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RESPONSE TO WINTER PRECIPITATION IN RING-WIDTH CHRONOLOGIES OF *PINUS SYLVESTRIS* L. FROM THE NORTHWESTERN SIBERIAN PLAIN, RUSSIA

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ABSTRACT

Six mean ring-width tree-ring chronologies were constructed for living Scots pine (*Pinus sylvestris* L.), growing near the species' upper and northern limits in the area between the Ob River and the subpolar Ural Mountains in Russia. All ring-width series were standardized by fitting cubic smoothing splines and chronologies were constructed as biweight robust means. The six chronologies ranged from 181 to 276 years in length. Response function analysis showed all chronologies to have negative responses to winter precipitation. Most chronologies also showed positive, but relatively low responses to temperatures of the current and previous summer. Total October–May precipitation was reconstructed back to A.D. 1843 using the lagged and unlagged chronologies as candidate predictors. In addition to reflecting an unstable and time-varying growth-climate link, moderate verification results may partly be due to problems with short verification periods. The reconstruction contains almost equal amounts of high-frequency (<8 years) and low-frequency (>8 years) variations, among them a significant 30-year variation. The precipitation signal may add an important aspect to reconstructing paleoclimatic fluctuations in the northern hemisphere. Continuing work with the Scots pine from this area depends on improving the quality of a precipitation reconstruction and finding older living and subfossil wood.

INTRODUCTION

In the last decade much effort has been put into developing the North Eurasian chronology network (Briffa *et al.* 1996b). Scots pine plays an important role in that work, especially west of the Ural Mountains. For example, two projects aim to build continuous multimillennial pine ring-width chronologies in northern Sweden and Finland spanning 7,000–8,000 years (Briffa *et al.* 1995a).

Less dendroclimatic research has been done on northern Scots pine east of the Urals. One pine-chronology has been published for a site in the northern Urals (Shiyatov 1986), and three chronologies are published for sites close to the Poluj River and the lower Tunguska River in Siberia, all of them based on ring-widths (Vaganov *et al.* 1996). Two chronologies, based on both ring-widths and maximum-latewood-densities, are published for sites near the Lena River (Briffa *et al.* 1996b). Detailed dendroclimatological study of Scots pine growing near its northern and upper distribution limits in the subpolar Urals has been missing to date.

DATA AND DATA PRETREATMENT

Tree-Ring Widths and Standardization

The tree-ring samples are from six sites near Scots pine's upper and northern distribution limit in the area between the subpolar Urals and the Ob River (Figure 1). Sites 1–3 are located in the foothills of the Urals (122–330 m.a.s.l.), while Sites 4–6 are farther east in the West Siberian Plain (Table 1). Between 23 and 41 cores from between 17 and 22 trees were collected at each site with an increment borer at breast height. Ring-width series were crossdated with each other, and each ring was assigned a calendar year based on the known collection date. The average length of the six series is 158 years. The majority of series have a length between 100 and 200 years (Table 2). No series is longer than 265 years in spite that much effort was

