

Summer temperature in northeastern Siberia since 1642 reconstructed from tracheid dimensions and cell numbers of *Larix cajanderi*

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Abstract: We reconstructed air temperature for two periods in the growth season from cell dimension and cell number variability in cross-dated tree rings of *Larix cajanderi* Mayr. from northeastern Siberia. Thirteen tree-ring chronologies based on cell size, cell wall thickness, and cell number were developed for AD 1642–1993. No clear evidence was found of an age-related trend in cell dimensions in the sampled materials, but cell numbers were correlated with cambial age. The chronologies contain strong temperature signals associated with the timing of xylem growth. We obtained reliable reconstructions of mean June temperature from the total cell number and July–September temperature from the cell wall thickness of latewood. June temperature and July–September temperature covaried for most of the period from AD 1642 to AD 1978. After that time, June temperature became cooler relative to July–September temperature. This difference caused disproportional changes in earlywood tracheids because of the late start of growth and cool conditions in June followed by warming during the rest of the season. The identification of this unusual recent change has shown that intraseasonal resolution may be achieved by cell dimension and cell number chronologies.

Résumé : Nous avons reconstruit la température de l'air durant deux périodes de la saison de croissance à partir des variations dans la dimension et le nombre de cellules dans des cernes annuels synchronisés de *Larix cajanderi* Mayr. dans le Nord-Est de la Sibérie. Treize séries dendrochronologiques basées sur la dimension des cellules, l'épaisseur des parois cellulaires et le nombre de cellules ont été construites pour les années 1642 à 1993. Aucun indice clair d'une tendance reliée à l'âge a été observé dans la dimension des cellules présentes dans le matériel échantillonné mais le nombre de cellules était corrélé à l'âge du cambium. Les séries dendrochronologiques contiennent de forts signaux reliés à la température associés au moment où est survenue la croissance du xylème. Nous avons obtenu des reconstitutions fiables de la température moyenne du mois de juin à partir du nombre total de cellules et de la température des mois de juillet à septembre à partir de l'épaisseur des parois cellulaires du bois final. La température du mois de juin et celle des mois de juillet à septembre ont varié de la même façon pendant presque toute la période allant de 1642 à 1978. Par la suite, la température du mois de juin est devenue plus fraîche relativement à celle des mois de juillet à septembre. Cette différence a entraîné des changements disproportionnés dans les trachéides du bois initial à cause du début tardif de la croissance et des conditions fraîches en juin suivies d'un réchauffement durant le reste de la saison. L'identification de ce changement récent et inattendu montre qu'on peut obtenir une résolution intra-saisonnière grâce à des séries dendrochronologiques basées sur la dimension et le nombre de cellules.

[Traduit par la Rédaction]

Introduction

Most quantitative, calibrated, and cross-validated reconstructions of past climate using tree rings are based on two tree-ring variables: total ring width and maximum latewood density (Hughes 2002). Each of these variables can be shown to respond to climate in a period determined by the biology of the tree species, seasonality of the region, and specific site conditions. In the case of *Larix* growing at high

latitudes in Siberia, temperatures during a few weeks at the beginning of the growth season largely determine total ring width (Hughes et al. 1999). In high-latitude conifers, maximum latewood density reflects conditions over most of the growing season, although the effect of temperature is greatest at the beginning and end of the season (Briffa et al. 1992; Jacoby and D'Arrigo 1995; Vaganov et al. 1999).

The characteristic times of the division, expansion, and maturation of conifer tracheids range from days to a few weeks, and their dimensions likely reflect climate conditions during a relatively short part of the growth season when compared with total ring width and especially maximum latewood density. Thus, they offer the possibility of enriching the information available from such tree rings. Strong evidence of the effects of temperature and drought stress on growth of wood elements has already emerged from tree physiology studies of variations in microcharacteristics of tree rings (Denne and Dodd 1981; Woodcock 1989; Orcel et al. 1992; Sass and Eckstein 1992; Danzer et al. 2001).

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Table 1. Overlap plot of tree-ring cell series and cambium age of the measurements.

Calendar years					Sample	Time span	No. of years	Cambial age of first measured tree ring*
1600	1700	1800	1900	2000				
.	.	.	.	_____	NAN1	1945–1994	50	286
.	_____				NAN3	1661–1993	333	158
.	.	.	.	_____	NAN8	1944–1993	50	No data
.	_____				LAK3	1642–1993	352	231
.	.	.	_____		LAK6	1850–1993	144	296
.	_____		.	.	LAK9	1641–1740	100	29
.	_____				GOF294	1642–1994	353	528
.	_____	.	.	.	GOF293a	1664–1769	106	541
.	.	_____	_____	.	GOF293b	1838–1944	107	716
.	IND113	1770–1838	69	No data
.	—	.	.	.	IND126	1642–1662	21	No data
.	_____	.	.	.	IND127	1640–1866	227	No data

Note: Sample GOF293 has a gap in measurements from 1770 to 1837.

*Where there are no data, the pith was absent.

An intriguing possibility is presented by work that shows no relationship over many hundreds of years between cambial age and the radial diameter of tracheids in *Pinus longaeva* (Connor and Lanner 1990). In dendroclimatology based on total ring widths or maximum latewood density, it is necessary to mathematically remove nonclimatic age- and size-related growth trend. The extent to which evidence of climate fluctuations on similar time scales is also removed is unknown (Fritts 1976; Briffa 2000; Briffa et al. 1992, 1998, 2001). A tree-ring measurement with a clear climate signal but no age- and size-related trend would be extremely valuable.

