Response of radial growth of tree species Dahurian larch (Larix gmelinii) and Mongolian pine (Pinus sylvestris var. mongolica) to extreme climate in the northern part of the Greater Khingan Range, China

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Abstract

In this study, we adopted tree ring climatology to understand the differences in the response of the radial growth of two typical tree species to extreme climate indices in the Greater Khingan Mountains region, Northeast China. In particular, we collected 231 samples of Dahurian larch (*Larix gmelinii*) and Mongolian pine (*Pinus sylvestris* var. *mongolica*) from four sampling points in the in the Genhe region of the Greater Khingan Range Mountains to establish a standardized chronology of Dahurian larch and evaluate extreme climate indices and their trends. Pearson correlation analysis was employed to analyze the growth response of Dahurian larch and Mongolian pine pine to extreme climatic factors at each sampling point, and the similarities and differences in the radial growth characteristics of each tree species and their response to climatic factors before and after a sudden change in temperature were investigated. The results revealed that after the sudden change in climate, the radial growth of larch and Mongolian pine pine exhibited the same upward trend that was more significant at high altitudes, while the radial growth of Mongolian pine pine had a more obvious upward trend at low altitudes. Correlation analysis with climate elements demonstrated that in May of the current year, the radial growth of high-elevation Dahurian larch was significantly positively correlated ($p < 0.05$)with the minimum temperature minima, while the radial growth of larch was significantly positively correlated with temperature, and the minimum temperature minima, maximum temperature minima and number of warm night days were significantly positively correlated with the number of cold day days. Following the sudden change in temperature, in May of that year, the radial growth of low elevation larch exhibited a significant positive correlation with temperature, a significant positive correlation with the maximum temperature minima and number of warm night days, and a significant negative correlation with the number of cold day days. Moreover, the radial growth of Mongolian pine showed a significant positive correlation with the number of warm night days and minimum temperature minima. After the abrupt climate change, the radial growth of trees in the low elevation areas of Greater Khingan Range were all inhibited by the high temperature in summer, while with the continuous increase of global temperature, the drought stress induced by the high temperature was the main factor inhibiting the growth of high-elevation larch. This study demonstrates that under global warming, the Greater Khingan Range area is becoming increasingly unsuitable for the growth of larch, the distribution area of the natural forest of Mongolian pine may expand, and the distribution area of natural larch forests may decline.

1. Introduction

Global warming has become an indisputable phenomenon in the past hundred years. The sixth report of the Intergovernmental Panel on Climate Change (IPCC) states that the temperature in the period of 2010–2020 was 1.07°C higher than that of 1850–1900, inducing a series of problems such as a rise in sea level and the increase in the number of extreme climatic events [1]. The enhanced frequency, intensity range, and duration of extreme climate events are critical features of global climate change [2]. Global temperatures experienced two warming surges in the mid-1920s and the late 1970s, and the decades following the second surge were the warmest in the last hundred years [3], resulting in an increase in the frequency, intensity, and range of extreme weather events. Moreover, the persistent high temperatures will have a great negative impact on natural ecosystems, particularly forests[4]. As an important component of terrestrial ecosystems, forests play a crucial role in terrestrial carbon cycling and biomass accumulation[5]. In the long-term adaptation with the surrounding environments, forests have formed a relatively stable and dynamic equilibrium with the corresponding environmental factors[6]. However, extreme climatic events can strongly impact the inherent equilibrium relationship between forest-environmental factors, significantly altering the phenology, productivity level, and successional status of forests [7], and consequently increasing the survival pressure of forest communities and the potential risk of local extinction [8]. Therefore, it is necessary to study the impacts of climate change on forest ecosystems in different regions. Tree annual rings provide an accurate dating methodology at a high resolution and wide distribution, and thus they are an important tool for annual-climate studies [4].

The impact of climate warming on forest ecosystems has become a current research hotspot. Numerous scholars have observed the effects of extreme climatic events on tree growth in studies on the response of tree whorl radial growth to climate. However, the effects of different extreme climatic events on different tree species in different regions are highly variable. In the tropics, tree growth is more susceptible to drought events, and in China and the tropical Amazon, extreme droughts have caused unusually high tree mortality rates [9]-[11]. At mid-latitudes, increasing temperatures enhance the sensitivity of trees to the environment [12], and regional droughts produce large variations in the growth trends of the same tree species in different regions[13]. Pinus nigra var. located in different regions of the Mediterranean basin are affected by drought events. Furthermore, warmer winter temperatures and reduced snowfall in the high latitudes of Canada are reported to produce an inhibitory effect on the radial growth of Callitropsis nootkatensis in the southern part of Graham Island. The forest area in the northern part of China accounts for 30% of the global forest area, and the Northern Hemisphere has experienced significant warming in recent decades. This has resulted in frequent droughts at high latitudes [14]-[15], prolonged growing seasons [16], the accelerated melting of snowpack [17], and the degradation of permafrost [18], all of which have a significant impact on the growth, structure, and dynamics of boreal forests.

The Greater Khingan Range, with a forest coverage of 74.1% [2], is an important forest resource and the largest state-owned forest area in northeastern China. Its widely-distributed forests are dominated by coniferous forests, with a large number of species, including Dahurian larch and Mongolian pine. The region exhibits the most obvious warming and greatest sensitivity to climate change in China [1]. Moreover, the rapid warming significantly affects the growth of plants in the Greater Khingan Range region, and thus is an ideal area for tree chronological studies. As the dominant tree species in high-latitude regions, larch and Mongolian pine, with a long lifespan and strong adaptive capacity, have obvious annual cycle boundaries and their radial growth is sensitive to climate change, making them suitable for dendrochronological analyses [6]. Numerous scholars have investigated the relationship between tree species and climate in the Greater Khingan Range region, where the radial growth of trees is limited by extreme drought and temperature events. The radial growth of both Mongolian pine and larch in this area has been subjected to significant drought stress, and the effects have been reported to intensify with increasing drought intensity and drought frequency[19]. Previous work has observed a significant negative correlation between Mongolian pine and temperature in the southern part of the Greater Khingan Range, with the increased average maximum temperature from April to September of the current year significantly inhibiting the growth of Mongolian pine in the south, while Mongolian pine in the north is more affected by minimum temperatures [20]. Chang et al. identified soil moisture deficit from regional warm-drying due to high temperatures as the main factor limiting the growth of larch, and observed the degree of drought to exacerbate the intensity of larch's response to temperature changes [21]. Currently research on larch and Mongolian pine in the Greater Khingan Range region focuses on the response of average temperature and precipitation to tree whorl width, while studies on the response of tree annual rings to extreme climatic events are limited. Furthermore, the majority of past studies are centered on the effects of extreme drought events on the radial growth of tree whorls, while the impacts of other extreme climate events are less considered. Therefore, analyzing the response of larch to extreme climate events in the Greater Khingan Range region is conducive to a comprehensive understanding of the environmental impacts on trees under a shadow climate warming scenario.

In this study, two different altitudes, two tree species, and four sampling sites were selected in the west side of the Greater Khingan Range to investigate the response of tree radial growth to extreme climate events. The specific aims of the study were to: 1) analyze the response of tree radial growth to extreme climate events under climate change conditions; and 2) provide a basis for forest ecology research and forest management. In particular, larch and Mongolian pine in the Mangui region of the Greater Khingan Range Mountains were taken as the study objects to evaluate the response of tree wheel width to extreme climate events. First, we determined 28 extreme climate indices, analyzed the trends and cycles of the indices in the Mangui region of the Greater Khingan Range Mountains, and investigated the changes in extreme climate. We then established a standardization system of tree wheel width of larch and Mongolian pine in the Mangui region and assessed the richness of the obtained climate information, further improving the tree wheel data in the Amur area of the Greater Khingan Range. Following this, we analyzed the response of the chronology to different extreme climate indices. The results of the analysis provide a reference for the impact of extreme climatic events on the radial growth of tree whorls under global warming, as well as a scientific basis for future climate change, extreme climatic events, and the protection and management of forests in the Greater Khingan Range region.

2. Materials and methods

2.1. Study area and climate

The study area is located in the northern part of Hulunbeier region, to the north of Genhe city, and on the southwest slope of the northern Greater Khingan Range. It belongs to the cold-temperate continental monsoon climate [22], with a long and cold winter, and a snow period that reaches 160 days. The average annual temperature is − 5.8°C, the extreme minimum temperature is − 52°C, and the extreme maximum temperature is 31°C. The average annual cumulative temperature greater than 10°C is 1400 hours, the average annual frost-free period is 80 days, and the average annual sunshine rate is 60%. Annual precipitation is 480 mm and is mostly concentrated in July and August. The soil type is primarily brown coniferous forest soil [23], as well as some gray-black soil, swampy soil and meadow soil, with a thickness of 20–40 cm. The forest type is cold-temperate coniferous forest. Typical tree species include Mongolian pine pine and Dahurian larch, which have become representative tree species in the northern region of China due to characteristics such as cold tolerance and strong adaptability [20], particularly in the Greater Khingan Range region where they are widely distributed. Therefore, Mongolian pine pine and Dahurian larch were selected as the main research objects in this study.The location of the sample site is shown in Fig. 1.

