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Assessment of non-stationary tree growth responses in the forest-tundra and southern taiga of central Siberia

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ABSTRACT

Anthropogenically induced climate change largely affects the functioning of vegetation communities worldwide. In the world's largest land biome, the boreal forest, a persistent decoupling of tree growth from rising summer temperatures has been recorded in recent decades. This so-called 'Divergence Problem' (DP) has been studied over the past 30 years, yet the causes and spatial patterns within the boreal forest zone are not well understood. Here, we present tree-ring evidence on varying DP in *Larix gmelinii* from the globally northernmost forest island on Taymyr Peninsula and *Larix sibirica* from the southern taiga in central Siberia. Tree-ring width and maximum latewood density data reveal DP to be substantially stronger in the south indicating that growth-climate relationships in Siberian larch passed beyond a tipping point under warmer climate and increased anthropogenic pressure. In the north, the temperature signal remained strong and temporally stable underscoring the skill of tree-ring chronologies for long-term climate reconstructions. These findings highlight the heterogeneity of tree growth responses to global warming within the boreal forest zone, from which spatially varying consequences for carbon and water cycle dynamics must be expected. Our study emphasizes the importance of updating tree-ring chronologies in remote regions within boreal forest zone to foster understanding of spatiotemporal patterns in biomass allocation, permafrost degradation, and DP across this large biome.

1. Introduction

Constantly increasing anthropogenic activity induces local to global environmental and climatic changes that largely affect the functioning of ecosystems worldwide with numerous consequences for terrestrial vegetation (Newbold et al., 2015; Piao et al., 2020; Weiskopf et al. 2020). Exceptionally vulnerable boreal forests are currently experiencing unprecedented rates of recent warming and increased frequency of weather extremes, intensity of wildfires, rates of permafrost degradation, scale of logging and technogenic emissions, etc. (Anisimov and Reneva, 2006; Box et al., 2019; Gauthier et al., 2015; Kharuk et al., 2021; Ponomarev et al., 2016, 2023; Anisimov, 2007; Holloway and Lewkowicz, 2020, Kirpotin et al., 2021). The effect of all these factors and processes may already be observed in the current status of different components of boreal forest ecosystems, including trees (Tei et al., 2017).

Tree radial growth at the circumpolar high latitude forest belt in the northern hemisphere was shown to be presumably limited by temperature variability (Jacoby and D'Arrigo, 1989; Anchukaitis et al., 2017; Björklund et al., 2023; Briffa et al., 2004; Büntgen and Esper, 2024; Davi et al., 2003; Vaganov et al., 1996, 1999). In recent decades, however, the decoupling of tree growth in these ecosystems to rising instrumental summer temperatures, the so-called 'Divergence Problem' (DP) (D'Arrigo et al., 2008), has been observed in high- or low-frequency

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domains or both. The DP questions the ability of northern forests to increase biomass productivity rates following the current warming. If the DP becomes a widespread phenomenon, it will also have great implications to the ability of tree-ring data to serve as a proxy for temperature during past warm periods (Büntgen et al., 2021a) and predict future response of forest growth to rising temperature (Camarero et al., 2021).

DP was first reported by Jacoby and D'Arrigo (1995) for white spruce in Alaska and lately described for a variety of sites and tree species, mostly in high-latitude and high-elevation ecosystems (see D'Arrigo et al., 2008 for a review). The evidence of the DP as a widespread phenomenon in circum-polar high latitude forests was provided from the analysis of tree growth regional composites in northern hemisphere (Briffa et al., 1998; Wilson et al., 2007). The DP was also found in several high-elevation forests in lower latitudes (Jiao et al., 2015; Li et al., 2020; Zhang et al., 2009). However, some studies since then show that the DP is not observed in all temperature limited sites, implying that the DP is a spatially heterogeneous phenomenon (Anchukaitis et al., 2013, 2017; Büntgen et al., 2021a; Yin et al., 2021).

Potential causes for the DP were detailed in D'Arrigo et al. (2008), and they include a number of biological and environmental issues: increased limiting effect of drought on tree growth that overcomes the influence of temperature, non-linear tree radial growth response to rising temperature under changing environment, changes in stratospheric ozone concentration. The choice of the correct target temperature variable was also related to the DP emergence. The dependence of the DP emergence on methodological pitfalls associated to tree-ring chronology development and the quality and applicability of the instrumental temperature measurements were reviewed by Esper and Frank (2009) and Frank et al. (2007). Recently, the role of industrial pollution and Arctic dimming as a major factor for the DP was examined in an extended portion of the high-latitude boreal forest belt in Siberia (Kirdyanov et al., 2020a; Büntgen et al., 2021b). However, the current understanding of the scale and causes of the DP, as well as the consequences of this phenomenon are far from being complete.