The objectives of this study were to (i) develop multi-century tree-ring chronologies of radial dimensions and cell numbers of tracheids, (ii) estimate the impact of climate on the annual and seasonal variability of tracheid dimensions and cell numbers in cool, high-latitude environments, and (iii) reconstruct intraseasonal patterns of temperature fluctuation from tree-ring cell chronologies. Trees from high-latitude sites were chosen because many annual resolution temperature reconstructions are based on tree rings from cool environments (Hughes 2002). These reconstructions provide a basis for comparison with the results of the present work. Larch was chosen because it lives for many centuries, strongly cross-dates over many hundreds of kilometres (Briffa et al. 2001; Vaganov et al. 1996), and is found throughout a large part of the Eurasian Subarctic.

Materials and methods

Eleven cross-dated larch (*Larix cajanderi* Mayr.) cross sections from the NAN, LAK, IND, and GOF sites established by Hughes et al. (1999) were used for this study (Table 1). One cross section (GOL293) was treated as two samples because the rings for AD 1770–1837 were unmeasurable (see Table 1). The sites are located in open-canopy larch forest in northeast Siberia between 69°27' and 70°30'N and 148°07' and 150°27'E. The NAN and LAK sites are at the northern timberline on the Indigirka coastal lowland and

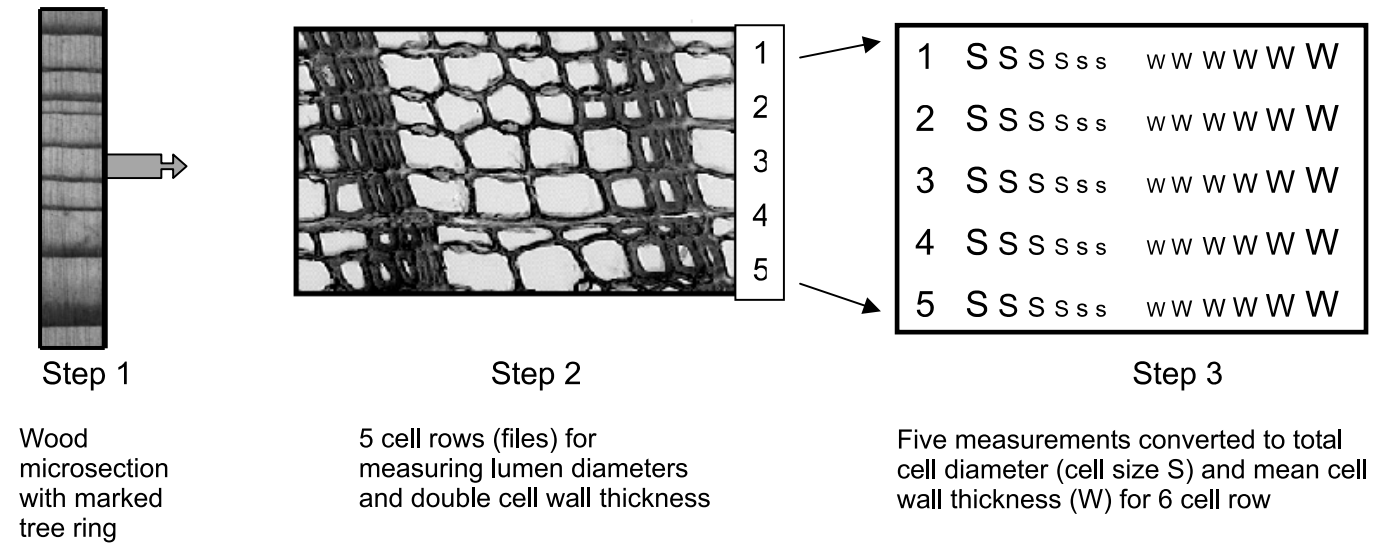
the others are at the upper timberline of the Alazeyskoe Plateau. The sites were within 100 km of each other.

We used image analysis to measure radial sizes of tracheids on thin sections of the larch samples. Surface preparation of anatomical slides was adopted from the techniques described by Smith (1965). We started by cutting 0.8 cm wide wood strips out of the tree cross sections. The cut wood strips did not contain reaction wood. To soften the wood surface, the wood strips were placed in water mixed with glycerol (five parts water to one part glycerol) and heated in a microwave oven for 20–30 s. A 20 to 35 µm thick section was shaved from the wood surface using a modified sledge microtome. The thin section was stained using acridine orange fluorescent stain to improve contrast between the cell wall and lumen. Finally, the stained thin section was placed between a glass slide and cover slip (Fig. 1, step 1).

Cell dimensions were measured using the equipment and procedures described by Munro et al. (1996). Radial tracheid dimensions along a complete radial row of cells (file) were made on a digital image of the tree ring captured using a transmitted light microscope fitted with a CCD camera, in turn linked to a computer (Munro et al. 1996). Successive images at high resolution were combined into a mosaic image. Measurements of double cell wall thickness in the radial direction, lumen diameter, and hence cell size were made along each radial file sampled. The resolution and precision of measurements were approximately 0.3 µm. For this study, we measured five cell files (five replications) of double cell wall thickness and lumen diameter for each cross-dated tree ring (Fig. 1, step 2). Images of 9460 cell files from 1896 tree rings in 11 tree samples were processed. We did not use the raw measurements of lumen diameter and double cell wall thickness directly but reduced them to estimates of total tracheid diameter (cell size) and mean cell wall thickness.

To permit direct comparisons of patterns of cell dimensions between rings (or even files of cells within the same ring) with different numbers of cells, we converted all measurement series to a constant number of cells. The cell sizes

Fig. 1. Diagrammatic representation of calculating cell dimensions of one year from radial tracheid measurements of one sample. Further cell dimensions from one sample are merged in the individual tree-ring cell series. The cell series is standardized to tree-ring cell indices.



and mean cell wall thickness were converted to a cell number of six by a weighted mean of the cell dimension within the tree ring (Terskov et al. 1981; Vaganov 1989) (Fig. 1, step 3). Six is the average number of cells in the larch tree rings that we studied. Individual cell size and cell wall thickness series for each of the six cells were calculated by averaging the five replicated files. Thus, we obtained six mean cell size series and six mean cell wall thickness series for each tree-ring sample. The mean tree-ring cell series is analogous to an individual tree-ring width series. In our case, a single tree ring has 12 cell characteristics (Fig. 2). Besides cell dimension series, the total numbers of tracheids in the measured files were counted and averaged within each tree ring to develop a tree-ring series of cell numbers.