2.2.Data and methodology

The meteorological data used in the study were obtained from the China Meteorological Data Network (http://data.cma.cn/). Meteorological data recorded from 1960–2020 at the nearest meteorological station to the sampling site of Genhe were selected based on the proximity principle. The principle climatic variables were daily maximum temperature, daily minimum temperature, and daily precipitation. Based on the daily temperature and precipitation observations of Genhe from 1960 to 2020, 27 extreme climate indices were obtained with RClimDex by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDI) in collaboration with the World Meteorological Organization (WMO) [24–25],the values of the individual parameters are shown in Table 2. The extreme climate indices were further divided into the extreme climate warm indices, extreme climate cold indices and other temperature indices, and the rainfall indices were divided into the rainfall frequency class indices and rainfall magnitude class indices for observation and analysis [26]. In order to investigate the differences in the response of the radial growth of different tree species to climatic factors in Greater Khingan Range, the width chronologies of the tree whorl of the Mongolian pine and the larch were correlated with the precipitation, average air temperature, maximum air temperature and minimum air temperature, respectively. Considering that climate factors have a certain lag effect on the tree-ring width indices [27], the meteorological data from September of the previous year to October of the current year were selected for monthly correlation analysis. In order to investigate the effect of temperature change on the growth of different tree species, we analyzed the response of the wheel width chronology with climatic factors before and after the sudden change, and employed Pettitt's method to test the meteorological data for the sudden change.The values of the individual parameters are shown in Table 1.

Table 1
Basic information of the meteorological station sites

Meteorological station	Longitude	Latitude	Elevation	Measurement period
Genhe	121°31'	50°46'	732.6	1960–2020

The average annual temperature in the Manqi area is − 3.97°C and up to seven months a year exhibit temperatures below 0°C. July experiences the highest temperature, while the lowest temperatures are concentrated in December, January and February, falling below − 20°C. The lowest and highest temperatures during the study period were − 49.6°C (January 23, 1960) and 38.5°C (June 26, 2010), respectively. The average annual precipitation is 441.93 mm, with July and August generally contributing to more than 50% of the annual precipitation. After eliminating two temperature anomalies, the average annual temperature exhibited an overall upward trend.The results of the study are shown in Fig. 2.

Table 2
Extreme climate indices

Type	ID	Indicator	Definition	Units
Extreme climate warming indices	TXx	Max T_{max}	Monthly maximum value of daily maximum temp	°C
	TXn	Min T_{max}	Monthly minimum value of daily maximum temp	°C
	TX90p	Warm days	Percentage of days with TX > 90th percentile	d
	TN90p	Warm nights	Percentage of days with TN > 90th percentile	d
	WSDI	Warm spell duration	Annual number of days with at least six consecutive days with TX > 90th percentile	d
	SU25	Summer days	Annual number of days with TX(daily maximum) > 25ºC	d
	TR20	Tropical nights	Annual number of days with TN(daily minimum) > 20ºC	d
Extreme climate cold indices	TNx	Max T_{min}	Monthly maximum value of daily minimum temp	°C
	TNn	Min T_{min}	Monthly minimum value of daily minimum temp	°C
	TX10p	Cool days	Percentage of days with TX < 10th percentile	d
	TN10p	Cool nights	Percentage of days with TN < 10th percentile	d
	CSDI	Cold spell duration	Annual number of days with at least six consecutive days with TN < 10th percentile	d
	FD0	Frost days	Annual number of days with TN(daily minimum) < 0ºC	d
	ID0	Ice days	Annual number of days with TX(daily maximum) < 0ºC	d
Other temperature indices	Temp	Average temperature	Annual and monthly average temperature	°C
	GSL	Growing season length	Annual (1st Jan–31st Dec in NH, 1st July–30th June in SH) number of days between first span of at least six days with TG > 5ºC and first span after July 1 (January 1 in SH) of 6 days with TG < 5ºC	d
	DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
Rainfall frequency indices	R10	Days with moderate precipitation	Annual count of days with ≥ 10 mm	d
	R20	Days with heavy precipitation	Annual count of days with PRCP ≥ 20 mm	d
	R25	Days with precipitation above 25 mm	Annual count of days with PRCP ≥ 25 mm	d
	CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	d
	CWD	Consecutive wet	Maximum number of consecutive days with RR ≥ 1	d

Type	ID	Indicator	Definition	Units
		days	mm	
Rainfall magnitude class indices	RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation amount	mm
	RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation amount	mm
	R95p	Very wet days	Annual total PRCP with RR > 95th percentile	mm
	R99p	Extremely wet days	Annual total PRCP with RR > 99th percentile	mm
	PRCP-tot	Annual total wet-day precipitation	Annual total PRCP of wet days (RR ≥ 1 mm)	mm
	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP ≥ 1.0 mm) in a year	mm

2.3 Sample collection and chronology creation

Based on the basic principles of dendrochronology [28], field sampling was performed in July 2022 in the Mangui area of the Greater Khingan Range. Growth cones with calibers of 5 mm and 10 mm were employed to collect at least three core samples from each tree at breast height (approximately 1.3 m). Sampling was performed along the perpendicular and parallel slope directions, selecting thicker trees that were farther away from human activities. Cores of Mongolian pine pine and Dahurian larch were sampled at different elevations, saved and numbered. Table 3 reports the key information of each sampling point.

The tree cores were pre-processed according to the international standard method of dendrochronology [29]. First, the cores were air-dried, fixed, polished, initially-dating and cross-dating of each sample. Wheel measurements were then made of the processed cores using the LINTAB6 system (RINNTECH, Heidelberg), with a measurement accuracy of 0.001 mm, to determine the exact age of each wheel [24]. COFECHA was then employed to perform a calibration test on the measured results, and sample cores exhibiting a low correlation with the main sequence were excluded in order to ensure the sample size, resulting in 116 samples of Mongolian pine and 115 samples of Dahurian larch. The negative exponential function de-trending method in the ARSTAN chronology development program [30] was used to fit and remove the tree growth trend. The sample cores were subsequently integrated by the double weight averaging method [30] to obtain the standardized chronology of tree-ring width (STD), a difference chronology (RES) and an autoregressive chronology (ARS). Statistical analysis of the width chronology parameters of Dahurian larch and Mongolian pine revealed that the standardized chronology of tree-ring width of the two species exhibited high quality and high-frequency information, and were thus employed for the subsequent analysis with climate factors.

Table 3
Tree ring sampling point information

Sample point	Tree species	Elevation (m)	Longitude (E)	Latitude (N)	Slope	Depression closure	Sample size
LYA	Dahurian larch	1120	121.47	52.18	5	0.8	51
LYB	Dahurian larch	900	121.50	52.16	5	0.9	64
ZZA	Mongolian pine	1150	121.47	52.19	5	0.8	57
ZZB	Mongolian pine	1150	121.47	52.19	5	0.8	59

3. Results

3.1 Analysis of chronological characterization coefficients

The sensitivity value reflects the content of the contained climate information and the limiting effect of climate factors on tree growth; the greater the sensitivity, the more climate information is contained in the samples and the less corresponding non-climate noise [31]–[32]. The mean sensitivity (MS) of the trees in the four sample sites exceeded 0.1. A time period with SSS(subsample signal strength) > 0.85 indicates that the chronology of tree-ring width sequence is reliable and can represent the overall characteristics of the chronology [34]. Thus, a sub-sample signal strength of SSS > 0.85 was used as the criterion [33] to determine the starting year of the drilling samples cores at the sampling sites Based on this, the reliable time periods of the sampling point cores for larch in LYA and LYB were 1759–2020 and 1904–2020, respectively, and the reliable time periods of the sampling point cores of Mongolian pine in ZZA and ZZB were 1910–2020 and 1814–2020, respectively.The values of the individual parameters are shown in Table 4. The normalized chronology of the tree ring width of the sampling points is shown in Fig. 3.

Table 4
Statistics of the standard chronology of Pinus sylvestris and Larch

Tree species	Sequence length	Mean sensitivity	Standard deviation	First-order auto-correlation	Mean within tree correlation	Signal-to noise ratio	Expressed population signal	First year with subsample signal strength > 0.85
LYA	1745–2020	0.155	0.211	0.77	0.626	26.87	0.964	1759
LYB	1820–2020	0.191	0.211	0.733	0.649	22.950	0.958	1904
ZZA	1909–2020	0.115	0.214	0.957	0.844	101.910	0.990	1910
ZZB	1791–2020	0.110	0.279	0.802	0.670	25.359	0.962	1814

3.2 Correlation of standardized chronology with annual average climate indices

In order to better characterize the response of tree-ring width index to extreme climate indices, the average annual climate indices were correlated with the annual-whorl width indices (Fig. 4). The LYA and LYB larch tree wheel width indices were strongly correlated with temperature indices Dtr, TX90p, TN90p, TX10p, TN10p, TNx, TXn and TXx. Significant correlations were also observed with the growing season length (GSL), frost-free period (FD0), summer days (SU25) and warm season days index (WSDI)($p < 0.05$). This suggests that extreme temperature events and growing season variations are closely linked with the Dahurian larch tree-ring width index at the LYA and LYB sampling sites. The Mongolian pine ZZA and ZZB tree tree-ring width index were also strongly correlated with several temperature indices, particularly Dtr, Tx90p, Tn90p, Tx10p, Tn10p, Tnn, Tnx, Txn, and Txx, as well as with the length of the growing season (GSL), the frost-free period (FD), the number of summer days (SU25) and warm season days index (WSDI). This indicates that the variation of Mongolian pine tree wheel width is closely related to the temperature conditions and length of the growing season. The results reveal the correlations of the tree tree-ring width index with Dtr, Tx90p, Tn90P, Tx10p, Tn10p, Tnn, Tnx, Txn, Txx, Temp, FD, GSL, SU, and WSDI to be strong in the four sampling site areas.The results are shown in Fig. 4.

