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Arctic amplification causes earlier onset of seasonal tree growth in northeastern Siberia

Alexander V Kirdyanov[1,2,3,*], Alexey I Kolmogorov[4], Stefan Kruse[5], Ulrike Herzschuh[5], Alberto Arzac[3], Lyudmila A Pestryakova[4], Anatoly N Nikolaev[4], Tatiana Bebchuk[1] and Ulf Büntgen[1,6,7]

1 Department of Geography, University of Cambridge, Cambridge CB2 3EN, United Kingdom
2 Sukachev Institute of Forest SB RAS, Federal Research Center 'Krasnoyarsk Science Center SB RAS', Akademgorodok, Krasnoyarsk 660036, Russia
3 Siberian Federal University, 79 Svobodnii, Krasnoyarsk 660041, Russia
4 North-Eastern Federal University, 58 Belinsky str, Yakutsk 677027, Russia
5 Polar Terrestrial Environmental Systems, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, 14473 Potsdam, Germany
6 Department of Geography, Masaryk University, 61137 Brno, Czech Republic
7 Global Change Research Centre, 61300 Brno, Czech Republic
* Author to whom any correspondence should be addressed.

E-mail: ak2118@cam.ac.uk

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Abstract

Although recent warming affects the high-northern latitudes at an unprecedented rate, little is known about its impact on boreal forests because *in situ* observations from remote ecosystems in Siberia are sparse. Here, we analyse the radial growth and climate sensitivity of 54 Cajander larches (*Larix cajanderi* Mayr.) from three sites across the northern treeline ecotone within the Omoloy river basin in northeastern Siberia. Three independent tree-ring width chronologies span 279–499 years and exhibit distinct summer temperature signals. These records further reveal evidence for sufficiently earlier onsets of growing seasons since the middle of the 20th century. This phenological shift coincides with rapidly increasing May temperatures and associated earlier snowmelt. Our findings reinforce the importance of high-precision ground measurements from remote regions in Siberia to better understand how warming-induced changes in the functioning and productivity of the boreal forest influence carbon, nutrient, and water cycle dynamics.

1. Introduction

The Arctic and subarctic are warming at historically unprecedented rate, which exceeds the global average temperature increase by four times (Rantanen *et al* 2022). Associated with this Arctic amplification (Francis *et al* 2017, Previdi *et al* 2021), the boreal forest zone is experiencing shifts in vegetation structure and productivity, northward vegetation expansion, permafrost degradation and greenhouse gas emission from permafrost thawing (Anisimov 2007, Schaefer *et al* 2011, Serreze and Barry 2011, Schuur *et al* 2015, Turetsky *et al* 2019). Understanding the speed and magnitude of these ecosystem changes is critical for assessing their impact on global carbon and water cycles (Chapin *et al* 2005, Bala *et al* 2007).

The dynamics of boreal forest ecosystems within the northern treeline ecotone, the transition from northern taiga to treeless tundra, is largely regulated by growing season temperatures (Paulsen and Körner 2014, Hansson *et al* 2023). Due to high climate sensitivity of the forest–tundra transition, these ecotones are widely used to monitor early responses to climate change (Shiyatov 1993, Esper and Schweingruber 2004, Kullman 2007, Dufour-Tremblay *et al* 2012). While a number of biotic and abiotic factors have to be considered when forest dynamics are studied (Rees *et al* 2019), current warming is believed to be among the main drivers initiating an expansion of trees into the tundra as well as forest densification within forest–tundra ecotones (Danby and Hik 2007, Fomin *et al* 2020, Dial *et al* 2022, Kruse *et al* 2023).

Tree-ring width (TRW) data are widely used as an indicator of past forest ecosystem response to climate change. In addition to tree establishment dates allowing identification of tree regeneration dynamics (Shiyatov 1993, Esper and Schweingruber 2004, Kharuk *et al* 2006, Devi *et al* 2008, Kirdyanov *et al* 2012, Grigor'ev *et al* 2019), TRWs provide approximations of tree growth and forest productivity (Knorre *et al* 2006, Devi *et al* 2008, Bouriaud *et al* 2015). Previous tree ring-based studies in Siberian high-latitude forest–tundra ecotones demonstrated a strong dependence of tree growth on summer temperature (Vaganov *et al* 1996, Naurzbaev *et al* 2002, Briffa *et al* 2004, D'Arrigo *et al* 2006, Hellmann *et al* 2016, Kirdyanov *et al* 2018, Büntgen *et al* 2021, Hantemirov *et al* 2021, 2022). However, Briffa *et al* (1998) described a persistent decoupling of tree growth from rising summer temperatures in northeastern Siberia. This so-called 'Divergence' phenomenon was also observed in northcentral Siberia (Kirdyanov *et al* 2020). Moreover, there is evidence that other climate-related factors can directly influence tree growth in Siberian forest–tundra ecotones, such as winter precipitation (Kharuk *et al* 2023), snowmelt dates (Vaganov *et al* 1999, Kirdyanov *et al* 2003), within-growing season frosts (Gurskaya 2014, 2021), floods (Tei *et al* 2019a, Meko *et al* 2020) and soil temperature and moisture (Nikolaev *et al* 2011, Fujii *et al* 2022, Kharuk *et al* 2023, Liang *et al* 2023). Despite a long history of local and large-scale tree-ring studies in the high-northern latitudes, uncertainties remain with reference to how current and future climate and environmental changes will affect tree growth and forest productivity in northeastern Eurasia.