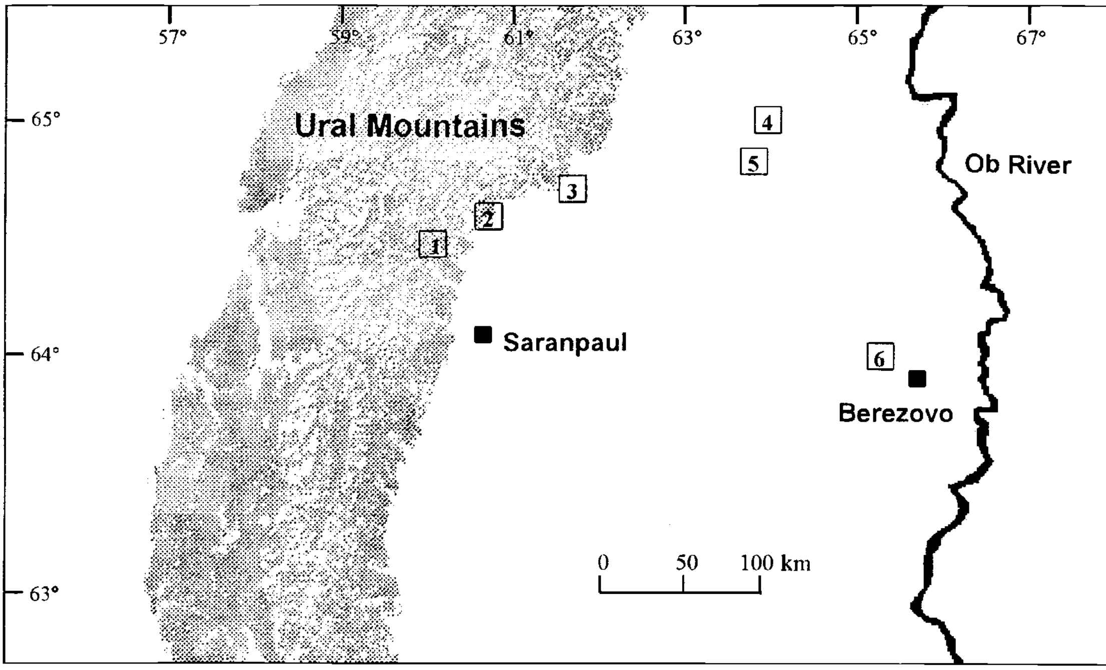


Figure 1. Map of the area between the subpolar Urals and the Ob River in western Siberia. Numbers 1 to 6 indicate sites where samples of Scots pine (*Pinus sylvestris* L.) were collected. Two meteorological stations in the area (Saranpaul and Berezovo) are shown.

put into finding sites with old living trees during the collecting. The reason for this is unknown, but frequent forest fires may be a possible explanation.

Inspection of time series plots of the measurements of each sample indicate that most have a decreasing biological growthtrend that is best described as a negative exponential. Removal of the growthtrend and subsequent computation of dimensionless tree-ring indices (known as "standardization") was done by using a cubic smoothing spline algorithm in the frequency domain (Cook and Peters 1981). By defining standardization as a frequency, spectrally-specific noise reduction method (Briffa *et al.* 1987), it is possible to estimate the growthtrend by some objective choice of the spline's frequency response function. The criterion for selection of the optimal spline is the so-called %*n* criterion (Cook 1985) which means that the 50% frequency-response cutoff in years for the filter should equal a large percentage of the series length, *n*. This ensures that little low-frequency variance, which is resolvable in the tree-ring series, is lost by standardization. The %*n* criterion acknowledges increasing emphasis on longer time scale changes in the interpretation of climatic variability reconstructed from tree-rings (Briffa *et al.* 1996a). However, retaining climatic information at all variances usually means removing less noise; thus, the method is far from perfect in estimating the growthtrend for dendroclimatological purposes. In the present case, the chosen percentage was 70%*n*, which follows Cook's (1985) suggestion.

Time-Series Consideration and Signal Strength

After standardization the ring-width indices were tested for significant autocorrelation. Partial autocorrelations computed for series of indices that belonged to an *a priori* defined common interval for each site were tested using the Ljung and Box-test (Ljung and Box 1978) to find whether the indices were from a white noise process. The stan-

Table 1. Site characteristics.

Site	Latitude	Longitude	Altitude (m.a.s.l.)	Geomorphology	Forest Type
1	64°37′	60°21′	220–230	Slope facing south/south-east in the foothills of Ural Mountains.	Open *Pinus sylvestris* stand with groundcover of *Vaccinium vitis-idaea.*
2	64°42′	60°55′	122	River terrace 5 m.a. river in a valley running south/north.	Mixed, multi-storied forest of *Pinus sylvestris, Pinus sibirica, Larix sibirica,* and *Picea abies* ssp. *obovata.* Groundcover of *Sphagnum fuscum, Pleurozium schreberi,* and *Aulacomniun palustre.*
3	64°46′	61°39′	320–330	Mountainside facing south/south-east. Exposed to wind.	Scattered trees of *Pinus sylvestris* with rare ground cover.
4	65°00′	63°40′	9	River terrace 5 m.a. river in flat land.	Stand of *Pinus sylvestris* with *Betula pubescens* and *Larix sibirica.* Groundcover of grass. Sign of forest fire.
5	64°53′	63°34′	62	Slightly hilly country close to the tundra limit. Exposed to wind.	Open stand of *Pinus sylvestris* with groundcover of *Vaccinium vitis-idaea.*
6	64°00′	64°47′	20–30	Slightly hilly country in middle boreal forest.	Mixed, multi-storied forest of *Pinus sylvestris, Pinus sibirica, Larix sibirica,* and *Picea abies* ssp. *obovata.* Groundcover of *Vaccinium myrtillus.*

dardized ring-width series from all sites had a high first order partial autocorrelation ($\rho = 0.49$–0.73), and the Ljung and Box-test was highly significant in all cases. As a result of this analysis, prewhitening of the series was tested (Meko 1981), but found not to improve the climate reconstructions. Therefore, prewhitening was rejected in favor of not prewhitening.

