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Summer temperatures in eastern Taimyr inferred from a 2427-year late-Holocene tree-ring chronology and earlier floating series

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Abstract: A brief review is presented of the progress, to date, in constructing a long, continuous ring-width chronology from living and subfossil Siberian larch (*Larix gmelinii*) in the eastern part of the Taimyr peninsula. A near 2500-year chronology running up to the present has been assembled and several shorter, earlier series have been produced that are dated approximately on the basis of radiocarbon dates. A description is given of the production of separate early summer and annual mean temperature histories based on the recent chronology, spanning more than 2000 years. These two reconstructions are based on alternative methods of statistical processing of the measured tree-ring data. The early summer and annual reconstructions agree well in the long-term components of their variability, providing evidence for anomalous warmth in the third, tenth to twelfth, and twentieth centuries, and a prolonged cool period throughout the sixteenth and seventeenth, and in the early nineteenth centuries. The mean growth and other statistical parameters of the earlier chronologies also suggest that conditions for tree growth were very favourable in the earlier Holocene, particularly in the fourth millennium BC. This is strongly indicative of an early Holocene Climatic Optimum in Taimyr at that time. Other material in hand, and earlier published radiocarbon dates, demonstrate the feasibility of constructing continuous ring-width chronologies and temperature estimates extending throughout all of the last 8000 years.

Key words: Dendroclimatology, tree rings, summer temperature, subfossil wood, larch, *Larix gmelinii*, Taimyr, Northern Siberia, Holocene.

Introduction

The 1990s saw a dramatic increase in global mean temperatures in the Northern Hemisphere. Peak summer warmth (June-August) was attained in 1998 (positive NH temperature anomaly above 0.75°C with respect to the mean for 1961-90: Jones *et al.*, 1998; Mann *et al.*, 1999). On the basis of historical analogues and scenarios based on climate models, such a warming is likely to be strongly represented in high latitudes (Budyko and Izrael, 1987). It has been speculated that the Northern Hemisphere warming will lead to a latitudinal redistribution of the main climatic variables (temperature and precipitation) and a consequent change of terrestrial ecosystem productivity (D'Arrigo and Jacoby, 1992; Cao and Woodward, 1998; Rind, 1998). Temperature changes in high latitudes are, therefore, a sensitive indicator of global temperature changes and a basis for verifying both model calculations and for testing the correctness of historical analogues. The supra-long tree-ring chronologies obtained from high latitudes where tree growth clearly reflects the influence of temperature variability are valid subjects for detailed and thorough analysis. They have a high resolution in time and present an opportunity for rigorous calibration of empirical transfer functions that is not possible using palaeoclimate proxies that have lesser temporal resolution, such as those contained in most lake sediments (Briffa *et al.,* 1992; 1998; Schweingruber, 1996; Shiyatov and Vaganov, 1998; 1999).

The east of Taimyr, where the most northern larch forests on Earth are to be found, is also a region where a great amount of

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dead and subfossil wood is preserved. This makes it one of the most important regions for long dendroclimatic studies in the circumpolar zone of the Northern Hemisphere. There is real potential in this area to obtain supra-long temperature reconstructions, extending through most of the Holocene, and to use them for comparison with other types of information on climatic changes (Vaganov *et al*., 1996b; Schweingruber and Briffa, 1996; Naurzbaev and Vaganov, 1999).

The objectives of this short article are: (1) to show the progress already achieved in building a continuous tree-ring chronology for the east of Taimyr stretching over several recent millennia; (2) to analyse the main statistical characteristics of the current absolute 2000-year chronology; (3) to present quantitative indications of past early summer and average annual temperature based on these tree-ring data; and (4) to compare the reconstructions with similar-based reconstructions for other high-latitude regions and with other indirect sources of climatic change in the Northern Hemisphere. This paper also serves to demonstrate the feasibility of, and progress towards, building a longer continuous series that will span 8000 years or more of the Holocene.

Material and methods

The sampling of likely dendrochronological material, that in this case consists of larch (*Larix gmelinii* (*Rupr.*) Rupr.) wood samples, was made within the northern taiga subzone at, and north of, the present polar timber-line (Figure 1). Increment cores of the old living trees, and of preserved dead trees, were taken. Other subfossil wood was collected using a chainsaw to cut radial discs when possible. The material consists of three basic types: (1) that derived from the present northern (latitudinal) larch timber-line, in the Stow Ary-Mas (72°28'N); (2) material from the present upper elevational timber-line at 200-300 m a.s.l. in the Kotuy river valley (70°30'-71°00'N); (3) wood recovered from alluvial deposits in flood-lands and terraces of the large tributaries of the Khatanga river (70°30'-73°00'N). The material was allowed to dry and was then prepared by thorough sanding to a fine polish, so that the detailed tree-ring cell structure could be clearly distinguished under the microscope. Radial ring widths were measured microscopically using an automated moving table device that has an accuracy of better than 0.01 mm. After rigorous cross-dating, that involves multiple visual and statistical comparisons of the different high-pass filtered ring patterns derived from multiple tree samples, the original ring-width measurement series from each sample were statistically processed using widely available software used in dendrochronological and dendroclimatological studies (Holmes, 1983; Cook *et al.,* 1990). Radiocarbon dates on samples from dead trees and subfossil wood were obtained at the University of Bern (Switzerland) and the Institute of Geology, Geophysics and Mineralogy, Siberian Branch of the Russian Academy of Sciences at Novosibirsk.

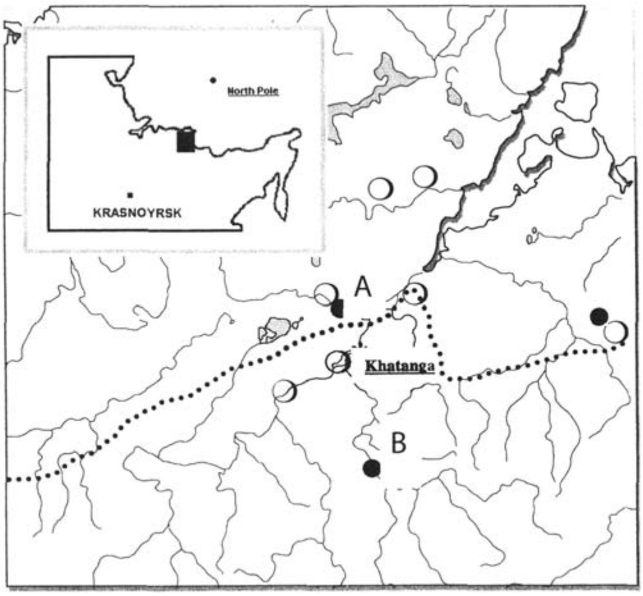

Figure 1 Location of the sites where wood samples were collected: sites of subfossil wood that constitutes the material for the 'floating' chronologies are shown by open circles. The sites of living and dead trees near the upper timber-line used to build the dated chronology from 431 BC to AD 1996 are shown as solid circles. The dotted line shows the position of the modern polar timber-line. (A) Kheta-Khatanga plain: (B) Moyero-Kotuy plateau.