Here, we explore the radial growth and climate sensitivity of three larch sites across the northern treeline ecotone within the Omoloy river basin of northern Yakutia. Although hardly accessible, this extremely remote region is of great importance for revealing the direct ecological response of undisturbed forest–tundra ecosystems to rising temperatures. We hypothesize that tree growth in this region is directly affected by Arctic amplification, and should be reflected in changing patterns of radial tree growth climatic response.

2. Material and methods

The study area is located at the northern treeline in northeastern Siberia between 70°31′36″ N and 70°56′00″ N along the 132°47′ E longitude (figure 1). This region is dominated by deciduous *Larix cajanderi* Mayr. that is well adapted to growing on nutrient-deficient permafrost soils under harsh winter climate and short growing season with 24 h daylight (Abaimov *et al* 1997). Climate in this region is extremely continental, with annual mean temperatures of −13.3 °C (WMO 226 609 'Yubileinaya'; 1936–2022; meteo.ru) (figure 2). The warmest and coldest months are July and January with monthly temperatures of 11.2 °C and −35.3 °C, respectively. June is usually the first month with positive temperature means (7.2 °C) that last until September (2.0 °C). Annual precipitation totals are 276 mm (1936–2015), of which 42% fall between June and August. Seasonal temperature means significantly increased since 1975 at a rate of 0.6 ($P < 0.005$), 0.6 ($P < 0.005$) and 0.5 °C/decade ($P < 0.05$), in June–July, summer (June–August) and annually, respectively (figure 2), whereas summer precipitation totals significantly decreased by 10.9 mm decade^{-1} ($P < 0.05$). Importantly, data on monthly precipitation totals available from the All-Russian Research Institute of Hydrometeorological Information—World Data Center (RIHMI-WDC) are corrected for systematic errors according to Bogdanova *et al* (2007) and Bogdanova and Gavrilova (2008).

Increment core samples were collected in undisturbed, uneven-aged Cajander larch stands at three sites along a north–south transect within the forest–tundra ecotone (figure 1). The northernmost site N was established in sparse forest on the first terrace of Omoloy river, the only forested area at this location (Miesner *et al* 2022a, 2022b). Stand density was 700–800 trees/hectare, with larch trees reaching 6.5 m in height and mean DBH (diameter at breath height, 1.3 m) of 10.0 cm. The middle site M represents a closed forest treeline, with varying stand density from 2100 trees/hectare in open forest to 6400 trees/hectare in closed forest. Trees were up to 8 m in height with a DBH of 11.3 cm. The southernmost site S was established in closed forest with the mean tree stand density of 5600 trees/hectare and individual trees being up to 10 m with a DBH of 10.6 cm. In late June 2014, the mean active layer thickness was 10–25 cm, 33–35 cm and ~35 cm at N, M and S, respectively. Detailed information on ground vegetation and stand parameters was provided by Miesner *et al* (2022a). During sampling, we mostly aimed at coring old-growth trees, which were distributed over an area of a one-two hectares. In total, from 16 to 21 trees per site were cored with the oldest trees reaching from 279 (site N) to 499 (S) and the mean segment length (MSL) ranging from 126 (N) to 281 (S) years (table 1).