3.3 Pettitt test for climate indices

A total of 27 extreme climate indices were obtained by running the RClimDex program on the meteorological data of Genhe from 1960 to 2020. The Pettitt test for the 27 climate indices revealed that 17 climate indices exhibited significant mutations. Among which, the number of warm day days (TX90p), number of warm night days (TN90p), number of summer days (SU), number of maximum temperature extremes (TXn), number of maximum temperature extremes (TXx), and number of warm day duration (WSDI) in the extreme warm climate index demonstrated highly significant mutations ($p < 0.01$). In terms of the extreme climate cold indices, the number of cold days (TX10p), number of cold night days (TN10p), number of frost days (FD), number of icing days (ID), number of cold day duration days (CSDI), minimum low temperature (TNn), and minimum maximum temperature (TNx) experienced highly significant mutations ($p < 0.01$). In addition, the monthly maximum temperature (TMAX), monthly minimum temperature (TMIN), mean temperature (Temp), and daily mean temperature difference (DTR) all experienced significant mutations ($p > 0.05$). Note that no significant mutations were observed for the extreme precipitation indices. The results reveal that the sudden climatic changes in the study area were mainly characterized by changes in temperature and insignificant changes in precipitation. Among the 17 climate indices with trends that passed the significance test, 10 exhibited significant mutations in the mid-1880s, and began to increase (or decrease) around 1987. Thus, the year of mutation was set as 1987 for all indices.The results of the sudden temperature change are shown in Fig. 5.

3.4 Tree tree-ring width index trend before and after mutation

We subsequently analyzed the change trend of the larch and Mongolian pine wheel width indices at different altitudes before and after the abrupt climate changes. The tree-ring width index of high altitude larch exhibited insignificant changes prior to the abrupt climate change, with an upward trend after the change. In contrast, the tree-ring width index of Mongolian pine exhibited a decreasing trend before the abrupt climate change, followed by a highly significant ($p < 0.01$)upward trend after the change. At low altitudes, the larch tree-ring width index demonstrated a decline before the abrupt climate change and subsequently increased after the change, while the Mongolian pine pine index showed non-significant variations prior to the change and a highly significant($p < 0.01$) increasing trend after. Figure 6 shows the trend of tree-ring width index.

3.5 Characterization of changes in extreme weather indices

Based on the correlation results between the standard chronology and annual mean climate indices, we selected Dtr, Tx90p, Tn90P, Tx10p, Tn10p, Tnn, Tnx, Txn, Txx, Temp, and Prcptot for the subsequently analysis and analyzed the effects of these indices on the tree-rotor width index. One-way linear regression of these 11 climate indices revealed that the number of warm day days (TX90p), number of warm night days (TN90p), maximum temperature extremes (TXx), and mean temperature (Temp) exhibited highly significant increasing trends ($p < 0.01$). Moreover, the number of cold day days (TX10p), number of cold night days (TN10p), and daily mean temperature difference (DTR) followed highly significant decreasing trends ($p < 0.01$). No significant changes were observed for the rainfall indices in the study area ($p > 0.05$).The variation characteristics of the extreme climate index are shown in Fig. 7.

3.6 Differences in the radial growth response to climate extremes in two typical tree species

Based on the analysis and results in Section 2, the differences in the response of radial growth of Mongolian pine and Xing'an Dahurian larchs to climate extremes in the Greater Khingan Range were analyzed and compared for two time periods, namely, 1960–1987 (pre-mutation) and 1988–2015 (post-mutation).

(1) Response of high-elevation area Mongolian pine pine to climate extremes before and after sudden changes in temperature

The correlation results of the standard chronology of the tree wheel width and climate indices of Mongolian pine pine in the high altitude area of Greater Khingan Range reveal that the response of tree growth to climatic factors before and after the sudden change of temperature changed significantly. The significant positive correlation between the tree whorl width index and the daily difference in temperature (DTR) with the previous winter before the sudden temperature change was transformed into a significant positive correlation after the change ($p < 0.05$). Following the sudden change in temperature, the significant negative correlation between the tree whorl width index and the minimum temperature extremes (TNx) and minimum temperature minima (TNn) in the winter of the previous year was weakened. Moreover, the significant negative correlation with the minimum temperature extremes (TNx) and minimum temperature minima (TNn) in May of the current year changed from significant negative prior to the change to positive after the change. In July of the current year, the correlation between the tree whorl width index and minimum temperature minima (TNn) changed from negative prior to the change to positive after the change, while that of the number of cold night days (TN10p) changed from positive before the change to significantly negative after the change ($p < 0.01$). In September of the current year, the tree whorl width index exhibited a significant positive correlation ($p < 0.01$) with the maximum temperature nadir (TXn) before the change, and a significant positive correlation ($p < 0.01$) with the maximum temperature epoch (TXx) after the change.The results are shown in Fig. 8.

(2) Response of larch to climate extremes at high altitudes before and after a sudden change in temperature

The significant correlation between the tree tree-ring width index and climate factors increased significantly following the sudden temperature change. Prior to the sudden change in climate, the tree whorl width index was significantly correlated ($p < 0.05$) with temperature (Temp), minimum temperature (TNn), and the number of cold night days (TN10p) only in August of the current year. After the sudden change in temperature, the tree whorl width index showed a significant negative correlation ($p < 0.05$) with the daily difference in temperature (DTR) in the winter of the previous year, as well as with the number of cold night days (TN10p) in September and October of the previous year. The tree whorl width index was significantly positively corelated ($p < 0.05$) with the maximum temperature extreme (TXx) and minimum temperature extreme (TNx) in November of the previous year. In May of the current year, the tree whorl width index exhibited significant positive correlations ($p < 0.05$) with the temperature (Temp), maximum temperature minima (TXn), minimum temperature minima (TNn) and number of warm day days (TX90p), and significant negative correlations ($p < 0.05$) with the number of cold day days (TX10p). Moreover, the tree whorl width index was significantly ($p < 0.05$) negatively correlated with precipitation (PRE) in October of the current year.The results are shown in Fig. 9.

(3) Response of Mongolian pine pine to climatic extremes at low altitudes before and after the temperature change

The significant correlation between the tree tree-ring width index and climate factors was reduced after the sudden temperature change. Before the change, the tree-ring width index index and daily difference in temperature (DTR) exhibited a significant negative correlation for several months ($p < 0.05$), while after the change, a significant negative correlation with (DTR) was only observed in the winter of the previous year ($p < 0.05$). Prior to the abrupt climate change, the tree whorl width index was significantly negatively correlated ($p < 0.05$) with temperature (Temp), the number of warm day days (TX90p) and daily difference in temperature (DTR) in May of the current year, and significantly negatively correlated ($p < 0.01$) with the number of cold day days (TX10p) and cold night days (TN10p) in September of the current year. After the abrupt climate change, the tree whorl width index exhibited significant negative correlations ($p < 0.01$) with precipitation (TX10p) and cold night days (TN10p) in May of the current year; after the abrupt climate change, the tree whorl width index showed significant negative correlations ($p < 0.01$) only in the winter of the previous year. The tree whorl width index was significantly and positively correlated ($p < 0.05$) with the precipitation (PRE), minimum temperature extremes (TNn), and warm night days (TN90p) in May of the current year, and significantly negatively correlated ($p < 0.05$) with the minimum temperature extremes (TNx) in September of the current year.The results are shown in Fig. 10.

(4) Response of larch to climate extremes before and after the sudden temperature change at low altitudes

Analyzing the response of each climate index revealed that before the abrupt climate change, the tree whorl width index was significantly positively correlated ($p < 0.05$) with the minimum temperature extremes (TNx) only in July of the current year. Following the abrupt climate change, the tree tree-ring width index exhibited a significant positive correlation ($p < 0.05$) with the number of cold day days (TX10p) in February of that year, a significant positive correlation ($p < 0.05$) with the temperature (Temp), maximum temperature extremes (TXn), and number of warm night days (TN90p), and a significant negative correlation ($p < 0.05$) with the number of cold day days (TX10p). Moreover, the tree tree-ring width index was significantly positively correlated with climate indices (minimum temperature extremes (TNx)) only in July of the current year. A significant negative correlation ($p < 0.05$) was observed with the number of cold day days (TX10p) in May of the current year, and with temperature (Temp) and maximum temperature minima (TXn) in September of the current year.The results are shown in Fig. 11.