Long-term trend in the various tree-ring cell series that might be related to tree size or age was tested for by attempting to fit a negative exponential curve or linear regression (Cook and Holmes 1998). Tree-ring cell indices were calculated by dividing actual cell value by the series' mean or an estimate of fitted age curve if necessary. Tree-ring cell chronologies merged averaged series of tree-ring cell indices from all tree samples.

Quality control of tree-ring cell chronologies was checked using general statistics routinely applied in dendrochronology: standard deviation (Fritts 1976, p. 255), autocorrelation (Fritts 1976, p. 257), percent variance retained by the first eigenvector, and subsample signal strength (Wigley et al. 1984). Some of these are commonly used in time series analysis, but others are more specific to dendroclimatology. Subsample signal strength is used to estimate how well a chronology based on a subset of *t'* trees estimates a larger *t* series chronology. Most commonly, the larger set of the *t* series chronology is that used in calibration of the chronology against modern instrumental climate records, and the smaller *t'* subset is from an earlier period for which fewer samples are available.

The climatic relationships of tree-ring cell data were determined through response function analysis using monthly

temperature and precipitation as predictors (PRECON program) (Fritts et al. 1991) and Pearson correlation with temperature mean for 5-day periods (pentads). The climatic response functions were run for a 13-month period from September of the previous year to September of the current year. The monthly and daily observations of temperature and precipitation from the Chokurdakh meteorological station (70°37'N, 147°53'E) for the period 1945–1989 were used (Razuvaev et al. 1993).

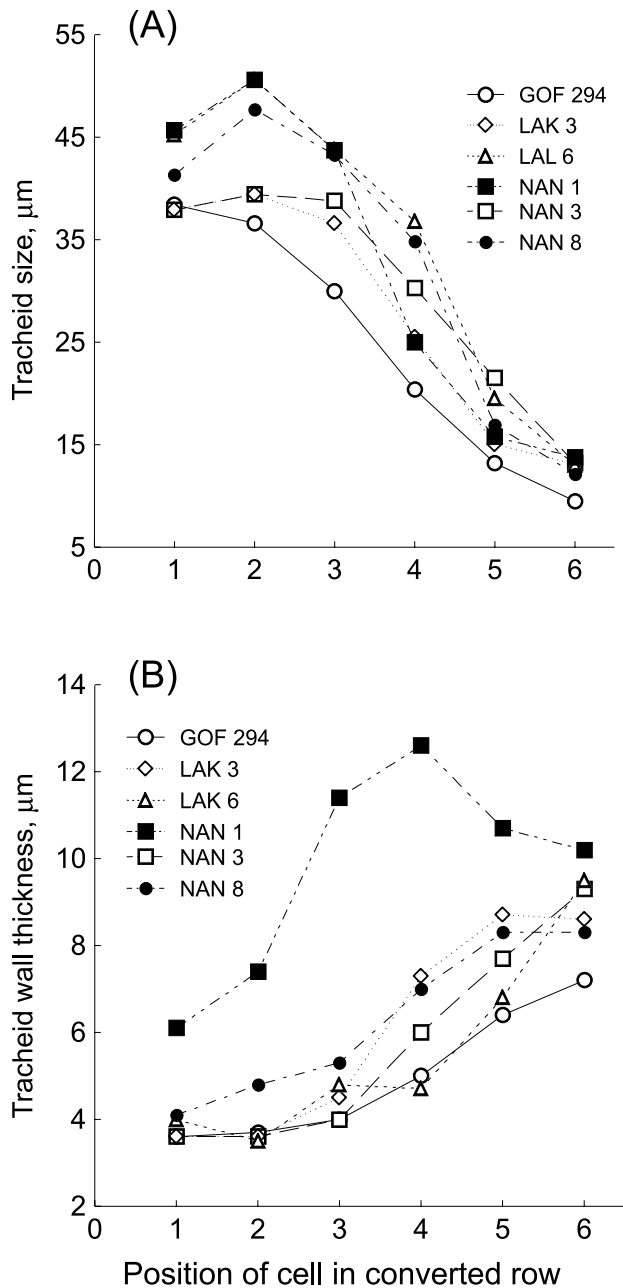
The tree-ring cell chronologies were calibrated with the pentads of daily temperature data using linear regression analysis to build a reconstruction model. The best subset of tree-ring predictors for a fitted regression equation was selected based on the best values of the following calibration statistics: (i) correlation coefficients and coefficient of determination adjusted for degrees of freedom, (ii) normal distribution of regression coefficients (standard deviation of regression line, *F* test with *p* ≤ 0.01), and (iii) low autocorrelation in residuals compared with the critical level of the Durbin–Watson statistic (Draper and Smith 1981). The reconstruction models were cross-verified using the PRESS statistic, which is computed from the error sum of squares in leave-one-out cross-validation (Gordon 1980).

Results

Tree-ring cell chronologies

The asymmetrical shape of the larch tracheidograms shown in Fig. 2 is a common pattern among all of the samples examined, suggesting a similar rate of xylem division in those annual rings (Terskov et al. 1981; Vaganov et al. 1985). The tracheidograms characterize larch xylem formation in the Arctic environment (Kandelaki 1979). The average size of the measured tracheids changes from 41.3 μm in the first cell formed to 12.3 μm in the last, and average cell wall thickness increases from 2.3 to 4.5 μm (Table 2). Mean correlation coefficients between the converted measurements for five files (within a tree) ranged from 0.5 to 0.8 (signifi-

Fig. 2. Example of larch tracheidograms (1964 year). Mean (A) radial cell size and (B) cell wall thickness plotted to six converted cells. The mean derives from averaged values of five files (measured replications). Each line represents an individual tree sample.



cant at $p < 0.05$). The correlation coefficients seemed to be independent of the location of the sampling sites, suggesting that merging cell measurements from different sites into one time series is valid.

