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Article

The Radial Growth of *Picea wilsonii* Was More Restricted by Precipitation Due to Climate Warming on Mt. Guandi, China

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Abstract: Transitional climate zones (TCZ) are characterized by instability due to rapid changes in climate and biological variables, and trees growing there are particularly sensitive to climate change. Therefore, knowledge about the shifted relationships of tree growth in response to climate warming will shape regional forest conservation and management strategies. China has experienced rapid warming in recent decades. However, how tree growth in semihumid to semiarid regions, such as the Guandi Mountains, responds to more sophisticated changes in the hydrothermal combination is not yet clear. In this study, we used tree-ring width data from three sites along an elevational gradient in the Guandi Mountains to present the response of *Picea wilsonii* Mast. radial growth to increasing temperature and elevational differences in the relationship between tree growth and climate. The results indicated that the Guandi Mountains have experienced rapid warming with a clear trend toward aridity. From 1959 to 1995, the radial growth of *P. wilsonii* was mainly influenced by temperature, while it was controlled by both temperature and precipitation after rapid warming in 1996. From 1959 to 2017, this species showed a generally consistent growth–climate relationship at different elevations in the Guandi Mountains. However, the radial growth of trees at higher elevations had a higher climatic correlation than at lower elevations, and it was more conditioned by higher summer temperatures and precipitation in December of the previous year. These results suggested that *P. wilsonii* was more susceptible to drought and high temperatures due to a warming climate and that more attention should be devoted to forest management, especially the adverse consequences of summer drought on *P. wilsonii*.

Keywords: climate warming; tree growth; abrupt change in temperature; response; dendrochronology

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1. Introduction

The global climate has shifted towards warmer and drier regimes during the past 100 years [1,2], and the trend in northern China has been stronger than that of the Asian regional average [3,4]. Studies also found that semiarid areas in China expanded rapidly and mainly transformed from subhumid/humid regions [5]. As a climatically sensitive zone, the East Asian summer monsoon (EASM) margin changed from a temperate climate to a dry climate due to changes in both temperature and precipitation over the past 60 years [2]. The hydrothermal pattern is considered more complex for mountain ranges in climate transition areas such as the EASM margin due to the highly diverse topography and altered atmospheric circulation. Whether such regions become drier under the condition of rapid warming still needs further clarification.

Tree growth–climate relationships provide bases for climate reconstruction and references for forest management. Variations in growth–climate relationships driven by climate change are also the focus of recent dendrochronology research. The limitation of low temperatures and short growing seasons on tree growth at high-latitude/altitude treelines may relax with warming [6], but moisture deficiency and drought caused by climate warming can lead to declines in forest productivity and shrinkage of forest distribution [7,8]. Studies have found that forests in semiarid regions are subject to seasonal or occasional drought stress [7,9], tree growth decline, and mortality due to a drier climate [10,11], and the upward movement of treelines caused by temperature increases in semiarid areas [12,13] has been reported. In contrast, trees in subhumid regions are generally controlled by temperature [14] because moisture does not act as the limiting factor. In the semihumid to semiarid climate transition zone, trees are commonly under the control of both temperature and precipitation [15]. Therefore, it is still unclear whether the factors controlling the growth–climate relationship shift from temperature control to precipitation control as a result of climate warming in semihumid to semiarid climate transition zones.

A general phenomenon found in tree physiological studies is that cool locations/high-altitude tree growth is primarily driven by temperatures, while warm locations/low altitudes are primarily driven by precipitation [12,16–19]. Different patterns of spruce growth have been reported in response to recent warming at various altitudes in mountains of semihumid and semiarid regions in China. *Picea jezoensis* var. *microsperma* (Lindl.) W.C. Cheng & L.K. Fu growth was enhanced by warming at high altitudes but reduced at low altitudes in two mountains of Northeast China [20]; in contrast, there was a significant increase in *Picea jezoensis* var. *komarovii* (V.N. Vassil.) W.C. Cheng & L.K. Fu radial growth at low altitudes and a significant decrease at high altitudes due to warming on Mt. Changbai [21]; there were also more diverse responses of *Picea meyeri* Rehd. et Wils. to elevated temperatures at different altitudes on Mt. Luya [22]. Spruce forests at low altitudes tend to bear more drought stress and, thus, experience harsher climate stress than those at high elevations in semiarid regions [23], as suggested by reports of reduced tree growth in low-altitude areas because of rapid warming [9,17]. The response of tree growth to climate change is extremely complex, and the climatic information in tree rings is highly regional due to the comprehensive effects of tree physiology, climate variations, and topographic conditions [24–26].

