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The Radial Growth Responses Differences of High-Elevation *Larix sibirica* to Climate Change in the Altay Mountains of China and Russia

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Abstract

Climate change has a profound impact on the spatio-temporal patterns and successional dynamics of forest ecosystems, particularly at forest edges. The Altay Mountains are located at the junction of China, Russia, Kazakhstan and Mongolia, and the southern edge of the boreal forest in interior Eurasia. It is highly necessary to compare the differences in the responses of forest ecosystems in large transnational mountain ranges to climate change under the background of climate change. This study analyzed 558 tree cores collected from 20 sample sites dominated by Siberian larch (*Larix sibirica* Ledeb.) in the high-elevation of Altay Mountains. Using tree-ring width data and meteorological observations from Altay Mountains both in China and Russia, we investigated how climate influences the radial growth of *L. sibirica* across these regions. The results indicate that temperature is the primary factor driving radial growth, with early summer temperatures acting as the main growth-limiting factor on both China and Russia. Notably, the radial growth-climate response is stronger in Russia than China. Despite ongoing climate change, the dominant climatic drivers of radial growth in the Altay Mountains have remained stable, with temperature continuing to exert a significant and consistent influence on *L. sibirica* growth in the high-elevation of Altay Mountains. This study enhances our understanding of the climate change impacts on boreal forest ecosystems and highlights potential risks to forest health in the Altay Mountains.

Keywords: tree rings; Siberian larch (*Larix sibirica* Ledeb.); Altay Mountains; climate change

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1. Introduction

Forest ecosystems are the largest terrestrial carbon sink and play a vital role in mitigating climate change. The boreal forest is the second largest biome in the world containing 33% of the Earth's forest cover [1] and 32% of the world's forest carbon storage [2,3]. The most widely distributed zonal forest in the middle latitudes, boreal forests are increasingly vulnerable to climate change and extreme climate events, which threaten their stability and lead to forest decline in certain regions [4]. The most affected areas include alpine zones and forests situated at the geographic and climatic margins of these ecosystems [5]. The

Altay Mountains are located on the southern edge of the boreal forest. Siberian larch (*Larix sibirica* Ledeb.) is one of the most widely distributed tree species in the Altay Mountains. This species, known for its shallow root system, drought-tolerance, and shade intolerance, typically grows at elevations between 1000 and 3000 m [6]. It is particularly well-suited for dendroclimatology and dendroecology research due to its formation of distinct annual rings, high sensitivity to climate changes, and ability to reach advanced ages. Although numerous dendroclimatology studies have been conducted in the Altay Mountains, many of those focus on specific countries or smaller sub-regions [6–11]. Other research has explored various tree-ring parameters, including tree-ring density [12], blue intensity [13] and stable carbon and oxygen isotopes in order to reconstructed the climate change in the region over the past thousand years [14–18].

The Altay Mountains span four countries (China, Russian, Mongolia, and Kazakhstan), with significant climatic variation between regions. For example, the northern Altay Mountains has experienced a Holocene drying trend, while the southern Altay shows a wetting trend [19–21]. There had been studies to reconstructed temperature and precipitation patterns in the southern Altay, revealing alternating wet and dry periods during the Little Ice Age (1580–1874) followed by more stable conditions until the onset of a wetting trend in the late 20th-century [22]. Meteorological observations over the past 50 years show a slight decrease in precipitation in the northern Altay (−1.41 mm/decade) and a significant increase in the southern Altay (8.89 mm/decade) [23].

These climatic differences may lead to variability or instability in the radial growth response of *L. sibirica* to climate. However, few studies have examined the Altay Mountains as a whole, and the differences in radial growth of *L. sibirica* responses in the northern (Russian Altay) and southern regions (Chinese Altay) remain unclear in the high-elevation of Altay Mountains. We hypothesize that *L. sibirica* responds differently to climate and climate change in the southern versus northern regions. Using a comprehensive dataset of tree-ring samples, this study analyses the relationship between *L. sibirica* radial growth and climate across both regions, identifies the main limiting factors, and explores potential drivers of the observed growth-climate responses. The research aims to deepen our understanding of how climate change impacts mountain forest ecosystems and provide a scientific basis for their assessment and conservation.

2. Data and Methods

2.1. Study Area and Tree-Ring Sample Collection

The Altay Mountains, one of the most complex mountain systems in Eurasia, span approximately 2000 km, encompassing the Gobi Desert, the Siberian plain, and parts of Mongolia, China, Russia, and Kazakhstan. Due to their distance from the ocean, the primary sources of water vapor supporting vegetation growth in the mountains are the Arctic Ocean and the North Atlantic Ocean [23]. Located on the southern edge of the boreal forest, the Altay Mountains are dominated by Siberian larch (*Larix sibirica*), with lesser occurrences of Siberian fir (*Abies sibirica*), Scots pine (*Pinus sylvestris*)and Siberian spruce (*Picea obovata*). Given its ecological importance and climatic sensitivity, *L. sibirica* was selected as the focus species for this study.