Here, we analyze tree-ring width (TRW) and maximum latewood density (MXD) data from two latitudinally distant forest regions in central Siberia to test tree growth for the loss of sensitivity to temperature under progressively warming climate and increasing anthropogenic pressure. We define the timing and the scale of the DP at these ecologically different environments and discuss the obtained results with respect to possible reasons and consequences of the DP.

2. Materials and methods

Wood samples were collected in two vegetation zones of boreal forest in central Siberia with considerably different climate conditions: forest-tundra ecotone and southern taiga (Fig. 1). Climate in the study area is characterized as extremely continental, with low annual mean temperatures of −12.5 °C in the northern region (WMO 20891 'Khatanga'; 1929–2022) contrasting to much warmer, but still negative mean annual temperatures of −1.7 °C in the southern region (WMO 29263 'Yeniseisk'; 1871–2022 and −1.3 °C during 1929–2022). The warmest and coldest months in both regions are July and January with monthly temperatures 12.6 °C and −32.1 °C in forest-tundra and 18.3 °C and −21.9 °C in southern taiga (18.5 °C and −21.5 °C for 1929–2022), respectively. Annual precipitation totals are around 280 mm in forest-tundra and around 480 mm in southern taiga, of which 42 % and 38 % fall during summer months (from June to August), respectively.

Summer (June–August) and annual temperature means at the forest-tundra region were first relatively stable or slightly decreasing from 1929 to 1989 at a rate of −0.04 ($P > 0.01$) and −0.20 °C/decade ($P > 0.01$), respectively (Fig. 1). From the 1990, temperatures are increasing by 0.86, and 1.01 °C/decade in summer and annually, respectively ($P < 0.005$). In southern taiga, seasonal temperature means exhibited slight increases from 1871 to 1969 with 0.05 °C/decade ($P > 0.01$) in summer and annually, and the increase accelerated since 1970 to 0.31 and 0.51 °C/decade ($P < 0.0001$) for summer and annual temperature means, respectively. The 1st order autocorrelation coefficients for summer temperature are 0.26 and 0.23 for forest-tundra and southern taiga, respectively, but it increases to 0.31 for May–August temperature in southern taiga. Annual and seasonal precipitation totals in both forest-tundra and southern taiga do not show statistically significant changes ($P > 0.01$).

The dominant tree species in northern central Siberia is *Larix gmelinii* (Rupr.) Rupr. (Abaimov et al., 1997; Tolmachev, 1931). In the south, larch is represented by *Larix sibirica* Ledeb. In 2010–2011, we collected wood cores at two sites in forest-tundra (FT1 and FT2, 72.5°N and 102.0°E) and one site in southern taiga (ST, 58.5°N and 92.0°E) (Table 1) to represent different tree growth conditions for *Larix* spp. in central Siberia. The distance between the regions is > 1600 km, and while the FT sites were established at the world's northernmost forest