To remove the effect of increasing tree age on the measured ring widths in individual samples, the measurement data were converted to indices by taking anomalies from the appropriate years of a single reference curve, a function of expected ring width against tree age for trees in this region. This was derived by fitting a negative exponential function through the simple averages of all the measured series, after aligning them by cambial age from the tree pith (that is according to the life cycle of the tree as opposed to any calendrical date): the so-called 'Regional Curve Standardization' or RCS (Briffa *et al.,* 1996). However, rather than assume that a single RCS reference curve was suitable for all the data, the sample measurement series were first divided into two groupings and RCS curves calculated for each: one derived from the living-tree and dead-tree samples where these were cored between 0.5 and 1.0 m above the ground; the second derived from the best-preserved subfossil samples and using growth right at the base of the tree (Figure 2). The age curves for the tree-base measurements show how the increase in radial diameter is slow for up to about 70 years before the long period of later diminishing ring width begins. These early years are not represented in the living-tree core samples because of the height of coring in the stem. Assuming that the pith (i.e., innermost) ring at this height was equivalent to the year of tree germination would obviously lead to a rather large error in assigning the relative life cycle age of the living samples. The slow early growth of these trees might be associated with competition by other low-level vegetation as well as the influence of snow cover (Gorchakovskii and Shiyatov, 1985; Abaimov *et al.,* 1997a). However, by aligning the living trees correctly, making allowance for the initial slow growth in these data, it is possible to derive a single appropriate RCS curve, as shown in Figure 2. This curve is also confirmed by reference to other material from living trees collected previously in the region (Vaganov *et al.,* 1996b).

Beside producing the general RCS chronology (the mean of the RCS indices aligned by correct calendar year), the so-called 'residual' chronology was also produced by averaging the residuals from an Autoregressive Moving Average (ARMA) model fitted to the measurement series (Cook *et al.,* 1990; Vaganov *et al.,* 1996b). Both chronologies, the RCS series (identified henceforth here as RCh), and the autoregressive residual chronology (RRCh) were used in further investigations of the dendroclimatic potential of this material.

A number of statistical descriptors of the chronologies, used commonly in dendroclimatological studies, are also used to characterize the modern and earlier chronologies and to allow some basic comparison of the time-dependent changes in tree growth throughout at least parts of the last 6000 years. The statistics used include the mean interseries correlation coefficient, mean sensitivity, standard deviation and autocorrelation coefficient (details given in Cook and Kairiukstis, 1990). Standard techniques were also employed for identifying the optimum climate growth forcing signals in the alternative modern chronologies and for producing reconstructions of these signals: so-called

Table 1 Radiocarbon dates of Taimyr samples in the absolute and floating chronologies (chronology identification numbers refer to Figure 2)

Lab. no.	Radiocarbon age			Dendrochronological dates, years AD/BC	Length, years
	Uncalibrated age, years BP	Calibrated age (s)***, years AD/BC	δ^{13}C, ‰		
Chronology Identification Number 1					
KTU-004	230 ± 65-3391**	-	-	AD 1750	592
KTU-030	400 ± 35-3392**	-	-	AD 1500	372
KTU-009	665 ± 50-3390**	-	-	AD 1300	470
MAY-923	910 ± 30 B-6089 *	AD 1161	-28.0	AD 1168	201
MAY-918	960 ± 30 B-6087 *	AD 1037	-27.2	AD 1108	169
MAY-920	1100 ± 30 B-6088 *	AD 974	-27.6	-	49
CHA-H3	1210 ± 30 B-7056 *	AD 827, 833, 856	-26.3	-	286
CHA-072	1520 ± B-7062 *	AD 554	-28.1	-	315
KTU-106	1840 ± 30 B-7058 *	AD 218	-27.5	AD 145	354
NOV-A20	2250 ± 30 B-7057 *	366, 273, 266 BC	-29.1	-	285
KTU-222	2320 ± 30 B-7059 *	392 BC	-26.3	350 BC	203
Chronology Identification Number 2					
MAY-925	2440 ± 20 B-6785 *	514 BC	-26.8	-	155
Not yet incorporated in chronology					
NOV-069	2890 ± 20 B-6788 *	1030 BC	-28.3	-	142
CHA-H2	2990 ± 30 B-7055 *	1254, 1243, 1213 BC	-27.2	-	230
CHA-H1	3110 ± 30 B-6083 *	1398 BC	-26.9	-	306
CHA-059	3400 ± 30 B-6427 *	1683 BC	-26.5	-	192
MAY-736	3500 ± 30 B-7060 *	1865, 1844, 1775 BC	-27.9	-	393
MAY-702	3930 ± 30 B-6784 *	2456 BC	-25.9	-	270
NOV-077	4240 ± 30 B-6789 *	2881 BC	-25.6	-	216
Chronology Identification Number 3					
NOV-001	4370 ± 40 B-6419 *	2923 BC	-27.1	-	182
LUK-005	4500 ± 30 B-7054 *	3298, 3236, 3173, 3168, 3107 BC	-27.0	-	225
CHA-H6	4510 ± 40 B-6086 *	3302, 3234, 3178, 3164, 3110 BC	-26.9	-	348
NOV-030	4570 ± 40 B-6082 *	3345 BC	-25.7	-	221
NOV-078	4600 ± 40 B-6420 *	3358 BC	-26.5	-	291
NOV-080	4640 ± 30 B-6421 *	3370 BC	-27.3	-	520
NOV-A02	4680 ± 40 B-6081 *	3497, 3457, 3378 BC	-27.7	-	286
CHA-005	4730 ± 30 B-6780 *	3611, 3608, 3513, 3391, 3390 BC	-26.5	-	197
CHA-023	4750 ± 30 B-6781 *	3617, 3588, 3528 BC	-26.5	-	89
LUK-001	4790 ± 40 B-7053 *	3628, 3563, 3543 BC	-28.1	-	384
NOV-029	4810 ± 40 B-6080 *	3634 BC	-27.0	-	310
Chronology Identification Number 4					
CHA-043	4900 ± 30 B-6783 *	3690, 3666 BC	-26.0	-	134
CHA-060	4970 ± 40 B-6418 *	3761, 3735, 3726 BC	-26.5	-	329
CHA-060	4910 ± 40-3390**	-		-	329
CHA-012	4980 ± 30 B-6423 *	3772 BC	-27.1	-	345
CHA-012	4855 ± 45-3388**	-		-	345
CHA-009	4990 ± 30 B-6424 *	3776 BC	-25.1	-	215
CHA-017	5010 ± 40 B-6425 *	3785 BC	-27.3	-	452
CHA-H4	5020 ± 40 B-6084 *	3792 BC	-26.9	-	176
CHA-036	5040 ± 30 B-6782 *	3899, 3884, 3801 BC	-26.2	-	180
CHA-032	5110 ± 30 B-6426 *	3950 BC	-25.8	-	
CHA-001	5150 ± 40 B-6085 *	3964 BC	-28.3	-	546
CHA-001	4865 ± 45-3387**	-		-	546
Not yet incorporated in chronology					
CHA-011	5250 ± 30 B-6422 *	4038, 4014, 4007 BC	-25.7	-	256
NOV-005	5400 ± 30 B-6787 *	4310, 4248 BC	-27.5	-	
MAY-743	6260 ± 30 B-7061	5227 BC	-25.1	-	