4. Discussion and conclusions

With the occurrence of global warming, the climate characteristics of the northern region have exhibited a shift towards a warm-drying climate. In order to determine variations in the response of larch and Mongolian pine pine distributed in the northern Greater Khingan Range to climate change, four sampling points of these species were selected in the study area. The samples were employed to construct a difference chronology and investigate the stability of the relationship between the radial growth of Dahurian larch and climatic factors.

The established chronologies of conifer species in the four sampling sites in the northwestern part of the Greater Khingan Range region contain a large amount of climate information, facilitating the analysis of the relationship between the tree-ring width indices and climate factors.

Compared with the period before the the abrupt climate change, a significantly increasing trend is observed for extreme high temperature events in the study area, while the extreme low temperature events exhibit a decreasing trend, and the trend in the annual differences in temperature is significantly larger. There is an obvious regional warming phenomenon in the Greater Khingan Range region, which is consistent with the significant increase in temperature in northern China [35]. Changes in temperature and precipitation are the main climatic factors affecting tree growth. Analyzing the relationship between the response of the annual tree-ring width index of typical tree species Mongolian pine and larch to climate factors in the Greater Khingan Range region reveals great differences in the response time and type of Dahurian larch and Mongolian pine to the extreme climate indices.

According to the response of the standardized chronology of the tree whorl width and climate indices in the Greater Khingan Range region, the tree growth is not only affected by the temperature of the current year, but also by the temperature of the previous year, which is known as the "time lag effect" [36]–[37].

At high altitudes, a significant negative correlation was observed between larch and the daily difference in temperature of the previous winter (November–January of the previous year). At low altitudes, larch and the daily difference in temperature in the previous winter exhibited a negative correlation, with a significant negative correlation in the previous winter November–December. Mongolian pine pine was also negatively correlated with the daily difference in temperature in the previous winter (November and December) at lower altitudes. A large daily difference in temperature can be interpreted as a high daily maximum temperature or a low daily minimum temperature, and either high or low temperatures in the previous winter can affect tree growth. In November of the previous year, after a sudden change in temperature, Mongolian pine pine and larch at high altitudes exhibited a significant positive correlation with the minimum air temperature maximum. This may be attributed to the enhanced enzyme activity of the dark reaction during photosynthesis following the increase in the minimum air temperature maximum, which can promote the accumulation of organic matter in the dark reaction process, thus facilitating the growth of trees.

In February of the current year, larch at high elevations was significantly negatively correlated with temperature and significantly positively correlated with the number of cold days. Enhanced spring transpiration was combined with increased air drought, yet frozen soil moisture availability remained limited [38]. When the rate of increase in the maximum air temperature exceeds the maximum surface temperature, both winter and early spring snowpacks melt earlier [38]. Low snowmelt evapotranspiration can lead to a rapid increase in soil moisture, resulting in a loss of effective water from early spring runoff, reducing the available effective water in the soil during the growing season and beyond, thus affecting the subsequent growth [38]. The high-altitude Dahurian larch tree-ring width index in May of the current year exhibited a significant positive correlation with temperature, a significant positive correlation with the minimum temperature minima, maximum temperature minima, and number of warm night days, and a significant negative correlation with the number of cold day days. This indicates that in the early part of the growing season, temperature is the main factor limiting tree radial growth, with elevated temperatures observed as favorable for tree radial growth, and vice versa. This is because temperatures lower than the optimal temperature for tree growth during the growing season will affect plant development, and low nighttime temperatures will cause plant frostbite [39]. The results of this study are in agreement with those of Shang et al. [40], who demonstrated the impact of low temperatures in the growing season. Prior to the abrupt climate change, the Dahurian larch tree-ring width index exhibited a significant positive correlation with the minimum temperature minima and a significant negative correlation with the number of cold night days in August of the current year. After the change, the promotion of temperature on larch growth weakened, indicating that in the growing season of Dahurian larchs, the enhancement of radial growth of larch was weakened by the increase in the temperature of the study area. This may be because in August, the temperature of the study area increased more than the larch optimum growth temperature during the growing season. This is linked to the acceleration of soil evaporation and water loss, as well as the increased vapor pressure difference, due to high temperatures during the growing season [41], resulting in insufficient soil moisture. In addition, the tree root system will not receive sufficient water to limit the radial growth of the tree [34], and extremely high temperatures during the growing season will also lead to high leaf temperatures that exceed the optimal temperature for photosynthesis. This reduces net photosynthesis and drives transpiration in vegetation, resulting in a water deficit in trees [42]. The greater temperature in August compared to the optimal growth temperature for larch may be linked to the increased temperature in the study area, which exceeds the optimal growth temperature for larch [42]. When the temperature surpasses the physiological threshold of trees [43], respiration increases, the photosynthetic rate decreases, and the photosynthetic organic matter in the body decreases, which negatively affects tree growth [44]–[46]. Therefore, high daytime temperatures are also unsuitable for tree radial growth. In October of the current year, the radial growth rate of larch exhibited a significant negative correlation with precipitation, while the temperature in the study area increased, and the extreme temperature indices (TX10p, TN10p, FD, ID) showed a decreasing trend, possibly prolonging the growing season of plants. As the growing season lengthens, the likelihood of plants experiencing frost damage increases [47]–[48]. In particular, compared to trees at low latitudes, high-altitude trees have narrower safety thresholds for frost and are thus at a greater risk [49].

At high altitudes, after a sudden change in temperature, Mongolian pine showed a significant positive correlation with precipitation and a significant positive correlation with the minimum temperature minima in May of the current year. This indicates that in the early part of the growing season, the increase in precipitation and minimum temperature favored the radial growth of trees. The sampling site is located in the northwestern part of the Greater Khingan Range, and the increase in minimum temperature advanced the activity of the formation layer [50] and also promoted xylemogenesis [51]. Thus, the minimum air temperature minima at the beginning of the growing season was significantly positively correlated with tree growth. This is in line with the findings of Li Junxia et al., who revealed that the positive response of trees to temperature has become more pronounced in the northern part of the Greater Khingan Range, with a significant increase in temperature in recent decades [43]. After a sudden change in temperature, the high-elevation area Mongolian pine exhibited a significant negative correlation with the number of cold day days in June of the current year, a significant negative correlation with the number of cold night days in July of the current year, and a significant positive correlation with the minimum temperature minima. This suggests that in the growing season of Mongolian pine at high elevations, cold days and nights are the main environmental factors limiting the growth of the trees. High temperature promotes photosynthesis, and in general, during the growing period of trees, the temperature is positively correlated with the width of the tree whorl within the range suitable for tree growth, and the temperature becomes the main climatic factor affecting tree whorl growth [45]. In September of the current year, Mongolian pine displayed a significant positive correlation with the maximum temperature maximum and the number of warm day days, and a significant negative correlation with the minimum temperature maximum. This indicates that with the prolongation of the growing season in September of the current year, the increase in midday temperature facilitated tree growth. In contrast, the enhanced nighttime temperature did not have this effect, perhaps due to the increase in respiration intensity, which is not conducive to the accumulation of organic matter in the plant.

At low altitudes, following a sudden change in temperature, larch exhibited a significant positive correlation with temperature in May of the current year, as well as with the maximum temperature minima and number of warm night days, and a significant negative correlation with the number of cold day days. This indicates that high temperatures at the early stage of tree growth favored the radial growth of trees, while low-temperature events limited tree growth. The sampling site was located in the northwestern part of the Greater Khingan Range, and the increase in minimum temperature advanced the activity of the formation layer [50] and promoted xylemogenesis [51], and thus the increase in temperature at the beginning of the growing season was significantly and positively correlated with tree growth. High soil temperatures facilitate the absorption of water and inorganic salts by the rootstocks, which favors cell division in the tree's formative layer and leads to wider annual rings. However, it is detrimental to tree growth and narrower annual ring widths [45]. Trees perform numerous activities within a certain temperature range, and under the optimal temperature conditions, these activities are the most vigorous, the photosynthesis efficiency is the highest, and the growth is the fastest [52]. Suitable temperatures enhance photosynthesis in trees, which increases the net accumulation of tree nutrients, leading to rapid tree growth and the formation of wide whorls in the current year [53]. This is in line with the results of Junxia Li et al., who reported that the positive response of trees to temperature in the northern Greater Khingan Range has become more pronounced with the significant increases in temperature in recent decades [43].

For the low elevation area, we observed that in July of the current year, the correlation between the Dahurian larch width index and the minimum temperature extreme value changed from a significantly positive before the temperature mutation to a negative correlation after. Moreover, in September of the current year the larch exhibited a significant negative correlation with the average temperature and minimum temperature extreme value.