Analysis of variance (ANOVA) was used to estimate the common signal in indexed ring-width series. A general linear model with random effects was defined as:

$$X_{ijk} = \mu + Y_i + T_j + C_{k(j)} + \epsilon_{ijk} \qquad (1)$$

where $i = 1, \ldots, y$ years, $j = 1, \ldots, t$ trees, $k = 1, \ldots, c$ cores within trees, X_{ijk} are observed ring-width indices, μ is the overall (fixed) mean of the sampling population, $\{Y_i\}$, $\{T_j\}$, $\{C_{k(j)}\}$, and $\{\epsilon_{ijk}\}$ are normal distributed, mutually uncorrelated random effects with zero means and respective variances σ_Y^2, σ_T^2, σ_C^2, and σ^2 (the variance components). Note that cores are nested within trees. The variance components were estimated by a restricted maximum-likelihood procedure (Patterson and Thompson 1971). As this procedure allows for unbalanced data all series in their full length were used to get the most precise parameter estimates. The signal strength of the samples was calculated as:

$$\frac{\hat{\sigma}_Y^2}{\hat{\sigma}_Y^2 + \hat{\sigma}_T^2 + \hat{\sigma}_C^2 + \hat{\sigma}^2} = \frac{\hat{\sigma}_Y^2}{Total\ Var} \qquad (2)$$

Table 2. Numbers of sampled trees and cores, chronology length, and distribution of sample lengths within each site.

			Chronology Length (years)		Sample Length (years)		
Site	Trees	Cores	Max. No. of Cores	Min. 5 Cores	<100	≥100 ∧ <200	≥200 ∧ <300
1	20	37	181	177	—	37	—
2	17	25	276	256	—	16	9
3	20	41	232	173	6	32	3
4	20	23	185	155	10	13	—
5	22	40	206	174	—	39	1
6	21	28	271	171	—	26	2

Table 3. Variance components and signal strength of the chronologies. The full lengths of all series were used in the estimation.

Chronology	Variance Components				Signal Strength $\hat{\sigma}^2_Y$/ Total Var
	$\hat{\sigma}^2_Y$	$\hat{\sigma}^2_T$	$\hat{\sigma}^2_C$	$\hat{\sigma}^2$	
1	487.29	—	—	696.40	0.41
2	792.67	—	—	794.96	0.50
3	618.19	—	—	864.38	0.42
4	757.13	—	—	955.14	0.44
5	998.32	—	—	793.08	0.56
6	521.45	29.58	—	734.72	0.41
Average	695.84	—	—	806.45	0.46

It should be kept in mind that "signal" in this context means any variance which is common for all cores from year-to-year. There is no guarantee that the standardization succeeded 100 percent. Thus, the measured signal strength may still be affected by exogenous factors other than climate. The theoretical domain of the signal strength is 0 ≤ *signal strength* ≤ 1 with 1 as the best possible value.

The results are shown in Table 3. Except for one case, the variance components for trees and cores were tested to be insignificant for all chronologies. This result means that the variance from year to year is a major contributor to the total variance in the whole data set. The variance attributable to the difference between trees and cores is obviously small compared to the total variance. The variance not attributable to any known factor, σ_2, usually amounted to more than a half of the total variance. It is interesting that the chronology from Site 6 was the only chronology with a significant σ^2_T. Site 6 is farther to the south than other sites, and this result confirms the principle of limiting factors. That is, there is more difference among the ring-width sequences of trees growing far from the margins of their natural latitudinal or elevational distribution limits (Fritts 1976). The signal strength values range from 0.41 (Sites 1 and 6) to 0.56 (Site 5).

Table 4. Chronology signal estimated with respectively maximum number of cores and five cores in chronologies. A value of 1 portrays the hypothetically perfect chronology.