Guandi Mountain is located at the edge of the EASM, which is at the transitional climate zone (TCZ) of semihumid and semiarid areas in Northern China. The region is characterized by its instability, which is related to the strong gradients of climate and biological variables [27]. The timing of rapid warming and the degree of variation in temperature and precipitation are not clear. *Picea wilsonii* is an endemic species and a widely distributed spruce species of the montane coniferous forest of China [28], and old-age trees with long-term ring recorders can provide valuable information for dendrochronology studies. Considering the Guandi Mountain to be an ideal area to study the relationship dynamics between tree growth and climate change in the TCZ, we collected core samples of *P. wilsonii* along an altitude gradient and attempted to answer the following questions: (1) What is the degree of climate warming in the past 60 years on Mt. Guandi, and were there abrupt changes in temperature and precipitation? (2) How did the tree growth–climate relationships change? Did the dominant climatic factors that control the radial growth of *P. wilsonii* shift with warming? (3) Were the growth–climate relationships consistent on the altitudinal gradient, and were there any altitudinal differences in the response of tree radial growth to warming?

2. Materials and Methods

2.1. Study Area

Mt. Guandi is located in the middle part of the Lvliang Mountains (37.33°~38.33° N, 110.3°~111.3° E), Shanxi Province, over the margin of the EASM [2,29], and at the alternating position of being semihumid and semiarid in the TCZ of North China. The region's annual average temperature is 3–4 °C, the January average temperature is 10.6 °C, and the average temperature is 16.1 °C in July. The frost-free period is approximately 100 days.

The mean annual precipitation is 830 mm, and July, August, and September account for 60% of the annual precipitation (Figure 1). The horizontal zonal vegetation of Guandi Mountain is a deciduous broad-leaved forest, with a complete vertical vegetation transect sequence from low to high as follows: deciduous broad-leaved forest (800–1600 m), coniferous and broad-leaved mixed forest (1600–1750 m), cold temperate coniferous forest (1750–2600 m), and subalpine shrub meadow (2600–2831 m). Natural and secondary forests comprise a large part of the study area, and the dominant species of cold-temperature coniferous forest are *Picea wilsonii*, *P. meyeri*, *Larix gmelinii* var. *principis-rupprechtii* (Mayr) Pilg., etc. According to the FAO soil classification system [30], the soil types of this region are Luvisols, Cambisols, and Phaeozems.

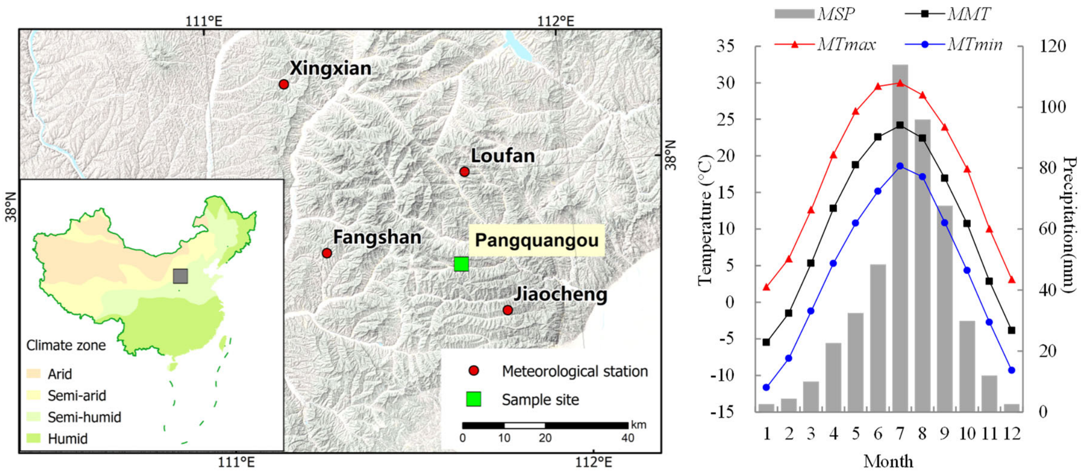

Figure 1. Site map and monthly mean temperature and monthly mean precipitation according to the records of meteorological stations in Jiaocheng County (1959–2017). MMT, Month mean temperature; MSP, Monthly sum of precipitation; MTmin, Monthly minimum temperature; MTmax, Monthly maximum temperature.

