is common to the ten standard fir chronologies, was considered for multivariate analysis, including a correlation matrix and principal components analysis (PCA). The main modes of common growth variability among the stands were represented by principal component (PC) scores or amplitudes (Jolliffe 1986; Filippo et al. 2007). Component loadings (eigenvectors), which display the pattern of association of chronologies with each component, were employed to detect groupings in the tree-ring network. Selection of PCs was guided by Kaiser's (1992) Rule, which identifies the factors with eigenvalues greater than 1.

## The climate-growth relationship

Although the Dengsheng Meteorological Station is the nearest climate station to the sample site (about 10 km from the study site), the short duration of its meteorological data (only available for several recent years) makes it difficult to perform reliable calibration with the targeted tree-ring data. More complete climate data were obtained from the nearby national meteorological station (Dujiangvan station, 698 m, about 60 km from the study site) to match the time duration of the target tree rings, including monthly mean temperature (TEM), monthly total precipitation (PRE), and monthly sunshine duration (SUN) over the 1956-2008 period. We further used gridded climate data for analyses because they provide a more regional signal than the station records. The gridded climate data included monthly mean temperature (TEM), monthly total precipitation (PRE), and cloud cover (CLD), which were obtained from the Climatic Research Unit (CRU), East (http://www.cru.uea.ac.cn:  $0.5^{\circ} \times 0.5^{\circ}$ ; Anglia, UK CRUts2.1; Mitchell and Jones 2005). Mean values were calculated from four grid-boxes covering the region between 20.75 and 31.25°N and 102.75-103.25°E over the 1950–2002 period. The climate diagrams for the climate station and CRU gridded data are plotted in Fig. 2. Relationships between site chronologies and monthly climate parameters were analyzed using correlation functions with the DendroClim2002 program, which is widely used for

**Fig. 2** Monthly variation of total precipitations (*bars*) and mean temperature (*line with triangles*) for the Dujiangyan Meteorological Station (**a**) and CRU grids (**b**), calculated for the periods of 1956–2002



modeling climate–growth relationships (Biondi and Waikul 2004). Correlations were made between the individual chronologies and PC scores identified in the PCA against the monthly series of both the climate station and CRU grid-boxes. We chose the common interval (1956–2002) between the tree-ring data and climate data for correlation analysis in order to refrain from the potential correlation discrepancy calculated over different time periods. Because the climate during months preceding the growing season often influence growth (Fritts 1976), explanatory climate variables spanning a 15-month window (from July of the previous-growth year to September of the current year) were used to determine the climate–growth relationships.

## Pointer year analysis

Pointer years are an accepted method of showing annual growth reactions caused by abrupt changes in environmental conditions (Schweingruber et al. 1990), particularly climatic variations (Neuwirth et al. 2007). This can overcome the weakness of the correlation analysis, which only provides information about the average climate–growth relationship (Desplanque et al. 1999; Liang et al. 2006). If the tree-ring data series in a given year is one standard deviation lower or higher than the mean, we consider that year as a negative or positive pointer year, respectively. The pointer years were restricted to the 1956–2002 period. The mean deviations of the climatic variables from their respective means were used to identify possible triggers for the negative or positive pointer years.

#### Results

## Characteristics of the tree-ring width chronologies

Table 1 lists the locations and descriptive statistics of the ten ring-width chronologies. The chronologies range in length from 92 years (B4) to 182 years (A3) (Fig. 3). Because most of the standing trees with a large diameter in the sample sites are rotted inside, the length of the chronologies is certainly not the actual age of the old-growth fir forests in the study area. Taylor et al. (2006) reported ages of more than 350 years of old-growth Faxon fir forests in the Wang Lang Natural Reserve in Western Sichuan Province. The chronologies generally display low year-to-year variability (MS = 0.16-0.24), which is typical for conifers growing in humid environments. AR1 range from 0.592 to 0.827, indicating that the chronologies contained low-frequency variance generated by climate and tree-physiological lag effects (Fritts 1976). The SNR and EPS statistics of the site chronologies range from 2.41 to 8.1 and from 0.71 to 0.89, respectively, and the six chronologies meet or exceed the 0.85 EPS criterion. The chronologies have high values of average cross-correlations (Rbt = 0.592-0.827) and percentage of common variance of the components (VFE = 22-33 %) shared by the ring series. Most of the site chronologies have high statistical quality and the tree-ring data appear to be sensitive parameters reflecting the exogenous influences.

SD is negatively correlated with elevation (r = 0.84-0.88, p < 0.01), with the value ranging from 0.47 to 0.58 mm in the lowland to 0.28–0.35 mm at the highest elevations, and the MS of the stands also has a negative correlation with elevation (r = 0.93-0.97, p < 0.01). Trees from arid forest habitats often show higher variability of inter-annual growth than trees from temperature-limited sites (Fritts et al. 1965; Liang et al. 2006). Trees at lower elevations probably face greater risk of potential water stress than those growing at higher elevation sites. However, the Rbt, SNR, and EPS statistics, considered as the degree of common signal among tree-ring series, are not linearly related to the elevation gradients and no obvious vertical zonation could be identified.

## Comparison of chronologies

Irrespective of differences in chronological statistics and local site factors, the site chronologies contain common patterns of interannual growth variability across the elevation gradients. All chronologies display significant intersite correlations (mean R = 0.647, p < 0.001) with the exception of A4 with B5 and B4 with B5, with the highest correlation found among the three high sites of both transects (R = 0.63-0.877, p < 0.01; Table 2). The first component of the PCA analysis (PC1) accounts for 68.32 % of the total variance (Table 3), showing a high percentage of similarity in growth variation among sites at the elevation gradients. The loadings of PC1 describe common variance shared by the site chronologies, which likely relate to large-scale climate patterns limiting tree growth in the study region.