Most cell series showed no systematic changes in cell dimensions with increasing cambial age. For example, in the case of cell No. 4, it was necessary to fit a negative exponential curve or linear regression line for only four of the 12 series for cell size and wall thickness. The cambial ages of the first measured tree rings in the four selected series were 29,

158, 231, and 296 years (Table 1). Variance for those series indicates that there are no changes in the relationship between the 10-year means and their standard deviations before and after detrending. Their relationships are independent for both cases and correlations between the means and variances are insignificant (r from 0.4 to 0.5, $p > 0.18$ for all cases). This suggests that changes in the mean values of cell dimensions of the tree-ring cell series may not be related to cambial age.

There is no strong relationship between cell size and cell wall thickness of cell No. 4 and cambial age in the full data set (Fig. 3). To determine how general this lack of correlation between cell dimensions and cambial age may be, additional study of various species, site conditions, and sample size will be needed.

In the absence of strong evidence for the dependence of cell dimensions on cambial age in the materials sampled, six cell size and six cell wall thickness chronologies were built without any detrending of the data. As a result, there was no loss of low-frequency variability resulting from the removal of the trend in the mean from short segments (Cook et al. 1995). The cell number chronology was derived using a different procedure. Because the total number of cells per ring decreases with increasing cambial age, each total cell number series was treated by conventional detrending and standardization procedures using negative exponential or linear regression.

The standardized cell series for each variable are well correlated among trees. The mean correlation coefficient varies from 0.32 to 0.87 at $p < 0.01$ and does not depend on the site from which the samples were taken. Mean series inter-correlation for cell sizes of the first and last tracheids is weaker than for the adjacent cells. Both cell size and cell wall thickness chronologies of converted cell Nos. 3, 4, and 5 have the highest variance (Table 3). The standard deviations of the cell chronologies from the middle of the tree ring to the end are 0.24 and 0.21 (cell size and cell wall thickness, respectively). Autocorrelation is low in the chronologies (Table 3). The cell size of latewood and the wall thickness of earlywood chronologies have less variability (Table 3). Although there are strong correlations between the series for individual samples, the relatively small number of sample series results in rather low percentage variance retained by the first eigenvector. This would be improved by the measurement of more samples. Subsample signal strength values indicate that 80% of the presently available signal is retained by as few as four samples (Table 3).

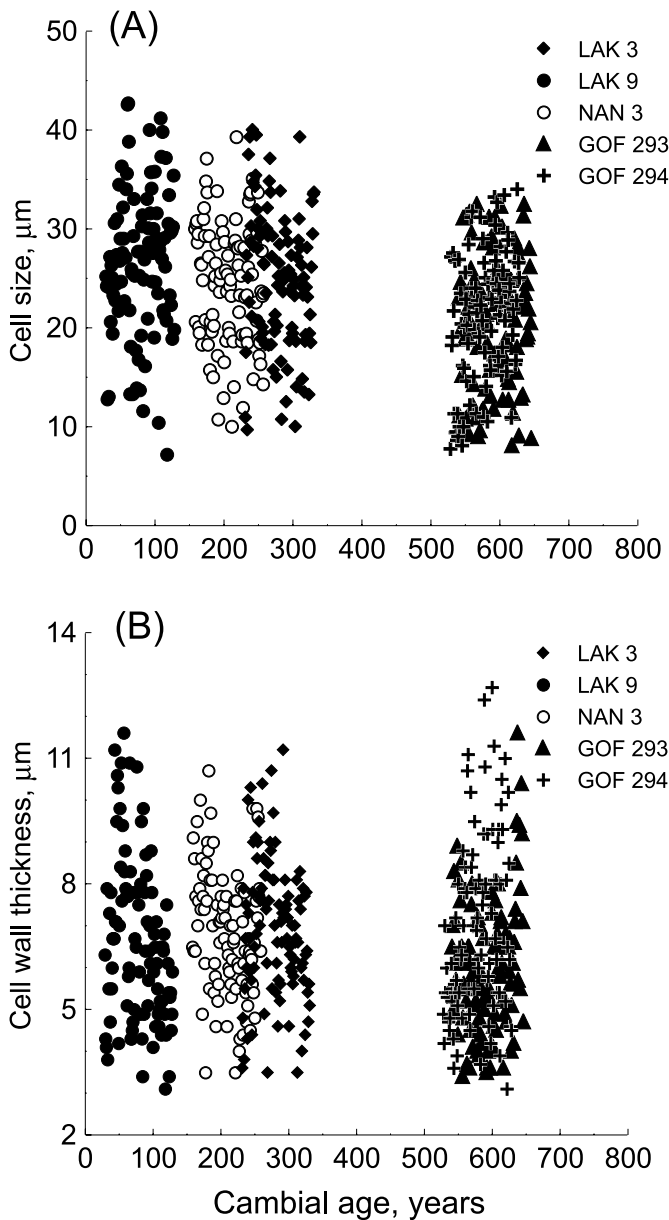
Table 4 shows correlation between the cell dimension chronology set and tree-ring width and maximum wood density chronologies from the same sites (Hughes et al. 1999) but based on a larger sample of larch trees (about 34 samples). The cell dimension chronologies, tree-ring width, and maximum wood density chronologies are generally well correlated. The maximum latewood density chronology shows the closest correlation with latewood cell wall thickness. Tree-ring width variability corresponds well to all cell dimensions with the exception of cell wall thickness of the first tracheid and cell size of the last tracheid. The chronology of the total number of cells correlates most strongly with tree-ring width, cell size of earlywood, and cell wall thickness of latewood (Table 4). The highest values of corre-

Table 2. Statistics of converted radial dimensions of larch tracheids from northeastern Siberia, 1642–1993.

