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Tree growth divergence from winter temperature in the Gongga Mountains, southeastern Tibetan Plateau

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ABSTRACT

The reduced sensitivity of tree growth to temperature in recent decades, commonly known as the tree-ring “divergence problem”, has been observed in many places of the world, which challenges the validity of dendroclimatic reconstructions. The manifestation and specific causes of the divergence vary in different environments, yet few studies have attempted to investigate its occurrence on the Tibetan Plateau. Here we report two temperature-sensitive ring-width chronologies of *Abies georgei* Orr and *Sabina tibetica* in the Gongga Mountains, southeastern Tibetan Plateau. Significant positive correlations were detected between tree-rings and minimum temperatures, in particular in the prior winter (previous December to current March). Pronounced warming of local temperature was identified in the late twentieth century, with the minimum temperature increasing more rapidly than the mean and maximum temperatures. Concurrently, the tree-ring divergence problem was observed after 2003 at our sampling sites. A loss of sensitivity to winter temperature is coincident with a strengthening of positive (negative) response to the current (previous) growing season temperatures, indicating the complexity and possible multi-causality of the divergence at our sites.

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KEYWORDS

Tree-rings; climate-growth relationship; divergence problem; Gongga Mountains; southeastern Tibetan Plateau

Introduction

Tree-rings have been widely used as a proxy to investigate the climate-tree growth relationships and for past climate reconstructions owing to their abundant resources, annual resolution, accurate dating, and high sensitivity to climate (Fritts 1976; IPCC 2013). However, a wide range of studies have reported that the climate-growth responses of mid- and high-latitude Northern Hemisphere (NH) tree-rings are temporally unstable, with a rapidly fading relationship during the recent decades that is commonly known as the “divergence problem” (Jacoby and D’Arrigo 1995; Briffa et al. 1998; D’Arrigo et al. 2004; Buntgen et al. 2006, 2008; Bai et al. 2016; Han et al. 2019). The divergence problem is most evident for tree growth response to temperature, and such a drop in temperature sensitivity makes it hard for trees to catch up with recent warming, challenging the validity of the uniformitarianism principle (Wilson and Luckman 2003; D’Arrigo

et al. 2007; Loehle 2009; Gai et al. 2017). Although it is commonly believed that the divergence is caused by anthropogenic warming, the manifestations differ among various regions and site environments (D'Arrigo et al. 2004; Jiao et al. 2015; Ge et al. 2016). Multiple site-specific causes have been proposed to explain the mechanism of this phenomenon, including drought stress due to rapid increase in temperature (Jacoby and D'Arrigo 1995; Yu et al. 2013), the varying trend between minimum and maximum temperatures (Wilson and Luckman 2003; Korner and Paulsen 2004), weakened solar radiation due to the increase of cloud cover or air pollution (Stanhill and Cohen 2001; Li et al. 2010, 2012), and the end effect from tree-ring data processing (Esper, Cook, and Schweingruber 2002; D'Arrigo et al. 2007; McIntyre and McKittrick 2009). In light of the vast impacts of warm-induced divergence on large-scale tree growth and forest ecology, a comprehensive dendrochronological investigation is needed in order to reveal its mechanism of occurrence and the implication for global carbon cycle (Li et al. 2010; Gai et al. 2017).

The Tibetan Plateau (TP) is an essential region for global climate change studies due to its high elevation of 4000 meters above sea level (a.s.l.) on average and large extent of 2.5 million km² (Wu and Zhang 1998; Zhang, Cui, and Li 2006). Primeval coniferous forests are well preserved in the Himalayas and on the eastern TP, providing abundant resources for ecological studies of tree growth and forest dynamics (Li et al. 2008). During the past two decades, a large number of tree-ring chronologies have been developed on the southern and eastern TP, many of which have been used to reconstruct long-term changes in regional temperature, precipitation or moisture conditions (e.g. Fan, Brauning, and Cao 2008; Fang et al. 2010; Li et al. 2011; Duan and Zhang 2014; Wang et al. 2014; Shi et al. 2017; Li and Li 2017). Although most of the chronologies from high elevation upper treelines are constrained by temperature, only a few exhibited the tree-ring divergence phenomenon (Shao and Fan 1999; Zhang and Wilmking 2010; Li et al. 2012; Li and Li 2017; Shi et al. 2017). In particular, there are very limited tree-ring records from the Gongga Mountains, the highest barrier on the east margin of the TP (Chen et al. 2010; Liu et al. 2011). Among them, only a few studies revealed the growth response to temperature, but no divergence phenomenon has been observed (Duan et al. 2010a, 2010b). Therefore, the tree-ring divergence phenomenon awaits further investigation on the TP, in particular in the Gongga Mountains.