## Climate-growth analysis

The results (Figs. 4, 5) show roughly similar climate– growth relations between the site chronologies and temperature data of the climate station and CRU grids. The site chronologies indicate no evident variations in the relative importance of temperature as an environmental control of tree growth along the elevational gradients. The chronologies at intermediate elevations (3,300 m; A3 and B3) exhibit a response to temperature that is particularly strong during the spring (March to April) and summer (June to July) in the current year, as well as July and September in the previous year. Other chronologies have the same Table 2Correlationcoefficients among the tenstandard chronologies of twoelevational gradients for thewell replicated period1925–2008

	A1	A2	A3	A4	A5	B1	B2	B3	B4
A2	0.798**	_							
A3	0.679**	0.676**	-						
A4	0.652**	0.527**	0.449**	-					
A5	0.8**	0.715**	0.566**	0.587**	-				
<b>B</b> 1	0.769**	0.85**	0.723**	0.567**	0.653**	-			
B2	0.836**	0.877**	0.63**	0.704**	0.775**	0.846**	_		
B3	0.721**	0.781**	0.869**	0.51**	0.639**	0.848**	0.789**	-	
B4	0.814**	0.656**	0.591**	0.873**	0.657**	0.663**	0.747**	0.59**	_
B5	0.442**	0.52**	0.304*	0.166	0.569**	0.495**	0.514**	0.511**	0.184

Table 3 Principal component
analysis for ten tree-ring
chronologies of two elevational
gradients for the common
period: 1925–2008

Significant at \*p < 0.05Significant at \*\*p < 0.01

Principal component	Eigenvalue	Variance (%)	Cumulative variance (%)		
PC 1	6.83	68.32	68.32		
PC 2	1.34	13.38	81.17		
PC 3	0.69	6.87	88.58		
PC 4	0.35	3.54	92.12		
PC 5	0.3	3	95.12		
PC 6	0.17	1.69	96.82		
PC 7	0.11	1.05	97.88		
PC 8	0.1	0.93	98.82		
PC 9	0.07	0.65	99.47		
PC 10	0.05	0.52	1		

response but a much weaker temperature signal than that noted for the intermediate elevations. The precipitation data of the CRU grids plays a minor role in explaining year-to-year variation in tree-ring width, and there are no significant correlations with CRU precipitation for any month. Statistically significant correlations between precipitation and tree growth are only observed for rainfall data from the climate station. The site chronologies are positively correlated with precipitation during October and December in the previous year, whereas radial growth is negatively affected by precipitation in January of the current year. These relationships are strongest for the lowest elevation sites (3,000 m; A5 and B5), while the weakest correlations are at the middle elevation sites (3,300 m; A3 and B3). No precipitation trends based on elevation were found.

Across the elevational gradients, the most striking feature is that site chronologies are positively associated with sunshine duration during January to March of the current year, although there are differences in the response strength of different months. The relationships are weak for only two sites (A3 and B4). Another defined feature of the correlation analysis is that radial growth along the elevational gradients is linearly and negatively related to cloud cover in March of the current year, with the exception of finding lower correlation at site A3. The cloud cover from January to February tends to be negatively correlated to radial growth, but most of those correlations are not significant.

In order to reflect the common growth responses to regional climate, we further explored the correlation analysis between PC1 and the climate data (Fig. 6). The most impressive pattern is the positive correlation of PC1 with sunshine duration in January to March of the current year, although significant negative correlations between PC1 and cloud cover in February to March of the current year are also observed. Additionally, PC1 has positive correlations with temperature in April and July of the current year and July of the previous year. Strong correlations are also found between PC1 and precipitation in October and December of the previous year (positive) and January of the current year (negative). These findings are generally in agreement with the response patterns calculated from the individual chronologies.

# Pointer years and climatic forcing

Extreme values for the PC1 series, or those that are one standard deviation lower or higher than the mean, are regarded to be pointer years recorded in our sampling area. Fig. 3 Tree-ring width chronologies of *Abies faxoniana* for the two elevational gradients in the Wolong Natural Reserve (Western Sichuan Province, China), smoothed using a 11-year low-pass filter. A1–A5 and B1–B5 are codes of the chronologies at two elevational gradients, which are consistent with those given in Table 1



The results confirm that negative pointer years (1968, 1970, 1981, 1985–1993, 1997–1999) occurred more frequently than positive pointer years (1952, 1958–1960, 1963) with this method of calculation. Furthermore, it is commonly accepted that extremely narrow years in treering series should be a more diagnostic parameter compared to extremely wide years when detecting the influence of climate on tree growth (Schweingruber et al. 1990). In this study, we only investigated climate factors that may modulate these negative pointer years (NPYs).

The climate in the NPYs is characterized by low sunshine duration and high cloud cover in March of the current year as well as by low temperature, especially for the periods of March to August in the current year and July to September in the previous year (Fig. 7). Our study also confirms that low precipitation in October and December of the previous year is relevant in explaining the occurrence of NPYs.