Tree-ring parameter	Mean size, μm	Minimum size, μm	Maximum size, μm	SD	Mean correlation among trees
Cell size					
Cell 1	41.3	17.1	53.2	6.37	0.48
Cell 3	23.7	9.6	38.9	6.42	0.48
Cell 6	12.3	7.9	18.3	2.01	0.52
Mean wall thickness					
Cell 1	2.3	1.2	3.6	0.81	0.43
Cell 3	3.8	1.8	6.8	1.98	0.60
Cell 6	4.5	2.1	6.9	1.77	0.53

Note: The number of the converted cell in the tree ring is given.

Fig. 3. Scatterplot of (A) radial cell sizes and (B) mean cell wall thickness against cambial age in the middle part the tree ring (the fourth cell of the converted file) for 1641–1740.



lation in the cell chronology set are observed within subsets of the same cell parameter.

The variability of the tree-ring cell indices within each tree ring represents patterns of seasonal xylem formation in larch. Consistently thin walls and small cells in the early, middle, and late parts of the ring were observed in 1790–1820 and thick walls and large cells around 1660–1680 and 1920–1950 (Fig. 4). There were two main periods of disproportionate change in the high-frequency variability of cell dimensions: 1740–1760 and 1960–1993. In 1740–1760, the cell-size indices were greater than those for cell wall thickness, indicating the occurrence of unusually large tracheids with thin cell walls. In 1960–1977, a considerable increase in annual tree-ring growth was observed, mainly through enlargement of tracheid size in the earlywood. Cell wall thickness declined between 1960 and 1977 and rapidly increased after 1978, resulting in an increase in the proportion of latewood-like cells in tree rings for 1978–1993. The rapid increase in cell wall thickness across the whole ring was found in 1940–1950 as well.

The seasonal patterns of larch tracheid formation during the second half of the 20th century are unusual in the context of the last 350 years. The unusual character of xylem formation occurred mainly in the earlywood. The anomalies in seasonal and annual variability of cell dimensions correspond to changes in external (e.g., climatic) factors that control xylem differentiation. Generally, there is a positive trend in changes in larch tracheid dimensions for the last 350 years that evidences a sustained positive trend in seasonal growth rate and wood production in Subarctic larch stands that was halted only during the period 1790–1890.

Climatic response of cell dimensions and temperature reconstruction

Response functions of the tree-ring cell chronologies account for 41–52% of variance in cell size, 40–69% of that in cell wall thickness (Table 5), and 72% of that in total cell number by the climate of the current year. All cell sizes respond positively to June temperature. Additionally, latewood cell sizes exhibit a negative response to July temperature, but cell wall thicknesses have a positive response. The total number of cells shows a positive response to June temperature and a negative response to May temperature.

The various cell chronologies have much weaker responses to precipitation. The chronologies of cell sizes in the

Table 3. Main statistics of tree-ring cell chronologies.

Chronology	SD	No. of trees for subsample signal strength ≥ 0.80	% variance of first eigenvector	First-order autocorrelation
Cell size				
Cell 1	0.15	3	69.4	0.12
Cell 2	0.15	4	66.6	0.10
Cell 3	0.20	4	65.8	0.09
Cell 4	0.24	4	65.6	0.03
Cell 5	0.16	4	67.2	0.12
Cell 6	0.16	3	69.2	0.23
Wall thickness				
Cell 1	0.11	5	63.7	0.21
Cell 2	0.13	4	64.9	0.26
Cell 3	0.18	4	67.2	0.20
Cell 4	0.21	2	74.2	0.22
Cell 5	0.18	3	73.3	0.20
Cell 6	0.16	3	69.2	0.28
No. of cells	0.30	4	65.6	0.08

Note: The number of the converted cell in the tree ring is given.

Table 4. Correlation matrix for cell dimension chronologies and conventional chronologies of tree-ring width (TRW) for the period 1644–1992 and maximum wood density (MWD) for the period 1890–1992.

Chronology	TRW	MWD	No. of cells	Size cell 2	Size cell 5	Wall cell 2
MWD	0.54					
No. of cells	0.78	0.58				
Size cell 2	0.63	0.32	0.52			
Size cell 5	0.36	0.08*	0.25	0.65		
Wall cell 2	0.16	0.24*	0.19	0.38	0.31	
Wall cell 5	0.62	0.57	0.51	0.63	0.57	0.67

Note: TRW and MWD chronologies are from Hughes et al. (1999). Cell chronologies are total number of cells (No. of cells), cell sizes (size), and cell wall thickness (wall).

*Insignificant ($p < 95\%$).

earlywood and latewood cell wall thickness display statistically significant negative responses to May precipitation. There is also a significant negative response of earlywood wall thickness to July precipitation. Variability in the total number of cells does not show any significant correlation with precipitation.

Correlation analysis of daily climate data and cell dimensions exhibits a finer temporal resolution of climatic interaction with tree growth and indicates time intervals when larch xylem formation was sensitive to temperature in northeastern Siberia (Fig. 5). Cell size in earlywood is most strongly correlated with the temperature pentads of 15 to 19 June, 1 to 5 July, and 6 to 10 July. The temperature of mid-March (12–16 March) negatively correlates with all cell sizes and latewood cell wall thickness. The cell wall thickness of converted cell Nos. 3 and 4 has the highest correlation coefficients during the interval 6 July – 3 October. There is a strong response of cell dimensions to temperature from June through September.

Because the cell chronologies carry such a strong signal of growing season temperature, tree-ring indices were cali-

Table 5. Some statistics of the climatic response functions of cell size and cell wall thickness chronologies.