In this study, we sampled tree-rings of *Abies georgei* Orr and *Sabina tibetica* at two upper treeline sites on the southwestern slope of the Gongga Mountains and developed two ring-width chronologies extending over the past 400 years. We aim to assess whether tree growth at the two upper treeline sites is temperature constrained, and if so, whether the divergence problem exists and what are the possible causes of the divergence in the area.

Data and methods

Tree-ring data

Our study sites (WAH and WHS) are located on the southwestern slope of the Gongga Mountains, southeastern TP (Figure 1, Table 1). The region is characterized by a chain of deep valleys and rivers from north to south. Two dominant tree species in the subalpine forest zone, *A. georgei* Orr and *S. tibetica* were sampled at WAH and WHS, respectively.

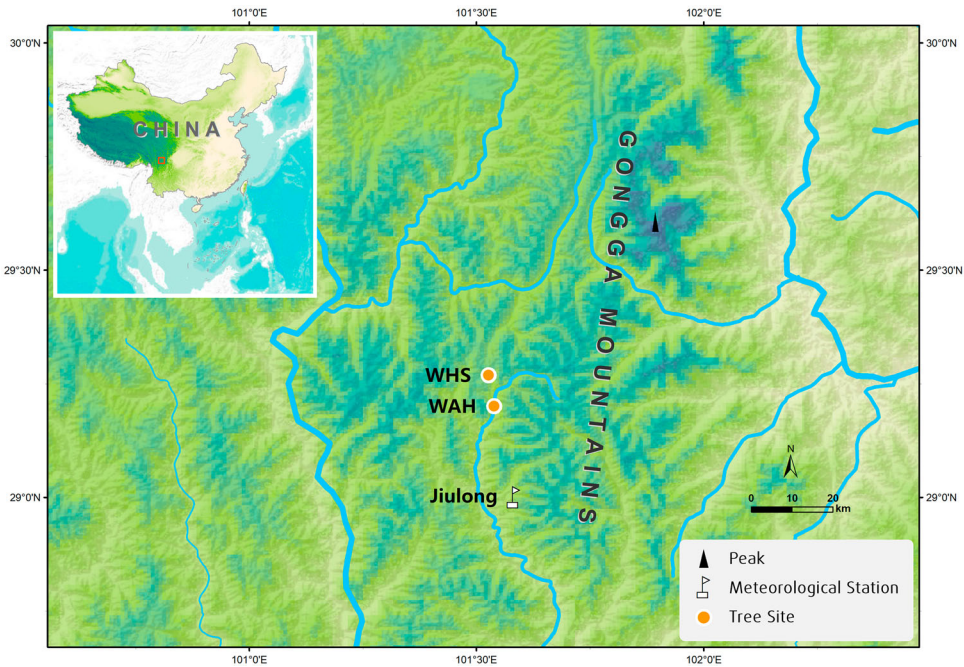


Figure 1. Map showing the locations of the two sampling sites in this study (WAH and WHS), Jiulong meteorological station, and the main peak of the Gongga Mountains.

A. georgei Orr is one of the major evergreen coniferous species distributed in a range of 3300–4500 m a.s.l. in southwest China. It is shade and humidity tolerant and is resistant to low temperature (Liu 2004; Wong et al. 2010). *S. tibetica* is a typical tree species distributed in the subalpine zone of the eastern TP, which is non-shade-tolerant and normally grows on the south-facing slopes (Zhu et al. 2011; Liu, Qin, and Kang 2013). In this study, both sampling sites are located at the upper treeline on south-facing slopes, where tree growth is generally constrained by temperature (Fritts 1976). Human activities were not evident at both sites.

Tree cores were taken from healthy and relatively isolated trees (no overlap in tree crowns) in order to obtain optimal climate signals. The samples were carefully mounted on slotted wooden boards, air-dried and polished in the lab. Tree-ring sequences were crossdated by visually comparing their growth patterns to assign the precise calendar year to each ring. Ring width of each tree core was then measured to 0.001 mm precision under a microscope with a Velmex measuring system (Velmex Inc., Bloomfield, NY, USA). Quality of visual crossdating was checked statistically with the COFECHA program (Holmes 1983).