#### Discussion

A considerable body of research for many regions indicates that climate-tree growth relationships may vary with the elevation gradient, ascribed to the variations in temperature and precipitation at different elevations (Fritts et al. 1965; LaMarche 1974; Wilson and Hopfmueller 2001; Zhang and Hebda 2004). Radial growth in tree species at high-elevation treelines has been traditionally associated with temperature, while tree growth at low elevations shows a strong, linear relationship with precipitation (Körner 1999; Dittmar et al. 2003; Filippo et al. 2007). The results in this study indicate that, in contrast with earlier predictions, the elevational environmental gradients introduce no discernible differences in the radial growth patterns or climategrowth relationships of Faxon fir in Western Sichuan Province, China. The tree-ring chronologies in this study showed pronounced similarity in growth variation across



Fig. 4 Correlation analysis between climate and site chronologies at elevational gradient A. **a** Correlations with monthly mean temperatures for weather station (*black bar*) and CRU gridded data (*white bar*). **b** Correlations with monthly total precipitations for weather station (*black bar*) and CRU gridded data (*white bar*), **c** Correlations with monthly sunshine duration of weather station (*black bar*) and CRU gridded data (*white bar*), **c** Correlations with monthly sunshine duration of weather station (*black bar*) and CRU gridded bar) and CRU gridded data (*white bar*), **c** Correlations with monthly sunshine duration of weather station (*black bar*) and CRU gridded bar) and cRU gridd

monthly cloud cover of CRU gridded data (*white bar*). *Horizontal dashed lines* denote the 95 % significance levels. Numbers on *x* axis refer to monthly values from prior July (-7) to September of the current year over the common period 1956–2002. Al to A5 are codes of the chronologies at the elevation gradient A, which are consistent with those given in Table 1

the elevational gradients, indicated by the high inter-site correlations (mean R = 0.647, p < 0.001) and a large portion of total variance (68.32 %) explained by the PC1 series. It is plausible that some common climatic factors, independent of stand elevation and local ecological factors,

account for the high degree of covariance among all of the tree-ring chronologies.

The correlations between the climate data with site chronologies, PC1, and pointer years all demonstrate that radial growth along the elevational gradients expresses a



Fig. 5 Correlation analysis between climate and site chronologies at elevational gradient B. **a** Correlations with monthly mean temperatures for weather station (*black bar*) and CRU gridded data (*white bar*). **b** Correlations with monthly total precipitations for weather station (*black bar*) and CRU gridded data (*white bar*), **c** Correlations with monthly sunshine duration of weather station (*black bar*) and CRU gridded data (*white bar*), **c** Correlations with monthly sunshine duration of weather station (*black bar*) and CRU gridded bar) and CRU gridded data (*white bar*), **c** Correlations with monthly sunshine duration of weather station (*black bar*) and CRU gridded bar) and cRU gridd

significant, positive response to sunshine duration during January to March of the current year. The radial growth of different elevation sites is also closely linked to cloud cover from January to March of the current year, but the statistical relationships point to a negative effect. Sunshine duration is a direct indicator of total solar irradiance received by the trees, whereas total cloud amount (cloud

monthly cloud cover of CRU gridded data (*white bar*). *Horizontal dashed lines* denote the 95 % significance levels. Numbers on x axis refer to monthly values from prior July (-7) to September of the current year over the common period 1956–2002. B1–B5 are codes of the chronologies at the elevation gradient B, which are consistent with those given in Table 1

cover) usually exhibits a significantly negative correlation with sunshine duration (Chen et al. 2002; You et al. 2010). Cloudiness is an important factor that could reduce growth through light limitation (Graham et al. 2003; Liepert et al. 2004). Furthermore, the negative pointer years recorded in our sampling area are mainly observed during cold years with lower temperatures. We suggest that winter (January



**Fig. 6** Correlation analysis between climate and the PC1 series of the site chronologies. **a** Correlations with monthly mean temperatures for weather station (*black bar*) and CRU gridded data (*white bar*). **b** Correlations with monthly total precipitations for weather station (*black bar*) and CRU gridded data (*white bar*). **c** Correlations with monthly sunshine duration of weather station (*black bar*) and monthly cloud cover of CRU gridded data (*white bar*). *Horizontal dashed lines* denote the 95 % significance levels. Numbers on x axis refer to monthly values from prior July (-7) to September of the current year over the common period 1956–2002

to March) freezing stress is the common climatic factor limiting tree growth along the elevational gradients. As recorded from the Dujiangyan station (about 700 m a.s.l.) in the sample area, the maximum, mean, and minimum temperatures in January to March averaged around 10.9, 7.4 and 4.6 °C, respectively. Using the adiabatic lapse rate for saturated air of 0.6 °C/100 m (for air at ca. 10 °C and 1,000 mb pressure; Buckley et al. 1997), the maximum, mean, and minimum temperatures from January to March for the mean elevation of our sample sites (ca. 3,200 m) averaged around -4.1, -7.6, and -10.4 °C, respectively. Faxon fir trees are notably shallow rooting, with a large percentage of fine roots in the upper 30 cm (Schenk and Jackson 2002), and low winter-season temperatures may cause freezing injury to roots, promoted by frost penetration in the absence of adequate snow cover (Auclair et al. 2010). Sakai and Larcher (1987) found that tree roots in northern hardwoods are by far the least affected by frost hardening of any tree tissue and can freeze at as little as -1 °C, and the importance of soil frost as the foremost mechanism of dieback in northern hardwoods remains the most compelling explanation to date (Kullman 1991; Boyce 1995; Lund and Livingston 1999; Auclair et al. 2010). Root kill exacerbates the effects of drought in the following growing season, and Faxon fir winter injury is caused by cold stress and (or) winter desiccation, which may result in the abscission of the most recent needles (Friedland et al. 1984; Jalkanen et al. 1998). Both foliar and bud mortality can accompany winter freezing injuries and severely disrupt the carbon economies of trees, thus reducing a tree's potential for photosynthesis and radial growth during the following year (Peart et al. 1992; Hadley et al. 1993; Lazarus et al. 2004). The influence of harsh winters on tree-ring width was also revealed in the southern Tibetan Plateau (Bräuning 2001) and the central Hengduan Mountains (Fan et al. 2009).