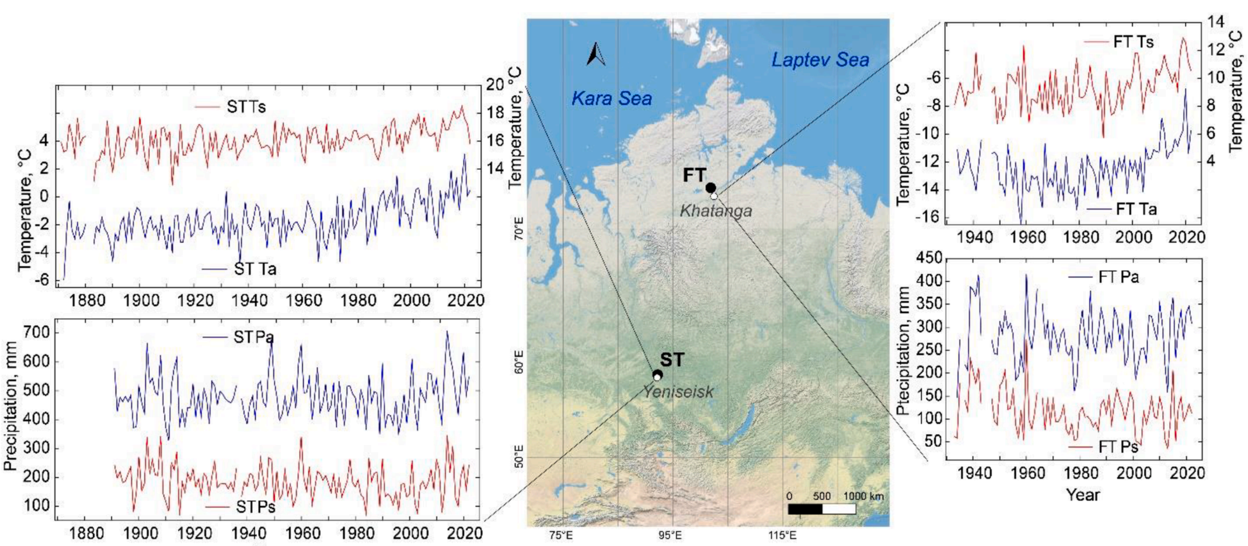

Fig. 1. Study sites and climate data. The map shows the location of tree-ring sites (black circles) and meteorological stations (white circles). The diagrams show summer (red) and annual mean (blue) temperatures and precipitation recorded at the Khatanga and Yeniseisk meteorological stations near the FT and ST tree sites. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Chronology characteristics (TRW = tree-ring width, MXD = maximum latewood density, MSL = mean segment length, Rbar = inter-series correlation. 1st order autocorrelation were calculated for the regional chronologies for the period of the available temperature data from the nearest meteorological stations Khatanga and Yeniseisk).

Region	Site	Tree-ring parameter	N of series	Period, years	MSL	Mean ± SD	Mean sensitivity	1st order autocorrelation
Forest-tundra	FT1	TRW	14	1708 – 2010	125	0.42 ± 0.28 mm	0.48	
	FT2	TRW	14	1924 – 2011	74	0.44 ± 0.25 mm	0.32	0.46
	FT3	TRW	41	1582–2019	217	0.26 ± 0.19 mm	0.58	
	FT1	MXD	14	1708–2010	125	0.85 ± 0.13 g/cm^3	0.16	
	FT2	MXD	14	1924–2011	74	0.79 ± 0.11 g/cm^3	0.12	0.36
Southern taiga	ST	TRW	24	1711–2021	131	1.05 ± 0.54 mm	0.22	0.64
	ST	MXD	15	1770–2009	126	1.01 ± 0.10 g/cm^3	0.05	0.37

island Ary-Mas characterized by harsh climate, the conditions at ST are milder (Fig. 1). Wood cores from these sites were used to measure tree-ring density profiles and obtain MXD data according to the standard procedure (Schweingruber, 1988). To update the tree-ring chronologies, the additional dendrochronological site was established in the forest-taiga region in 2019 close to the existing sampling plots, and the southern taiga site was revisited in 2022. The wood material from 2019 to 2022 was used for tree-ring width (TRW) measurements on a LINTAB measuring system (RINNTECH e.K., Heidelberg, Germany). The obtained individual series were visually cross-dated using the TSAP-win (Rinn, 2003). Cross-dating was statistically verified with COFECHA (Version 6.02P; https://www.geog.cam.ac.uk/research/projects/dendrosoftware/.

Individual TRW series were standardized with negative exponential line using the ARSTAN software (https://www.geog.cam.ac.uk/research/projects/dendrosoftware/, last accessed on 14.02.2024). For MXD series, cubic smoothing splines with 50 % frequency-response cutoff at 2/3 of the individual series length were used. Bi-weight robust means of the individual measurement series were used to produce dimensionless index chronologies. The standard version of the chronologies was chosen for most of the further analyses. The residual version was only used for correlating with monthly and seasonal precipitation totals, which do not show statistically significant changes. For the forest-tundra region, we developed three local TRW and two MXD chronologies, which have different sample depth (Table 1) and were highly significantly correlated (at least $P < 0.001$). To avoid overweighting the influence of the site with the higher sample replication, we first developed local chronologies individually and then averaged the local index chronologies into regional chronologies for FT. In the southern taiga region, tree-ring parameter chronologies were obtained for the combined material from the two field campaigns. To estimate the quality of the chronologies, their standard dendrochronological statistics were calculated: the coefficient of sensitivity, 1st order correlation coefficient and expressed population signal (EPS).

To assess the climate sensitivity of the TRW and MXD chronologies, Pearson's correlation coefficients were calculated against monthly temperature means and precipitation totals from the nearest meteorological stations (Fig. 1) from previous year September to September of a current year. June–July (JJ) and summer (JJA) temperatures in forest-tundra and summer and May–August (MJJA) temperatures in southern taiga, as well as total precipitation during summer (JJA) and the season with mean monthly temperature below 0 °C (w) were used to assess seasonal climate influences. For the cold season, precipitation totals were calculated from previous September to current year May in forest-tundra and from previous October to current year April in southern taiga. To evaluate the temporal stability of the relations between tree-ring chronologies and climate records, we used the running correlations calculated for a 31-year window with one-year step. For this, we mostly used temperature means for at least two warm months (including May in southern taiga) as the variables most correlated with tree-ring data. Finally, spatial correlation between the MXD chronologies and gridded seasonal temperature means (CRU TS4.07, Harris et al., 2020) were calculated for the first and last ~ 40-year long periods of the available instrumental temperature measurements from the nearest meteorological stations and covered by MXD data. For this, the temperature variables correlating the highest with the regional MXD chronologies were used. In the forest-tundra region, we slightly increased the window for the spatial correlations to 41 and 42 years to cover the entire period of meteorological observations in Khatanga. Presenting spatial correlations for the same period starting in 1901 for the two studied sites is not reliable because of lack of valid temperature records in the forest-tundra region that correctly represent conditions before the installation of the meteorological station in Khatanga.