Site	Chronology Signal	
	Max. No. of Cores	5 Cores
1	0.96	0.86
2	0.96	0.90
3	0.97	0.87
4	0.95	0.88
5	0.98	0.92
6	0.95	0.86

Estimation of Mean Chronologies

Six chronologies were constructed as biweight robust means of the indexed series from each site in order to remove effects of endogenous stand disturbances that may act as outliers (Cook *et al.* 1990). The six chronologies span between 181 and 276 years (Table 2). In order to estimate the degree to which a sample chronology at a particular years portrays the hypothetically perfect chronology, the chronology signal was estimated as:

$$\frac{\hat{\sigma}^2_Y}{\hat{\sigma}^2_Y + \frac{\hat{\sigma}^2_T}{t} + \frac{\hat{\sigma}^2_C}{c} + \frac{\hat{\sigma}^2}{c}}, \quad (3)$$

where y is the year in question. t is the number of trees and c is the total number of cores in the chronology (all of them at the year of question). In a year where the "chronology" consists of a single series, chronology signal equals the signal strength estimated in (2). The domain of the chronology signal is 0 ≤ *chronology signal* ≤ 1 with 1 as the best possible value (the hypothetically perfect chronology). With maximum number of cores the chronology signal is 0.95 or higher for all chronologies (Table 4). Even with only five cores the chronology signal does not reduce to any smaller than 0.86.

Climate Data

Monthly mean temperatures and monthly sums of precipitation for two meteorological stations in the region were selected from a data file published by Oak Ridge National Laboratory in the USA

(Vose *et al.* 1992). The meteorological stations are Berezovo (63°56′N, 65°06′E) and Saranpaul (64°17′N, 60°53′E) (Figure 1). Gaps in these records were filled with data from the Institute of Plant and Animal Ecology in Ekaterinburg or with linear regression estimates based on data from neighboring meteorological stations. For years in which neighboring meteorological stations also had missing observations, a grid point temperature anomaly data set (Jones *et al.* 1985) was used as predictor with great success. The complete temperature records ranged from 1932–1990 and 1879–1990 for Saranpaul and Berezovo, respectively. The complete precipitation records ranged from 1934–1993 and 1891–1993 for the same stations. The annual sum of precipitation is 480 mm for Berezovo, while it is 508 mm for Saranpaul (based on total station records). The temperature record shows that the winter is very harsh in this region. The monthly mean temperature is below the freezing point from October to April inclusive and the annual mean temperature is −3.7°C for both stations.

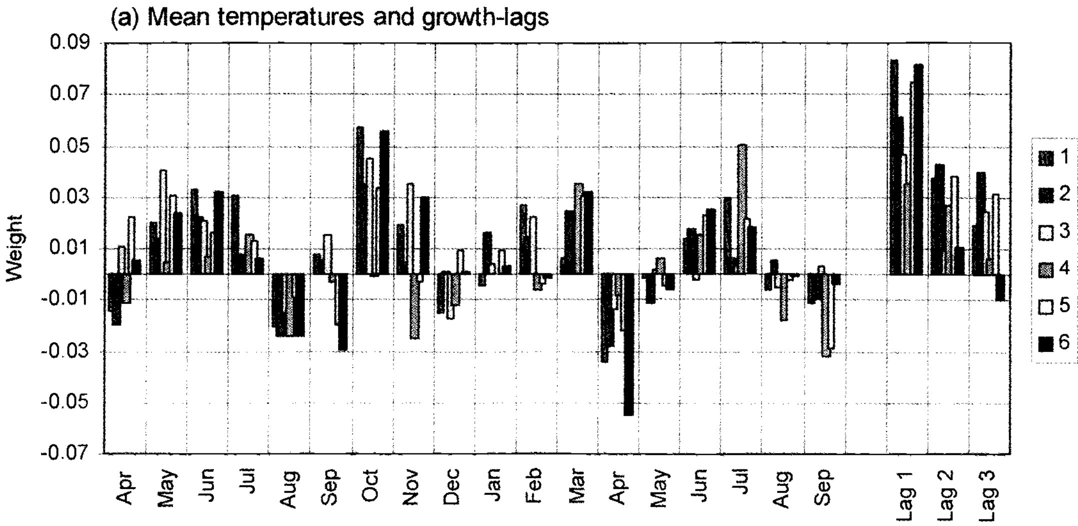
RESPONSE FUNCTION ANALYSIS

Multiple linear regression between the chronology indices and the principal components (PCs) of the climatic data (Fritts 1976; Briffa and Cook 1990) was used as a statistical tool to describe the climate-growth link in the chronologies. The total amount of the chronology variance explained is taken to be a measure of the strength of the climate-forcing signal. The sign and the magnitude of the regression coefficients on individual monthly climate variables characterize the nature of the tree-growth/climate link. The method involves a two-step selection procedure of PCs. In the present study only the PCs necessary to account for 90% of the variance of the whole set were retained after the first selection. At this point further selection of the PCs was made *a posteriori,* based on the regression significances as recommended by Briffa and Cook (1990). As was the case with the initial screening, the selection criterion was arbitrarily chosen, so a 15% probability level of rejecting the true hypothesis of null correlation when it is false was used. On average, this resulted in selection of 9 predictors for the response functions.