Table 1. Site information and tree-ring chronology statistics.

| Site code | Location | Elevation (m a.s.l.) | Number (core/tree) | Time span (A.D.) | MS | AC1 | EPS | Species |
|-----------|-------------------|----------------------|--------------------|------------------|------|------|------|--------------------------|
| WAH | 29°12'N, 101°32'E | 3610 | 37/19 | 1638–2014 | 0.20 | 0.86 | 0.92 | <i>Abies georgei</i> Orr |
| WHS | 29°16'N, 101°32'E | 3970 | 58/29 | 1601–2014 | 0.20 | 0.82 | 0.94 | <i>Sabina tibetica</i> |

In order to preserve variations that reflect climate signals, non-climatic biological trends of the raw ring-width series need to be removed through the process of tree-ring standardization (Fritts 1976). Negative exponential curves or linear regression curves of any slope were fitted to detrend all series (Cook and Peters 1997). Tree-ring indices were calculated as the ratios of the raw measurements to the fitted curves. All the tree-ring indices from each site were merged to build site chronology with a biweight robust mean method, with the variance stabilized using the Rbar weighted method (Osborn, Biffa, and Jones 1997; Frank, Esper, and Cook 2007). The expressed population signal (EPS; Wigley, Briffa, and Jones 1984) with a threshold value of 0.85 was applied to determine the reliable span of the chronology.

Climate data

Monthly climate data were obtained from the Jiulong meteorological station (29°00'N, 101°30'E), which is the nearest to the sampling sites (Figure 1). The Jiulong station is approximately 20–30 km away from the sampling sites with relatively high elevation (2994 m a.s.l.). Climate data from the station are available from 1953 to 2014. Monthly mean (Tmean), maximum (Tmax), and minimum temperature (Tmin) and monthly total precipitation (Pre) data were used in this study. In addition, the self-calibrating Palmer Drought Severity Index (scPDSI, van der Schrier et al. 2013) with 0.5° grid resolution was employed as a drought metric to examine the impact of soil moisture on tree growth (Palmer 1965).

The Jiulong meteorological record for 1953–2014 indicates an annual mean temperature of 9.0°C, with monthly Tmean below 10.0°C and monthly Tmin below 0.0°C from November to March (Figure 2). July (15.3°C) and January (1.2°C) are the warmest and coldest month, respectively. The annual total precipitation is 910 mm on average, with merely 25 mm from December to March and the majority (96.0%) received from April

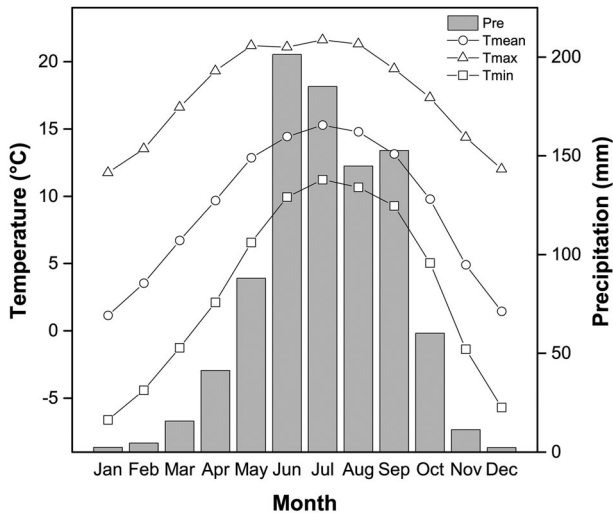


Figure 2. Monthly mean, maximum, minimum temperatures and monthly total precipitation at the Jiulong meteorological station over the period 1953–2014.