In July of the current year, larch was significantly positively correlated with precipitation, and in September of the current year it was significantly negatively correlated with the minimum temperature extreme value. This indicates that under the significant warming of the study area, the increase in temperature led to a slowdown of the radial growth rate of larch in the low altitude area. Summer is the highest period of cell production in coniferous species [54], and is also a critical stage for Dahurian larch to synthesize carbohydrates and undergo rapid growth [55] Moreover, the tree needs to consume a large amount of water to meet its metabolic needs while growing rapidly in the summer [49] However, high temperatures in the summer enhance the evaporation of the soil water content. Increasing soil water loss and raising the vapor pressure difference resulted in insufficient soil moisture, reducing the available water for trees. As a consequence, the root system of trees could not get enough water and limited the radial growth of trees [56]. In addition, in warm regions, high temperatures may accelerate the water evaporation and transpiration of trees, which reduces the available water in the soil. This result was the same as that of Yuan Yujiang et al [57]. In May of the current year, the low altitude area of Mongolian pine exhibited a significant positive correlation with precipitation, and a significant positive correlation with the number of warm night days and minimum temperature minima. This reveals that in the low altitude area, temperature and precipitation are the main factors limiting Mongolian pine's growth during the pre-growing season, and the increase in temperature and precipitation is favorable to the growth of this species. At this time, rising temperatures advance the growing season, and the pine ends its "dormant" state earlier. This is conducive to the tree's absorption of water and inorganic salts and accelerates its growth, which agrees with the results of Jiang Qianqian et al. [45].

In conclusion, global warming has a great impact on the growth of larch and pine in the Greater Khingan Range region, and the drought stress caused by high temperatures is the main factor affecting the growth of larch and pine in the growing season. As the growing season lengthens, the likelihood of larch experiencing frost damage in winter increases. Larch at higher latitudes are at greater risk of frost damage compared trees at lower latitudes. With global warming, the radial growth of Dahurian larch and Mongolian pine in the study area exhibited a differentiated response to extreme temperatures. This suggests that close attention should be paid to the stability of the response of tree growth to extreme climatic elements when carrying out tree-ring climatology studies on the influence of forest ecosystem development trends in the Greater Khingan Range region.

Declarations

Statement

All authors in this paper declare that all experiments in the paper comply with relevant institutional, national, and international guidelines and legislation.

Author Contribution

Xiaohan Zhang wrote the paper and analyzed the data. Dongyou Zhang put forward some suggestions for revision of the paper.Zhaopeng Wang, Taoran Luo and Xinrui Wang collected the data needed for the article.

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Figures

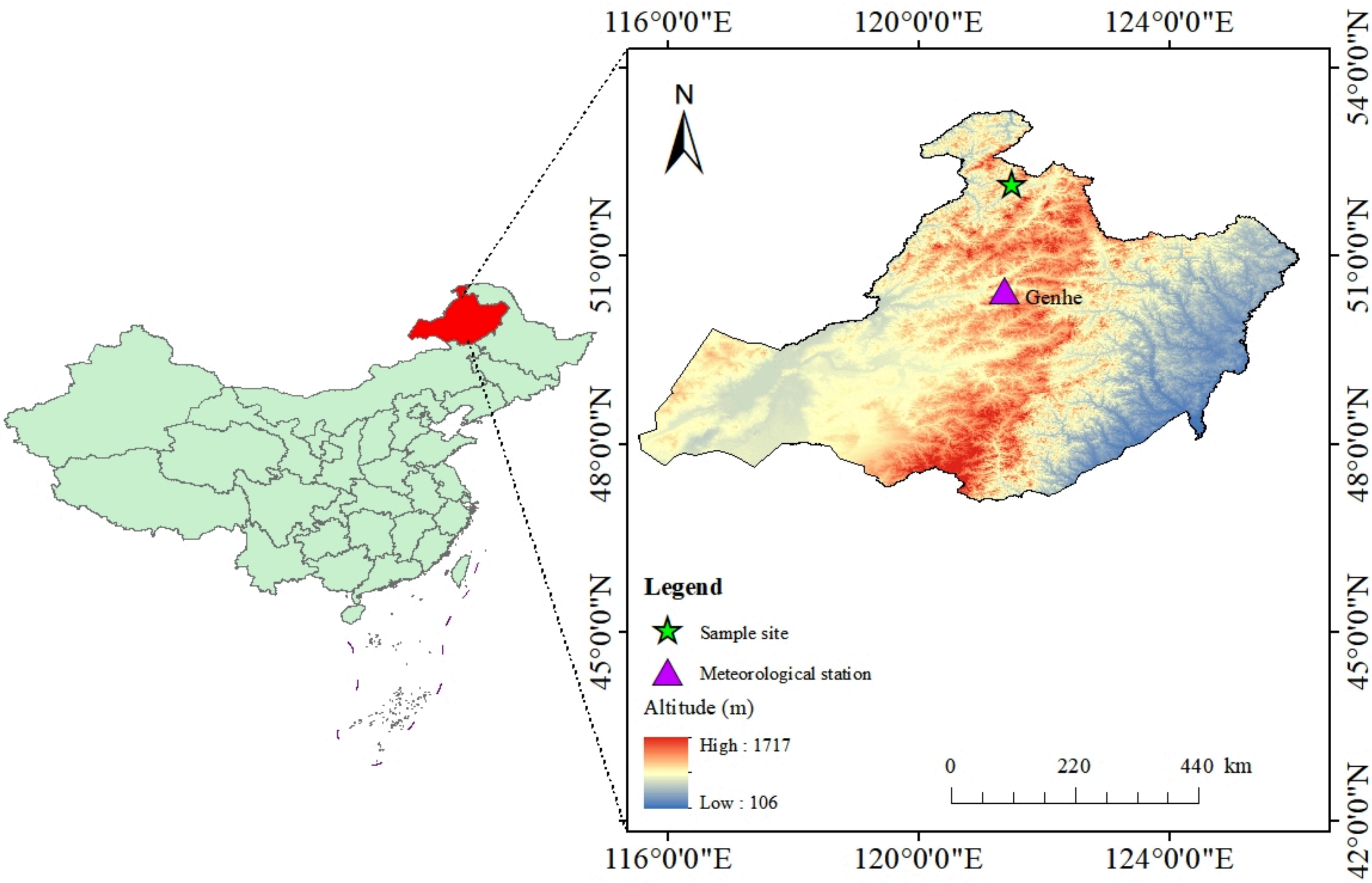

Figure 1

Location of sample site

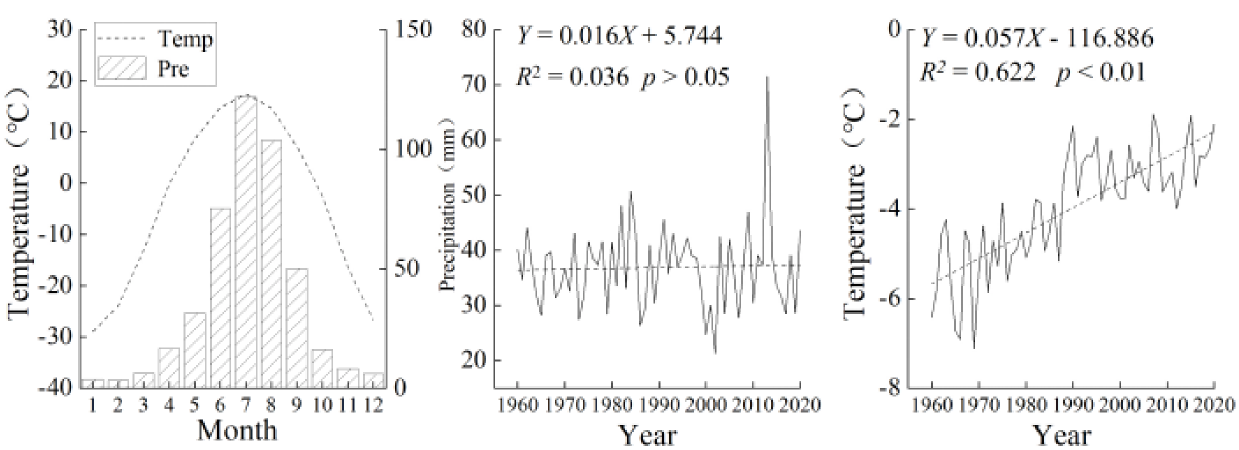

Figure 2

Monthly mean temperature, precipitation distribution and annual mean temperature variation trends of the Tulihe meteorological station