As noted by Briffa and Cook (1990), there are problems in calculating confidence limits for PC-based response functions. The authors mention the uncertainty regarding the correct numbers of degrees of freedoms as the selection of the final PC predictors is made *a posteriori.* Another problem, and probably more important, is that the standard error of the monthly climatic weights are calculated without paying attention to the standard errors of the estimated principal components. Cropper (1982) used simulation to evaluate confidence limits calculated for response functions and he found the calculated limits to be overly narrow. Due to these uncertainties, no attempts were made to calculate confidence limits for the response function. This study attempted to interpret only the gross features of individual analyses. Chronologies 1–3 were compared with the Saranpaul station and chronologies 4–6 were compared with the Berezovo station. The period of analysis was standardized. That is, response functions derived by comparison of chronologies with climatic data from Saranpaul and Berezovo stations were calculated using a common overlap of 56 years (1935–1990). Monthly sums of precipitation and mean temperatures from the prior April to the current September were used in the analysis. The first three lags of ring-width indices were included in the predictor data set in order to take into account the high autocorrelation in the ring-width indices. In total there were 39 predictor variables.

Figure 2a indicates that there is a positive response to temperatures of previous May–July. The weights are negative for prior August and the current April, while the weights for prior October and the current March are positive and dominant. Positive weights are also found for current June–July.

Figure 2b shows that the response to precipitation is less uniform between chronologies than the response to temperatures. This confirms what one intuitively would expect, because precipitation usually is a more localized phenomenon than temperature. However, some tendencies may be found. There seems to be a positive response to precipitation of previous June–July, while a negative response is found to the precipitation from prior Oc-



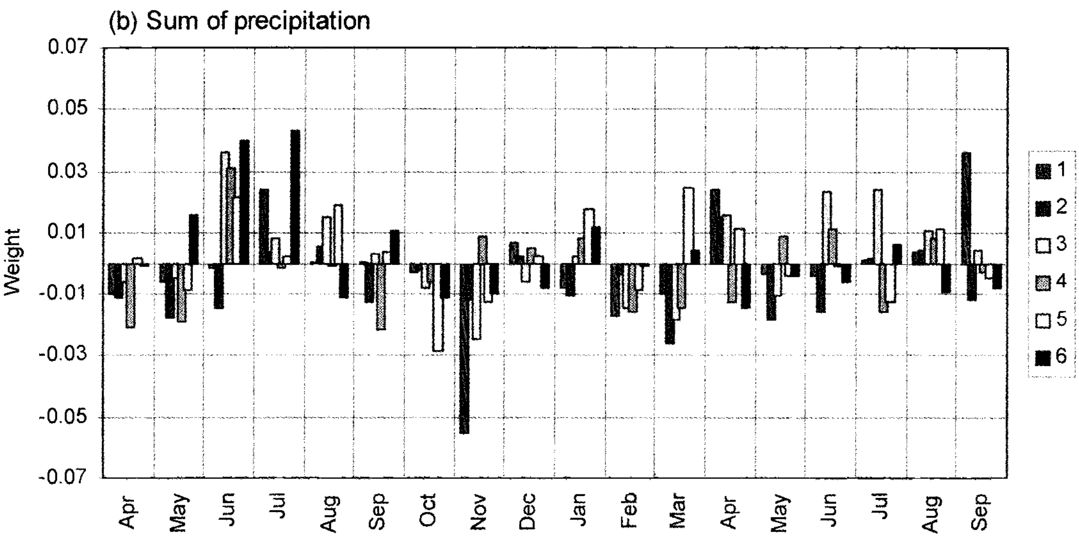


Figure 2. PC-based response functions for chronologies 1–6 (in the mentioned order within each group of bars): (a) response to monthly mean temperatures (prior April to current September) and the first three lags of ring-width indices; (b) response to total monthly precipitation for the same period. Chronologies 1–3 and 4–6 are compared with climatic data from Saranpaul and Berezovo, respectively. The period of analysis is 1935–1990.

tober through current May. There are some significant deviations from these tendencies for single chronologies in March and April.

All chronologies show a decreasing positive response to lags of growth (Figure 2a). All response functions had high values of explained variances (50%–76%). The explained variance for Chronology 4 is relatively small compared with chronologies from other sites (50% compared to an average of 67% in the rest of the chronologies). This result agrees with the field observation that growth conditions for trees from Site 4 are very different from those of the other sites. In many years, factors other than climate such as forest fires, soil type, soil water potential, *etc.* are probably more limiting to growth in many of these trees.