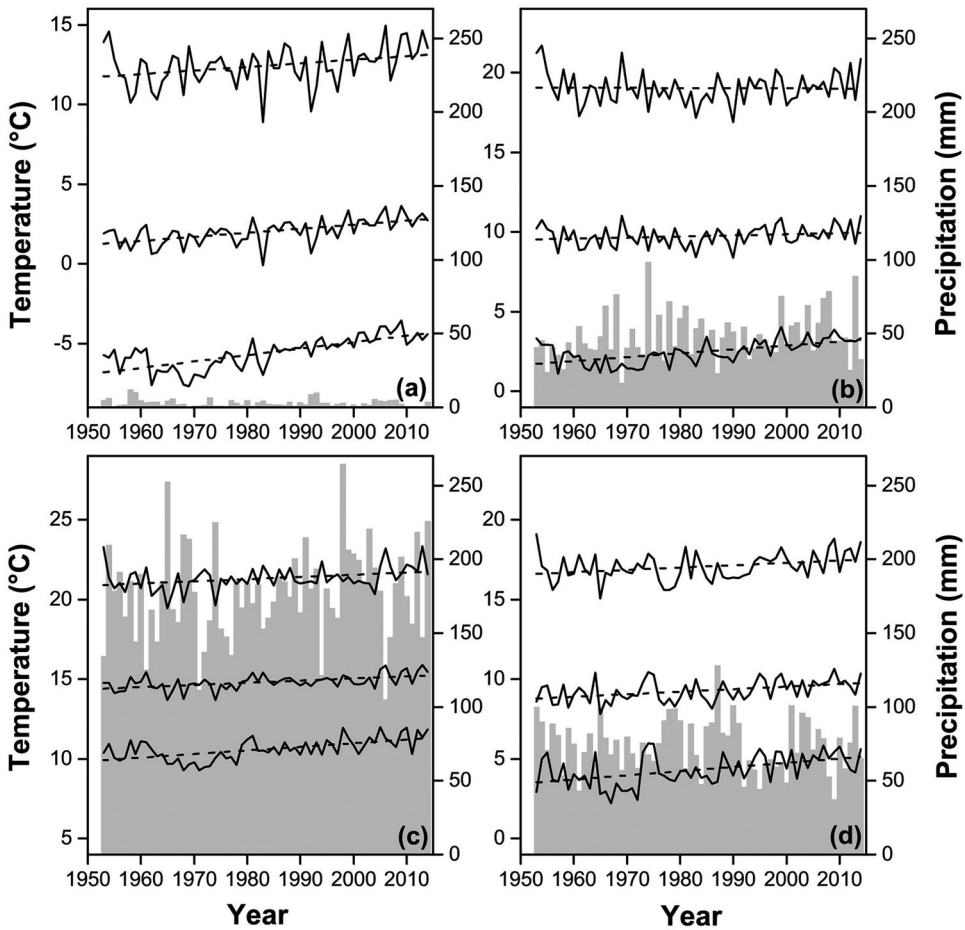


Figure 3. Seasonal maximum, mean, and minimum temperatures and seasonal precipitation at the Jiulong meteorological station over the period 1953–2014 ((a) Dec-Feb, (b) Mar-May, (c) Jun-Aug, (d) Sep-Nov).

to October. Therefore, the seasonality of temperature and precipitation reflects a typical monsoon climate in the study area (Wu et al. 2013).

The temperatures at Jiulong station show overall warming trends during 1953–2014, with T_{min} rising more rapidly than T_{mean} and T_{max} and winter temperature increase higher than all other seasons (Figure 3). Meanwhile, there is no discernible trend in precipitation for the four seasons.

Analytical methods

Pearson's correlation between tree-rings and monthly climate parameters was calculated to assess the climate-growth relationship at each site. The correlation was also calculated at seasonal scale to reveal the controlling climate factor. We further calculated a 21-year running correlation between climate and tree-ring data and their first differences to test the time-dependence of the climate-growth relationship. A 21-year low-pass filter was

applied to examine the low-frequency fluctuations in the chronologies (Visser and Moleenaar 1988; Cook and Kairiukstis 1990). We also performed standardization (z-score) to facilitate the visual assessment of the time-dependence of the climate-growth relationship.

Results

The ring-width chronologies cover 376 years (1638–2014) and 413 years (1601–2014) for WAH and WHS, respectively (Figure 4a, b). Based on the EPS cutoff value of 0.85, the reliable period of WAH and WHS is 1744–2014 and 1760–2014, respectively, with at least 11 cores (Figure 4c, d). Rbar ranges from 0.256 to 0.424 for WAH and from 0.232 to 0.424 for WHS, with the mean value equal to 0.338 at both sites (Figure 4c, d). The mean sensitivity (MS) of the two sites is 0.12 and 0.10, and the first-order autocorrelation (AC1) of the two sites is 0.71 and 0.67, respectively (Table 1). These statistics together indicate the reliability of our tree-ring chronologies.

The Pearson's correlations were calculated for the two chronologies on an 18-month window from previous May to current October, during which climate may affect ring formation of the current growing season (Figure 5). Significant positive correlations ($p < 0.05$) are found between January Tmean and the tree-ring chronologies of both sites, and there are also relatively strong positive correlations in the prior winter months of November, December, and February (Figure 5). Therefore, we further tested the tree-