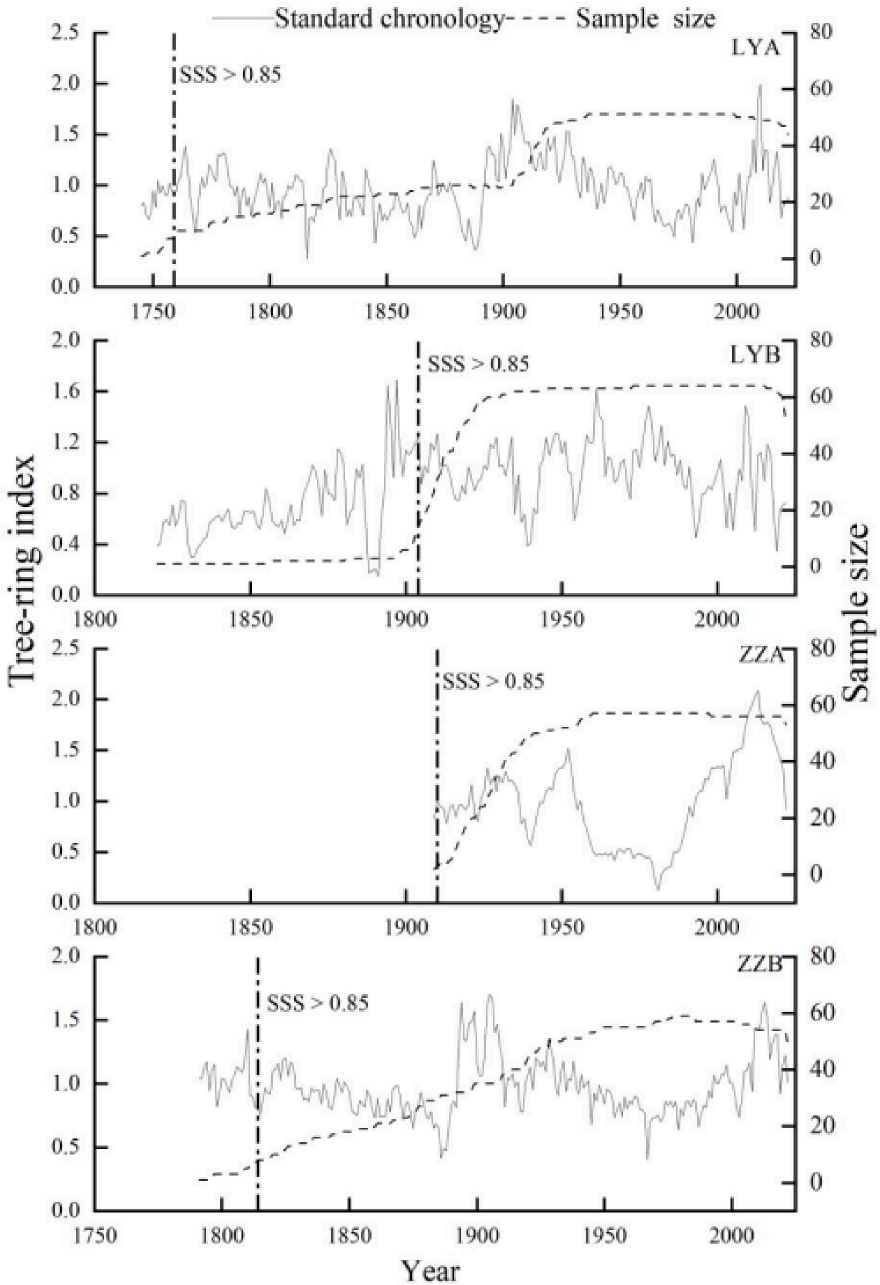

Figure 3

Standardized chronology of tree ring widths at four sampling points in the Genhe area of Greater Khingan Range

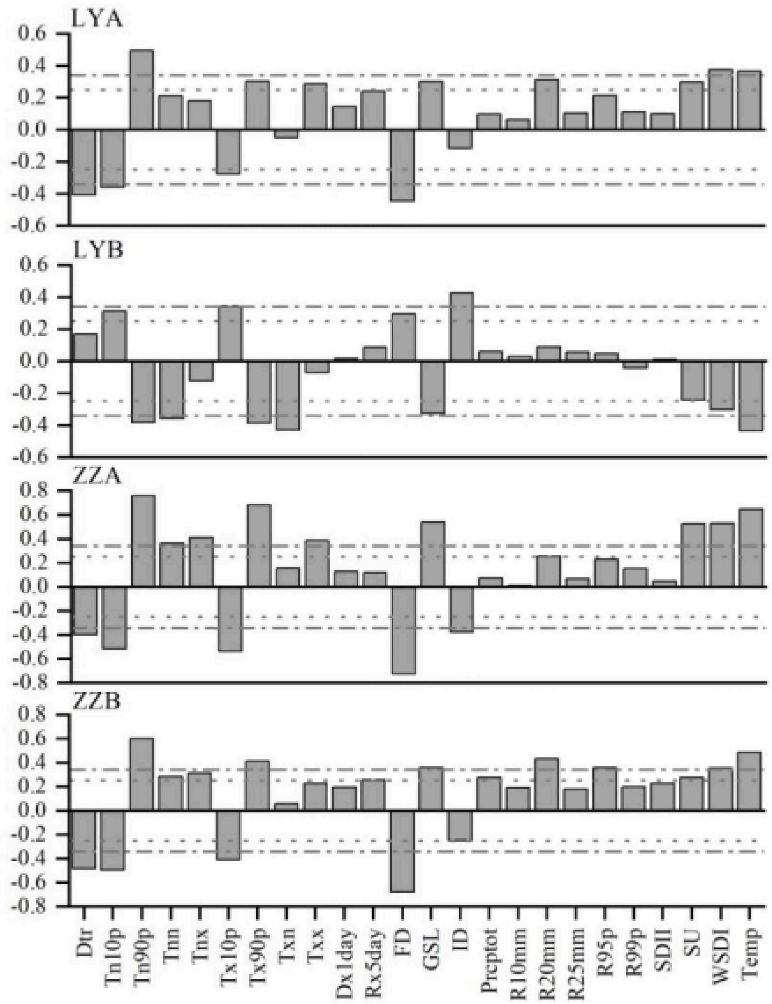

Figure 4

Correlation between the standard chronology and average annual climate index

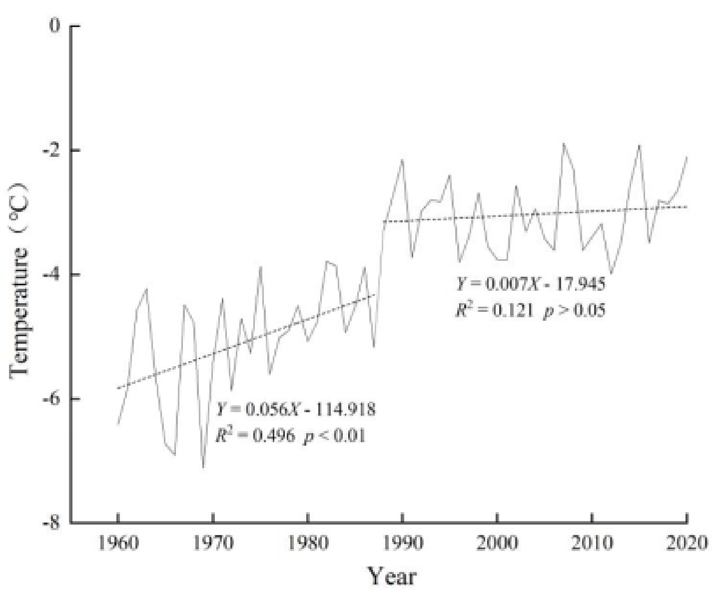

Figure 5

Variations in the average temperature before and after the sudden temperature change