In regards to the site chronologies in our study, the temperature signal is most pronounced for the intermediate closed forests (3,300 m), and less so for the higher timberline (3,400 m) and treeline (3,450 m) sites. This does not agree with the principle of limiting factors, which describe how a tree species is more sensitive to temperature at the upper elevational limits of its range (Fritts et al. 1965; Wilson and Hopfmueller 2001). There are some common patterns in the relationships between temperature and radial growth across the elevational gradients, such as positive correlations between radial growth and temperature in the spring (March to April) and summer (June to July) of the current year, as well as July and September of the previous year. Remobilization of the carbohydrate reserves in spring is of major importance for leaf and root expansion, and affects the subsequent bole increment of trees (Misson et al. 2004). A warm spring may induce the breaking of dormancy and the resumption of physiological activity in the tree, thus increasing the duration of the current growing season (Lebourgeois et al. 2005). Spring temperature was also found to be the most crucial factor limiting the radial growth of trees in the Himalaya



Fig. 7 Standardized value of mean deviations of climatic variables from their long-term (1956–2002) mean values for all the negative pointer years of the PC1 series of the site chronologies. **a–c** Indicate

monthly temperature, precipitation and sunshine duration of weather station, respectively. d-f Indicate monthly temperature, precipitation and cloud cover of CRU grids, respectively

Mountains in India (Yadav et al. 1997; Yadav and Singh 2002) and Nepal (Cook et al. 2003). Conifer tracheids usually divide and enlarge most actively during the warmest period of the growing season (Deslauriers et al. 2003; Rossi et al. 2008). A warm summer is critical for tree growth because it can promote cambium activity and contribute to the accumulation of photosynthates, which is essential for latewood cell-wall thickening (Hughes 2001; Rossi et al. 2006). In contrast, low summer temperatures in mountainous regions can limit the growth of roots and their function in water uptake, thus suppressing cell division and radial growth (Oberhuber et al. 1998; Liang et al. 2008). Warm conditions in middle summer and early autumn during the previous year may increase carbohydrate storages for growth during the next year, and similar results have been reported for other forests at high elevations (Oberhuber 2004; Büntgen et al. 2007; Liang et al. 2008).

Generally, positive correlations with precipitation during October and December in the previous year likely reflect positive carryover effects. In the study site, precipitation during October and December of the previous year was mainly in the form of snow. The growth increase after high precipitation can probably be explained by the typical snowpack in winter, which insulates and protects tree roots from deep frost. In contrast, the lack of accumulated snow can result in deep soil frost and roots kill in the event of particularly cold air temperatures (Auclair et al. 1996; Villalba et al. 1997). Furthermore, trees can assimilate the water from melting snow in spring, which works to enrich the soil moisture storage so crucial for tree growth in the coming year (Linderholm and Chen 2005; Fan et al. 2008). Interestingly, radial growth is also negatively correlated with precipitation during January of the current year. A possible explanation is that heavy precipitation during January combined with cold temperatures at high elevations might produce deep snowpacks, possibly persisting well into the spring months (Graumlich 1993; Peterson and Peterson 2001). As a result, tree growth appears to be limited by late snowmelt and short growing seasons (Ettl and Peterson 1995; Woodward 1998).

In the context of increasing temperatures in recent decades, an anomalous reduction in forest growth (attributed to probable temperature-induced drought stress) has been detected in many northern latitude sites in the later part of the 20th century (Briffa et al. 1998; Wilmking et al. 2005). Thus, temperature reconstructions in recent decades have become more unreliable as tree-ring growth has become less responsive to climate (Büntgen et al. 2007; D'Arrigo 2008). Interestingly, the PC1 series of site chronologies in this study demonstrates the sustained negative growth anomalies experienced during the second half of the 20th century. PC1 and temperature variables have increasingly diverged since the temperature increased around 1990 (Fig. 8). In contrast, the PC1 series closely follow the decadal trend in sunshine duration from January to March (R = 0.632, p < 0.01). Another notable feature is that cloud cover from January to March yields a significantly negative association (R = -0.672, p < 0.01) with the PC1 series. Based on the sunshine duration data of 71 stations with elevations above 2,000 m in the eastern and central Tibetan Plateau, You et al. (2010) observed an overall significant decrease of sunshine duration at a rate of -20.6 h/decade over the 1961-2005 period. The identified causes are currently ascribed to observed increases in cloud cover frequencies due to more cloud water and more aerosols in recent decades (Cohen et al. 2004; Che et al. 2005). This led us to hypothesize that the consistently declining trend of solar radiation, with an overall significant increase in cloud amount, is typically coincident with a high frequency of winter freezing stress of Western Sichuan, which will precondition Faxon fir trees to climatic injury. This is the likely explanation for the sustained reduction of tree growth across the elevation gradients in this study in the late 20th century.