3. Results

The regional TRW and MXD chronologies from forest-tundra (FT) continuously cover the past 438 years (1582 – 2019) and 304 years (1708 – 2011), respectively (Table 1, Fig. 2). The TRW and MXD chronologies from southern taiga (ST) extend over the past 311 years (1711 – 2021) and 240 years (1770 – 2009), respectively. The mean TRW in forest-tundra varies within a wide range from 0.26 ± 0.19 mm to 0.44 ± 0.25 mm with lower values recorded for older trees and a chronology with longer mean segment length (MSL). Trees in southern taiga grow faster at a mean TRW > 1.00 mm and with denser latewood (MXD > 1.00 g/cm^3) compared to forest-tundra. The standard TRW chronologies statistics (the coefficient of sensitivity, the expressed population signal (Wigley et al., 1984) since 1867) and high correlation coefficients between local tree-ring chronologies ($P < 0.005$) in forest-tundra show that the regional chronology FT and local chronology ST are suitable for dendroclimatic analysis.

TRW indices from FT demonstrate a clear increasing trend from the mid-1990s ($P < 0.001$, from 1995), which follows the TRW decline after the peak in the 1940s ($P < 0.00005$ for the 1941–1994 period) (Fig. 2A). In southern taiga, TRW demonstrated an increase from 1949 ($P < 0.0001$ for 1949–2021), but with a drop in 2013–2016 and the following highest values in 2020 and 2021 (Fig. 2C). In general, MXD indices were relatively stable in forest-tundra from 1930s ($P > 0.05$), but with a slight decrease in the 1990s and consequent recovery (Fig. 2B). In southern taiga, MXD indices decreased from the 1910s to the early 1980s ($P < 0.0005$ for 1915–1982), then increased into the 1990s ($P < 0.05$ for 1983–1994) and decreased after the mid-1990s ($P < 0.05$ for 1995–2009).

The growth-climate response analysis of the local TRW index chronologies from forest-tundra since 1929 shows that the main factor influencing tree radial growth is July temperature (up to $r = 0.43$, $P < 0.01$ for FT2) (Fig. 3A). Dependence of TRW on summer seasonal temperature means (June–July and June–August) is site-specific, with significant ($P < 0.01$) correlations only for FT3. The correlations of the MXD index chronologies with summer monthly and seasonal temperature means are generally higher and more consistent between the sites than that of TRW, and reach $r = 0.64$, $P < 0.01$ for JJA temperature means (Fig. 3B).

The regional TRW indices in forest-tundra significantly positively correlate with mean July temperatures ($P < 0.01$) (Fig. 4A). However, MXD demonstrates higher correlations and for a longer summer period

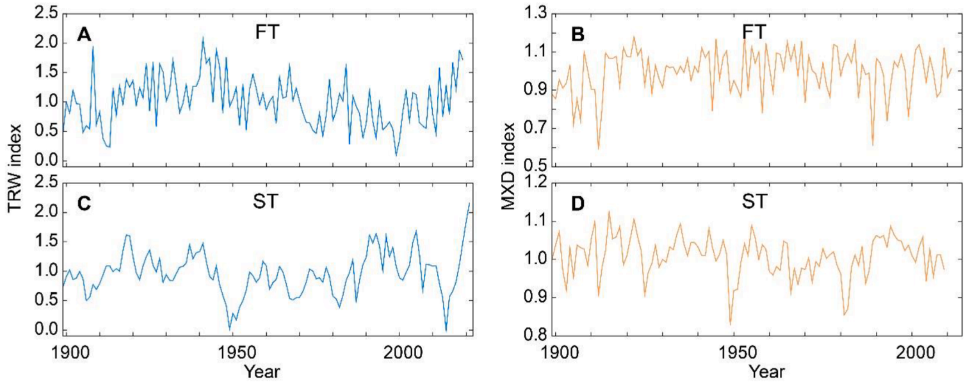

Fig. 2. Tree-ring data. Tree-ring width (A, C) and maximum latewood density (B, D) standard chronologies for the forest-tundra (FT) and southern taiga (ST) sites.