The northern Altay region primarily in Russia (marked as northern Altay or N), and the southern Altay region, mainly in China's Xinjiang (marked as southern Altay or S), were chosen as study site to compare climate-growth relationships. In the northern Altay, 207 cores were collected from 11 sites spanning from west to east, with data sourced from the International Tree-Ring Data Bank (ITRDB, https://www.ncei.noaa.gov/products/paleoclimatology/tree-ring (accessed on 6 September 2022)). For the southern Altay, 351 cores were collected from 9 sites, also spanning west to east. These samples were

gathered by our research team between 2005 and 2022. The elevation of all sampling sites exceeded 2000 m a.s.l, and the tree species was the *L. sibirica* (Table 1 and Figure 1).

Table 1. Basic sampling sites information in the northern and southern Altay Mountains.

Location	Code	Site Name	Latitude (°N)	Longitude (°E)	Elevation (m)
Northern Altay Mountains (Russia)	Russ248	Chind	49°12′	87°01′	2250
	Russ247	Ak-ha	49°14′	87°14′	2200
	Russ250	Jelo	49°31′	87°30′	2250
	Russ251	Kokcy	49°22′	87°34′	2200
	Russ135	Aktasch Valley	50°25′	87°35′	2000
	Russ137	Ust Ulagan Lake	50°29′	87°39′	2150
	Russ133	Ust Ulagan Bog	50°30′	87°41′	1950
	Russ229	Altay KUR2	50°18′	87°50′	Miss
	Russ226	Altay AT2	50°05′	87°56′	Miss
	Russ227	Altay Djaza	49°37′	88°06′	Miss
	Russ257	Tara	49°23′	88°08′	2250
Southern Altay Mountains (China)	HNN	Kanasi	48°47′	86°55′	2150
	KLN	Kalakelike	48°22′	87°34′	2000
	AZB	Azubai	47°53′	88°49′	2200
	ALS	Alasan	47°34′	89°24′	2200
	BYZ	Bozhayiduergen	47°47′	89°42′	2350
	ZGE	Zhengge	47°42′	89°53′	2150
	TYT	Tayate	47°10′	90°00′	2400
	ALL	Arshatehe	47°10′	90°16′	2150
	XNL	Xianangou	45°17′	90°42′	2250

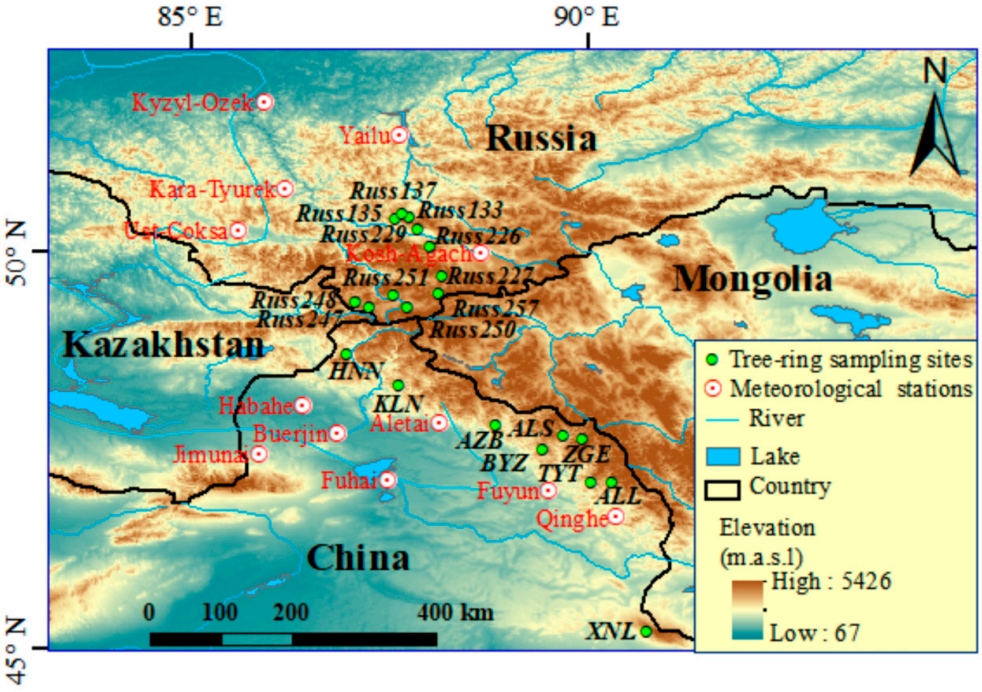

Figure 1. Tree-ring sampling sites and meteorological stations in the Altay Mountains.