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***Stuiver and Reimer (1993).

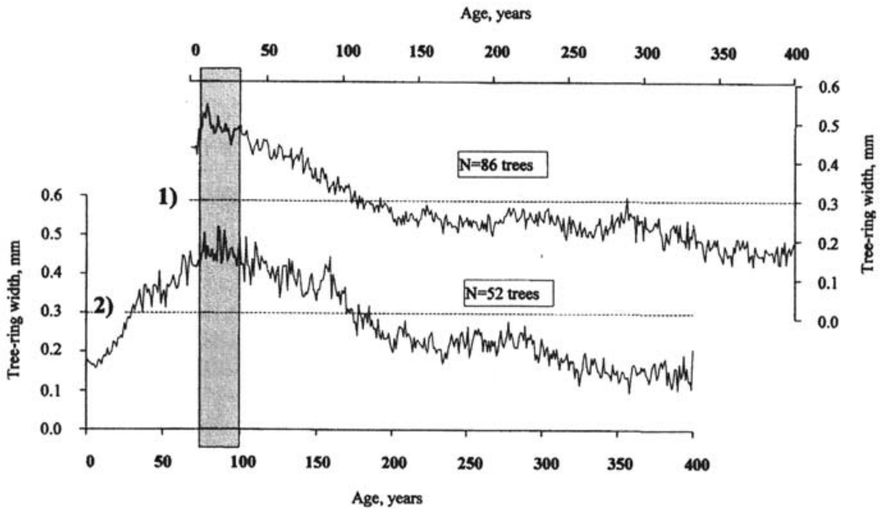

Figure 2 The two 'regional' age curves (1) obtained for cores and stem wood samples taken at a height of 0.5-1.0 m above ground and (2) as derived from discs of dead trees where the lower part of the stem is preserved. An offset in the curves is required to account for the sampling height bias and to produce a single valid standardization reference curve.

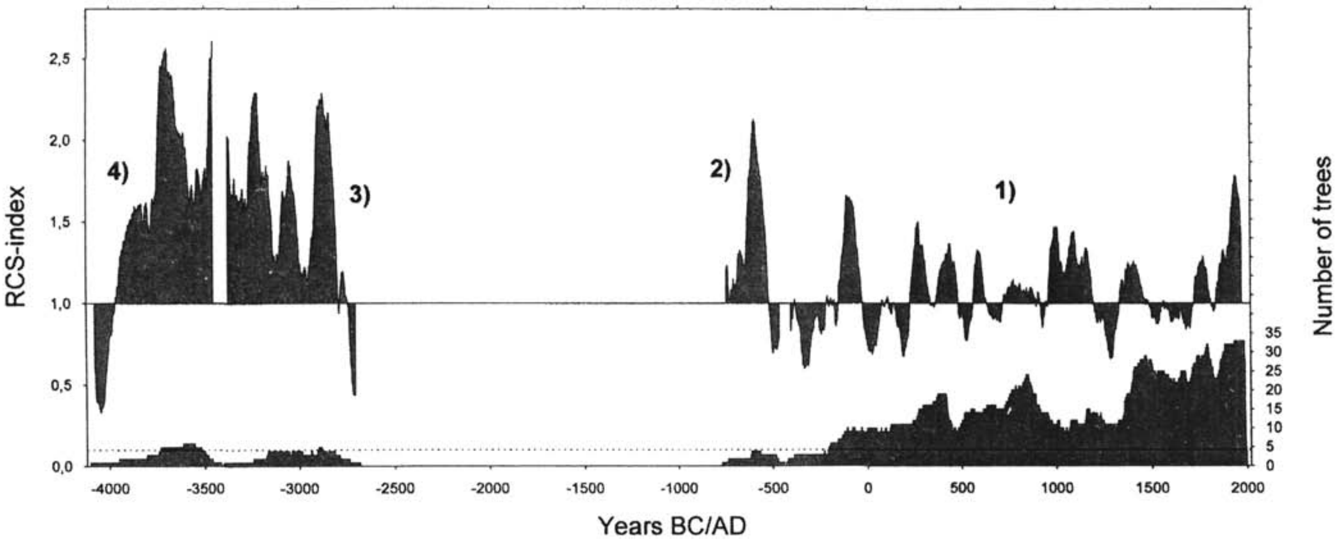

Figure 3 The low-frequency component of ring-width growth in the RCS chronologies (upper curves) created from the modern firmly dated series (1) and several earlier 'floating' radiocarbon dated series (numbered 2-4 for cross-referencing to Table 1). The lower curves show the number of constituent tree-ring series that make up these chronologies.

Table 2 The main statistical characteristics of tree-ring-width chronologies

Characteristics	Tree-ring chronologies	
	Absolute	Floating
Calendar period (BC/AD)	431 BC-AD 1996	4140 ± 40-2698 ± 40 BC*
Length (years)	2427	1443
Number of dated trees	138	27
Mean (and maximum) number of rings in samples	273 (840)	262 (548)
Mean series intercorrelation	0.75	0.59
Mean tree-ring width (mm)	0.30	0.45
Mean sensitivity	0.40	0.33
Lag 1 autocorrelation	0.51	0.65
Variance due to ARMA (%)	20	42

*Calibrated radiocarbon age (see Table 1).

response function and transfer functions techniques, respectively (Fritts, 1976; Fritts *et al.,* 1990; 1992; Schweingruber, 1996). The adequacy or validity of the calibrated regression models was also assessed using well-known verification tests such as the Durbin Watson test for assessing the autocorrelation in the regression residuals (Himmelblau, 1973).