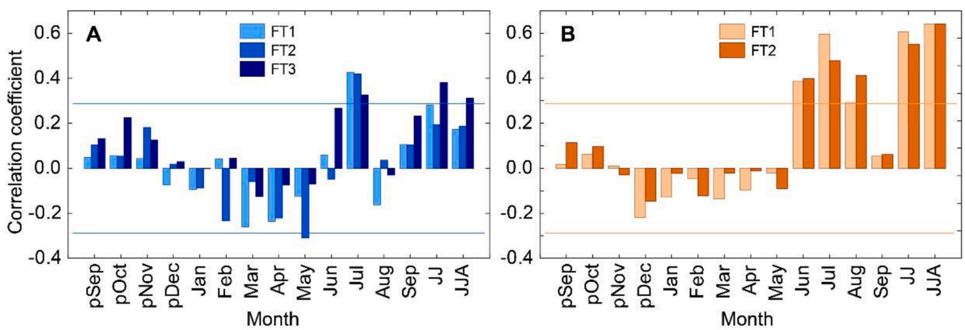

Fig. 3. Climate signals of northern local chronologies. Correlation coefficients of the local TRW (A) and MXD (B) standard chronologies in the forest-tundra with monthly and seasonal temperature means from previous-year to current-year September of ring formation (since 1929). Seasonal means were calculated for June – July (JJ), and summer (JJA). Horizontal lines indicate significance level $P < 0.01$.

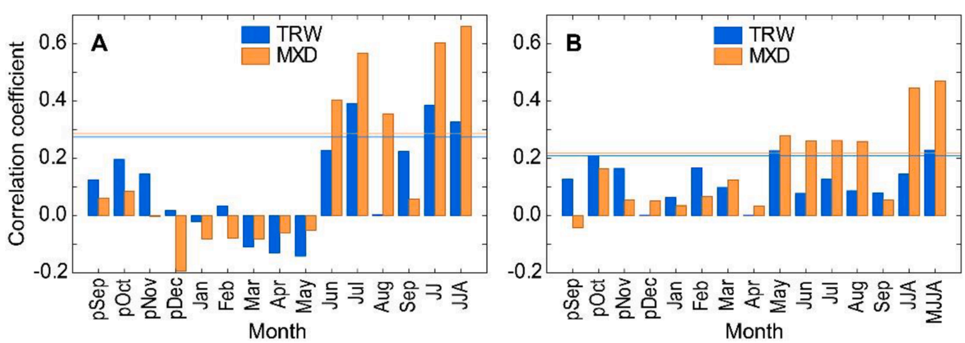

Fig. 4. Climate signals. Correlation coefficients of the standard TRW and MXD chronologies with monthly and seasonal temperature means from previous-year to current-year September of ring formation in the forest-tundra (A) (since 1929) and southern taiga (B) (since 1871) sites. Seasonal means were calculated for June – July (JJ), summer (JJA), and May – August (MJJA). Two horizontal lines indicate significance level $P < 0.01$ for TRW and MXD.

from June to August. Both the regional FT chronologies positively correlate with summer seasonal temperature means (up to $r = 0.66$, $P < 0.01$ for MXD and summer temperature). Since 1871, TRW at ST significantly correlates only with May and May-August temperature ($r = 0.23$, $P < 0.01$) (Fig. 4B). On the contrary, MXD shows a strong dependence on monthly and seasonal temperature means with the highest correlations with JJA and MJJA temperature means (up to $r = 0.47$, $P < 0.01$). The dependence of tree-ring parameters on precipitation is generally weaker (Fig. S1). Correlations of the FT chronologies with neither monthly nor seasonal precipitation totals are statistically significant ($P > 0.01$) (Fig. S1A). In southern taiga, TRW also does not show a statistically significant relation to precipitation, but MXD negatively correlates with July and summer precipitation totals ($r = -0.32$ and -0.36, $P < 0.01$, respectively) (Fig. S1B).

Running correlations of the local TRW standard chronologies from forest-tundra confirm the importance of June temperature means for tree radial growth at all the three sites (Fig. S2). However, there are inconsistencies in TRW response between the sites (Fig. S2C), and in time (for example, recent changes in correlations for FT3 (Fig. S2A and B)). MXD response to seasonal temperature means is similar at the sites FT1 and FT2, and stable in time (Fig. S3), especially to summer temperature means (JJA) (Fig. S3C). Running correlations of the regional MXD index chronology from FT with summer temperature means are high, and reach $r = 0.79$ and 0.82 ($P < 0.001$) for summer and July – August temperatures, respectively (Fig. 5A). Correlations with the mean temperature of the first two summer months (JJ) are slightly lower (mean $r = 0.63$, $P < 0.001$). Temporal stability of the temperature signal in MXD is confirmed by a vast spatial coverage of strong field