Chronology	Variance explained by climate	Variance explained by prior growth
Cell size		
Cell 1	0.51	0.17
Cell 2	0.52	0.19
Cell 3	0.45	0.17
Cell 4	0.43	0.18
Cell 5	0.41	0.25
Cell 6	0.41	0.29
Wall thickness		
Cell 1	0.40	0.15
Cell 2	0.40	0.16
Cell 3	0.55	0.15
Cell 4	0.69	0.08
Cell 5	0.66	0.09
Cell 6	0.52	0.13

Note: Monthly temperature and precipitation from the Chokurdakh weather station for 1945–1989 were used. The number of the converted cell in the tree ring is given.

brated with temperature pentads from March through September to select the best subset of predictors and the temperature reconstruction window. Finally, two models were built to reconstruct 2 June – 11 July temperature (JT) from the total cell number chronology and 2 July – 30 September temperature (JST) from the cell wall thickness chronology of converted cell No. 4. Statistics in Table 6 illustrate the reliability of the reconstruction models. The cell predictors account for 54% and 65% of the variance in temperature in the calibration period (1945–1989) and 51% and 61% of the explained variance in cross-validation models (PRESS test), respectively. Estimated and observed temperatures (Fig. 6) have strong agreement between them. The model performs poorly over the interval 1986–1988 for JT and in 1945–1949 and 1982 for JST, equivalent to about 7–15% of the years of the whole calibrated period.

Fig. 4. Cell tree-ring chronologies of larch from 1642 to 1993 for converted cell Nos. 1, 3, and 5. The thin line represents cell size and the thick line is mean cell wall thickness.

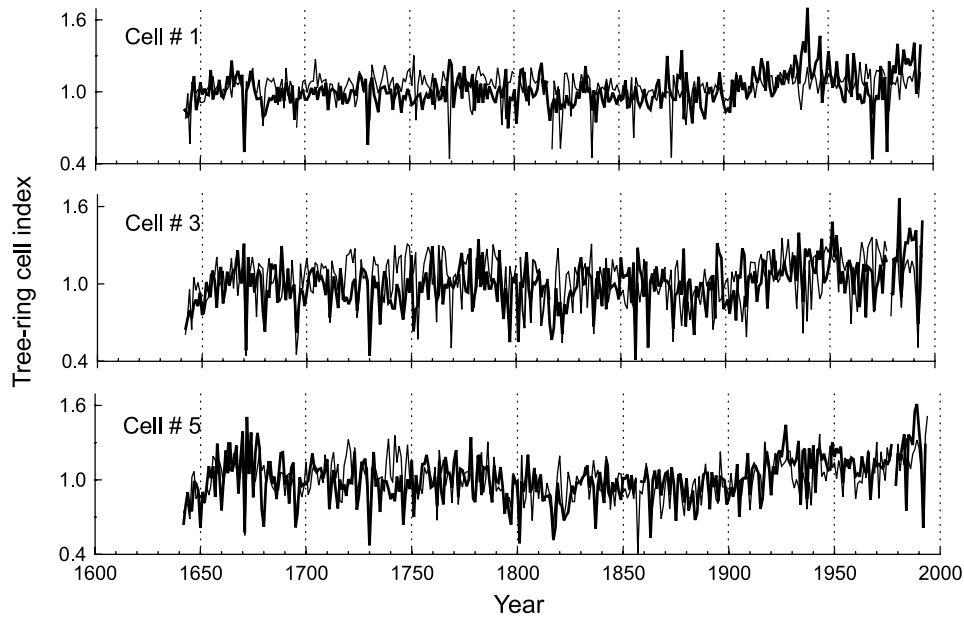


Fig. 5. Correlation coefficients of tree-ring cell chronologies with temperature pentads of the Chokurdakh weather station. Asterisks mark the coefficients significant at $p < 0.05$. The calculation runs from 1 September of the previous year to 31 August of the current year, but pentads were numbered in calendar order from 1 January. Pentads: 13–30, spring; 31–48, summer; 49–55 and 56–67 $n-1$ (previous year), fall; 1–12 and 68–73 $n-1$, winter. The vertical broken line shows the 1–5 June pentad (31).