All increment cores were air-dried and mounted on wooden supports, with their surface cut and contrasted with chalk to increase the visibility of tree-ring boundaries. TRW was measured on a LINTAB measuring system (RINNTECH e.K., Heidelberg, Germany). The individual TRW series were cross-dated using the TSAP-Win (Rinn 2003), and cross-dating accuracy was statistically verified with COFECHA (Version 6.02P). Individual

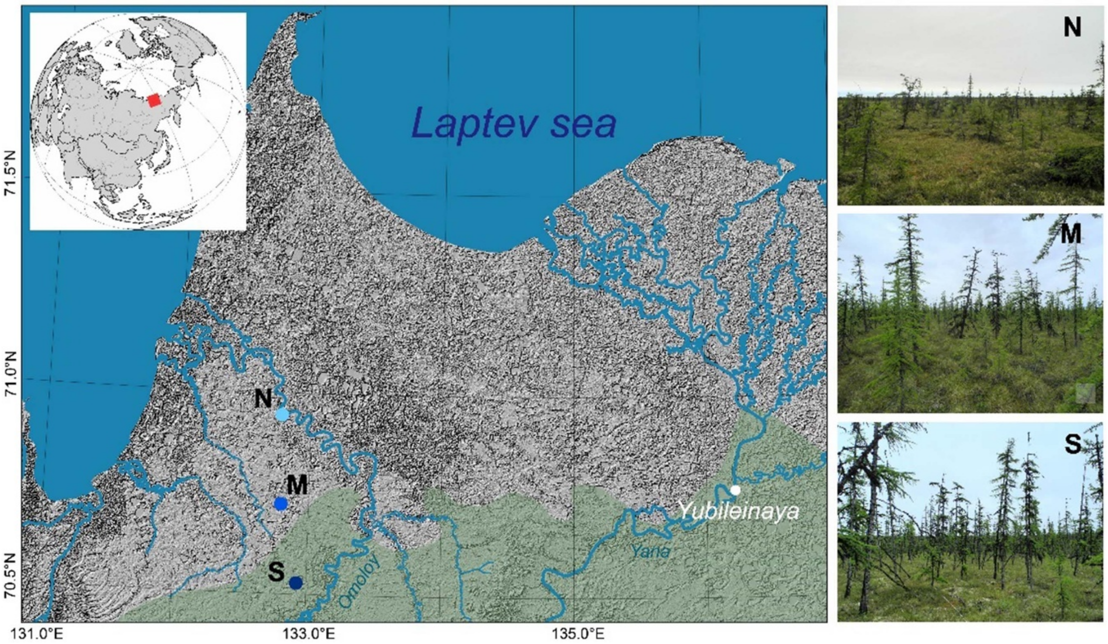

Figure 1. Location of the tree-ring sampling sites (three blue circles of different intensity) and the meteorological station in Yubileinaya (white circle). Green shading refers to the taiga zone. The upper left inset places the study region in the context of the Northern Hemisphere, and the three pictures on the right show the three sampling sites (N = north, M = middle, S = south). Basemap was developed with a Digital Elevation Model (DEM) produced by Shuttle Radar Topography Mission (SRTM) and Sentinel satellite image, using the QGIS software.

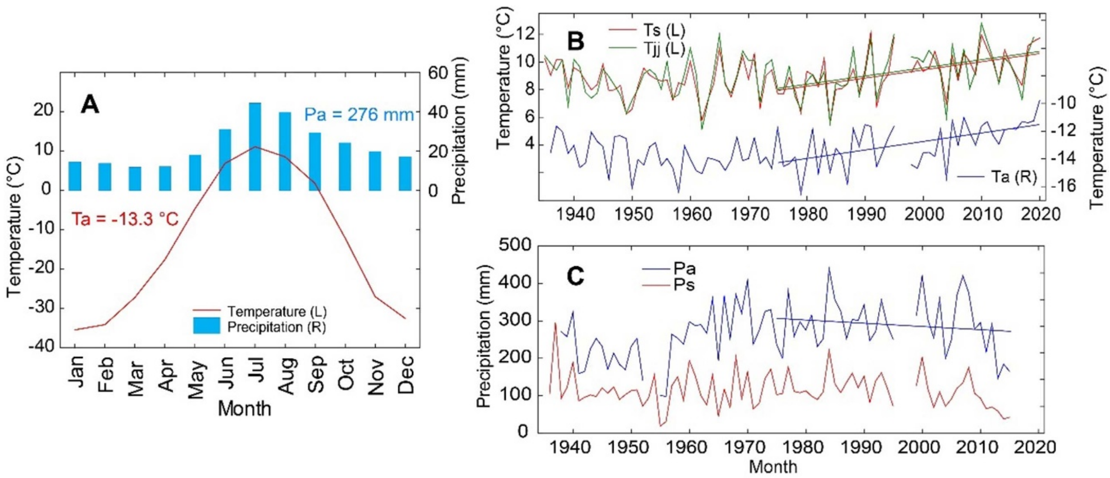

Figure 2. (A) Annual climate cycle from the meteorological station in Yubileinaya averaged the period 1936–2022. (B) Annual (Ta), summer (Ts) and June–July (Tjj) temperature changes, and (C) annual (Pa) and summer (Ps) precipitation changes. Linear trends in the temperature data show significant increases since 1975 ($P < 0.05$).