2.2. Tree-Ring Data Sampling

The sampling sites were situated in Pangquangou, the hinterland of Guandi Mountain. Within the altitude range of 1900–2300 m that was out of human disturbance, three sampling sites with altitudes of 2020 m (L-site), 2090 m (M-site), and 2220 m (U-site) were arranged in the forest. Well-growing sample trees were selected at each sampling site, and two tree cores were drilled at the diameter at breast height (DBH) position in each tree along two perpendicular cardinal directions (north–south, and east–west). At least 25 trees and 50 tree cores were collected at each sampling point. The collected tree cores were placed in a fine paper tube, marked, and sealed.

2.3. Chronology Development

All tree-ring samples were dried and polished for cross-dating. The ring width of the tree cores was measured using a LinTab5 system (precision of 0.001 mm; Rinntech, Heidelberg, Germany), and the time series were cross-dated using COFECHA [31] to eliminate the core samples with difficulty calibrating or poor correlation with the main sequence. The modified negative exponential curve [32] was used to remove nonclimatic growth effects, such as age-related trends or other long-term trends [33]. The standard chronologies of *P. wilsonii* were synthesized by using the double-weighted average method, and then the residual chronologies were produced by removing the autocorrelation effect in the standard chronologies (Figure S1) [34]. Residual chronologies were recommended for detecting the climatic influence on tree growth because they had better responses to high-frequency signals [35–37]. The quality of the chronologies was assessed, including the expressed population signal (EPS) [38,39], mean sensitivity (MS) [40], first order autocorrelation (AR1), and pairwise correlation between all cross-sections using *dplR* packages [34] in R version 3.6.3 [41].

2.4. Climate Data

A valid method was recommended for the growth–climate analysis in the regions located at the boundaries of the climate zones, i.e., taking temperature from the closest station but precipitation from the closest station within the same precipitation zone [42]. Considering that the spatial distance between the sample site and the nearby climate stations, and geographic direction could influence the correlation, the inverse distance weighted (IDW) method was used when calculating the average climate to reduce the correlation bias in growth–climate relationship analysis [15]. There were four climate stations around the sample site, including Fangshan, Jiaocheng, Loufan, and Xingxian. Jiaocheng and Xingxian have not been relocated. Climate data from the two stations were used for analysis, including monthly precipitation, monthly mean temperature, monthly maximum temperature, and monthly minimum temperature (1959–2017), which were downloaded from the China Meteorological Data Sharing Service Platform (http://data.cma.cn, accessed on 8 August 2021).

2.5. Data Analysis

Since the structure change (strucchange) method is more stable than other methods in terms of looking for potential change points [43,44], it was used for change-point detection of the annual and monthly temperature and precipitation of the meteorological station from 1959 to 2017 in the study area, and the optimal breakpoints were given according to the minimum residual sum of squares (RSS) and Bayesian Information Criterions (BIC). The Pearson correlation coefficient between the residual chronology and monthly climate temperature and precipitation was calculated [33] before and after the temperature breakpoints, to confirm the variation in the relationship between radial growth of spruce and climate factors before and after rapid temperature increase. Considering the lag influence of the previous year's climate on the growth in current year, the climate factors from previous June to current September (a 16-month window) were selected for the correlation analysis [45]. We employed a moving correlation function approach [46] to obtain interannual dynamics of radial growth response to rapid warming by calculating the Pearson correlations between the chronologies and monthly climate variables over a 30-year window from 1960 to 2017 and testing for significance using the 95% percentile range method [47]. All statistical analyses were performed using the *strucchange* [48] and *treeclim* [49] packages in R version 3.6.3 [41].

3. Results

3.1. Climate Variations in the Study Area

Strucchange analysis (Figure 2) showed that there was a sudden rise in the annual mean temperature in 1996 (RSS = 10.815, BIC = 83.647), which rose from 10.0 °C (before 1996) to 11.5 °C (after 1996) with a 1.5 °C increase. Concurrently, the annual precipitation decreased from a mean value of 457.6 mm to 439.8 mm. A significant decrease in precipitation was observed from 1997 to 2008. The monthly climate analysis results (Table S1) showed that the monthly mean temperature (MMT) increased by approximately 1.47 °C after 1996 in the winter and spring, which was approximately twice as high as that in the summer and autumn. The monthly sum of precipitation (MSP) mainly decreased in summer (1.19–15.03 mm) and spring (2.62–6.59 mm), with little change in autumn and winter.