2.2. Development of Regional Chronologies

To develop tree-ring width chronologies, we re-cross-dated and verified the northern Altay data using the COFECHA_v6.06p [24,25]. Similarly, southern Altay data were reanalyzed and combined to produce robust chronologies. Chronology development utilized two software tools: Arstan_v44xp and RCSsigFree_v45. Given the region's complex topography,

which transitions from mountainous areas to basins, three detrending methods were used to remove non-climatic growth trends: 1. Spline function with a 100-year step length (SPL100): Fits ring width using continuous, smooth interpolation without assumptions about growth trends, suitable for humid areas. 2. Negative exponential curve (NEC) [26]: Assumes a single growth-limiting factor and minimal interspecific competition, ideal for arid environments. 3. Signal-free regional curve standardization (sfRCS) [27]: Retains low-frequency climate signals by fitting growth curves for each sample, allowing recovery of climate information beyond tree-ring chronology lengths. The standardized chronology (STD) derived from these methods was used for all subsequent analyses (Figure 2a,b). We stabilized the variance of the chronology using the r-bar weighted method in Arstan_v44xp [24], and the Subsample signal strength (SSS) was used to assess the adequacy of replication in the early years of the chronology, which ensures the reliability [26] (Figure 2c,d). In this study, the reliable time period for the regional chronology of the Altay Mountains in Russia is 1461–2012, while that for the Altay Mountains in China is 1647–2020 (Figure 2a,b).