In the context of a global warming scenario, an increase in extreme climate events (e.g., extended cold spells in winter) have contributed to the destabilization of various ecosystems (Perkins and Adams 1995; Stanhill and Cohen 2001; Alexander et al. 2006; Sillmann and Roeckner 2008; Choi et al. 2009). Several studies have reported how a single extreme low-temperature and freezing event in winter, such as China's snow disaster in 2008 (Wang et al. 2008; Hui 2009) or the severe red spruce winter injury of the northern USA in 2003 (Lazarus et al. 2004) can seriously impact forest ecosystems within a short period. Auclair et al. (1996) found that the link between forest



Fig. 8 PC1 and climate variables over the past 47 years (1956–2002). a Smoothed PC1 series and targeted climate variables. b The difference series (growth minus climate variable), *shaded* to emphasize negative values of each pair of curves. PC1 (*dotted lines*) and the targeted climate variables (*lines*) have been scaled to have zero mean and vary between 0 and 1 over the period 1956–2002. All data series have been smoothed with a 7-year low-pass filter. *R* indicates the linear correlation

coefficients between PC1 and climatic variables over the period 1956–2002 and *p* denotes their significant levels. djy.tem (-7/9) and cru.tem (-7/9) are annual (from previous July to current September) mean temperatures for Dujiangyan weather station and CRU gridded data. djy.sun (1/3) is January–March sunshine duration for Dujiangyan weather station and cru.cld (1/3) is January–March cloud cover for CRU gridded data

dieback in the mid-latitudes and the increasing global annual mean temperature appears to be in agreement with a rise in extreme freezing stress on a regional scale. Under the future warming world, it is plausible that the sharp reduction in tree growth during the second half of 20th century found in this study might continue in the future due to the elevated extreme freezing stresses in winter.

It must be pointed out that the theoretical lower Faxon fir forest border in Western Sichuan would be about 2,700 m (Liu 2002; Zheng et al. 2006). The lowest sample sites (A5 and B5, 3,000 m) in this study are about 300 m above this theoretical limit and trees may therefore not express as strong a signal with precipitation as they would if they were growing at a "true" precipitation-controlled lower forest border sites (Fritts et al. 1965; Wilson and Hopfmueller 2001). The rather limited elevation gradient (450 m) means the interpretation of the correlation analysis results in this study should, however, be approached with caution. Interestingly, at a lower Faxon fir forest border of the Wolong Natural Reserve (Western Sichuan Province, China), Li et al. (2010a) noted an anomalous reduction in growth indices at 1977-2008 period, and this recent progressive decline in growth has been ascribed to the limited amount of solar radiation available for plant growth due to the combination of decline in sunshine time and more cloud cover. These findings parallel the generally observed results of this study. However, the development of a dense tree-ring network with data coverage at lower elevations is pivotal to a more thorough understanding of environmental impacts on Faxon fir forest growth along elevational gradients in Western Sichuan.

#### Conclusions

We present an analysis of ten tree-ring sites of Faxon fir (A. faxoniana) sampled over two parallel elevation gradients (ranging from 3,000 to 3,450 m) of Balang Mountain of the Wolong Natural Reserve (Western Sichuan Province, China) in order to illustrate the climatic signals captured in tree-ring data in this region. The chronologies demonstrate high suitability for dendroclimatological analysis. Growthclimate relationships suggest that winter freezing stress (January to March), which is caused by low solar radiation and high cloud amount, is the dominant factor determining radial growth along the elevation gradients. In contrast, site chronologies respond weakly to elevation-dependent temperature and precipitation. This is inconsistent with the concept of differing environmental signals captured in treering data dependent on elevation. Several environmental changes during recent decades such as the atmospheric input of nitrogen, increased atmospheric CO<sub>2</sub> content, higher temperatures, and an extended vegetation period (Myneni et al. 1997; Rennenberg and Gessler 1999) should improve growth conditions, especially at higher altitudes in mountainous regions. Our data, however, cannot confirm a general increasing growth trend. Increased winter freezing stress in recent decades could negatively affect the cambial activity of Faxon fir forests, the most productive and abundant forest type in Western Sichuan Province, China, thereby affecting carbon storage in this region.

**Acknowledgments** This research was supported by Natural Science Foundation of China (Grant No. 41071039, 31000210) and National Science Foundation for Post-doctoral Scientists of China (Grant No. 20100470560). We greatly thank Hong-Yan Qiu and Cai-Yun Liu of the Tree-Ring Laboratory, Institute of Botany, Chinese Academy of Sciences for the assistance of ring-width measurement. We are grateful to Patricia Fisher for language correction of this manuscript, Jin-Long Zhang, Guo-Fang Liu and Yu Liu for the help of data analysis. We are also appreciative of the field assistance received from Desheng Forest Ecology Station in the Wolong Natural Reserve.

## References

- Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Tank AMGK, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Kumar KR, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res Atmos 111:D05109. doi:05110. 01029/02005JD006290
- Auclair AND, Lill JT, Revenga C (1996) The role of climate variability and global warming in the dieback of Northern Hardwoods. Water Air Soil Poll 91:163–186
- Auclair AND, Heilman WE, Brinkman B (2010) Predicting forest dieback in Maine, USA: a simple model based on soil frost and drought. Can J Forest Res 40:687–702
- Bertrand R, Lenoir J, Piedallu C, Riofrío-Dillon G, Ruffray Pd, Vidal C, Pierrat JC, Gégout JC (2011) Changes in plant community composition lag behind climate warming in lowland forests. Nature 479:517–520
- Biondi F, Waikul K (2004) DendroClim2002: a C++ program for statistical calibration of climate signals in tree-ring chronologies. Comput Geosci 30:303–311
- Böhner J, Lehmkuhl F (2005) Environmental change modelling for central and high Asia: pleistocene, present and future scenarios. Boreas 34:220–231
- Boyce RL (1995) Patterns of foliar injury to red Spruce on Whiteface Mountain, New-York, during a high-injury winter. Can J Forest Res 25:166–169
- Bräuning A (2001) Climate history of the Tibetan Plateau during the last 1000 years derived from a network of juniper chronologies. Dendrochronologia 19:127–137
- Briffa KR, Schweingruber FH, Jones PD, Osborn TJ, Shiyatov SG, Vaganov EA (1998) Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. Nature 391:678–682
- Buckley BM, Cook ER, Peterson MJ, Barbetti M (1997) A changing temperature response with elevation for *Lagarostrobos franklinii* in Tasmania, Australia. Clim Change 36:477–498
- Büntgen U, Frank DC, Kaczka RJ, Verstege A, Zwijacz-Kozica T, Esper J (2007) Growth responses to climate in a multi-species tree-ring network in the Western Carpathian Tatra Mountains, Poland and Slovakia. Tree Physiol 27:689–702