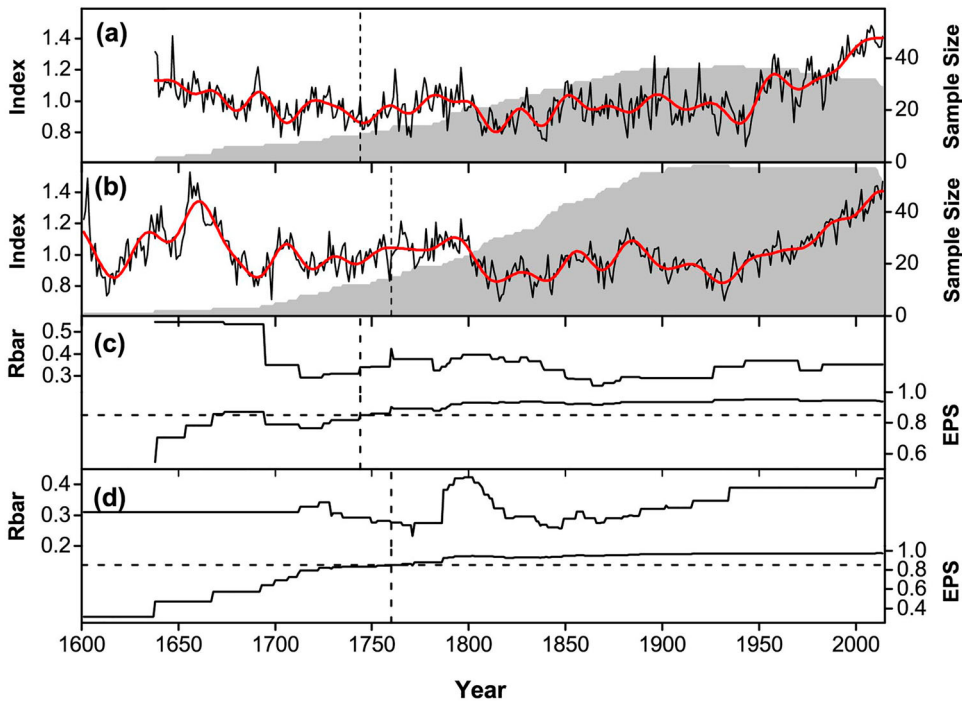


Figure 4. Tree-ring width chronologies from (a) WAH and (b) WHS (black curve), their 21-year low pass filter (red curve), and their corresponding sample size (shaded area). The running Rbar and EPS statistics of the chronologies at (c) WAH and (d) WHS. Horizontal dash lines denote the 0.85 EPS cutoff value. The vertical dash lines denote the year that the EPS value equals to 0.85.

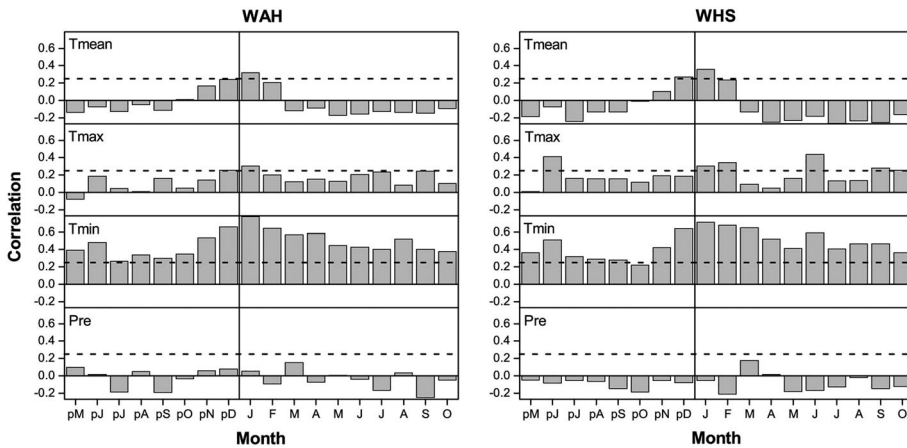


Figure 5. Correlation coefficients between climate factors (monthly Tmean, Tmin, Tmax, and Pre) and tree-ring indices of WAH (left) and WHS (right) during 1953–2014. The dash lines denote the 95% confidence level.

ring correlations with monthly Tmin and Tmax. Except for prior October for WHS, all monthly Tmin show significant positive correlations with the two chronologies, especially during the winter season from previous December to current March. In contrast, Tmax shows significant correlations with the two chronologies in a few months, including current January for both sites, current February and September and previous and current July for WHS only. The correlations between monthly precipitation and tree-rings are all nonsignificant, indicating that moisture is not a limiting factor on tree growth. The above results indicate the dominant effect of the prior winter Tmin on tree growth at both sites. Further analysis of seasonal Tmin suggests that the average Tmin from previous December to current March (pDec-cMar) has the highest correlation with the chronologies at both sites (WAH: $r = 0.798$, $p < 0.05$; WHS: $r = 0.804$, $p < 0.05$). Therefore, the pDec-cMar Tmin is the most important limiting factor of tree growth at our sampling sites.

To assess the time-dependence of the climate-growth relationship, we compared the two chronologies with the instrumental pDec-cMar Tmin after their standardization. No obvious divergence was identified through visual inspection, and the regression model explained 63% (WAH) and 64% (WHS) of the total variance during their common periods (Figure 6). However, a further investigation using 21-year running correlation revealed a time-dependent climate-growth relationship (Figure 7a). Although the response to winter Tmin at both sites remained positive in the late twentieth century, it dropped markedly after 2003, with the correlations nonsignificant for WHS and marginally significant for WAH. To eliminate the effect of the warming trend, we calculated the first-differences of the data. The results show a more pronounced loss of sensitivity after 2003 (Figure 7a), indicating that the weakening of sensitivity is distinct at high- instead of low-frequency components.