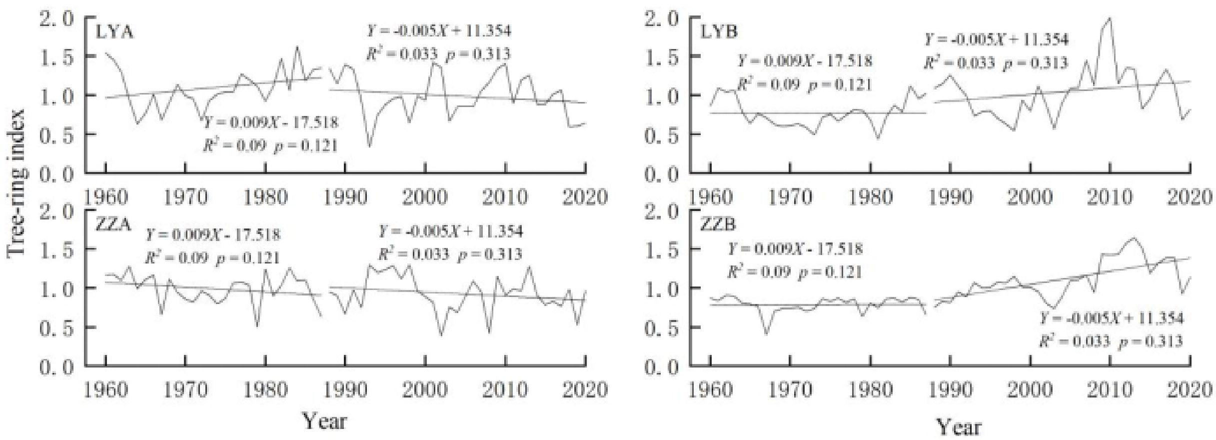

Figure 6

Exponential trend of tree ring width at the four sampling points around 1987

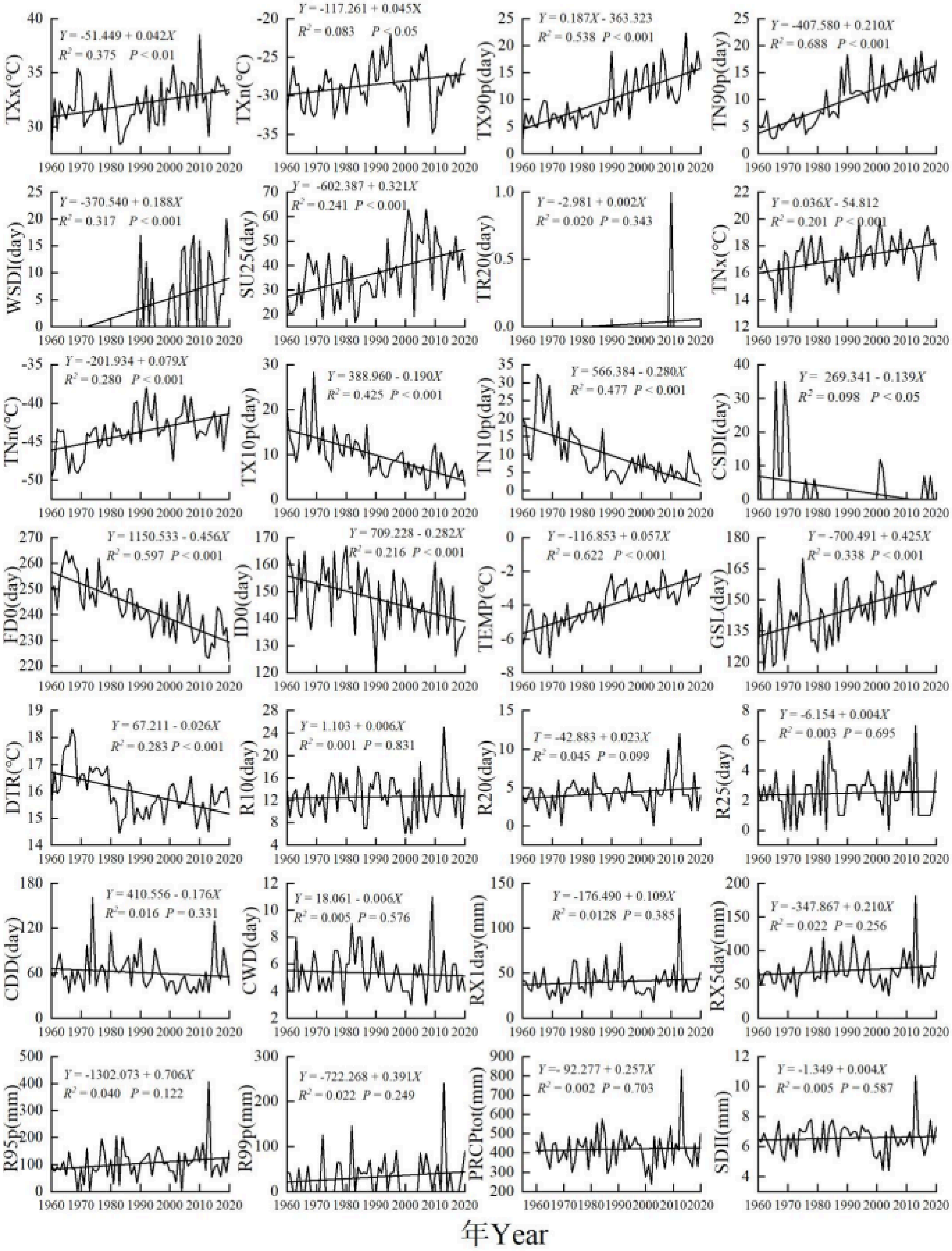

Figure 7

Inter-annual variation of extreme climate indices in the study area

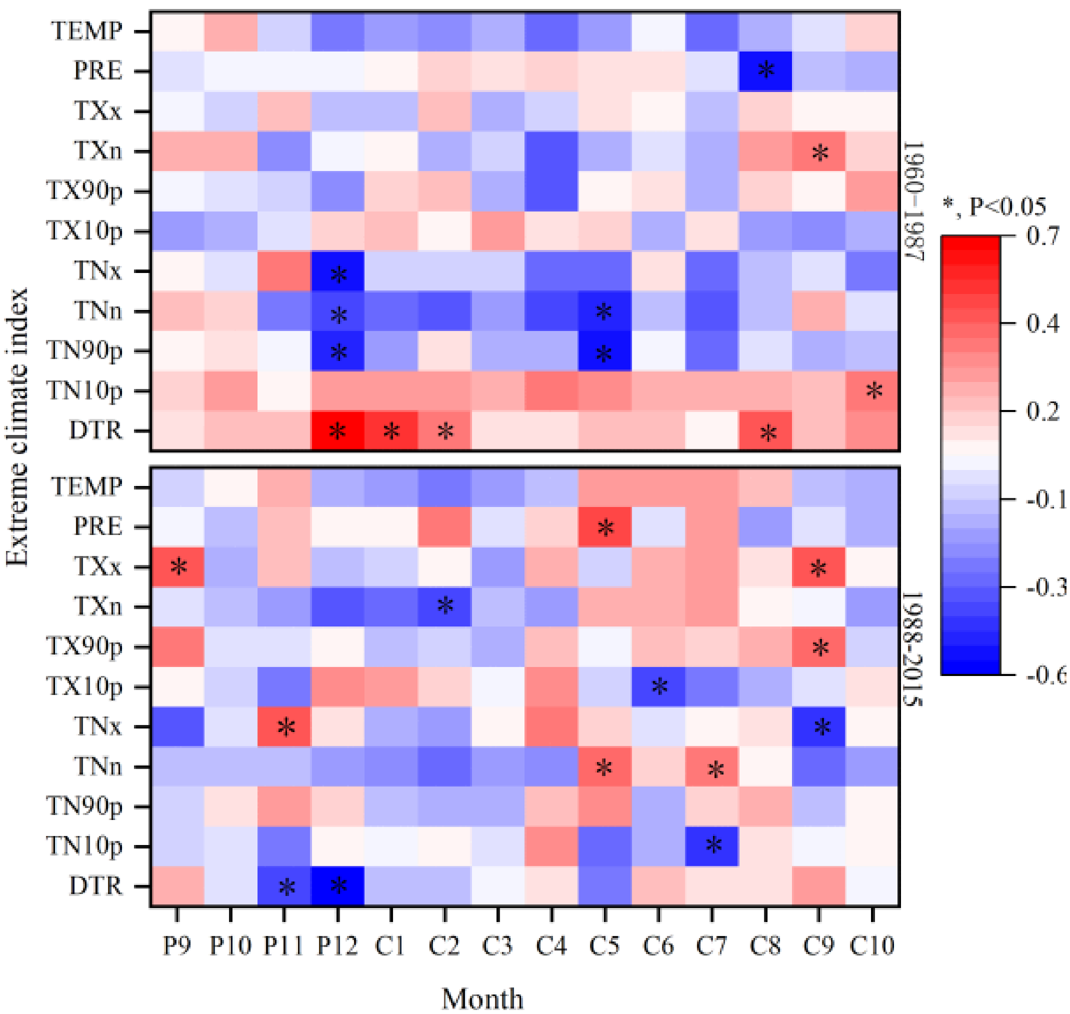

Figure 8

Correlation between the standardized chronology of the tree wheel width (ZZA) and climatic indices for high-elevation Mongolian pine pine trees