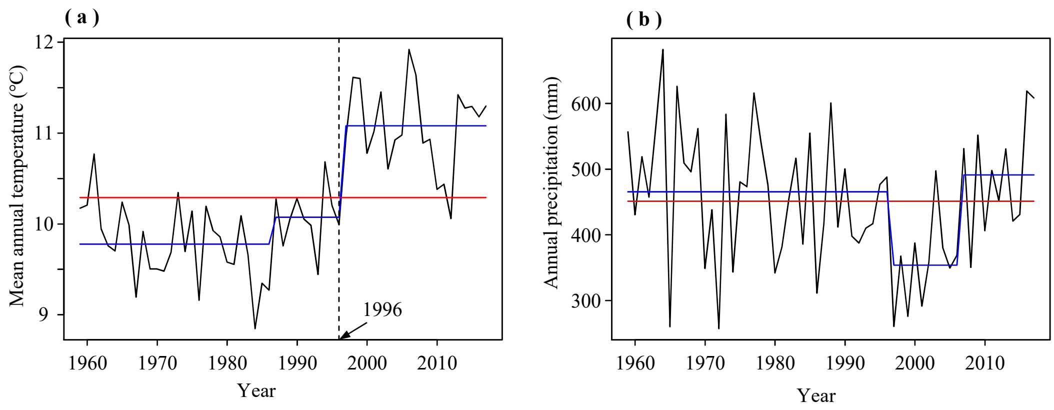

Figure 2. Annual mean temperature and annual precipitation during 1959–2017 around Mt. Guandi, Central China. (**a**) Mean annual temperature; (**b**) Annual sum of precipitation. The black dashed line marks the breakpoints with significant change. The red line indicates the mean value of the whole period, and the blue line shows the fitted levels by the identified breakpoints.

3.2. Chronologies Statistics of Picea wilsonii

The mean sensitivity (MS) and signal to noise ratio (SNR) reflect the change in tree-ring width between adjacent tree rings, mainly representing short-term or high-frequency climate change. As the chronology statistics for established residual chronologies of *P. wilsonii* at three elevations (Table 1) showed, the MS of the three chronologies at different elevations were approximately 0.173–0.188, with an SNR of 29.156–34.169, indicating that the radial growth of spruce was under the control of climate factors. The MS value of *Picea* spp. tends to decrease with increasing humidity: it was reported to be only approximately 0.17 of *P. meyeri* at higher elevations on Mt. Luya in subhumid climates [22]. The mean inter-series correlation coefficient (Rbar) and express population signal (EPS) are statistical parameters reflecting the synchronicity of each sample sequence in the chronology. A higher value of Rbar and EPS means that more restrictive growth was under the control of climate factors, with more climate information contained in the chronology [50]. It was pointed out that *Picea* spp. usually display lower Rbar values than other tree species, which reduces the chance of attaining high correlation coefficients [51]. However, the Rbar of these chronologies was 0.426–0.564, which all reached a high level. In addition, EPS (0.967–0.972) was also above the critical value (0.85), which indicated that the chronologies had adequate signal strength during their common period [39]. The first order autocorrelation (AR1) reflects the degree of influence of climate conditions in the previous year on the growth of ring width in the current year. All the AR1 values were below zero, which indicated that the effects of autocorrelations were eliminated in the residual chronologies. The effective chronology signal (Reff) was 0.543–0.564. Therefore all parameters indicate that there was sufficient signal strength in the chronologies and could be applied to address the growth–climate relationship in this region.

Table 1. Chronology statistics for residual chronologies of *Picea wilsonii* in Mt. Guandi, Central China.

Sample Information					Time Span SSS > 0.85	Eigenvalue of Residual Chronology				Common Interval Analysis (1949–2017)			
Site	Altitude (m)	Slope	Trees	Cores		MS	SD	MC	AR1	EPS	SNR	Rbar	Reff
U-site	2220	5°	27	54	1923–2017	0.188	0.158	1.003	−0.111	0.972	34.169	0.564	0.564
M-site	2090	15–30°	25	50	1906–2017	0.176	0.159	0.984	−0.077	0.967	29.156	0.440	0.543
L-site	2020	15–30°	27	54	1917–2017	0.173	0.150	0.996	−0.127	0.969	30.899	0.426	0.549

SSS, Sub-sample signal strength; MS, Mean sensitivity; SD, Standard deviation; MC, Mean indices; AR1, First order autocorrelation; EPS, expressed population signal; SNR, Signal to noise ratio; Rbar, Mean inter-series correlation coefficient; Reff, Effective chronology signal.