Further analysis was performed on all single- and multi-month 21-year running correlations and their first differences to reveal the time-dependence of the climate-growth relationship among all climate parameters. The results show that accompanied with the

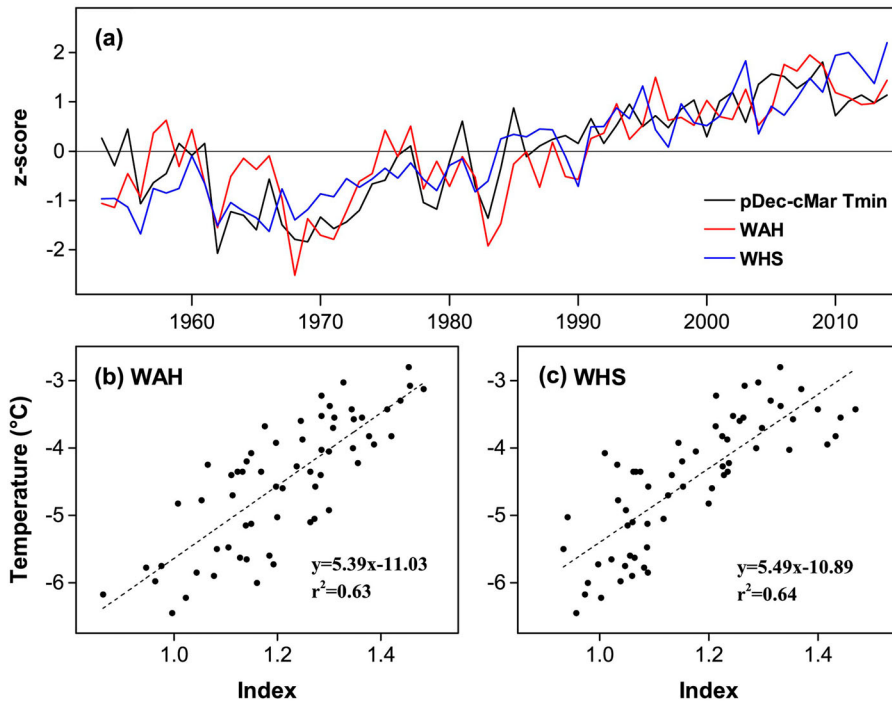


Figure 6. (a) Standardized (z-score) series and (b) & (c) scatter plot of pDec-cMar Tmin of Jiulong versus WAH and WHS chronology over the period 1953–2014.

weakening of the correlation with pDec-cMar Tmin, the response to current Jul-Oct Tmin strengthened after the 1980s and became significant ($p < 0.05$) after 2003 at both sites (Figure 7b). Besides, the previous Jul-Oct Tmin exhibits stronger negative correlations with tree growth at both sites with the first-difference running correlations of WHS becoming significantly negative, further complicating the climate-growth relationship under recent warming (Figure 7c). Meanwhile, the correlations of tree-rings with precipitation and the scPDSI exhibit no obvious tendency throughout their common period.

Discussion

Based on the above correlation analysis, we found that tree growth at both sites is mainly constrained by prior winter Tmin. An extremely low winter Tmin may form ice crystal that breaks vacuoles, dehydrates cells, and damages the root tissues and tree cambium (Pallardy and Kozłowski 2008). Frozen soil inhibits water absorption and results in winter desiccation, reducing trees' potential for future growth (Korner 1998). A colder winter season also signifies a later onset of spring and reduces the length of the growing season in the next year (Gou et al. 2007), which is supported by a significant positive correlation between winter and spring Tmin at Jiulong station ($r = 0.744$, $p < 0.05$). Several studies suggested a 5–6°C Tmin threshold for xylem activity (Gruber et al. 2010; Swidrak et al. 2011), while one recent study indicated a $0.7 \pm 0.4^\circ\text{C}$ Tmin threshold for the growth of *A. georgei* var. *smithii* on the southeastern TP (Li et al. 2017). The December, January, and February Tmin in the study region is -5.7°C , -6.6°C , and