Table 1. Chronology characteristics (MSL = mean segment length, TRW = tree-ring width, CS = coefficient of sensitivity; Rbar = inter-series correlation, EPS = expressed population signal).

Site	N of series	Period CE	MSL	Mean TRW, mm	Mean TRW >150 y., mm	Mean CS	Mean Rbar	Mean EPS
N	21	1736–2014	126	0.56 ± 0.30	0.12 ± 0.06	0.397	0.415	0.905
M	17	1740–2014	190	0.27 ± 0.20	0.12 ± 0.06	0.415	0.538	0.946
S	16	1516–2014	281	0.21 ± 0.15	0.10 ± 0.05	0.408	0.469	0.914

Note: All statistics except Mean TRW and Mean TRW >150 y. were calculated for standardized chronologies.

TRW series were standardized with cubic smoothing splines of 50% frequency-response cutoff at 2/3 of the individual series lengths. Bi-weight robust means of the individual measurement series were calculated to produce dimensionless TRW index chronologies (Cook 1985). The standard version of the chronologies was chosen for further analyses to preserve potential longer-term variability for comparison against different climate parameters. The coefficient of sensitivity (CS), mean interseries correlation (Rbar) and expressed population signal (EPS) were calculated using the latest version of the ARSTAN software (www.geog.cam.ac.uk/research/projects/dendrosoftware/, last accessed on 25 March 2024).

To determine the most important climatic factors that control tree radial growth, the TRW standard chronologies were correlated against instrumental records of monthly and seasonal temperature means and precipitation totals from the nearest meteorological station Yubileinaya over the common period 1936–2014. Pairwise correlations were calculated, which ignore missing climate data values. To assess the temporal changes in the relationships between TRW chronologies and climate records, Pearson's correlation coefficients were calculated over 1936–1974 and 1975–2014, as well as using moving 25 year windows. To eliminate the influence of climate data trends on tree growth response to climate, we correlated the residual TRW index chronologies with the detrended climate records (Ols *et al* 2023). We also evaluated time shifts in snowmelt dates available for the meteorological station Yubileinaya.

3. Results

3.1. Tree radial growth

Trees at the study sites are characterized by low radial stem growth rate, and up to 3.3% of tree rings can be locally absent (M) (table 1). The mean TRW increases from 0.21 ± 0.15 mm (S) to 0.56 ± 0.30 mm (N) with decreasing chronology length and MSL. The mean growth rate of trees at a mature stage (cambial age $>$150 years), when the age trend in tree radial growth is least pronounced, is similar among the sites, with slightly lower values at S. All the index chronologies are characterized by high CS $>$0.3 and Rbar $>$0.4. Mean EPS (calculated for the 50 year periods shifted by 25 years) is $>$0.9 since at least 1840. These statistics indicate a strong common signal in individual TRW series from each site and confirm that the sample depth is sufficient for dendroclimatic analysis at all the study sites.

The three TRW chronologies demonstrate a high coherence of inter-annual and multi-decadal variation (figure 3). The coefficient of correlation for the period since 1809, with data for at least three trees in each chronology, ranges from 0.70 ($P < 0.001$) for the most distant sites N and S to 0.85 ($P < 0.001$) for two southern sites M and S. Since 1900, the highest TRW indices were observed in the 1930s and the early 1940s, followed by a gradual TRW decrease until the 1970–80 s, and a growth increase afterwards (figure 3).

3.2. TRW climate response

The growth-climate response analysis of the local chronologies back to 1936 shows that TRW indices at the northernmost site N correlate significantly positively with mean June and July temperatures ($P < 0.01$) (figure 4(A)). TRW data from the other two sites exhibit positive relations with mean June temperatures ($P < 0.001$). All three local chronologies correlate positively with summer (June–July and June–August) temperature means (r ranges from 0.26 to 0.42, $P < 0.05$). The strongest correlation is found for the southernmost site S with June temperature ($r = 0.56$, $P < 0.001$). Correlations of standard TRW chronologies with observed monthly and seasonal precipitation (figure S1(A)) and residual TRW chronologies with detrended precipitation (figure S1(B)) do not show any consistent results between the sites.