3.3. Tree Ring—Climate Relationship Changes with Increasing Temperature

3.3.1. Years 1959–1995 versus 1996–2017

Since there were significant differences in temperature conditions before and after 1996, the effects of temperature and precipitation on the growth of *P. wilsonii* were evaluated separately in two periods (1959–1995 and 1996–2017). All tree-ring widths at three altitudes showed consistent relationships that responded to climatic factors, and the tree–climate relationship was significantly enhanced (Figure 3) after 1996.

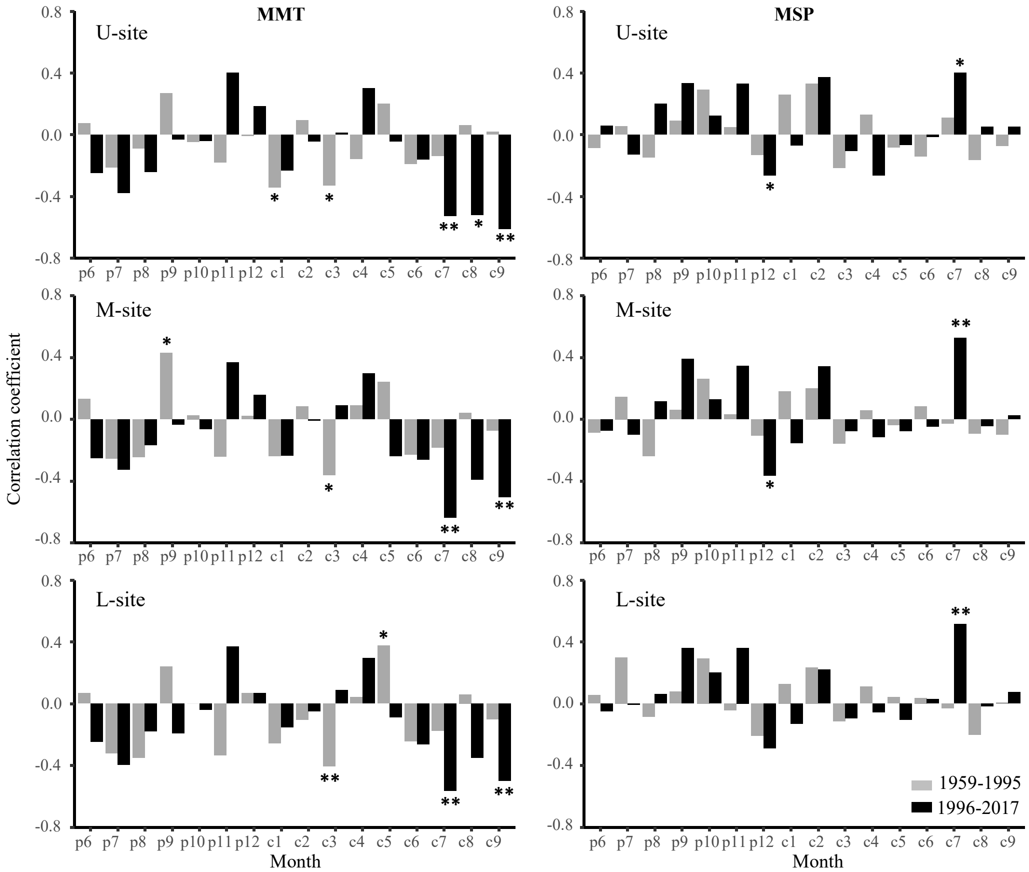

Figure 3. Correlation coefficients between the growth index and monthly climate for the previous June to current September (1959−1995 and 1996−2017). Star marks significant correlation (*, $p < 0.05$; **, $p < 0.01$). Three sample sites were L-site at 2020 m, M-site at 2090 m, and U-site at 2220 m. The letter p before months indicates the months of previous year, and letter c indicates the months of current year. MMT, Monthly mean temperature; MSP, Monthly sum of precipitation.

Before 1996, temperature had a more significant impact on radial growth than precipitation. Negative correlations between ring width and monthly mean temperature (MMT) from the current March at all three altitudes were found at a significant level ($p < 0.05$). Tree-ring widths at the Lower-site were positively correlated with MMT of the current May ($p < 0.05$), those at the Middle-site were positively correlated with MMT of the previous September ($p < 0.05$), and those at the Upper-site were negatively associated with MMT of the current January ($p < 0.05$). After 1996, the correlation coefficients between radial growth and MMTs in later summer and early autumn intensified overall. Negative relationships between ring widths and the MMTs of the current July and September changed from nonsignificant to a significance level of 0.01 at all three sites. Similar to the MMT of the current August, a significant negative correlation was only exhibited at the Upper-site ($p < 0.05$).