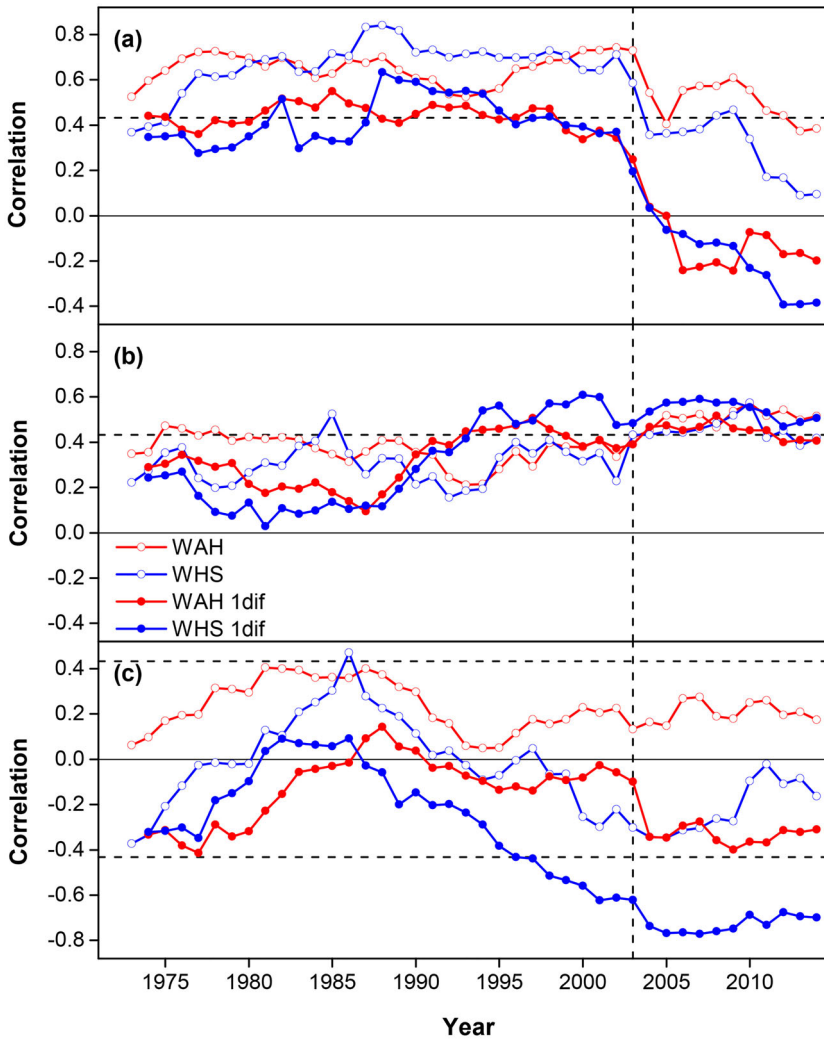


Figure 7. 21-year running correlations of WAH and WHS chronology with seasonal Tmin ((a) pDec-cMar, (b) cJul-cOct, (c) pJul-pOct), and their first differences. Each point denotes the last year of a 21-year interval. The horizontal dash lines denote 95% confidence level. The vertical dash line highlights the year of 2003.

−4.4°C respectively, while the Tmax of these months is all above 10.0°C. Therefore, a low night temperature can hinder the lignification process of the xylem during the winter months. In contrast, a warm winter temperature helps maintain the root condition for water absorption and effective wood cell growth in the coming growing season. Similar Tmin responses were reported at many high-altitude sites on the eastern and southeastern TP (Gou et al. 2007; Zhang et al. 2014; Li and Li 2017; Shi et al. 2017), showing a coherent climate-growth response in similar environments.

Our results indicate a marked sensitivity decline of year-to-year response to winter Tmin at both sites and an enhanced positive response to the growing season temperature under recent warming (Figure 7). In winter, extreme cold temperature harms tree tissues

and curbs xylem activity, which may further limit the radial growth in the coming growing season (Korner 1998; Gou et al. 2007; Pallardy and Kozłowski 2008). As temperature rises rapidly, winter coldness exhibits less control on tree growth. Meanwhile, the temperature-sensitive trees at the upper treeline are still limited by the growing season temperature. Therefore, the overall rise of temperature after 2003 has benefitted the accumulation of tree biomass during the growing season (Fritts 1976).

Our results revealed that previous Jul-Oct T_{min} had a stronger negative impact on the radial growth at both sites since 2003 (Figure 7c), suggesting a rather complex climate-growth relationship under recent warming. WHS demonstrated a stronger sensitivity to the variation of previous Jul-Oct T_{min} with its high-frequency response becoming significantly negative ($p < 0.05$), while the negative impact at WAH was still nonsignificant. The disparity between the two sites may be related to the difference in tree species and their altitude. *A. georgei* Orr at WAH is more shade and humidity tolerant than *S. tibetica* at WHS, and the latter grows at a higher elevation than the former. As a result, the *S. tibetica* chronology at WHS may exhibit extra sensitivity to temperature change (Wong et al. 2010; Zhu et al. 2011; Liu, Qin, and Kang 2013). However, due to the limited knowledge on the ecophysiology of the two species, more studies are needed in order to quantify their sensitivity to climate warming.