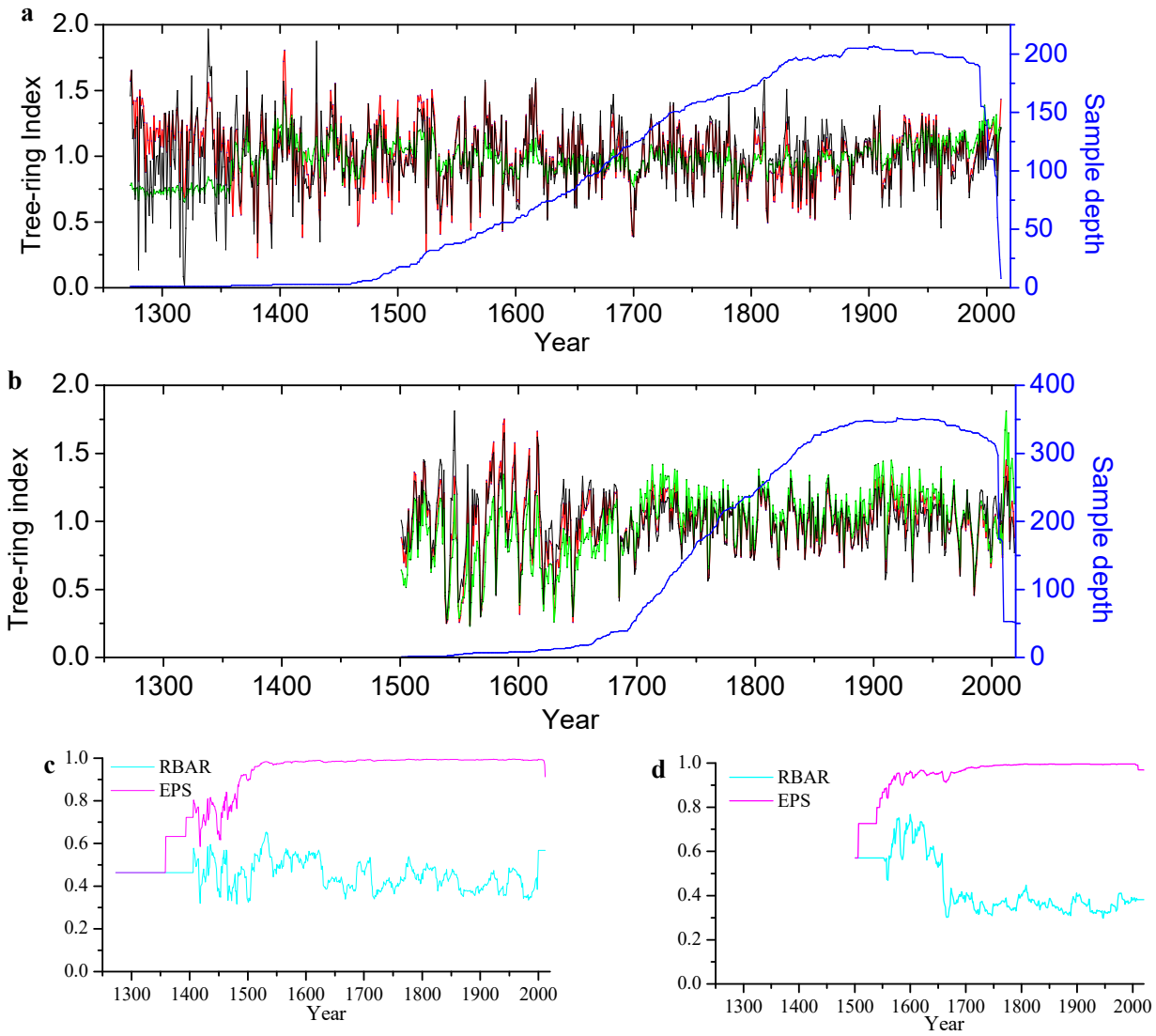

Figure 2. Tree-ring index and sample depth for the northern (**a**) and southern (**b**) Altay Mountains. RBAR and EPS statistics for the northern (**c**) and southern (**d**) Altay Mountains. (Red line: SPL100; green line: NEC; black line: sfRCS; blue line: sample depth; magenta line: EPS, cyan line: RBAR).

2.3. Meteorological Data

Monthly mean temperature (1940–2015) and precipitation (1966–2015) data for the northern Altay Mountains were obtained from meteorological stations at Kyzyl-Ozek, Kara-Tyurek, Ust-Coksa, Yailu, and Kosh-Agach. These datasets, sourced from the Russian Scientific Research Institute of Hydrometeorological Information (http://meteo.ru/english/data/) (accessed on 1 December 2016), cover the entire northern Altay from west to east, and have been widely used in prior studies of climate change in the region [23] (Table 2).

Table 2. Basic information on meteorological stations in the Altay Mountains.

Location	Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	Mean Temperature (°C)	Total Precipitation (mm)	Start and End Years
Northern Altay Mountains (Russia)	Kyzyl-Ozek	50°54′	86°00′	324	2.14	745	1940/66–2015
	Kara-Tyurek	50°02′	86°27′	2601	−5.51	599	1940/66–2015
	Ust-Coksa	50°16′	86°37′	977	−0.61	473	1940/66–2015
	Yailu	51°46′	87°36′	482	3.79	893	1940/66–2015
	Kosh-Agach	50°00′	88°40′	1759	−4.95	120	1940/66–2015
Southern Altay Mountains (China)	Habahe	48°03′	86°24′	535	5.02	198	1960–2021
	Buerjin	47°42′	86°52′	476	4.77	145	1960–2021
	Fuhai	47°04′	87°28′	503	4.40	126	1960–2021
	Aletai	47°44′	88°05′	738	4.60	199	1960–2021
	Fuyun	46°59′	89°31′	811	3.22	196	1960–2021
	Qinghe	46°40′	90°23′	1220	0.96	177	1960–2021

For the southern Altay Mountains, monthly mean temperature (1960–2021) and precipitation (1960–2021) data were collected from meteorological stations in Habahe, Buerjin, Fuhai, Aletai, Fuyun, and Qinghe. These stations span the southern Altay from northwest to southeast. Data were retrieved from the Meteorological Big Data Cloud Platform (Tianqing, CMA). Preliminary analysis indicates a significant warming trend across both the northern and southern Altay region. Precipitation has increased significantly in the southern Altay Mountains, whereas changes in precipitation in the northern Altay have been minimal (Figure 3).

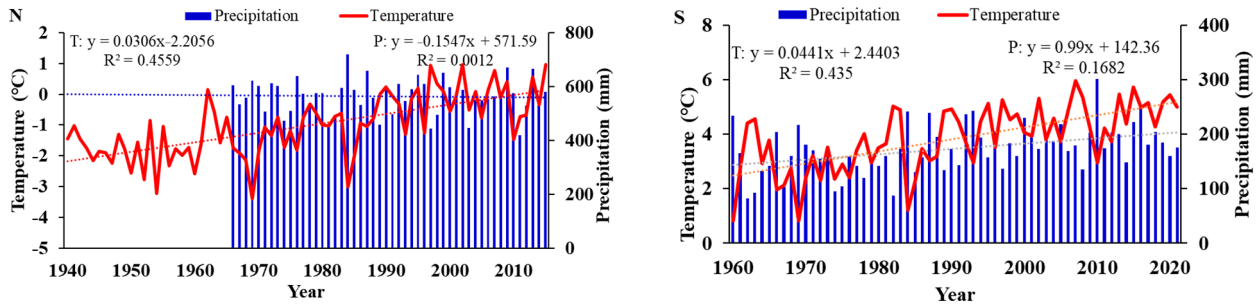

Figure 3. Meteorological changes in the northern (N) and southern (S) Altay Mountains. T and P represent temperature and precipitation, respectively.