No significant correlations were detected between ring widths and the monthly sum of precipitation (MSP) before 1996; nevertheless, it strengthened obviously after the temperature rose in 1996. The nonsignificant correlations of radial growth with the MSPs of the current July before 1996 changed to significant positive correlations at all three sites ($p < 0.05$) later, and negative correlations between the ring widths and MSPs of December also reached significant levels ($p < 0.05$) at both the Middle- and Upper-site.

3.3.2. Moving Correlations between Radial Growth and Climate

The influence of climatic factors on the radial growth of Wilson spruce showed overall temporal stability, as the result of the 30-year moving window correlation analysis (Figure 4) suggested. The MMTs in the later growing season (June to September) had a significant limiting effect on the growth of trees at all three sites. The MMTs of the previous July and August, and the current July and September were negatively related to the radial growth, and these relationships gradually became significant. Additionally, significant negative correlations between MMTs of the current March and tree-ring width gradually weakened.

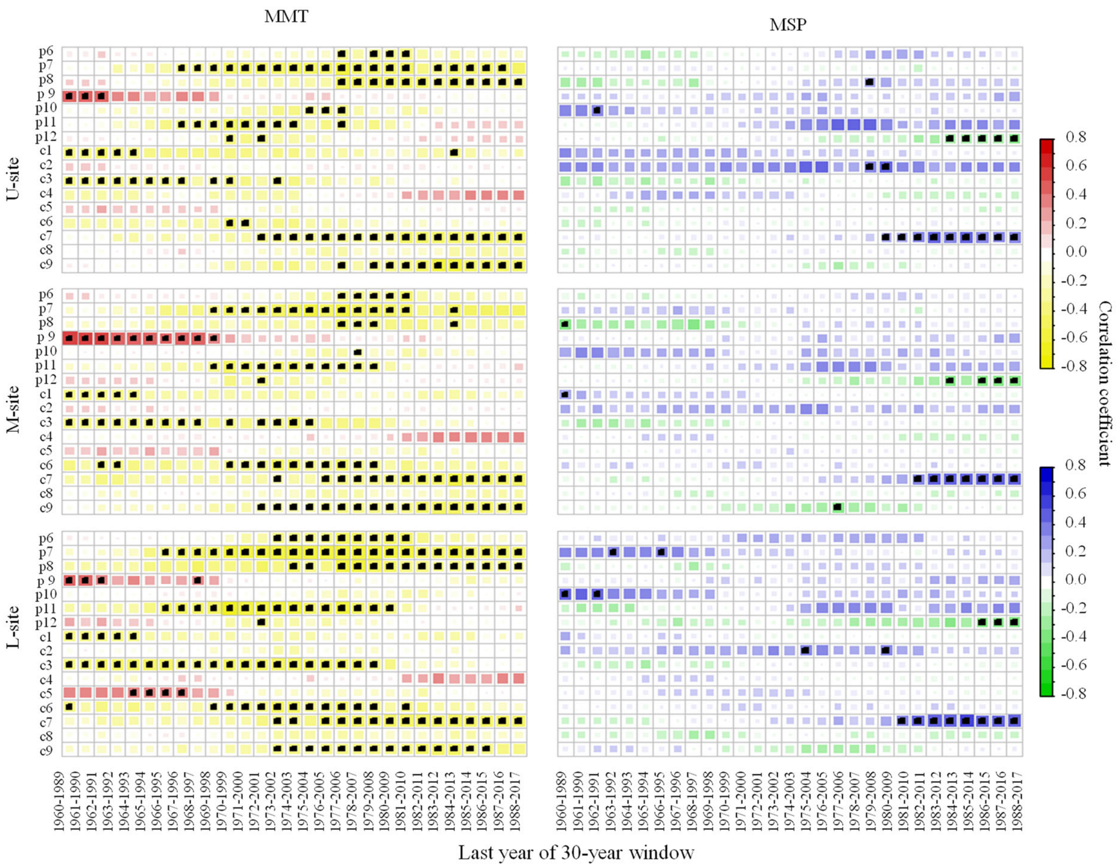

Figure 4. Temporal stability of the correlation between monthly temperature and precipitation and *Picea wilsonii* growth response (30-year period). Darker colour and larger box indicate higher R values ($p < 0.05$). Three sample sites were L-site at 2020 m, M-site at 2090 m, and U-site at 2220 m. The letter p before months indicates the months of previous year, and letter c indicates the months of current year. MMT, Monthly mean air temperature; MSP, Monthly sum of precipitation.