Modern and subfossil tree-ring chronologies

The radiocarbon dates and the calibrated ages of numerous wood samples are listed in Table 1. They are presented in various groups: including those for selected samples from among the ring-width data included in the continuous firmly dated chronology and those selected from the samples whose ring-width series comprise three earlier 'floating' series. The absolute chronology runs from the year 431 BC up to AD 1996, a total of 2427 years (Table 2). The longest floating chronology is made up of data from 27 internally cross-dated samples, and is 1443 years long, dating to approximately 4140-2700 BC according to the calibrated radiocarbon sample ages. From Table 1, it is not difficult to see that the radiocarbon dates agree well with precise dendrochronological dates. It is invariably the case that, within the longest floating chronology, the radiocarbon dates have the same relative locations as the dendrochronological dates. The length of the individual tree series derived from the subfossil wood varies from 93 to 546 years, providing a generally favourable basis for achieving reliable cross-dating. The radiocarbon dates of the subfossil wood are distributed evenly through the whole Holocene period from the present day back to 6000 years ago. Subfossil material has also been shown to exist for an even earlier period, back to 9000 years ago, in the east of Taimyr (Vaganov *et al.*, 1996a). The laboratory of the Institute of Forest now holds a rather voluminous store of subfossil wood, for which sample measurements have been made but are not, as yet, matched with, or incorporated within, the existing 'floating' chronologies or the absolute recent chronology. On the basis of some radiocarbon dates (also shown in Table 1), these series fall within the period 1000-2500 BC.

The data in Table 2 summarize the main statistical characteristics of the absolute and three 'floating' chronologies. The average tree-ring width for the floating series is distinctly higher than that for samples from the last 2000 years of the Holocene. Mean between-series correlation coefficients are somewhat lower in the 'floating' chronologies, indicating a somewhat weaker common growth forcing of ring widths at these times, interpretable as evidence of less stress and so probably indicative of milder conditions. A similar interpretation is suggested by the lower coefficients of mean sensitivity and higher values of the Lag 1 autocorrelation, the latter demonstrating less dependence of growth in the current year on growth in the previous one, in these earlier series. The stable ^{13}C values for the wood (Table 1) are also relatively high in the early subfossil chronologies with typical values in the period between 6000 and 5500 cal. BP, between -26.5 and -25.5 ^{13}C‰ and an isolated sample at 7200 cal. BP at -25.0. This may be compared with typical values in the last two millennia of between -27 and -29‰. Taken together with the statistics shown in Table 2, considerably better growth conditions are indicated during 4000-3000 BC, consistent with the concept of a 'Climatic Optimum' of the Holocene (Lamb, 1977).

The use of the RCS approach to preserve long-timescale variation in the ring-width data has also provided direct evidence of good growth conditions in the earlier Holocene in Taimyr, as is clear from the low-frequency plot shown in Figure 3. All of the data have been scaled by reference to the same single mean growth curve expressing expected ring width for specific tree age, and the relative growth of rings in the early floating chronology is clearly much above that of more recent trees. The average value of the indices for the period roughly between 3000 and 4000 BC is 1.5 times higher than that for the last two millennia.

Identifying and reconstructing climate signals

It has been established that the main driver of tree-ring variability at the polar timber-line is temperature (Vaganov *et al.*, 1996b; Briffa *et al.*, 1998; Schweingruber and Briffa, 1996). Most earlier studies of this relationship between growth and climate have been based on relatively crude temperature measures, such as mean monthly temperatures. In this study, local daily mean temperatures were available for the period 1933-89 and allowed better resolution in defining the seasonal growth-forcing signal. The results are summarized in Figure 4, where the influence of mean temperature on the RRCh chronology for specific pentads is shown. A clear optimum seasonal window of response is evident for the period from 17 June to 11 July. This can be considered as an 'early summer signal', and it corresponds to the period when air temperature in this region rises from about 5° to 12°C. The long-term mean for this period is well correlated with mean June temperature (0.76) and reasonably with that for July (0.52), but it is even more strongly correlated with longer multimonth averages such as June-September (0.68) and June-July (0.84). However, the correlation against mean annual temperature is much weaker (0.20). The strong association between the RRCh series and early-summer temperatures, therefore, provides a good basis for the reconstruction of summer warmth (Table 3), though this is not expected to preserve as much long-term (century and longer timescale) variance as is possible using the RCh chronology. The RCh series is strongly correlated with local temperatures averaged over the extended warm season from June to September (0.69) but also, remarkably, with mean annual temperature (0.70). However, if another independent variable, a series that measures the

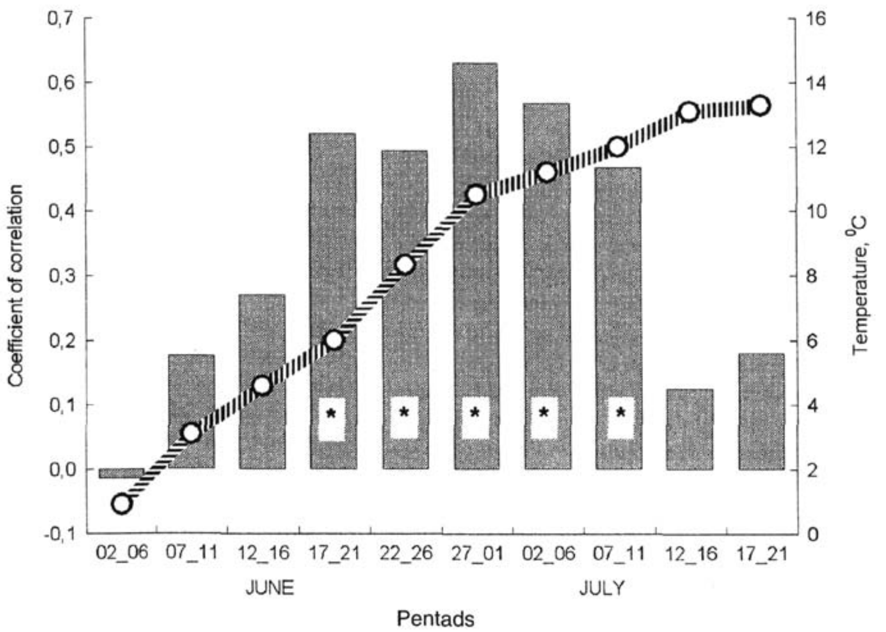

Figure 4 Histograms showing the correlation coefficients for the comparison of the recent ring-width chronology (RRCh), with pentad temperature means. Significant values are indicated by stars. Open circles show the long-term mean temperature values (right axis).