2.4. Statistical Analysis

All statistical analyses followed standard dendrochronological methods [24–26]. Pearson correlation analysis was used to evaluate relationships between climate variables and tree-ring parameters, with computations performed using SPSS Statistics 21. The correlation analysis results of the tree-ring chronologies and climatic factors with significance levels exceeding 0.01 and 0.05 are considered meaningful and worthy of discussion.

To examine temporal variations in the relationship between climate factors and radial growth, a 21-year running correlation analysis was conducted. To focus on high-frequency variations and avoid spurious trend correlations, first-order difference correlation analysis was also employed.

3. Results

3.1. Relationship Between Tree-Ring Widths and Climate Factors

Analysis revealed that early summer temperature is the primary limiting factor for the radial growth of *L. sibirica* in both the northern and southern Altay Mountains. Warmer June temperatures had a positive effect on tree growth, with correlation coefficients reaching 0.570 ($n = 45$, $p < 0.01$) in the southern Altay (SPL method) and 0.752 ($n = 45$, $p < 0.01$) in the northern Altay (NEC method).

Precipitation during the early growing season also influenced radial growth, but its effects varied by region. In the northern Altay, early summer precipitation showed a negative correlation with radial growth, with the most significant correlation of −0.523 ($n = 45$, $p < 0.01$) (Figure 4). This suggests that northern Altay tree growth reflects stronger climatic signals than the southern region.