- Che HZ, Shi GY, Zhang XY, Arimoto R, Zhao JQ, Xu L, Wang B, Chen ZH (2005) Analysis of 40 years of solar radiation data from China, 1961–2000. Geophys Res Lett 32:L06803. doi: 06810.01029/02004GL022322
- Chen JY, Carlson BE, Del Genio AD (2002) Evidence for strengthening of the tropical general circulation in the 1990s. Science 295:838–841
- Choi G, Collins D, Ren GY, Trewin B, Baldi M, Fukuda Y, Afzaal M, Pianmana T, Gomboluudev P, Huong PTT, Lias N, Kwon WT, Boo KO, Cha YM, Zhou YQ (2009) Changes in means and extreme events of temperature and precipitation in the Asia-Pacific Network region, 1955–2007. Int J Climatol 29:1906–1925
- Cohen S, Liepert B, Stanhill G (2004) Global dimming comes of age. Eos Trans Am Geophys Union 85:362–363
- Colwell RK, Brehm G, Cardelus CL, Gilman AC, Longino JT (2008) Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics. Science 322:258–261
- Cook ER, Kairiukstis LA (1990) Methods of dendrochronology: applications in the environmental sciences. Kluwer, Dordrecht
- Cook ER, Krusic PJ, Jones PD (2003) Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal. Int J Climatol 23:707–732
- Crowley TJ (2000) Causes of climate change over the past 1000 years. Science 289:270–277
- D'Arrigo R (2008) On the 'divergence problem' in northern forests: A review of the tree-ring evidence and possible causes. Glob Planet Change 60:289–305
- Deslauriers A, Morin H, Urbinati C, Carrer M (2003) Daily weather response of balsam fir (*Abies balsamea* (L.) Mill.) stem radius increment from dendrometer analysis in the boreal forests of Quebec (Canada). Trees 17:477–484
- Desplanque C, Rolland C, Schweingruber FH (1999) Influence of species and abiotic factors on extreme tree ring modulation: *Picea abies* and *Abies alba* in Tarentaise and Maurienne (French Alps). Trees 13:218–227
- Dittmar C, Zech W, Elling W (2003) Growth variations of common beech (*Fagus sylvatica* L.) under different climatic and environmental conditions in Europe-a dendroecological study. Forest Ecol Manag 173:63–78
- Esper J, Frank DC, Wilson RJS, Büntgen U, Treydte K (2007) Uniform growth trends among central Asian low- and highelevation juniper tree sites. Trees 21:141–150
- Ettl GJ, Peterson DL (1995) Growth response of subalpine fir (*Abies lasiocarpa*) to climate in the Olympic Mountains, Washington, USA. Glob Change Biol 1:213–230
- Fan ZX, Bräuning A, Bao Y, Cao KF (2008) Tree ring density-based summer temperature reconstruction for the central Hengduan Mountains in southern China. Glob Planet Change 65:1–11
- Fan ZX, Bräuning A, Cao KF, Zhu SD (2009) Growth-climate responses of high-elevation conifers in the central Hengduan Mountains, southwestern China. Forest Ecol Manag 258:306–313
- Filippo AD, Biondi F, Cufar K, Luis Md, Grabner M, Maugeri M, Saba EP, Schirone B, Piovesan G (2007) Bioclimatology of beech (*Fagus sylvatica* L.) in the eastern Alps: spatial and altitudinal climatic signals identified through a tree-ring network. J Biogeogr 34:1873–1892
- Friedland AJ, Gregory RA, Karenlampi L, Johnson AH (1984) Winter damage to foliage as a factor in red spruce decline. Can J For Res 14:963–965
- Fritts HC (1976) Tree rings and climate. Academic Press, New York
- Fritts HC, Smith DG, Cardis JW, Budelsky CA (1965) Tree-ring characteristics along a vegetation gradient in northern Arizona. Ecology 46:393–401
- Graham EA, Mulkey SS, Kitajima K, Phillips NG, Wright SJ (2003) Cloud cover limits net CO<sub>2</sub> uptake and growth of a rainforest tree during tropical rainy seasons. PNAS 100:572–576