Table 3 Statistical evaluation of the regression models used for reconstructing temperature histories in eastern Taimyr

Calibration				Verification			
Period	Explained variance (%)	F value (random probability)	Durbin Watson statistic	Period	Explained variance (%)	F value	Durbin Watson statistic
Early-summer mean based on the yearly RRCh series (see text)							
1933-89	59	79.6 ($p < 0.001$)	1.91				
1960-89	72	72.7 ($p < 0.001$)	1.91	1933-59	45	20.5 ($p < 0.001$)	1.88
Annual Mean based on five-year average RCh chronology values and running concordence coefficient							
1934-93	67	45.9 ($p < 0.001$)	2.51				

five-year moving interseries agreement, is included along with the RCh chronology in a multiple regression, even more of the annual temperature variance is captured. This additional variable series is calculated using the 5-year running concordence coefficient (Kendall, 1975). This multiple regression accounts for 67% of the annual temperature variance (Table 3). Figure 5 shows the goodness of fit between the ring-width-based regression estimates and instrumental observations of early-summer and mean annual temperatures, respectively. Extended reconstructions, over the period covered by the dendrochronologically dated larch series, are shown in Figure 6. In the reconstructed early-summer series, the total range of the variability is 13.9°C (from 2.3 to 16.2°C). This is higher, by 4°C, than that seen in modern instrumental data. After 50-year smoothing to emphasize the history of multidecadal variability, the values are encompassed within a range of about 2°C.

Long-term changes of early-summer and annual temperatures agree well (Figure 6). Similar cool periods are distinguished during the first and second, early fifth, thirteenth, sixteenth to seventeenth, and early nineteenth centuries. The warmest periods over the last two millennia in this region were clearly in the third, tenth to twelfth, and during the twentieth centuries. A long period of cooling began in the fifteenth century and it continued cool up to the middle of the eighteenth century, corresponding with the timing of the so-called 'Little Ice Age', as noted by several authors in Bradley and Jones (1993). Table 4 provides a list of the warmest and coldest early summers and shows the most extreme reconstructed centuries. Only one of the most extreme individual summers, the warm AD 1941, falls in the last 500 years, but the century AD 1870-1979 is reconstructed as the second warmest (after 144-43 BC). The warmth of the two centuries AD 1058-1157 and 950-1049 attests to the reality of relative mediaeval warmth in this region. The fifth coolest summer reconstructed, AD 536, is well known as an extremely cold year in many areas of the Northern Hemisphere (e.g., Baillie, 1999). The frequency of extreme early summers (as defined by those greater or less than two standard deviations) increases in warm periods and decreases in cool periods. This can be seen particularly during the fifteenth to nineteenth centuries. The second coolest 100-year period (366-265 BC) corresponds to the time when both the Swedish and Finnish long chronologies could not be bridged for some considerable time, implying severe disruption of tree growth in Fennoscandia, possibly associated with cool and very wet conditions (Grudd *et al*., this issue; Eronen *et al*., this issue).

Discussion and comparison with large-scale temperature data

The fact that high-frequency changes of growth, as presented in the RRCh-chronology, are determined mainly by early-summer temperature is not unexpected. Similar results have been obtained for other Subarctic regions (Hughes *et al*., 1999; Kirdyanov *et al*., 2002). What is perhaps more surprising is that variability of the tree growth indices in the RRCh-chronology is determined by the temperature variability in such a short season. This represents not more than 35% of the whole period for which positive temperatures would generally permit tree growth (Kirdyanov *et al*., 2002). As the period that apparently governs growth here does not exceed one twelfth of the year, only high-frequency variability is likely to be registered in the growth indices in the RRCh-chronology. The range of variability in the reconstructed temperatures is only about 14°C, which is equal to the maximum temperature in midsummer.

The reconstructed early-summer temperature data for eastern Taimyr may be compared with mean temperatures for the Northern Hemisphere, focusing on the period from the early AD 1880S up until 1993 and the average for the month of June, that corresponds most closely with the non-standard season used here to calibrate the reconstruction (Figure 7). In this comparison, it is possible to distinguish three periods. From AD 1880 to 1940, both series increase linearly. From AD 1940 to 1963, both Taimyr and hemispheric temperatures decline linearly. From the early AD 1960s, however, the strong wanning seen in the hemisphere curve is clearly absent in Taimyr. Hence this Taimyr series cannot be considered, in isolation, to represent the course of Northern Hemisphere temperatures.

The association between the long-term changes in average annual temperatures and both growth and the synchroneity of growth changes of different trees through time can be explained partly methodically: the increase of tree-ring width is associated with a lower relative error in the measurement of rings. However, the more significant cause is probably the fact that the frequency of extreme years is lower in the cold periods. The more severe conditions therefore lead to a reduction in the synchroneity of growth response in tree growth. In the RCh-chronology the long-term changes better represent absolute measures of tree-growth change than are represented in the indices of the RRCh series (Briffa *et al*., 1996; Naurzbaev and Vaganov, 1999). At the polar timber-line, one factor affecting the value of absolute tree growth is the depth of the permafrost layer, or more specifically the depth to which the soil thaws out during the growing season (Pozdnyakov, 1986; Abaimov *et al*., 1997a). This process is largely influenced by the thickness of moss cover. When this is destroyed, for example due to fire, the soil is warmed to a greater depth. This promotes a deeper active layer, better warming of the tree root layer and accelerated tree growth (Arbatskaya, 1998; Abaimov *et al*., 1997a, 1997b). Increased thickness of the moss cover (i.e., a positive balance of phytomass accumulation over destruction) will restrict heat penetration from the surface and