The correlation of radial growth with MMT of the previous September gradually transformed from positive to negative. The significantly negative correlations ($p < 0.05$) with MMT of the previous November in the middle term turned positive in the end. Additionally, the positive correlation between ring widths and MMT in May weakened gradually, replaced by the positive correlation strengthening with the MMT of April.

Most correlations between radial growth and MSPs, particularly those of the previous year, remained positive. The positive correlation between ring widths and the current July MSP reached a significance level of 0.05 in the late phase. Concurrently, negative associations with MSPs in December also gradually became significant.

4. Discussion

The results of climate analysis for the region around Guandi (1959 to 2017) showed that the tipping point of temperature rise in 1996 was synchronized with the nearby Mt. Luya, which is also located in the semihumid region [52], but later than that of East Qilian (the 1980s) in the semiarid region [53]. As the annual mean temperature increased significantly, however, annual precipitation decreased for the same period (Table S1), which suggested a climatic change in the region from semihumid to semiarid. The chronologies of *P. wilsonii* show that the majority of the climate–growth relationships at the three elevations showed similar responses to climate warming. Before 1996, there were obvious temperature signals but no precipitation signals in the chronologies; in contrast, temperature signals remained while precipitation signals were significantly enhanced after 1996 (Figure 3). This result suggests that temperature control was replaced by moisture control for the climate–growth relationship [16,54] on Mt. Guandi, which agrees with results in other TCZ regions of North China, such as Mt. Changbai in the semihumid zone [21], and Mt. Helan in the semiarid zone [11].

Previous studies have pointed out that the correlations between ring parameters of *P. wilsonii* and temperatures are complex, varying during the growing season and across biogeographic zones [51]. However, it has usually been found that in summer, inverse relationships between temperature and spruce growth [21,55–59] are also exhibited on Mt. Guandi after 1996 (Figure 3). The moving correlation analysis results showed that strong and persistent negative correlations of the growth–temperature in the previous year strengthened in the mid–late period due to warming (Figure 4). Studies have shown that high temperatures in summer inhibit or damage the photosynthetic apparatus in *P. wilsonii* leaves, resulting in heat-induced physiological drought stress even though water was provided sufficiently; additionally, respiration was enhanced but carbohydrate accumulation was reduced [25,51,60]. Since earlywood formation strongly relies on photosynthates from the previous year and secondary growth may even mobilize carbon reserves that have been stored for several years if necessary [61–63], adverse effects of elevated temperature on spruce growth may occur not only in the current season but also in the subsequent years due to the lagged resource use strategy.

The growing season for *P. wilsonii* generally starts in April [26,64]. The onset of wood formation in spring is controlled by the interaction of the chilling and forcing temperature [65,66]. However, it has been proven that the heat requirement is negatively correlated with chilling, and winter temperature increases will lead to chilling shortening and require more spring temperature accumulation to trigger wood growth [67]. Our results showed that more temperature forcing was required for *P. wilsonii* in April due to the reduction in chilling in winter as the temperature rose [66,67], the significantly negative correlation of growth–temperature in March before 1996 disappeared, and the positive correlations in May moved up to April and increased gradually after 1996 (Figures 3 and 4). This result indicates that the earlier start of the tree growing season owing to the rapid increase in temperature in April satisfied the demand of trees to trigger wood growth, which was consistent with the finding that spring phenology had advanced in China [68].

The radial growth of the *P. wilsonii* annual ring had no obvious relationship with precipitation before 1996 but a significant positive correlation with precipitation in July later. This change indicated that summer droughts began to affect tree-ring growth on Mt. Guandi. After 1996, precipitation in spring and summer decreased significantly in the study area, while there were no significant growth–precipitation relationships in May and June, which suggested that water deficit did not appear in early summer. In July, there was a large amount of precipitation, but the majority was showery, which resulted in soil respiration being inhibited due to soil moisture rapidly increasing [69], and reducing the utilization efficiency of trees for precipitation [26]. However, since most wood cells had formed and matured during this period, the spruce diameter expanded only moderately, although adequate rainfall was provided in August and September [51,60]. In addition, there were positive correlations between ring widths and precipitation in autumn of the previous season, which indicated that soil moisture replenished by autumn precipitation, especially deep precipitation, helped earlywood formation in the next year [70,71]. We noted that winter precipitation after warming did not benefit spruce growth because warmer winter conditions led to more precipitation as rain than as snow [72], earlier melting of snow-pack [73], and more frequent thaw–freeze cycles [74], which caused damage to fine roots and led to physiological drought in trees [75]. Snow cover also helped soil temperature remain at approximately 0 °C, enhanced soil respiration, and accelerated nutrient decomposition [26,76,77]. Additionally, it was pointed out that higher temperatures in winter increased the loss of spruce needles under better nutrient conditions [78], which would lead to the decline in forest productivity in the following seasons [79].