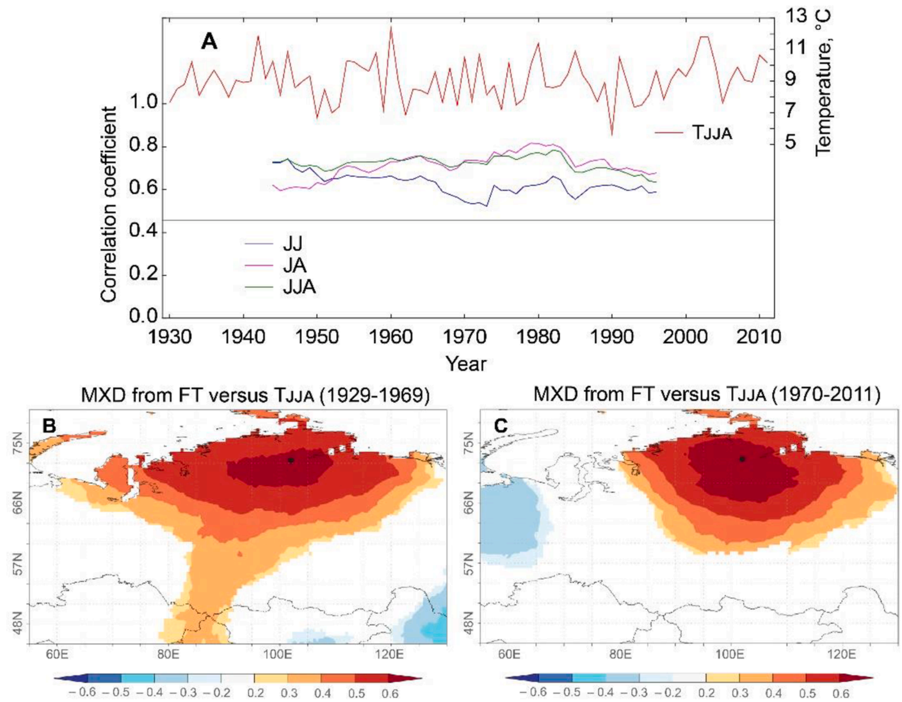

Fig. 5. JJA temperature means in Khatanga (red) with 31-year window running correlations between the maximum latewood density (MXD) standard chronology and summer month temperature means at the forest-tundra site FT (A). Corresponding correlation fields from 1929 – 1969 (B) and 1970 – 2011 (C). Horizontal line indicates the significance level $P < 0.01$.

correlations with gridded summer temperature means over the two ~ 40-year long periods (Fig. 5B and C). Over the first four decades of the available climate data in forest-tundra from 1929 to 1969, the correlations $r > 0.4$ ($P < 0.01$) reach 60°N in the south and spread between the Ob' Bay (the Gulf of Ob') in the north-west and Lena Delta in the north-east (Fig. 5B). Over the 1970–2011 period, the area covered with statistically significant correlations of the FT chronology slightly decreased in the west, but the area with highest correlations $r > 0.6$ increased in the north-to-south direction (Fig. 5C).

Running correlations of TRW from ST with May and MJJA temperature means are mostly insignificant at $P < 0.01$, except for short periods before 1910s and in the 1980s (Fig. S4). Correlations for MXD are

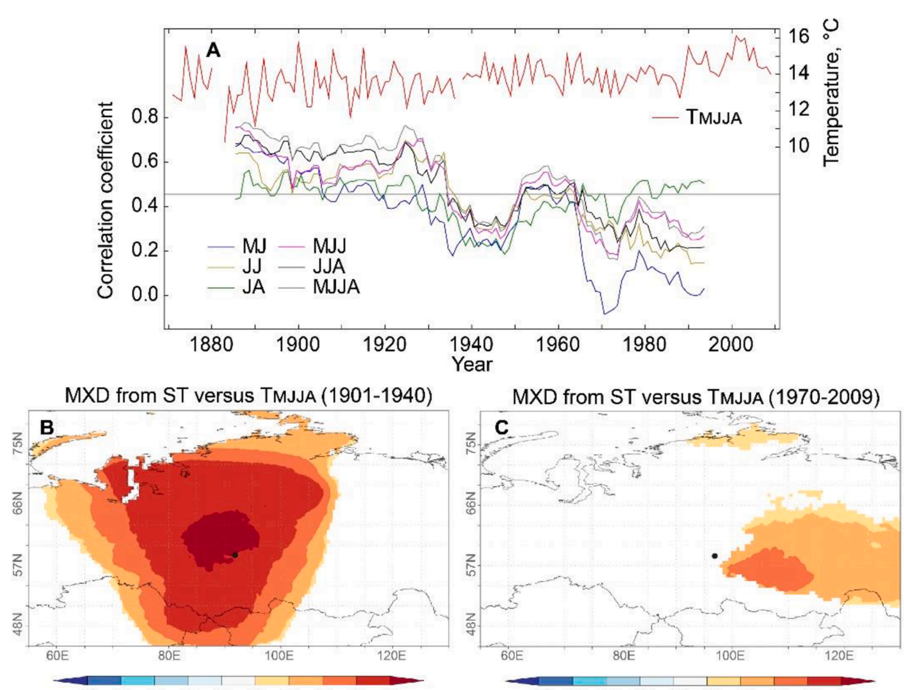

Fig. 6. MJJA temperature means in Yeniseisk (red) with 31-year window running correlations between the maximum latewood density (MXD) standard chronology and warm month (from May to August) temperature means at the southern taiga site ST (A). Corresponding correlation fields from 1901 to 1940 (B) and 1970 to 2009 (C). Horizontal line indicates the significance level $P < 0.01$.