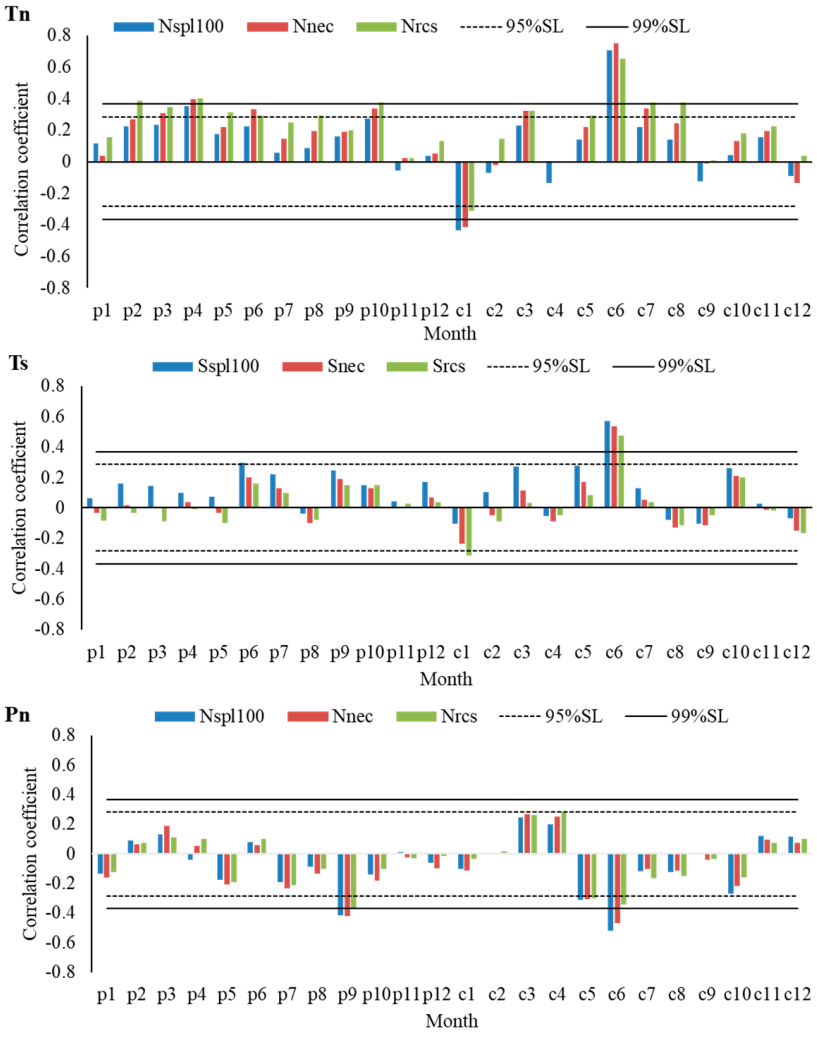

Figure 4. *Cont.*

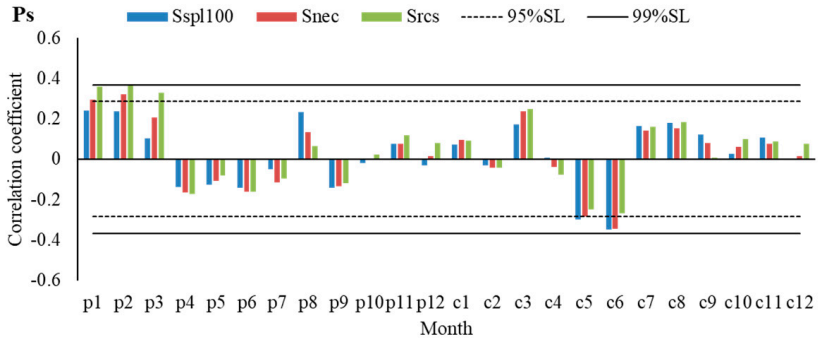

Figure 4. Correlation coefficients between tree-ring parameters and key meteorological variables in the northern (N) and southern (S) Altay Mountains (1967–2012). Spl, nec and rec represent Spline function, Negative exponential curve and Signal-free regional curve standardization de-trending method, respectively. Tn, Ts, Pn, Ps represent mean temperature and precipitation in the northern (n) and southern (s) Altay Mountains, respectively. 95% SL and 99% SL indicate confidence levels of 95% and 99%, respectively. Variables p1 to p12 and c1 through c12 denote months from January to December in the previous and current year, respectively.

Comparing different detrending methods, SPL and NEC retained more climate-related information, whereas the RCS method produced weaker signals. These findings were consistent with first-order difference correlation results (Figure 5).

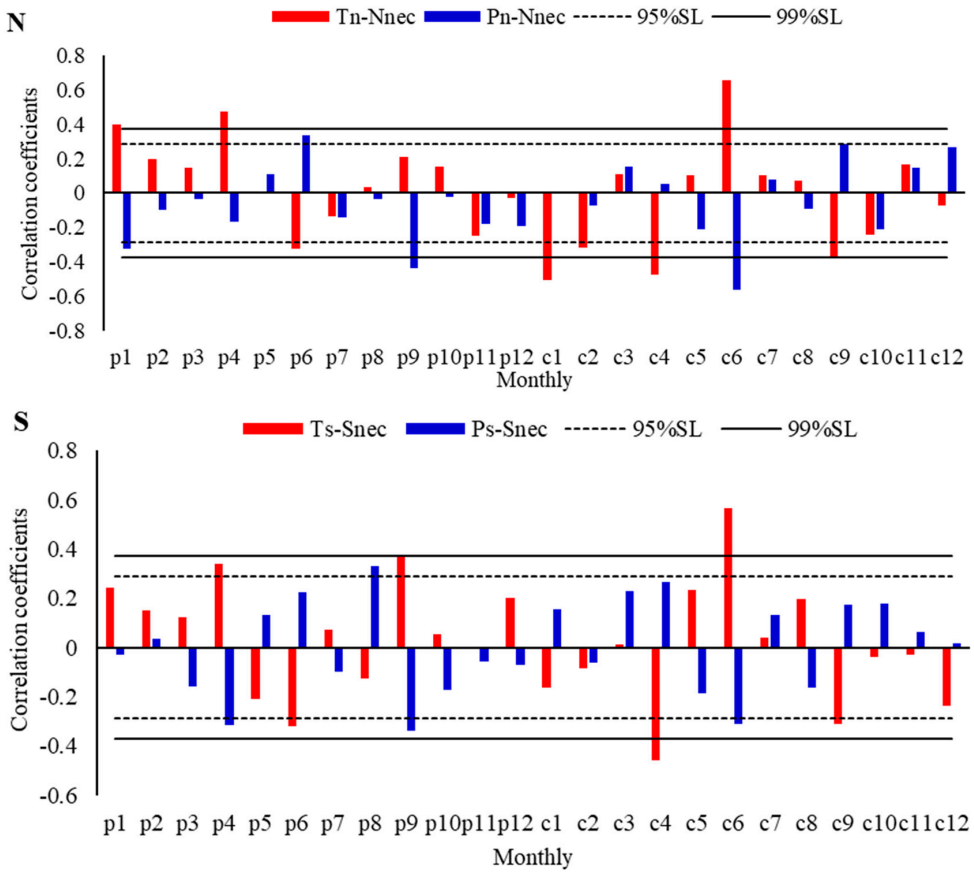

Figure 5. Correlation coefficients between first-order differences of tree-ring parameters and climate variables (1967–2012). Spl, nec and rec represent Spline function, Negative exponential curve and Signal-free regional curve standardization de-trending method, respectively. Tn, Ts, Pn, Ps represent mean temperature and precipitation in the northern (n) and southern (s) Altay Mountains, respectively. 95% SL and 99% SL indicate confidence levels of 95% and 99%, respectively. Variables p1 to p12 and c1 through c12 denote months from January to December in the previous and current year, respectively.