Detailed dendroclimatic analysis with temperatures shows that TRW mostly depends on June and JJ temperatures during the 1936–1974 period ($P < 0.05$) (figure 4(B)). TRW chronology from the northernmost site N significantly ($P < 0.05$) correlates also with JJA temperature. However, the correlation pattern considerably changes for the later period from 1975 (figure 4(C)). June temperature is still the most important climate variable for tree growth at all three sites ($P < 0.05$), and N continues to depend on July temperatures ($P < 0.05$). However, N and M also show a strong dependence ($P < 0.01$) on May temperature. In the case of seasonal temperature means, correlations remain statistically significant only for N and S ($P < 0.05$). Importantly, correlations of the residual TRW chronologies with detrended temperature variables show a similar pattern with increasing importance of May temperature for N and M over the 1936–1974 period (figure S2).

Running correlation analysis of growth-climate relation shows a continuously increasing influence of May temperatures on TRW at all three sites (figure 5(A)). At site N, correlations become significant during the 1959–1983 period and remain high since then. At sites M and S, May temperature is important only during a short interval, with the first significant correlations observed for the 1987–2011 period. June temperatures significantly influence tree radial growth at all the three sites throughout most of the period from 1936, with the generally higher correlations up to $r = 0.77$ ($P < 0.001$) at S (figure 5(B)). The role of July temperature fluctuated at the $P < 0.05$ significance level at N, whereas at M and S, it is mostly insignificant throughout the period (figure 5(C)). Surprisingly, running correlations with monthly precipitation totals do not demonstrate increased positive influence of precipitation for the period of temperature increase (figure S4). On the contrary, TRW chronologies significantly ($P < 0.05$) negatively correlate with June precipitation totals (figure S4(B)) in recent decades. Positive correlations are observed

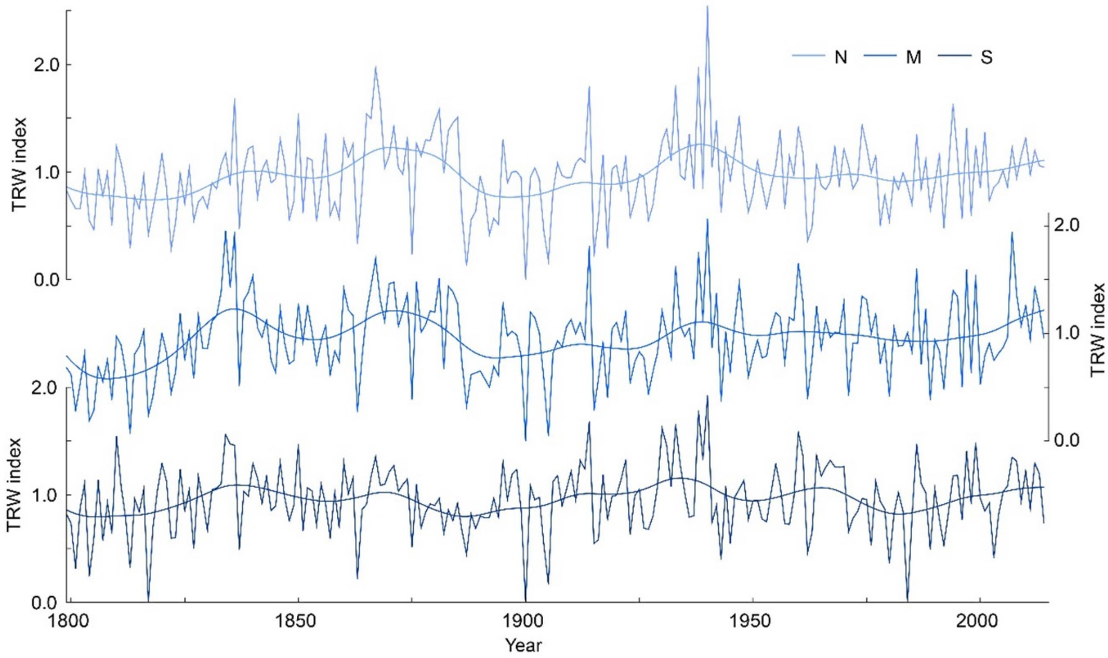

Figure 3. Standard tree-ring width (TRW) chronologies. The chronologies were smoothened with a 30 year spline.