The climate–growth relationship for *P. wilsonii* in Mt. Guandi changed significantly before and after rapid warming. Before 1996, there were only temperature signals but without precipitation signals in the chronologies at three altitudes. This disagreed with the principle that describes how tree growth is more sensitive to temperature in upper treeline environments, because stronger temperature–growth relationships appeared at middle and low elevations than higher elevations, the same as mountains located in semihumid climate regions [80]. This result accounted for the growth of *P. wilsonii* at low altitude being subjected more to growth inhibition induced by high temperature [25,26]. After the temperature's rapid increase in 1996, both temperature and precipitation signals were enhanced significantly in the chronologies, with stronger correlations found at high altitudes (Figure 3). The growth of *P. wilsonii* at all elevations in Mt. Guandi was deeply influenced by summer droughts after 1996, especially at lower elevations (L-site $r = 0.515$, $p < 0.01$; M-site $r = 0.527$, $p < 0.01$; U-site $r = 0.401$, $p < 0.05$). However, spruces at middle and high elevations suffer from physiological drought caused by elevated temperatures in winter, even with precipitation compensation [81]. The TCZ boundaries and surrounding regions in future are more prone to drastic dry–wet variability [82], and with an increase in the frequency and intensity of drought in the context of global warming [83], it is detrimental for *P. wilsonii*, which is more susceptible to drought and high temperatures [25,54] in the Guandi Mountains. Since the chronologies of trees at higher altitudes had higher standard deviations, mean sensitivities, mean correlations between all series, and signal to noise ratios than those at lower altitudes [84], this indicates that high-altitude trees are more sensitive to drought with weaker resistance to drought stress, and have stronger resilience than trees at lower altitudes [85]. In contrast, trees at lower altitudes showed a decreased growth recovery and resilience to extreme drought after they experienced frequent droughts [86], which resulted in an increase in potential tree mortality [11]. Thus, it is necessary to pay more attention to the management of the trees at lower altitudes during periods of extreme drought but to focus on trees at higher altitudes when less severe droughts occur.

5. Conclusions

Based on tree-ring width data of *Picea wilsonii* collected from three elevation sites in Guandi Mountain, the relationships between radial growth and climate were analysed to determine how spruces in such a semihumid to semiarid transitional zone of China responded to rapid warming after 1996. The main conclusions can be summarized as follows: The study area exhibited a climatic aridification trend with annual precipitation decreases in recent decades. Before 1996, the radial growth of *P. wilsonii* responded mainly to temperature not precipitation. However, after 1996, it presented negative correlations with summer temperature, combined with positive correlations with precipitation in the current July, which indicated the formation of a moisture-stressed growth pattern in a drier climate for the spruce. Due to the strategy of lagged resource uses for *P. wilsonii*, the adverse influence of summer drought on wood formation occurred not only in the current season but also in the following years. Wilson spruces at high altitudes responded significantly to both summer drying and precipitation in winter after the temperature increase. In contrast, those at low altitudes responded more to summer drought. The shrinkage in biomass productivity and carbon sequestration for *P. wilsonii* in the whole forest ecosystems of the region is a prospect. Therefore, regional forest management should pay more attention to the adverse effects of summer droughts on conifer forests, especially those for *P. wilsonii*. For natural forests, changing the canopy density can partially alleviate the decline in tree growth due to drought. Meanwhile, spruce species that are less sensitive to drought could be selected for afforestation in the area.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/f12111602/s1, Figure S1: Standard chronologies (STD) and residual chronologies (RES) of *Picea wilsonii* (1950–2017) at the three sites in Guandi Mountain. Table S1: Variations of monthly temperature and precipitation around Guandi Mountain before and after 1996.

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Conflicts of Interest: The authors declare no conflict of interest.

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