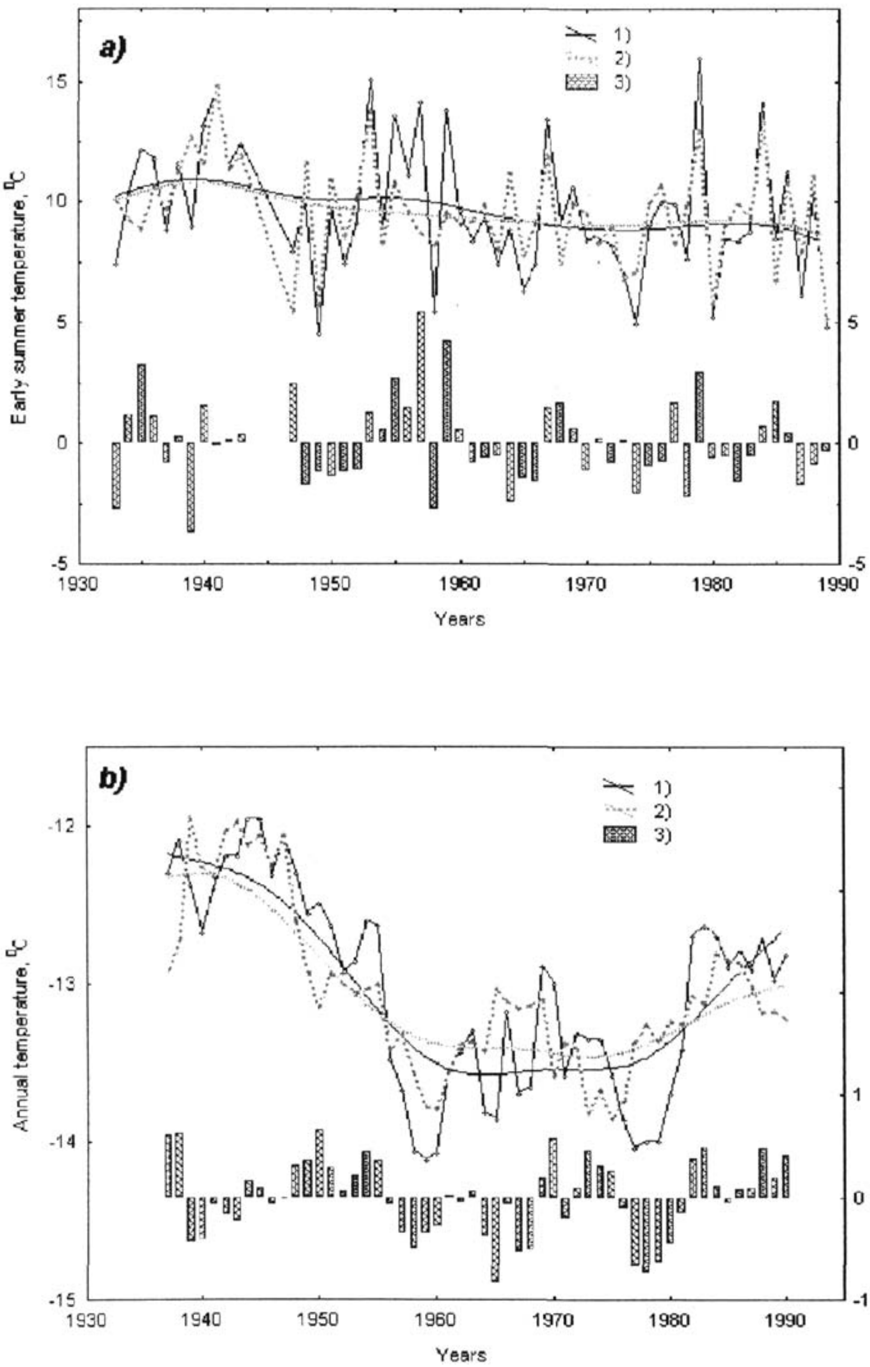

Figure 5 Comparison between observed and regression-based estimates of early summer (a) and mean annual (b) temperatures for Taimyr, based principally on the RRCh and RCh chronologies, respectively. Solid lines with circles show the instrumental observations (1); dotted lines show the estimated values (2); histograms show the residuals of observed minus estimated values (3) in degrees Celsius (right axis).

allow permafrost to move nearer to the surface, restricting and reducing tree growth (Pozdnyakov, 1986). Natural regeneration of larch forests in the northern taiga is often impossible without prior destruction of ground moss cover (Abaimov *et al.*, 1997a). So, while any increase of average annual temperature is related, in the first instance, to a June-September temperature increase, the depth of the soil thawing is maximum by August-September. In the warm summer seasons, the decomposition of the lower moss layers is greater than surface growth, and net moss layer thickness decreases. This results in enhanced warming of the upper soil layers, reduced permafrost and increased radial tree growth. In cold periods, the situation is reversed. Hence changes in the moss layer thickness, which are slower than the direct changes in temperature, probably cause a delay in the tree-growth response.

Dendroclimatic studies on maximum density of tree rings may provide some indirect proof of such a delay. Several authors have described how maximum density variability depends on the temperature of a longer warm season (May-September) (Briffa *et al.*, 1992; D'Arrigo and Jacoby, 1992; Briffa *et al.*, Part 1, this issue). The long-term variations in growth variability are represented less strongly, however, in maximum density as compared with radial ring-width changes (Briffa *et al.*, 1996). It may be that the lagged heat transfer, due to groundcover changes, is responsible for the longer-term response in ring growth. Other authors have demonstrated a very close relationship between the long-term (annual) changes of ring-width indices for chronologies from Alaskan and Canadian northern forests and average annual temperature of the Northern Hemisphere (Jacoby and D'Arrigo, 1989). Even with local variations in the conditions for tree growth, such a relationship could not manifest itself without an extended-period response