generally high during the first decades of the 20th century and the influence of three-month and MJJA temperature means remains statistically significant ($P < 0.01$) till 1933 (r calculated for the 1918–1948 period) (Fig. 6A). The MXD dependence on MJ and JA is lower, but still mostly significant at $P < 0.01$ till the 1920s. The correlations rapidly decrease in the 1930s, but become significant for the majority of temperature means in the early 1950s for about a decade. From 1965 (r calculated for the 1950–1980 period) correlations are generally insignificant ($P < 0.01$), except for July-August mean temperatures. Over the 1901–1940 period, correlations with MJJA temperature means $r > 0.4$ ($P < 0.01$) for the southern taiga MXD chronology spread between 45°N and 75°N from south to north (Fig. 6B). The area with high correlations extends from 65°E to 105°E in the northern latitudes and from 75°E to 100°E in the south of Siberia. For the period from 1970 to 2009, low, but still statistically significant correlations were found for a remote region to the east of the study site ST (Fig. 6C). Importantly, low correlations of MXD with MJJA temperature at ST were observed already for the 1929–1969 period (Fig. S5).

Surprisingly, running correlations with monthly and seasonal precipitation totals did not identify any significant ($P < 0.01$) positive influence of precipitation on MXD during the recent decades in forest-tundra and southern taiga of central Siberia (not shown).

4. Discussion

Our results show that larch trees in forest-tundra of central Siberia are generally older and form narrower tree rings compared to southern taiga. These findings, as well as the higher sensitivity of TRW and MXD chronologies from the harsh climate at the northern treeline in comparison to tree-ring statistics from milder conditions are not surprising (Fritts, 1976). Seasonal growth of trees in northern Siberia starts later and demonstrates stronger dependence on summer temperature (Kirdyanov et al., 2024a; Bryukhanova et al., 2013; Esper et al., 2010; Kirdyanov et al., 2007; Knorre et al., 2006; Vaganov et al., 1996, 1999; Rinne et al., 2015; Büntgen et al., 2021a; Hantemirov et al., 2022; Kharuk et al., 2023c). Although the dependence of tree-ring parameters on climate variables is site-specific and may change through time, our results generally confirm these earlier findings, especially for regional chronologies. On the contrary, the effect of climate on trees growing under a more favorable temperature regime and hydroclimate in southern taiga is less pronounced, which explains the low correlation of TRW from ST with climate variables. However, MXD from the southern taiga site ST contains a surprisingly strong temperature signal confirming the superiority of this tree-ring parameter for dendroclimatology not only at high latitudes and elevations (Briffa et al., 1988, 2004; Büntgen et al., 2024), but also for the conditions with lower climate constrains of tree growth in southern Siberia.

Despite some differences in TRW responses to temperature variability at our three sites in forest-tundra, the regional TRW index chronology generally follows summer temperature dynamics, including the recent warming (see Figs. 1 and 2A). In addition, a strong response of MXD to temperature is constant in time and shows similar spatial coverage over the two consecutive ~ 40-year long periods. The absence of a marked increase of MXD in recent decades following the regional summer warming since the 1990s can be considered as the only evidence of the DP in our FT study sites. However, we have no MXD data for the most recent decade and cannot judge MXD changes during the period of the most striking temperature increase. On the contrary, the MXD record in the southern taiga site demonstrates a strong decline of latewood formation dependence on late spring and summer temperatures starting from the 1930s. Such de-coupling of previously tight relation of tree growth on temperature is a typical manifestation of the DP (D'Arrigo et al., 2008). Moreover, the spatial coverage of significant correlations also crucially decreased in space (see Figs. 6B, 6C and S5). These shifts in tree-growth response to temperature between the study sites from different vegetation zones of boreal forests demonstrate the heterogeneity in the strength and timing of the DP within central Siberia. Spatial heterogeneity of the DP was earlier described in literature (Briffa et al., 1998; D'Arrigo et al., 2008). However, in this study we provide evidence for the DP in the southern taiga region in Siberia, which is located >1600 km south of forest-tundra. This finding partly contradicts to earlier literature stating that the DP phenomenon is mostly expressed at high latitudes and to a lesser extent at lower latitudes (Briffa et al., 1998; Büntgen et al., 2008, 2016; Cook et al., 2004; Büntgen et al., 2024). Spatial DP heterogeneity cannot be explained by species-specific responses to summer temperature. Widespread Siberian larch, which demonstrates strong DP in southern central Siberia, traces recent temperature increase quite well at the northern treeline in Yamal (Hantemirov et al., 2022) and the upper treeline in the Altai Mountains (Kirdyanov et al., 2024b). On the other hand, climatic responses of Gmelin larch are stationary in our northern study region, but demonstrate notable shifts due to the impact of changing environmental conditions in northern taiga of central Siberia (Kirdyanov et al., 2020b).