Tree-ring divergence at many sites has been suggested as a result of warm-induced drought stress. For instance, the white spruce at the upper treeline in Yukon Territory, Canada lost response to July-August temperature due to the dwindled soil moisture under recent warming (D'Arrigo et al. 2004). However, the running correlation results showed no obvious change in the nonsignificant relationship with precipitation and the scPDSI at our sites. Abundant moisture from the summer monsoon facilitates tree growth during the growing season, leaving temperature to be the major constraint of tree growth. This phenomenon has been found in many humid regions in eastern and southern China (Fan et al. 2010; Li et al. 2011; Shi et al. 2013; Duan and Zhang 2014; Liang, Lyu, and Wahab 2016). Nonetheless, it remains uncertain whether future drought stress would affect the study sites due to an intensified evapotranspiration, although the local meteorological records indicate no increase in precipitation despite the overall temperature rise during the past few decades.

Divergence phenomena have been reported on the eastern and southeastern TP. A loss of sensitivity to winter temperature after 1992 was found for *Picea yunnanensis* Franch in the central Hengduan Mountains of southeastern TP, and the cause was attributed to winter drought stress (Shi et al. 2017). It was reported that *Abies faxoniana* in the Wolong National Natural Reserve on the eastern TP shifted its response from early spring T_{mean} to winter T_{min}, and the increased correlation with solar radiation after 1977 was attributed to an increase in warming-induced cloud cover (Li et al. 2010). A study of *Picea purpurea* in Songpan on the eastern TP revealed a possible influence of slope aspects on the divergence phenomenon, with the divergence occurring on the northwest slope but absent on the southeast slope (Guo, Zhang, and Wang 2016). The study on *Abies faxoniana* and *Cupressus chengiana* from different altitudes in Markang on the eastern TP also revealed divergence but with a varied climate-growth relationship at each site, indicating the impact of elevation on tree growth sensitivity (Guo et al. 2015). Nonetheless, the divergence phenomenon was not reported in previous studies on the eastern slope of the Gongga Mountains (Duan et al. 2010a,

2010b), although they are only about 50 km away from our study sites and have similar environments.

Unlike the divergence phenomenon reported in other literature where the loss of sensitivity can be visually identified from raw data comparison (Briffa et al. 1998; D'Arrigo et al. 2004; Shi et al. 2017), the samples at our sites did not lose the ability in tracking the overall warming trend but failed to respond to year-to-year climate variability (Figure 6, 7a). This indicates that the divergence phenomenon at our sites mainly manifests in the high-frequency components. One possible explanation is that, although the dominant limiting factor changed from winter temperature to the growing season temperature under rapid warming, the radial growth is still constrained by temperature. As the temperature has increased rapidly in all seasons (Figure 3), trees are still able to catch the low-frequency warming signal. On the other hand, the seasonal shift in the limiting factor leads to the loss of growth sensitivity to the high-frequency signal. Therefore, the manifestation of the divergence phenomenon at our sites is distinct from those under warm-induced drought stress (Jacoby and D'Arrigo 1995; D'Arrigo et al. 2004; Guo et al. 2015). The response to the high-frequency signal is similar to the early twentieth-century divergence in northern Fennoscandia (Schneider et al. 2014), despite the latter found that the reduced high-frequency sensitivity recovered after the warming reached the same level as before. As the tree growth divergence occurred rather recently at our sites, further investigations are needed in order to reveal the generality of the phenomenon in the study area and other parts of the TP.

Conclusion

The tree-ring width chronologies of *A. georgei* Orr and *S. tibetica* were developed for the Gongga Mountains, southeastern TP. The prior winter (pDec-cMar) minimum temperature was identified as the dominant controlling factor on tree growth at both sites, and a total of 63% and 64% of the instrumental data variance was explained by the chronology at the WAH and WHS site, respectively. Both chronologies revealed a marked loss of sensitivity to the prior winter T_{min} in high-frequency components and a possible shift of the limiting factor to the growing season temperature, which may indicate that recent rapid warming has weakened the impact of winter coldness on tree growth. Nonetheless, the complexity of the response shift to other limiting factors and the site-specific difference between the two chronologies are not fully understood. The distinct manifestation of the divergence problem in high-frequency components further attests the complexity of environmental influence on tree growth, which may compromise the use of tree-rings for climate reconstructions. Therefore, more studies on different tree species and growing environments are needed in order to perceive the generality of the divergence problem and the response of forest ecosystems to climate change across regions.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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