- Graumlich LJ (1993) Response of tree growth to climatic variation in the mixed conifer and deciduous forests of the upper Great Lakes region. Can J For Res 23:133–143
  - Grissino-Mayer HD (2001) Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Res 57:205–221
- Guan ZT, Chen Y, Xu RQ (1984) Study of the forest type Omei fir (*Abies fabri*). Acta Phytoecologica Sin 8:133–145 (in Chinese with English abstract)
- Hadley JL, Amundson RG, Laurence JA, Kohut RJ (1993) Red spruce bud mortality at Whiteface Mountain, New York. Can J Bot 71:827–833
- He YQ, Zhang ZL, Yao TD, Chen T, Pang HX, Zhang D (2003) Modern changes of the climate and glaciers in China's monsoonal temperature-glacier region. Acta Geogr Sin 58:550–558 (in Chinese with English abstract)
- Hoch G, Körner C (2003) The carbon charging of pines at the climatic treeline: a global comparison. Oecologia 135:10–21
- Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull 43:69–78
- Hughes MK (2001) An improved reconstruction of summer temperature at Srinagar, Kashmir since 1660 AD, based on tree-ring width and maximum latewood density of *Abies pindrow* [Royle] Spach. Palaeobotanist 50:13–19
- Hui G (2009) China's snow disaster in 2008, who is the principal player? Int J Climatol 29:2191–2196
- Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: impacts, adaptation and vulnerability. Cambridge University Press, Cambridge
- Jalkanen R, Aalto T, Kurkela T (1998) Revealing past needle density in *Pinus* spp. Scand J For Res 13:292–296
- Jolliffe IT (1986) Principal component analysis. Springer, New York
- Kaiser HF (1992) On Cliff's formula, the Kaiser–Guttman rule, and the number of factors. Percept Mot Skills 74:595–598
- Kerr RA (2007) Climate change: global warming is changing the world. Science 316:188–190
- Körner C (1999) Alpine plant life: functional plant ecology of high mountain ecosystems. Springer, Berlin
- Kullman L (1991) Cataclysmic response to recent cooling of a natural boreal pine (*Pinus sylvestris* L.) forest in northern Sweden. New Phytol 117:351–360
- LaMarche VJ (1974) Frequency-dependant relationships between tree-ring series along an ecological gradient and some dendroclimatic implications. Tree-Ring Bull 34:1–20
- Lazarus BE, Schaberg PG, DeHayes DH, Hawley GJ (2004) Severe red spruce winter injury in 2003 creates unusual ecological event in the northeastern United States. Can J For Res 34:1784–1788
- Lebourgeois F, Breda N, Ulrich E, Granier A (2005) Climate–tree-growth relationships of European beech (*Fagus sylvatica* L.) in the French Permanent Plot Network (RENECOFOR). Trees 19:385–401
- Lenoir J, Gegout JC, Marquet PA, de Ruffray P, Brisse H (2008) A significant upward shift in plant species optimum elevation during the 20th century. Science 320:1768–1771
- Li ZS, Liu GH, Fu BJ, Zhang QB, Hu CJ, Luo SZ (2010a) Evaluation of temporal stability in tree growth-climate response in Wolong National Natural Reserve, western Sichuan, China. Chin J Plant Ecol 37:1045–1057 (in Chinese with English abstract)
- Li ZS, Liu GH, Zhang QB, Hu CJ, Luo SZ, Liu XL, He F (2010b) Tree ring reconstruction of summer temperature variations over the past 159 years in Wolong National Natural Reserve, western Sichuan, China. Chin J Plant Ecol 34:628–641 (in Chinese with English abstract)
- Liang EY, Shao XM, Eckstein D, Huang L, Liu XH (2006) Topography- and species-dependent growth responses of *Sabina przewalskii* and *Picea crassifolia* to climate on the northeast Tibetan Plateau. Forest Ecol Manag 236:268–277

- Liang EY, Shao XM, Qin NS (2008) Tree-ring based summer temperature reconstruction for the source region of the Yangtze River on the Tibetan Plateau. Glob Planet Change 61:313–320
- Liang EY, Wang YF, Xu Y, Liu BM, Shao X (2010) Growth variation in *Abies georgei* var. *smithii* along altitudinal gradients in the Sygera Mountains, southeastern Tibetan Plateau. Trees 24:363–373
- Liepert B, Feichter J, Lohmann U, Roeckner E (2004) Can aerosols spin down the hydrological cycle in a moister and warmer world? Geophys Res Lett 31:L06207. doi:06210.01029/02003GL019060
- Linderholm HW, Chen DL (2005) Central Scandinavian winter precipitation variability during the past five centuries reconstructed from *Pinus sylvestris* tree rings. Boreas 34:43–52
- Liu Q (2002) Ecological research on subalpine coniferous forests in China. Sichuan University Press, Chengdu (in Chinese)
- Lund AE, Livingston WH (1999) Freezing cycles enhance winter injury in *Picea rubens*. Tree Physiol 19:65–69
- Maclean IMD, Wilson RJ (2011) Recent ecological responses to climate change support predictions of high extinction risk. PNAS 108:12337–12342
- Misson L, Rathgeber C, Guiot J (2004) Dendroecological analysis of climatic effects on *Quercus petraea* and *Pinus halepensis* radial growth using the process-based MAIDEN model. Can J Forest Res 34:888–898
- Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25:693–712
- Morales MS, Villalba R, Grau HR, Paolini L (2004) Rainfallcontrolled tree growth in high-elevation subtropical treelines. Ecology 85:3080–3089
- Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR (1997) Increased plant growth in the northern high latitudes from 1981 to 1991. Nature 386:698–702
- Neuwirth B, Schweingruber FH, Winiger M (2007) Spatial patterns of central European pointer years from 1901 to 1971. Dendrochronologia 24:79–89
- Oberhuber W (2004) Influence of climate on radial growth of *Pinus cembra* within the alpine timberline ecotone. Tree Physiol 24:291–301
- Oberhuber W, Stumbock M, Kofler W (1998) Climate tree-growth relationships of Scots pine stands (*Pinus sylvestris* L.) exposed to soil dryness. Trees 13:19–27
- Orvis KH, Grissino-Mayer HD (2002) Standardizing the reporting of abrasive papers used to surface tree-ring samples. Tree-Ring Res 58:47–50
- Osborn TJ, Briffa KR, Jones PD (1997) Adjusting variance for sample size in tree-ring chronologies and other regional mean timeseries. Dendrochronologia 15:89–99
- Peart DR, Poage NJ, Jones MB (1992) Winter injury to subalpine red spruce: influence of prior vigor and effects on subsequent growth. Can J For Res 22:888–892
- Perkins TD, Adams GT (1995) Rapid freezing induces winter injury symptomatology in red spruce foliage. Tree Physiol 15:259–266
- Peterson DW, Peterson DL (2001) Mountain hemlock growth responds to climatic variability at annual and decadal time scales. Ecology 82:3330–3345
- Qin NS, Shi XH, Shao XM, Wang QC (2008) Average maximum temperature change recorded by tree rings in west Sichuan Plateau. J Sichuan Meteorol 28:18–24 (in Chinese with English abstract)
- Rennenberg H, Gessler A (1999) Consequences of N deposition to forest ecosystems—recent results and future research needs. Water Air Soil Poll 116:47–64
- Root TL, Price JT, Hall KR, Schneider SH, Rosenzweig C, Pounds JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421:57–60