Possible causes for the DP emergence have already been previously indicated and tested in literature (D'Arrigo et al., 2008; Esper and Frank, 2009; Frank et al., 2007). These causes may considerably vary between regions, but the inability of tree-ring data to follow temperature increase was specified as one of the most remarkable reasons. In our northern study region, summer temperature is still generally < 12 °C. This is likely below the threshold above which temperature ceases direct limiting of tree growth (Vaganov et al., 2006) and cannot cause the DP. On the other hand, it has been earlier shown that there is clear evidence for the DP at a regional scale in northern central Siberia (Briffa et al., 1998; Kirdyanov et al., 2020a), which was likely to be initiated by dimming due to SO_2 emissions from Norilsk industry and long-distance atmospheric transport from lower latitudes (Kirdyanov et al., 2020a; Büntgen et al., 2021b). The direct and indirect effect of airborne pollution on vegetation in the region was also detected by Panyushkina et al. (2016) and Kharuk et al. (2023a, 2023b). However, a relatively small DP in our northern study sites is not surprising because it has been shown earlier that the DP can be a site-specific phenomenon even within the same region (Büntgen et al., 2021a, 2024; Yin et al., 2021). This allows us to consider tree rings as a valuable proxy for summer temperatures under an accurate choice of tree-ring sites and parameter.

In southern taiga, summer temperature was increasing throughout the period of the instrumental records since the 1870s (Fig. 1). Taking into account relatively high mean summer temperatures of up to 19.4 °C in 2012 and generally > 15.5 °C for the 31-year long periods, we may assume that even slight warming could lead temperature to reach the threshold, above which it does not directly limit tree-ring growth during most of the growing season (Vaganov et al., 2006). To find out the cause of the DP in the southern region, we have to also consider the fact that the only our ST site was established in a human-populated area. Although we have chosen a location that is remote from settlements, and with no marks of direct anthropogenic or natural disturbance, we may not exclude the influence of some of these factors on tree growth in the past. Thus, the broader studied area was heavily logged in the 20th century (Danilin and Crow, 2008; Mironov, 2009), which induced changes in the regional hydrological regime (Jones et al., 2022; Onuchin et al., 2017; Wei et al., 2022; Zhao et al., 2021), further affecting forest ecosystem biogeochemistry and dynamics, as well as tree growth over vast territories (Kreutzweiser et al., 2008; Thaxton et al., 2023). Similarly, insect outbreaks and low-intensity fires may also affect the dependence of tree growth on temperature (Chebakova et al., 2022; de Andrés et al., 2022; Gustafson et al., 2010; Itter et al., 2019; Trindade et al., 2011; Wirth et al., 2002). Therefore, more data on the site and regional forest history are needed to make a proper conclusion about the causes that initiated DP at our study site in the first half of the 20th century.

Although here we analyzed data from a limited number of sites in only two regions in central Siberia, we found a large heterogeneity in the DP strength and possible causes for the phenomenon emergence. At the same time, a recent study demonstrated the evidence for a regional-scale DP in the high-latitude forest belt within the same area (Kirdyanov et al., 2020a). These two somehow controversial findings point out the need for a better understanding of the spatiotemporal changes in tree growth sensitivity to temperature within various regions of boreal forests, and especially Siberia (Büntgen and Rees, 2023), which is poorly represented in the international tree-ring data bases. It can only be achieved with an accurate site-by-site study of newly collected and updated tree-ring data from remote locations in boreal forests. These data are also urgently needed to further unravel the effect of changing climate on forest ecosystems, their carbon sequestration and the environment (López-Blanco et al., 2024).

5. Conclusions

Our results demonstrate the 'Divergence Problem' in tree-ring maximum latewood chronologies at a site level from two distant and environmentally different vegetation zones within boreal forests in central Siberia: forest-tundra and southern taiga. The DP at our sites in these two regions differs in intensity and may be caused by different climatic and environmental factors. Nevertheless, we report the current suitability of the carefully selected tree-ring records from the north of central Siberia for temperature reconstructions. Although our data are limited, we claim that further increase of decoupling between tree growth and temperature may have significant consequences for carbon and water cycle dynamics under a warmer climate and has to be investigated with a denser network of updated tree-ring data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.agrformet.2024.110296.

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