We further use partial correlation analysis in order to further confirm the influence of temperature on the radial growth. When controlling for precipitation, the correlations between June temperature and the northern Altay Mountains chronology were notably high (SPL: 0.590, NEC: 0.670; $n = 44$, $p < 0.01$). Conversely, when controlling for temperature, the correlation with June precipitation was minimal (SPL: −0.224, NEC: −0.093). These results suggest that the apparent correlation between radial growth and precipitation is mediated by temperature. Similarly, the correlations between temperature in June and radial growth in the northern Altay Mountains were relatively high (SPL: 0.495, NEC: 0.455; $n = 44$, $p < 0.01$) when controlling for June precipitation, and lower between growth and June precipitation (SPL: 0.136, NEC: −0.149) when controlling for June temperature.

3.2. Effects of Climate Change on Relationship Between Tree-Ring Parameters and Climate Response

Analysis of the relationship between tree growth and meteorological factors under climate change revealed that early summer temperature has a significant and stable influence on the radial growth of the *L. sibirica* across the Altay Mountains. In the northern Altay Mountains, correlation coefficients between radial growth and June temperature consistently exceed the 99% significance threshold. However, in the southern Altay Mountains, the first-order difference correlation coefficient between radial growth and temperature was weaker, indicating less stable climate sensitivity.

While there was no significant correlation between radial growth and precipitation in the southern Altay Mountains, precipitation showed a significant and stable negative correlations with tree growth in the northern region. These results suggest that precipitation is not a primary limiting factor for radial growth in the southern Altay Mountains, though it has a stronger influence in the northern region (Figure 6).

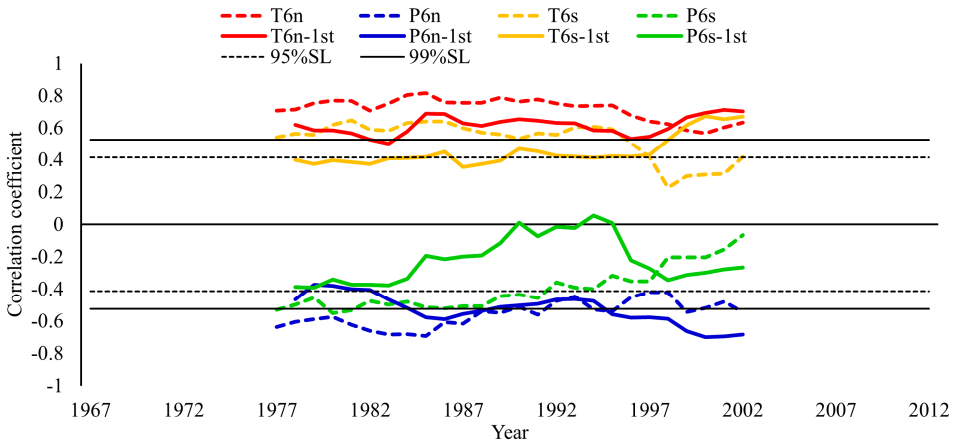

Figure 6. 21-year sliding correlation coefficients and first-order difference correlation coefficients between tree-ring width (SPL) and climate factors (1967–2012). T6n and T6s represent the correlation coefficients between tree-ring width and June temperature in the northern and southern Altay Mountains, respectively. P6n and P6s represent the correlation coefficients between tree-ring width and June precipitation in the northern and southern regions, respectively. T6n-1st, T6s-1st, P6n-st, P6s-st represent the first-order difference correlation coefficients between tree-ring width and climate factors. The dotted black line and solid black line represent confidence levels of 95% and 99%, respectively.

4. Discussion

4.1. Early Summer Temperatures Dominate the Radial Growth Pattern of L. sibirica in the High-Elevation of Altay Mountains

Previous studies show that temperature plays a critical role in initiating xylem growth [28]. The cell enlargement and wall thickening in *Larix sibirica* typically begin

in early summer, marking a vital period for its growth in the Altay Mountains [29]. Consistent with these findings, this study confirms that early summer temperature is the primary limiting factor for *L. sibirica* radial growth. Rapid warming during this period promotes active division and expansion of cambium cells, leading to the formation of wider earlywood. Conversely, cooler early summer temperatures delay growth initiation and inhibit the cell division and expansion. Since earlywood constitutes over two-thirds of the annual ring width, early summer temperature significantly influences the overall ring width. Some studies have shown that temperature's limiting effect on radial growth intensifies with latitude in the Northern Hemisphere [30]. As a result, the correlation between radial growth and early summer temperature is stronger in the northern Altay than in the southern Altay.

In arid and semi-arid regions, precipitation during the growing season is typically positively correlated with radial growth, whereas temperature is the main limiting factor in humid, mid- to high-latitude areas. However, this study reveals a puzzling negative correlation between early summer precipitation and tree-ring width. Given the observed strong positive correlation between early summer temperature and radial growth, it is likely that precipitation and temperature are interrelated. To investigate further, partial correlation analyses were conducted.