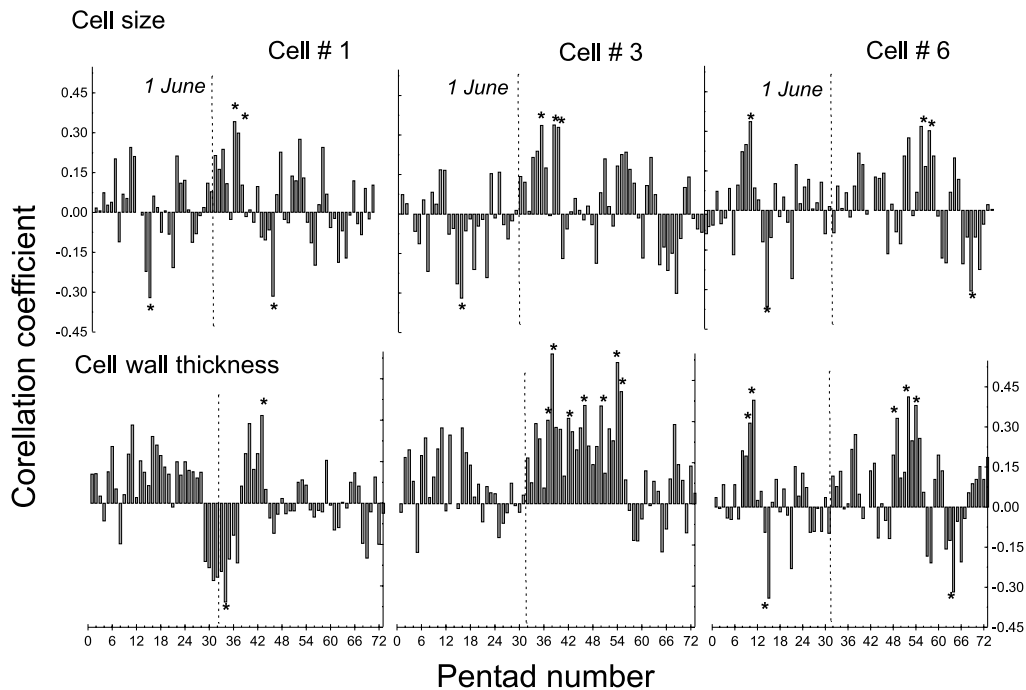


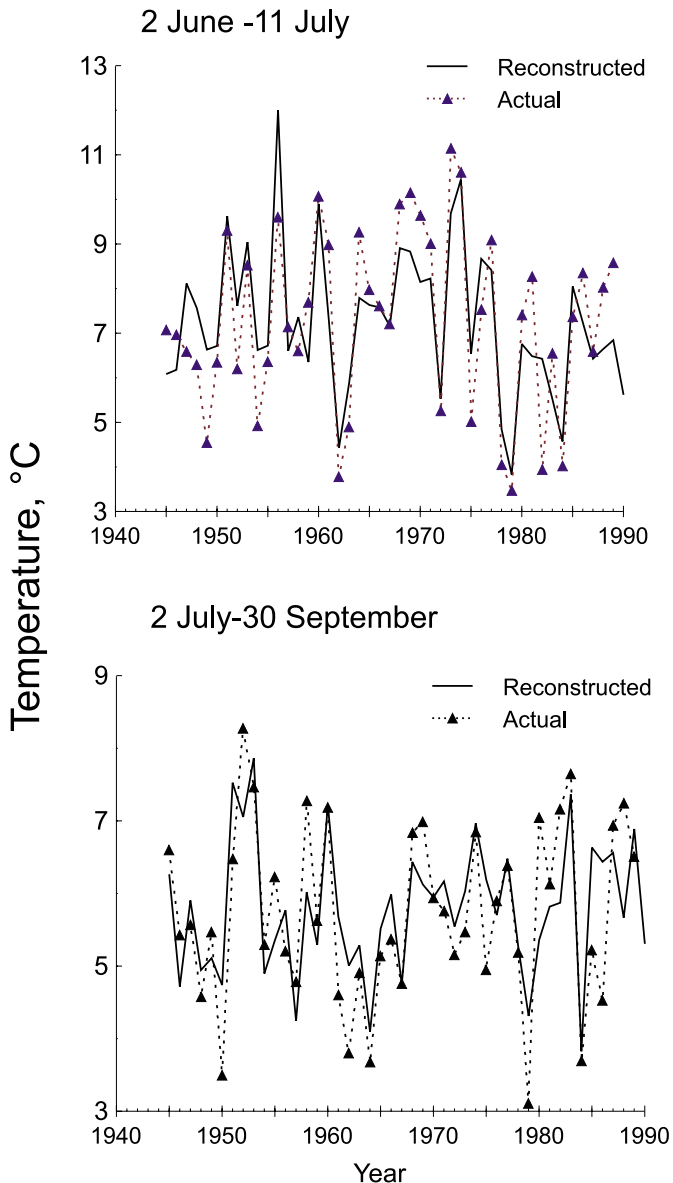
Figure 7 shows 10-year smoothed curves of reconstructed temperatures transformed to standard deviation units to compare the temperature pattern for the growing season in the context of the last 350 years. The low-frequency variability in the reconstructed temperatures is different, and the magnitude of this variability was higher after 1750. Temperature records at the decadal scale diverged around 1750–1765, 1810–1825, and after 1978. The mean reconstructed JT was

calculated as 7.3 °C, and the mean of JST was 5.8 °C. The highest JST values were registered around 1925–1960 with a maximum in 1940 (8.1 °C). However, the highest reconstructed values of JT (11.1–11.8 °C) occurred in the 1760s. The warmest decades of growing season temperature occurred in the 20th century with two distinct patterns since 1928 (Fig. 7): JT and JST covary from 1928 through 1978 and diverge after 1978, with JT, but not JST, having a lower

Table 6. Calibration statistics of the temperature reconstruction models for 1945–1989.

Temperature predictand	<i>R</i>	<i>R</i> ² (adj.)	<i>F</i> ratio, <i>p</i> < 0.000	Durbin–Watson statistic	AR residual	PRESS test	Cell chronology predictor
Early growth season, 2 June – 11 July	0.81	0.65	81.8	1.76	0.09	0.61	Total number of cells
Late growth season, 2 July – 30 Sept.	0.74	0.54	52.3	1.73	0.08	0.51	Wall thickness of fourth cell

Note: *R*, correlation; *R*² (adj.), coefficient determination adjusted for degrees of freedom; *F* ratio, Fisher test; AR residual, autocorrelation in residuals.

Fig. 6. Comparison of instrumental and reconstructed temperatures for the calibration period 1945–1989.

mean. Both periods differ from the intraseasonal temperature patterns reconstructed for the last 350 years. A sustained cooling of growing seasons was found between 1790 and 1885 when temperatures were lower than average instrumental temperature by 1 °C (JT) and 1.9 °C (JST).

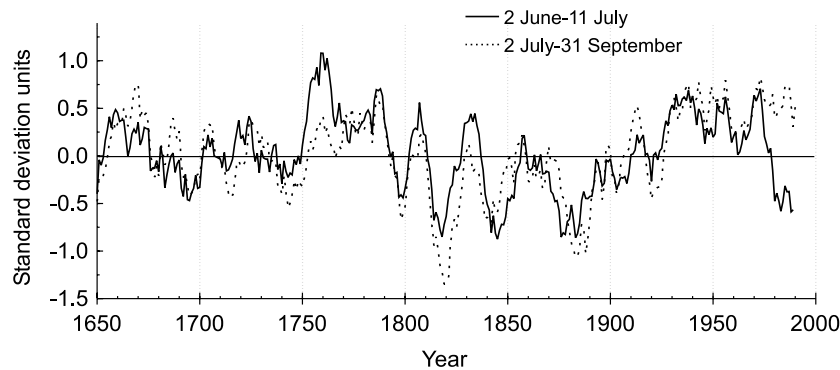
Discussion

There is the potential to develop a chronology of radial cell dimensions of larch that is a proxy of climate variability in the Siberian Subarctic. Two main questions arise from the reconstruction: (i) which temporal and spatial scales do cell chronologies represent and (ii) how do the reconstructed temperature patterns of growing seasons improve our understanding of the relationship between summer temperature and tree-ring growth?