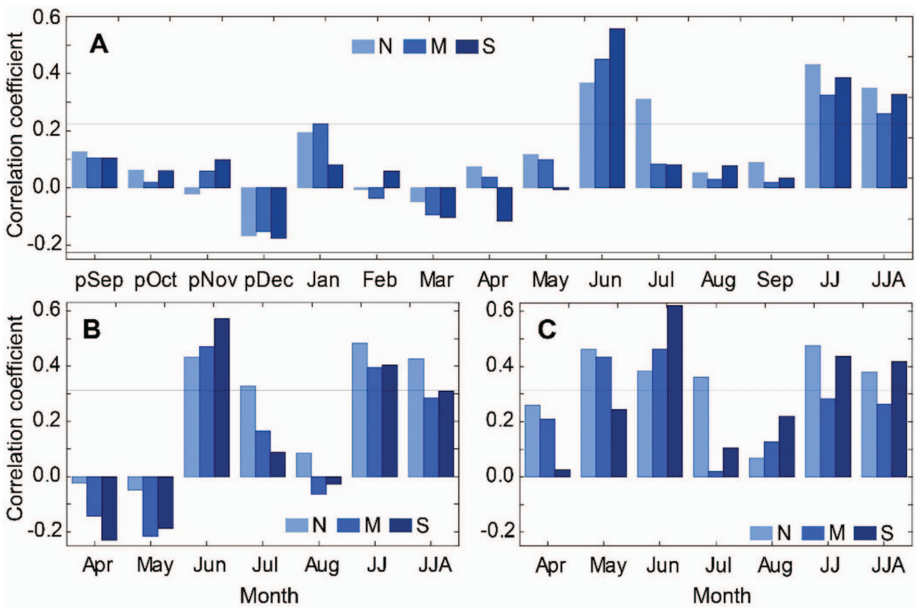

Figure 4. Correlation coefficients of standard tree-ring width chronologies and monthly temperature means from previous September to current September, and seasonal temperature means for June–July (JJ) and summer (JJA) for the period 1936–2014 (A) and selected months and seasonal means (JJ and JJA) for the 1936–1974 (B) and 1975–2014 (C) periods. Horizontal line indicates the significance level $P < 0.05$.

with July (figure S4(C)) and August (figure S4(D)) precipitations during some intervals during the first half of the analysed period from 1936. The running correlations of the residual TRW index chronologies with detrended monthly temperature means (figure S3), and precipitation totals (figure S5) demonstrate similar tendencies, with the only major difference of significant negative correlations between the TRW residual chronology from N and detrended July precipitation starting from the 1973–1997 period (figure S5(C)).

3.3. Changes of climate parameters crucial for tree growth onset

To reveal factors leading to the shift of the temperature dependency of tree growth to earlier dates, the dynamics of May temperatures and snowmelt dates were explored (figure 6). Mean May temper-

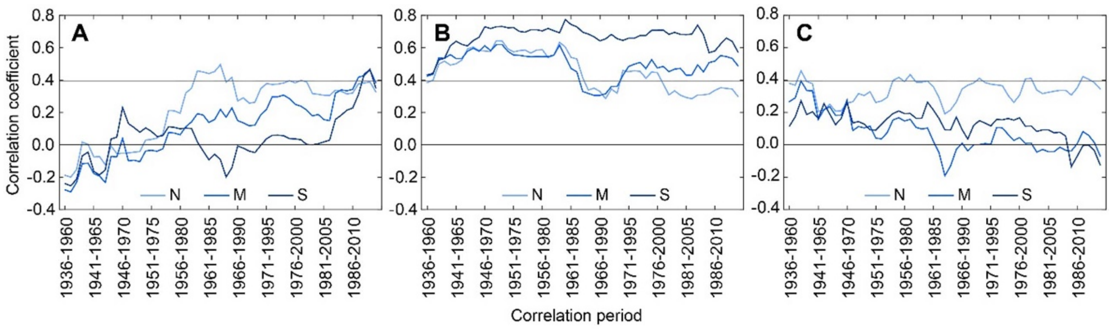

Figure 5. 25 year window running correlations between the standard tree-ring width chronologies N, M and S and monthly temperature means of May (A), June (B) and July (C). Grey horizontal line indicates the significance level $P < 0.05$.