When controlling for precipitation, the correlations between June temperature and the northern Altay Mountains chronology were notably high (SPL: 0.590, NEC: 0.670; $n = 44$, $p < 0.01$). Conversely, when controlling for temperature, the correlation with June precipitation was minimal (SPL: −0.224, NEC: −0.093). These results suggest that the apparent correlation between radial growth and precipitation is mediated by temperature. Similarly, the correlations between temperature in June and radial growth in the southern Altay Mountains were relatively high (SPL: 0.495, NEC: 0.455; $n = 44$, $p < 0.01$) when controlling for June precipitation, and lower between growth and June precipitation (SPL: 0.136, NEC: −0.149) when controlling for June temperature.

These findings align with prior studies of boreal forests, which consistently identify early summer temperature as the primary determinant *L. sibirica* radial growth [31–34]. This relationship holds across the Altay Mountains, regardless of region—whether in China [12,14–16], Russia [7–9,16], Mongolia [13,35], or Kazakhstan [11]. Precipitation, in contrast, has a negligible effect on *L. sibirica* radial growth in this region.

4.2. The Dynamic Changes in the Response Relationship Between Radial Growth of Trees and Climate Under the Background of Climate Change

The response relationship between radial growth and climatic factors has changed over time due to climate change. The ongoing climate change would redistribute growth responses to climate factors [30]. The radial growth-climate response is highly variable due to its extremely short growing season, with growth response to temperature fluctuating annually [36]. Despite these complexities, this study demonstrates a stable and significant response of *L. sibirica* growth to early summer temperature in the Altay Mountains.

Temperature records indicate a significant increase in both the northern and southern Altay Mountains. However, precipitation trends differ: precipitation has increased significantly in the south, while changes in the north remain negligible. Despite warming, average temperatures in both regions remain below the optimal range for photosynthesis, suggesting that temperature continues to be the primary limiting factor for *L. sibirica* in the Altay Mountains.

5. Conclusions

Numerous studies have demonstrated that temperature is the main limiting factor for radial growth in boreal forests, with summer temperature playing a key role in promoting

forest greening. However, significant controversies remain. The Altay Mountains, located at the southern margin of the boreal forest and bordering the inland arid regions in the middle latitudes, present a unique ecological transition zone. While most research agrees that temperature is the dominant factor influencing the growth of *L. sibirica* in this region, the role of precipitation has often been overlooked. Moreover, differences in the radial growth response of trees in the northern versus southern Altay Mountains to climate have not been thoroughly investigated.

The results of this study clearly indicate that early summer temperatures dominate the radial growth pattern of *L. sibirica* in the high-elevation of Altay Mountains. The positive impact of temperature on radial growth is stronger in the northern Altay Mountains compared to the southern region. At the same time, increased early summer precipitation negatively affects *L. sibirica* growth, with a more pronounced negative response observed in the northern Altay Mountains. Over the past 50 years, early summer temperature has remained a stable and significant driver of *L. sibirica* radial growth patterns. The findings offer insights for forest management in these transitional regions and underscore the importance of addressing climate change risks to forest ecosystems.

The study provides further evidence that the effects of climate change on the radial growth of *L. sibirica* at the boreal forest edge are both intense and complex. The findings offer insights for forest management in these transitional regions and underscore the importance of addressing climate change risks to forest ecosystems.

However, there are some limitations to this study. The meteorological data used were sourced exclusively from meteorological stations, which may introduce unavoidable uncertainties, such as inconsistencies in observation standards, data coverage periods in China and Russia. In addition, the altitude difference between meteorological stations and sampling sites may cause significant errors in the relationship between the radial growth and precipitation. Further research should prioritize strengthening cooperation between China and Russia to facilitate in-depth dendroclimatological studies in the Altay Mountains. Such collaborative efforts will enhance our understanding of climate-tree growth relationships and provide a more comprehensive basis for managing boreal forest ecosystems under changing climatic conditions.

Author Contributions: Conceptualization, L.Q. and R.Z.; data curation, L.Q., R.Z. and D.Z.; data acquisition, Y.Y., T.Z., S.Y., H.S., D.Z. and R.Z.; formal analysis, L.Q. and R.Z.; funding acquisition, L.Q., Y.Y. and R.Z.; investigation, R.Z., L.Q., Y.Y., T.Z., H.S., S.J. and S.Y.; methodology, L.Q. and R.Z.; resources, Y.Y. and R.Z.; validation, L.Q.; writing—original draft, L.Q. and R.Z.; writing—review and editing, L.Q. and R.Z. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original data of tree rings in Russian can be downloaded at the International Tree-Ring Data Bank (ITRDB, https://www.ncei.noaa.gov/products/paleoclimatology/tree-ring, accessed on 6 September 2022). The meteorological data in Russian can be downloaded at the Russian scientific research institute of hydrometeorological information (http://meteo.ru/english/data/, accessed on 1 December 2016). The other data presented are available on request from the corresponding author.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

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