In the Siberian Subarctic and northern boreal forests, the tree-ring width growth of larch is highly correlated over large distances (occasionally, more than 1200 km). Thus, a regional tree-ring chronology can capture tree-ring patterns under several climate subdivisions or even an entire Siberian sector of the Subarctic geographical zone (Briffa et al. 1998; Vaganov et al. 1996). Jones et al. (2001) also reported a significant correlation between gridded instrumental summer temperatures in the Siberian Subarctic over about 1000 km. The northern Yakutia chronology of larch based on tree-ring widths represents the Arctic sector between the Lena and the Kolyma rivers, which is about 1800 km from west to east (Hughes et al. 1999). Large correlations between cell dimension chronologies and the northern Yakutia tree-ring width chronology (Table 4) suggest that seasonal patterns of tree-ring formation apparently cover the same large area. It also means that the temperature signal of radial cell size and cell wall thickness of larch estimated through calibration with the Chokurdakh climate data is not just local and might represent a regional signal.

The temporal resolution of cell chronologies tends to be finer than tree-ring width or maximum latewood density. The periods with high correlation between temperature pentads and cell chronologies suggest some intervals that might be associated with climatically sensitive stages of cell development (Fig. 5). The cell size chronology of earlywood represents the beginning of summer from 2 June to 11 July. The cell wall thickness chronology of latewood corresponds to the second half of growing season from July to September, and the cell-size chronology of latewood is related to the August–September period. Thus, the temporal resolution of cell tree-ring chronologies varies from 1 to 3 months within a growing season. However, we believe that more precise evaluation of temporal resolution for cell chronologies needs to be investigated through long-term observations of annual larch cell production in northeastern Siberia.

The reconstructed intraseasonal patterns of temperature provide a picture of climate variability in the East Siberian Subarctic that differs in some details from the reconstruction of early summer temperature using tree-ring width. The

Fig. 7. Ten-year moving-average curves of reconstructed temperatures from cell dimension chronologies.

main difference in the decadal variability in 6 June – 7 July temperature reconstructed from tree-ring widths (Hughes et al. 1999) and 2 June – 11 July temperature predicted from cell numbers appeared between 1835 and 1920. Tree-ring widths recorded general warming starting about 1830, but tree-ring cell numbers showed that it began about 1885, resulting in a greater magnitude of temperature increase in the 20th century. However, the cell number chronology is the only cell chronology based on detrending of the cell data, and given the shortness of the samples used and their relatively small number compared with those used in the ring-width based chronology, its low-frequency variations should be viewed with caution.

We assume that the intraseasonal patterns of reconstructed temperature (Fig. 7) derive from particular temperature conditions at the beginning or the end of growing seasons and the length of the season. Coherence in variability of both warming summer temperatures (JT and JST) might correspond to prolonged growing seasons, resulting in the production of large radial growth as was observed in 1653–1673, 1764–1789, and 1925–1960 (Fig. 7). The reconstructed rate of temperature increases for the beginning of the growing season (JT) exceeded the slow JST rise around 1705–1720, 1740–1765, 1825–1835, 1870–1890, and 1920–1930. This may be associated with an early start of larch growth and very warm conditions at the time of greatest cambial division. This pattern suggests a continuous period of extended growing seasons with an early start of cell growth and hence increased realization of their growth potential. Three very cold episodes were reconstructed: 1870–1890, 1838–1853, and 1810–1825 (Fig. 7). Higher tree-ring growth between those cold episodes in the middle of the nineteenth century and the 1830s was probably related to very warm June conditions (Fig. 4).

A unique change in the relationship between early summer and mid- to late summer temperatures is seen in the period since 1978. There is a uniquely large difference between reconstructed JT and JST from 1978 to present (Fig. 7), which is also seen in the instrumental temperature of the Chokurdakh station (Fig. 6). This change is recorded in earlywood structure as smaller cells with thicker walls, appearing somewhat rounded. This unique change in the seasonal progression of temperatures is consistent with the scenario described by Vaganov et al. (1999) in which a positive trend in winter precipitation leads to increased snowpack at the end of the winter, delayed thaw of the active layer, and

hence a late start to the growing season. The region from which our samples were taken is one of several where a decoupling at decadal time scales of the correlation between summer temperatures and maximum latewood density was not observed for the last few decades (Briffa et al. 1998). It would be of interest to examine climate records for the regions where the decoupling was observed to see if any analogous change in seasonal progression of temperatures occurred and how it affected tree-ring formation.

In summary, we conclude the following:

- (1) It is possible to build long-term chronologies of cell dimensions.
- (2) Cell wall thickness and cell size may not depend on cambial age, but further study is needed. Cell number depends on cambial age.
- (3) There are sufficiently strong correlations between cell size and cell wall thickness, including total cell number, and temperature for them to be considered useful proxies for past growing season temperature.
- (4) The cell dimension and cell number chronologies, when combined with ring width and maximum latewood density chronologies, permit the independent reconstruction of different parts of the season, some as short as 1 month.
- (5) A striking change in the seasonal progression of temperatures occurred in the late 1970s. In the last two decades, early summers have been consistently cool compared with the rest of the summer to an extent that is unique in the past 350 years.

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