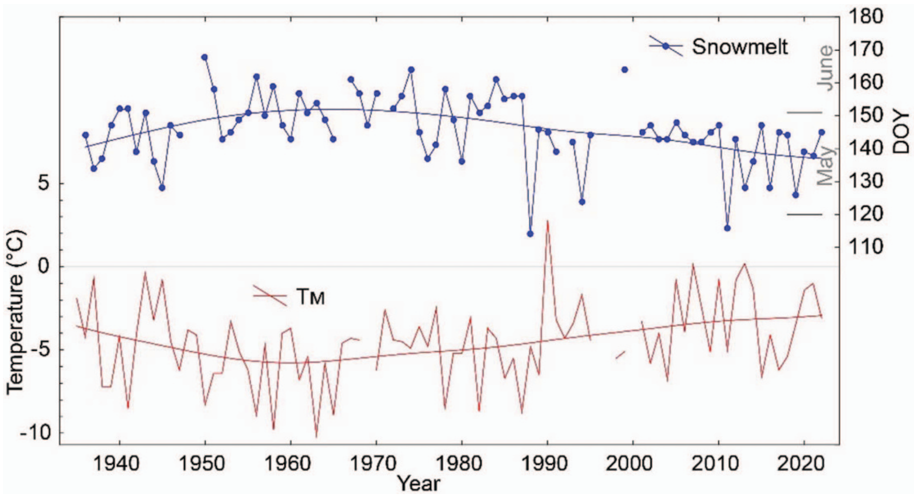

Figure 6. May temperature (TM) and the day of a year (DOY) of complete snowmelt (Snowmelt) based on data from the nearest meteorological station Yubileinaya. The lines are smoothed with distance-weighted least squares fitting in STATISTICA 64 (StatSoft, Inc.).

ature demonstrates a clear positive trend from the late 1950s. During the last decades, May temperature was on average higher than for any other decade-long interval over the period of instrumental meteorological observations and increased from a decadal-long mean −6.8 °C during the 1956–1965 period to −2.0 °C in 1995–2014. Importantly, positive (>0 °C) May temperature means started to appear in recent decades and were recorded in 1990 (2.8 °C), 2007 (0.1 °C) and 2013 (0.2 °C). On the contrary, snowmelt dates demonstrate a decreasing trend from the 1960s, evidencing a shift to earlier snowmelt from 154th day of the year (DOY) as a mean for the 1949–1958 period to 135th DOY in 2011–2020.

4. Discussion

Radial tree growth at the northern treeline ecotone in Siberia is usually extremely low due to harsh climate conditions, which synchronize tree growth not only within single sites, but also at distances of several hundred kilometers (Vaganov *et al* 1996, Esper *et al* 2010, Hellmann *et al* 2016, Shestakova *et al* 2016, Büntgen *et al* 2021, Hantemirov *et al* 2021, 2022). Low mean annual increment, high inter-series correlations of tree growth in our study region and the results of the dendroclimatic analysis confirm the importance of summer temperature as a primary climatic driver that modulates year-to-year variability of tree radial growth in northern Yakutia, with the early summer period (June) showing the highest impact. These results coincide with previous findings for Siberia (MacDonald *et al* 1998, Hughes *et al* 1999, Vaganov *et al* 1999, Kirdyanov *et al* 2003, 2018, Hantemirov *et al* 2022, Kolmogorov *et al* 2023), as well as for the wider area of Eurasia and the Northern Hemisphere (Briffa *et al* 2004, 2013, St. George 2014, Hellmann *et al* 2016, Devi *et al* 2020). The period of the growing season with significant correlations between TRW and monthly temperature may considerably vary between regions from one to four-five months (Büntgen *et al* 2021), but early summer temperature usually demonstrates higher correlations, especially in Siberia (Vaganov *et al* 1999, Kirdyanov *et al* 2018). Rapid onset of tree cambial activity after snowmelt and daily temperature increase above the physiologically defined threshold at the beginning of the growing season is the key adaptation of treeline larch in Siberia (Vaganov *et al* 1999, Kirdyanov *et al* 2003). Trees take advantage of a 24 h photoperiod, which enables them to complete tree-ring formation within several weeks of the short and cold growing season (see data on seasonal tree radial growth at the more southern location, but with short seasonal growth in Bryukhanova *et al* 2013, Rinne *et al* 2015a, 2015b). However, neither the crucial temperature threshold nor the timing of growing seasons of larch at the northern treeline are currently known despite the importance of these parameters for understanding the physiology of larch trees and predicting future vegetation shifts in the boreal zone in Siberia. Remote sensing data (Buitenwerf *et al* 2015, Dronova and Taddeo 2022) and tree-ring growth modelling (Vaganov *et al* 1999, 2006, Shishov *et al* 2016, Kang *et al* 2023, Shishov *et al* 2023) may provide rough estimates of these values, but require on-site validation.