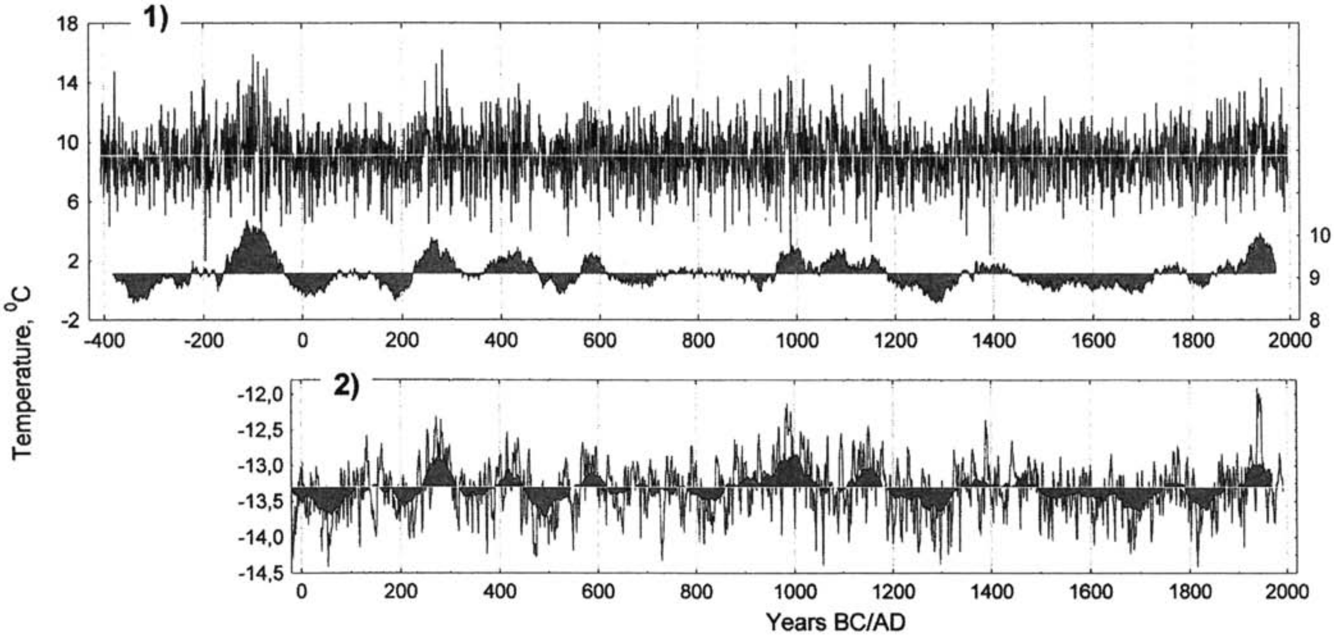

Figure 6 Reconstructions of Taimyr early-summer temperatures (1) shown as yearly values and roughly 50-year smoothed values and reconstructions of mean annual temperatures (2) shown as five-year and superimposed 50-year smoothed values.

Table 4 Extreme years in the East Taimyr and Putoran early-summer temperature reconstruction during last 2427 years

Coldest			Warmest		
Years or periods	Estimated Temperature °C	Standard deviation	Years or periods	Estimated Temperature °C	Standard deviation
Extreme years (σ ≥ 2.5)					
196	2.3	-3.6	282	16.2	3.7
1393	2.4	-3.5	98 BC	15.9	3.6
987	2.6	-3.4	88 BC	15.5	3.3
1151	3.3	-3.0	1150	15.2	3.2
536	3.7	-2.8	270	15.2	3.2
1345	3.7	-2.8	70 BC	14.9	3.0
83 BC	3.9	-2.7	983	14.5	3.0
967	3.9	-2.7	77 BC	14.4	2.8
380	3.9	-2.7	1177	14.3	2.8
854	4.0	-2.7	1941	14.3	2.7
460	4.1	-2.6	197 BC	14.3	2.7
389 BC	4.3	-2.5	1014	14.2	2.7
42 BC	4.3	-2.5	128 BC	14.2	2.7
1068	4.4	-2.5	989	14.2	2.6
903	4.4	-2.5	247	14.1	2.6
707	4.4	-2.5	130 BC	14.0	2.6
870	4.4	-2.5	437	14.0	2.6
			107 BC	14.0	2.5
			1073	13.9	2.5
Extreme 100-year periods (σ ≥ 1.5)					
1208-1307	8.58	-1.9	144-43 BC	9.99	3.3
366-265 BC	8.64	-1.7	1870-1979	9.65	2.1
33-65 AD	8.68	-1.6	228-327	9.57	1.8
1599-1698	8.69	-1.5	1058-1157	9.56	1.7
			950-1049	9.51	1.5

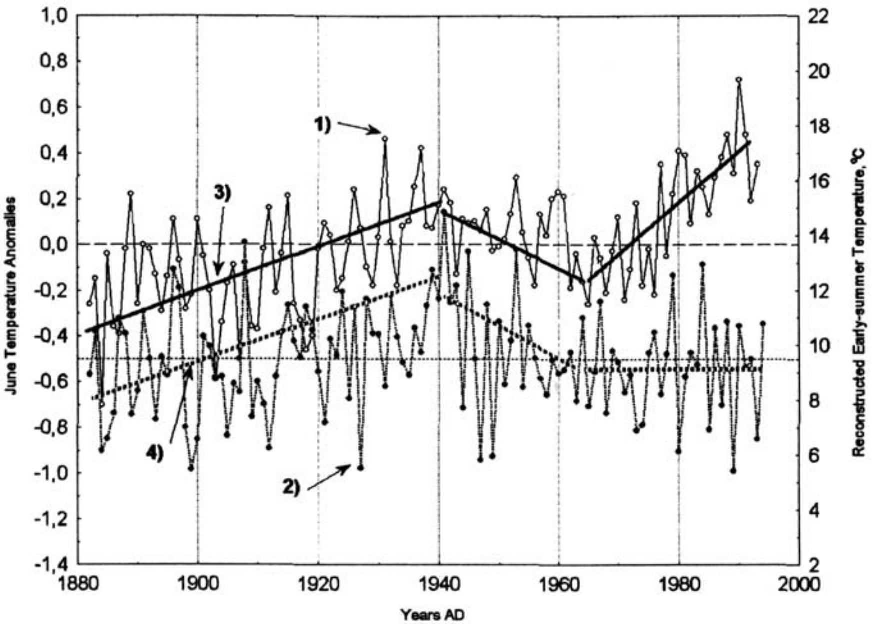

Figure 7 A comparison of anomalies of mean Northern Hemisphere temperatures for June (1) and the reconstructed early-summer temperatures for the east of Taimyr (2). Trend lines (3, 4) are superimposed for three periods, as discussed in the text.

mechanism. We propose that such a mechanism operates by the interaction of permafrost and groundcover. Hence, changes in local air temperature may exert a direct, short-term and indirect (longer-term) effect on the growth of trees in this and other high-latitude regions.

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References

Abaimov, A.P., Bondarev, A.V., Zyryanova, O.A. and **Shitova, S.A.** 1997a: *The forests of polar sector of Krasnoyarskii Krai.* Novosibirsk: Nauka, 207 pp. (in Russian).

Abaimov, A.P., Prokushkin, S.G., Zyrynova, O.A. and **Kaverzina, L.N.** 1997b: The specifity of formation and function of larch forests on permafrost. *Lesovedenie (Russian Journal of Forestry)* 5, 13-23 (in Russian).