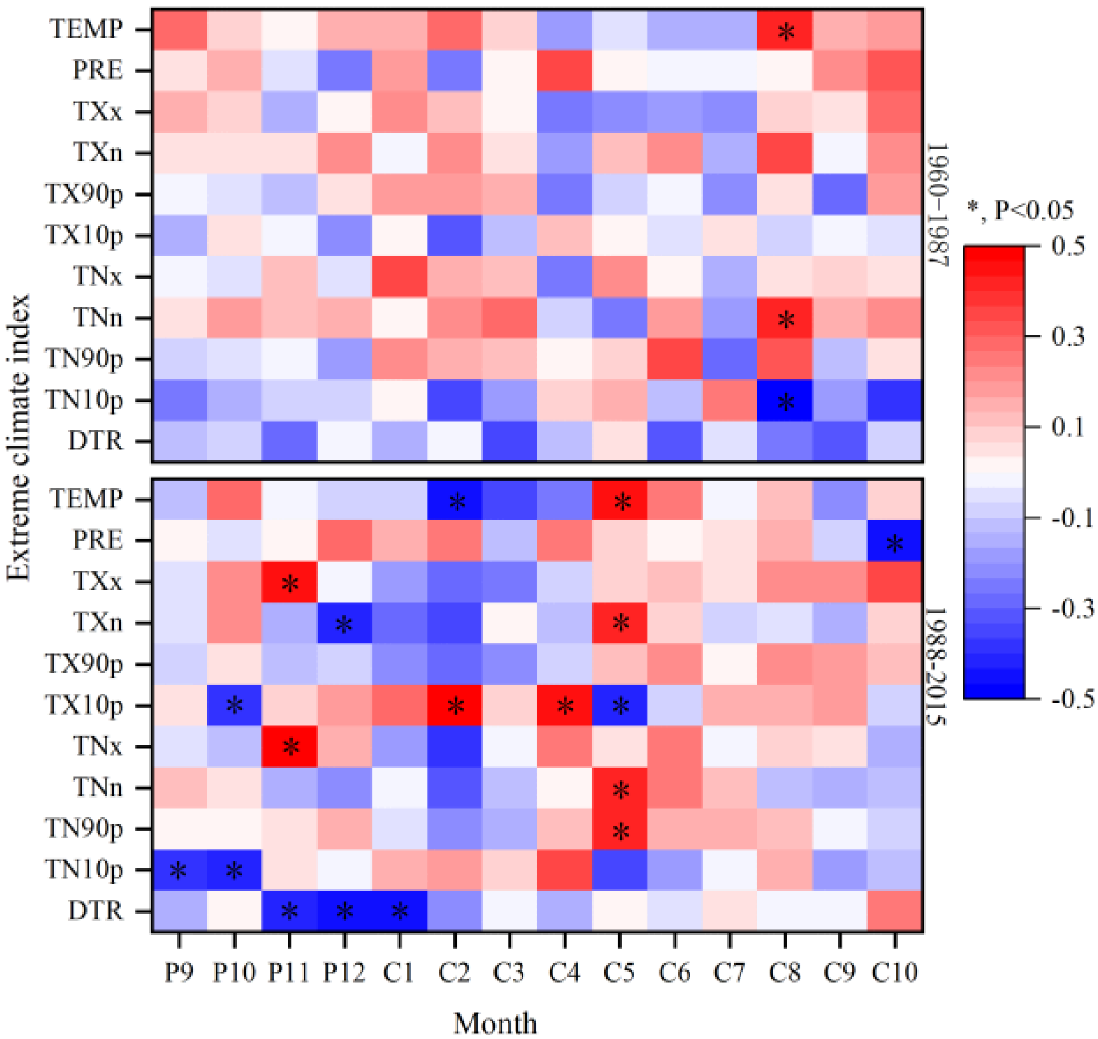

Figure 9

Correlation between the standardized chronology of the tree wheel width (LYA) and climate indices in high-elevation Dahurian larchs

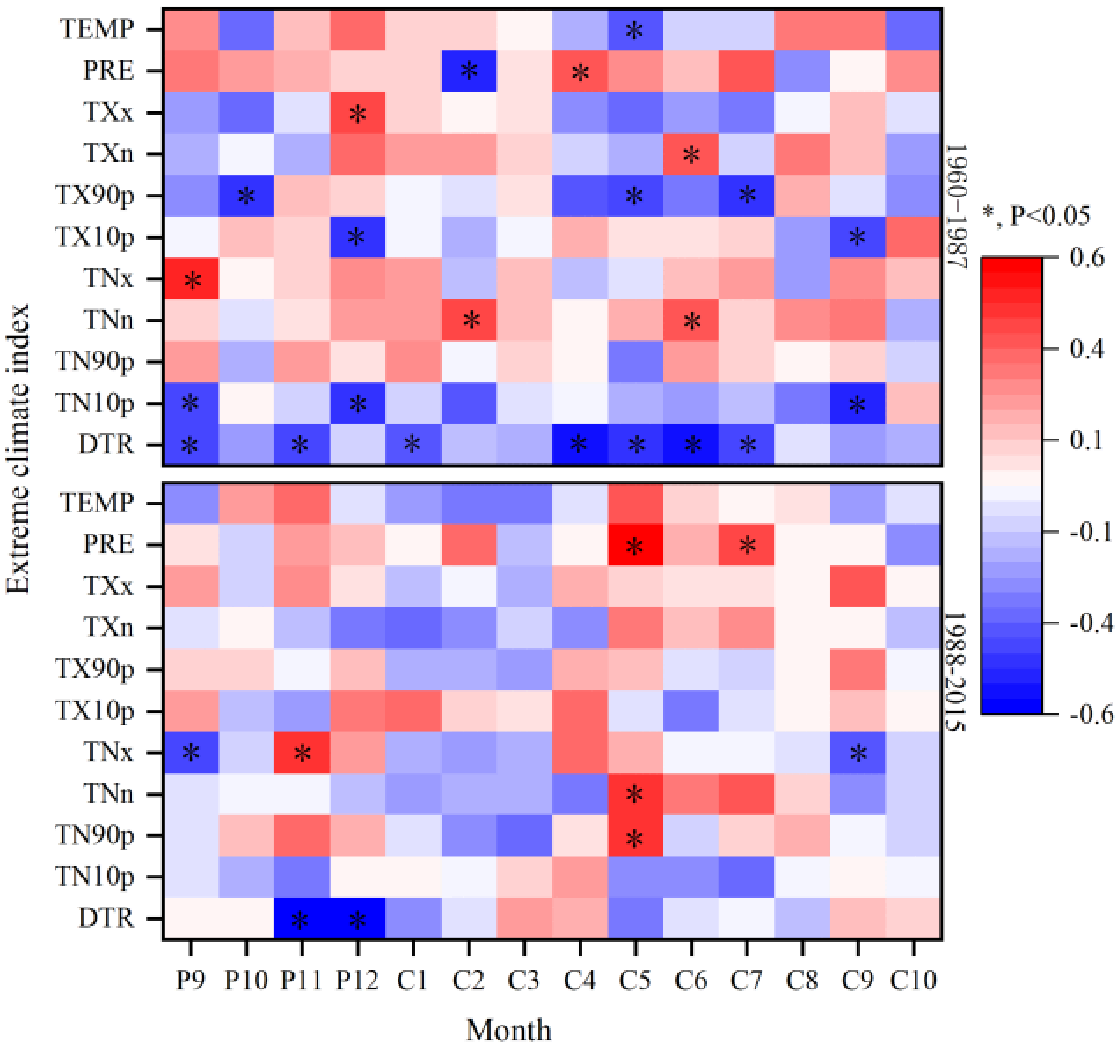

Figure 10

Correlation between the standardized chronology of the tree wheel width (ZZB) and climatic indices for low-elevation Mongolian pine pine trees

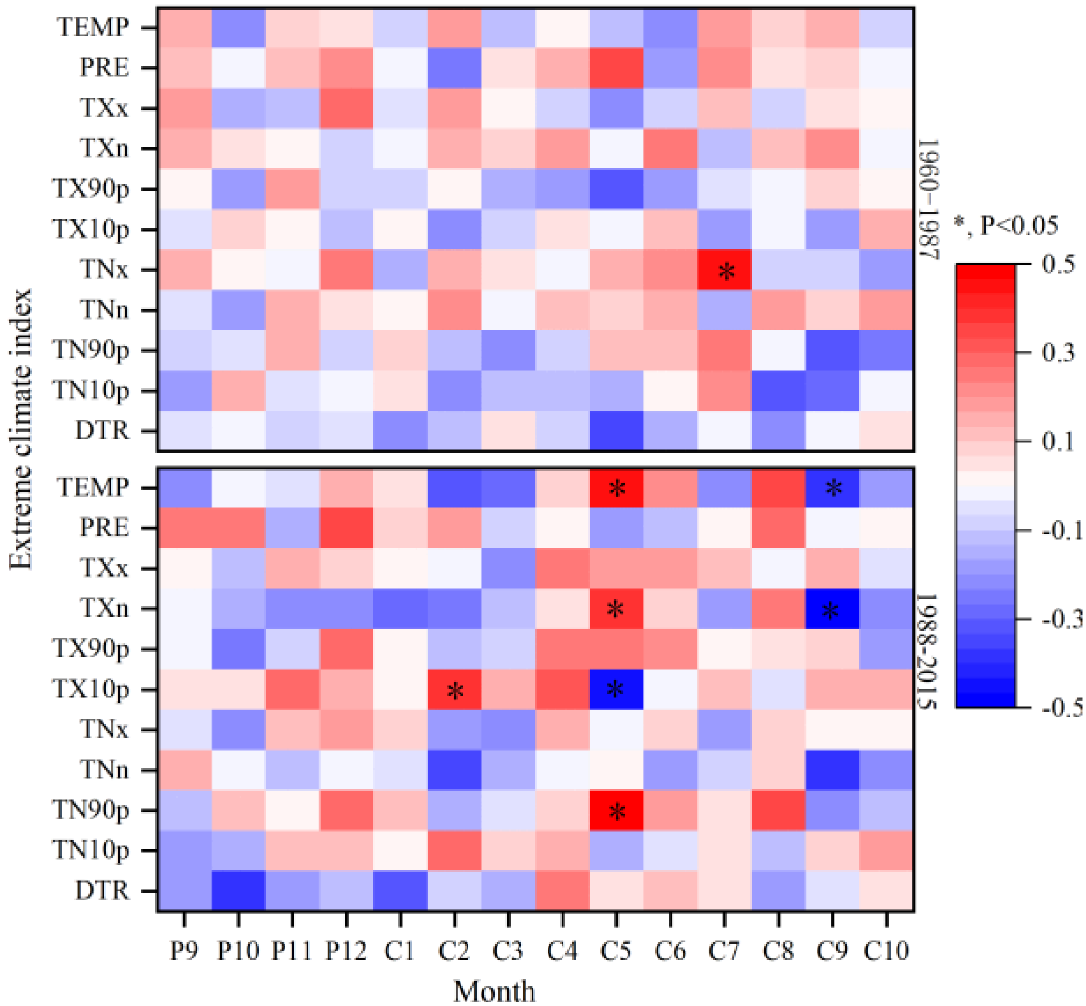

Figure 11

Correlation between the standardized chronology of the tree wheel width (LYB) and climate indices in low-elevation Dahurian larchs