Our TRW chronologies demonstrate a recent shift of tree growth dependence on temperature to earlier dates, which can indicate an earlier start of the growing season (Gao *et al* 2022). This shift coincides with the temporal changes of two climate parameters that directly affect the timing of the growing season onset: snowmelt and temperature preceding and during early growing season (Vaganov *et al* 1999, Kirdyanov *et al* 2003, Livensperger *et al* 2016). An approximately 19 d earlier snowmelt and 4.8 °C higher May temperature in recent decades compared to the middle of the 20th century can indeed induce earlier activation of seasonal growth, which is currently observed in extratropical ecosystems in the Northern hemisphere (Linderholm 2006, Menzel *et al* 2006, Piao *et al* 2015, Büntgen *et al* 2022). Surprisingly, the significant correlations between TRW chronologies and May temperature during the period from 1975 were found for the two northern sites N and M, but not the southern site S, meaning the slower reaction of tree growth at the southernmost location to temperature increase. Unfortunately, there are no instrumental meteorological observations in the region that could be representative to each of the study sites and confirm the site-specific tree growth response to warming. The only meteorological station Yubileinaya is latitudinally located in the middle of the study transect, but within closed forest of the treeline ecotone, correspondent to site S. However, due to the proximity of the sites and the flat topography of the study area we can consider the regional climate rather homogeneous, with slightly lower air temperature at the northern sites.

The site-specificity of TRW climatic response to warming observed in the study region is a known phenomenon for the boreal permafrost zone: trees at geographically close locations can demonstrate different climate response due to local soil thermo-hydroclimate conditions (Kirdyanov *et al* 2013, Bryukhanova *et al* 2015, Kirdyanov *et al* 2024). Intra- and inter-species competition can also act as a factor influencing tree radial growth dynamics and climatic response because soil temperature conditions, active layer thickness and nutrient availability largely depend on tree stand density and ground vegetation (Brown 1966, Shur and Jorgenson 2007, Yin *et al* 2017, Fedorov *et al* 2019, Knorre *et al* 2019, Stuenzi *et al* 2021). Trees at site S are prone to the highest level of competition due to the highest tree density and most developed ground vegetation (Miesner *et al* 2022a). Although the active layer thickness at site S is similar to site M and 10–25 cm deeper than at N, higher root competition for water and nutrients can explain a delayed reaction of TRW to warming (figure 4(A)) (Wieczorek *et al* 2017). Denser ground vegetation at site S can trap and insulate snow delaying snowmelt and leading to later start of growing season. However, the exact reason of the difference in timing of tree seasonal growth activation between the study sites may not be resolved due to the lack of on-site data.

The statement on site-specific tree growth response in the permafrost zone may seem to contradict earlier observations on high similarity of tree growth at distant sites in northern Siberia (for example, Vaganov *et al* 1996, Hellmann *et al* 2016). However, the approaches to sampling in dendroclimatology and dendroecology are different (Fritts 1976, Schweingruber 1996). While dendroclimatic studies in northern Siberia are often focused on extracting summer temperature signal, and researchers pay special attention to cool and moist sites with similar environmental settings (Vaganov *et al* 1996, Hughes *et al* 1999, Jacoby *et al* 2000, Briffa *et al* 2004, Esper *et al* 2010, Büntgen *et al* 2021, Hantemirov *et al* 2022), dendroecology is focused on understanding the effect of different environmental and climatic drivers on tree growth, and sampling is usually conducted in environmentally diverse ecosystems (Kirdyanov *et al* 2020, Gurskaya *et al* 2021, Buchwal *et al* 2023, Kharuk *et al* 2023).

Our study underlines the importance of the on-ground data for detecting the current changes in vegetation. Such data are especially important for remote regions exposed to rapid climate change, like northern Siberia (Gauthier *et al* 2015, Hantemirov *et al* 2022). Generally, despite recent advances in data collection, analyses, and modelling (Lloyd *et al* 2011, Büntgen *et al* 2014, 2021, Tei *et al* 2019b, Tei and Sugimoto 2020, Miesner *et al* 2022a, 2022b, Buchwal *et al* 2023, Liang *et al* 2023, etc), the way treeline forests behave in northeastern Siberia is still poorly understood. Sufficient efforts are needed to obtain *in situ* field data and gain knowledge, for example, on tree cambium activity and the exact timing of growing season, vegetation productivity and plant-permafrost interactions to define the adaptation potential of trees growing under extreme environmental conditions that are currently rapidly changing.

5. Conclusion

Our study demonstrates that radial growth of Cajander larch trees within the treeline ecotone in northeastern Siberia mainly depends on early summer temperature. In recent decades, a shift to earlier growing seasons is observed due to warmer May conditions and earlier snowmelt. The climatic response of tree growth is site-specific, being partly dependent on local conditions that include ecological settings of the sites and intra- and interspecies competition. To detect current ecosystem changes caused by global warming, on-ground data are required, especially for remote regions that are characterized by low anthropogenic pressure, but sensitive to global climate change.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iDs

Alexander V Kirdyanov https://orcid.org/0000-0002-6797-4964
Stefan Kruse https://orcid.org/0000-0003-1107-1958

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