Arbatskaya, M.K. 1998: Long-term variations of climate, tree growth and fire frequency in the middle taiga of Central Siberia. Unpublished PhD dissertation, Krasnoyarsk, Institute of Forest, Siberian Branch of the Russian Academy of Sciences, 166 pp. (in Russian; available from author).

Baillie, M.G.L. 1999: *Exodus to Arthur.* London: Batsford, 272 pp.

Bradley, R.S. and **Jones P.D.** 1993: 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. *The Holocene* 3, 367-76.

Briffa, K.R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlén, W., Zetterberg, P. and **Eronen, M.** 1992: Fennoscandian summers from AD 500: temperature changes on short and long timescales. *Climate Dynamic* 7, 111-119.

Briffa, K.R., Jones, P.D., Schweingruber, F.H., Karlén, W. and **Shiyatov, S.G.** 1996: Tree-ring variables as proxy-climate indicators: problems with low-frequency signals. In Jones, P.D., Bradley, R.S. and Jouzel, J., editors, *Climatic variations and forcing mechanisms of the last 2000 years*, NATO ASI Series 141, Berlin, Springer-Verlag: 9-41.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Osborn, T.J., Shiyatov, S.G. and **Vaganov, E.A.** 1998: Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* 391, 678-82.

Budyko, M.I. and **Izrael, Yu. A.**, editors 1987: *Anthropogenic climate changes.* Leningrad: Gidrometeoizdat, 406 pp. (in Russian).

Cao, M.K. and **Woodward, F.I.** 1998: Dynamic response of terrestrial ecosystem carbon cycling to global climate change. *Nature* 393, 249-52.

Cook, E.R. and **Kairiukstis, L.A.**, editors 1990: *Methods of dendrochronology. Applications in the environmental sciences.* Dordrecht: Kluwer, 394 pp.

Cook, E.R., Briffa, K.R., Shiyatov, S.G. and **Mazepa V.S.** 1990: Tree-ring standardization and growth-trend estimation. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of dendrochronology. Application in the environmental sciences*, Dordrecht: Kluwer, 104-23.

D'Arrigo, R.D. and **Jacoby, G.C.** 1992: Dendroclimatic evidence from northern North America. In Bradley, R.S. and Jones, P.D., editors, *Climate since* AD *1500*, New York: Routledge, 296-311.

Fritts, H.C. 1976: *Tree rings and climate.* London: Academic Press, 567 pp.

Fritts, H.C., Guiot, J., Gordon, G.A. and **Schweingruber, F.H.** 1990: Methods of calibration, verification and reconstruction. In Cook, E.R. and Kairiukstis, L.A., editors, *Methods of dendrochronology*, Dordrecht: Kluwer, 163-217.

Fritts, H.C., Vaganov, E.A., Sviderskaya, I.V. and **Shashkin, A.V.** 1992: Climatic variation and tree-ring structure in conifers: a statistical simulative model of tree-ring width, number of cells, cell wall-thickness and wood density. *Climate Research* 1, 37-54.

Gorchakovskii, P.L. and **Shiyatov, S.G.** 1985: *Phyto-indication of environmental conditions and nature processes in high latitudes.* Moscow: Nauka, 362 pp. (in Russian).

Himmelblau, D. 1973: *Process analysis by statistical methods.* Moscow: Mir, 947 pp. (translated into Russian).

Holmes, R.L. 1983: Computer-assisted quality control in tree-ring dating and measurements. *Tree-Ring Bulletin* 44, 69-75.

Hughes, M.K., Vaganov, E.A., Shiyatov, S., Touchan, R. and **Funkhouser, G.** 1999: Twentieth-century summer warmth in northern Yakutia in a 600-year context. *The Holocene* 9, 629-34.

Jacoby, G.C. and **D'Arrigo, R.** 1989: Reconstructed Northern Hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. *Climate Change* 14, 39-59.

Jones, P.D., Briffa, K.R., Barnett, T.P. and **Tett, S.F.B.** 1998: High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. *The Holocene* 8, 455-71.

Kendall, M.G. 1975: *Rank correlation methods* (4th edition). London: Griffin.

Kirdyanov, A.V., Hughes, M.K., Vaganov, E.A., Schweingruber, F.H. and **Silkin, P.P.** 2002: The importance of early summer temperature and date of snow melt for tree growth in Siberian Subarctic. *Trees*, in press.

Lamb, H.H. 1977: *Climate: present, past and future.* Volume 2, climatic history and the future. London: Methuen, 835 pp.

Mann, M.E., Bradley, R.S. and **Hughes, M.K.** 1999: Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Research Letters* 26, 759-62.

Naurzbaev, M.M. and **Vaganov, E.A.** 1999: A 1957-year tree-ring chronology of the eastern part of Taymir. *Siberian Journal of Ecology* 6, 67-78.

Pozdnyakov, L.K. 1986: *Forestry on permafrost soils.* Novosibirsk: Nauka, 232 pp. (in Russian).

Rind, D. 1998: Latitudinal temperature gradient and climate change. *Journal of Geophysical Research* 103(D6), 5943-71.

Schweingruber, F.H. 1996: *Tree rings and environment. Dendroecology.* Bern: Paul Haupt, 608 pp.

Schweingruber, F.H. and **Briffa, K.R.** 1996: Tree-ring density network and climate reconstruction. In Jones, P.D., Bradley, R.S. and Jouzel, J., editors, *Climatic variations and forcing mechanisms of the last 2000 years*, NATO ASI Series 141, Berlin: Springer-Verlag, 43-66.

Shiyatov, S.G. and **Vaganov, E.A.** 1998: Methodological basis of system of dendroclimatic monitoring in forests of Asian part of Russia. *Siberian Journal of Ecology* 5(1), 31-38.

——1999: The importance of dendroclimatic and dendrohydrological research in global and regional ecology. *Siberian Journal of Ecology* 6, 3-11.

Stuiver, M. and **Reimer, P.J.** 1993: Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *Radiocarbon* 35, 215-30.

Vaganov, E.A., Naurzbaev, M.M., Schweingruber, F.H., Briffa, K.R. and **Moell, M.** 1996a: An 840-year tree-ring width chronology for Taimyr as an indicator of summer temperature changes. *Dendrochronologia* 14, 193-205.

Vaganov, E.A., Shiyatov, S.G. and **Mazepa, V.S.** 1996b: *Dendroclimatic study in Ural-Siberian Subarctic.* Novosibirsk: Nauka, 246 pp. (in Russian).