- Rossi S, Deslauriers A, Anfodillo T, Morin H, Saracino A, Motta R, Borghetti M (2006) Conifers in cold environments synchronize maximum growth rate of tree-ring formation with day length. New Phytol 170:301–310
- Rossi S, Deslauriers A, Gricar J, Seo JW, Rathgeber CBK, Anfodillo T, Morin H, Levanic T, Oven P, Jalkanen R (2008) Critical temperatures for xylogenesis in conifers of cold climates. Glob Ecol Biogeogr 17:696–707
- Sakai A, Larcher W (1987) Frost survival of plants: responses and adaptation to freezing stress. Springer, Berlin
- Schenk HJ, Jackson RB (2002) The global biogeography of roots. Ecol Monogr 72:311–328
- Schweingruber FH, Eckstein D, Serre-Bachet F, Bräker OU (1990) Identification, presentation and interpretation of event years and pointer years in dendrochronology. Dendrochronologia 8:9–38
- Shao XM, Fan JM (1999) Past climate on west Sichuan Plateau as reconstructed from ring-widths of Dragon Spruce. Quat Sci 19:81–89 (in Chinese with English abstract)
- Shen ZH, Liu ZL, Fang JY (2004) Altitudinal changes in species diversity and community structure of *Abies fabri* communities at Hailuo Valley of Mt. Gongga, Sichuan. Biodivers Sci 12:237–244 (in Chinese with English abstract)
- Sillmann J, Roeckner E (2008) Indices for extreme events in projections of anthropogenic climate change. Clim Change 86:83–104
- Stanhill G, Cohen S (2001) Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agr For Meteorol 107:255–278
- Stokes MA, Smiley TL (1968) An introduction to tree-ring dating. The University of Chicago Press, Chicago
- Taylor AH, Jang SW, Zhao LJ, Liang CP, Miao CJ, Huang JY (2006) Regeneration patterns and tree species coexistence in old-growth *Abies-Picea* forests in southwestern China. Forest Ecol Manag 223:303–317
- Villalba R, Boninsegna JA, Veblen TT, Schmelter A, Rubulis S (1997) Recent trends in tree-ring records from high elevation sites in the Andes of northern Patagonia. Clim Change 36:425–454
- Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395
- Wang ZY, Zhang Q, Chen Y, Zhao SS, Zeng HL, Zhang Y, Liu QF (2008) Characters of meteorological disasters caused by the extreme synoptic process in early 2008 over China. Adv Clim Change Res 4:63–67 (in Chinese with English abstract)
- Wigley TM, Briffa KR, Jones PD (1984) On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J Clim App Meteorol 23:201–213
- Wilmking M, D'Arrigo R, Jacoby GC, Juday GP (2005) Increased temperature sensitivity and divergent growth trends in circumpolar boreal forests. Geophys Res Lett 32:L15715. doi: 15710.11029/12005GL023331
- Wilson RJS, Hopfmueller M (2001) Dendrochronological investigations of Norway spruce along an elevational transect in the Bavarian Forest, Germany. Dendrochronologia 19:67–79
- Woodward A (1998) Relationships among environmental variables and distribution of tree species at high elevation in the Olympic Mountains. Northwest Sci 72:10–22
- Wu P, Wang LL, Shao XM (2005) Reconstruction of summer temperature from maximum latewood density of *Pinus densata* in west Sichuan. Acta Geogr Sin 60:998–1006 (in Chinese with English abstract)
- Yadav RR, Singh J (2002) Tree-ring analysis of *Taxus baccata* from the western Himalaya, India, and its dendroclimatic potential. Tree-Ring Res 58:23–29

- Yadav RR, Park WK, Bhattacharyya A (1997) Dendroclimatic reconstruction of april-may temperature fluctuations in the western himalaya of india since AD 1698. Quat Res 48:187–191
- You QL, Kang SC, Flugel WA, Sanchez-Lorenzo A, Yan YP, Huang J, Martin-Vide J (2010) From brightening to dimming in sunshine duration over the eastern and central Tibetan Plateau (1961–2005). Theor Appl Climatol 101:445–457
- Zhang WR (1983) The forest soils and its vertical distribution laws of Wolong Nature Reserve. Scientia Silvae Sinicae 19:254–268 (in Chinese with English abstract)
- Zhang QB, Hebda RJ (2004) Variation in radial growth patterns of *Pseudotsuga menziesii* on the central coast of British Columbia, Canada. Can J For Res 34:1946–1954
- Zheng SW, Li YQ, He F, Chen H, Su YM, Liu XL (2006) Comparison analysis and research on principal meteorology factors inside and outside Wolong forest ecology station. J Chengdu Univ 25:210–213 (in Chinese with English abstract)