To supplement the PC-based response functions, multiple linear regression models describing each chronology as a function of few significant climatic variables for which significance levels can be calculated were calibrated. Only those variables that had been found to be important in the PC-based response function analysis and had some physiological justification were used as predictors. This rigorous criterion is applied because a false effect of a visible variable may, in fact, be caused by an unmeasured latent variable. Provided the system operated across the entire time range in the same way as during the period of overlap between the tree-ring and climatic data, this will not be misleading. However, unobserved changes in unmeasured latent variables may cause the equation to become unreliable when used for reconstruction purposes. The significant proportion of unexplained variance in the response functions confirms the existence of umeasured latent variables, and the risk of including such variables decreases when the selection criterion mentioned above is used. On the other hand, this criterion increases the risk of excluding variables with direct significant effects on tree-growth.

Based on the specified selection procedure the following four climatic variables were chosen as candidate predictors.

1. Mean May–July temperature of the year prior to growth.
2. Mean June–July temperature of the current growth-year.
3. Mean July temperature of the current growth-year.
4. Total October–May precipitation prior to growth.

Mean May–July temperature prior to growth had positive weights in the PC-based response function analysis. As the chronologies showed the same response after prewhitening, this lagged response to summer temperatures is genuine and not caused by autocorrelation in the ring-width series. Tranquillini (1979) explained how important the length and warmth of a previous growing season is for resistance to drought during the following winter when water potential cannot be recovered because of frozen soil. The longer and warmer the growing season, the more the shoots are able to mature, the less water is lost through the cuticle, and the less evident is desiccation damage in the following winter. On the other hand, a short and cool growing season in the previous year is followed by desiccation damage during the winter and reduced growth in the subsequent summer. According to this theory, it would have been logical to include August in the prior growing season; however, for unknown reasons, prior August always exhibited negative response function weights that are difficult to interpret physiologically. The negative correlation may be an indirect effect connected to the fact that high late summer mean temperature coincides with less precipitation, which in turn may have a negative effect on the tree-growth the next year. Because biological evidence was missing, prior August was not accepted as a candidate predictor in spite of its unequivocal negative weight in the response function analysis.

The positive growth-response to summer temperatures in the current growthyear was a general feature in most of the PC-based response functions. Tranquillini (1979) explained why fluctuations in annual ring-widths in the mountains and at high latitudes reflect small changes in mean summer temperature. At cooler temperatures there is a tendency for photosynthate to be transformed to sugars and starch rather than cellulose, which can limit diameter growth. Differences in the duration of the growing season may explain why the same summer months do not always show the highest correlations. Thus, both the mean July and the mean June–July temperatures were selected as candidate predictors.

Negative weights for precipitation in the winter months prior to growth were common to most of the chronologies. Negative growthresponse to winter precipitation has also been found in Scots pine in northern Norway (Kirchhefer and Vorren 1995) and in some unpublished Scots pine ring-width chronologies near the lower Jenissej River in Siberia (S. Shiyatov, personal communication 1997).

A possible physiological explanation for the negative growthresponse is that deep snow may delay the start of the growing season by maintaining low soil temperature. The limiting influence of low soil temperature on treegrowth has been confirmed by Tranquillini (1979) in field measurements of net photosynthesis in *Pinus cembra* at the timberline. The negative correlation with winter precipitation may also be related to a deep layer of snow's delaying thawing of the soil at a time when evapotranspiration increases with increasing air temperature. Thus, the trees will suffer longer and more intensively from frost drought if the snow hinders soil thawing in the late spring. The fact that the negative growth-response to winter precipitation is more significant in some months than in others may be due to the distribution of precipitation within the winter season. Because much of the winter precipitation in the region usually falls in October–November, precipitation variance in these months explained more of the variance in the ring-width indices than did that of other winter months. Intercorrelations within the climate system may explain why April mainly showed up with positive weights. The period from October–May was chosen with reference to many years' observations of snow depth in the area (Anonymous 1956). In most years the snow was permanent from the beginning or middle of October through the middle or end of May. It could very well have been that a better predictor would be mid-October through mid-May. Unfortunately, the monthly climatic data did not allow such a predictor.

Temperature in current April always exhibited strong negative response function weights which are difficult to interpret physiologically. One possible explanation is that high temperature in the spring may increase evapotranspiration at a time when the soil is frozen. This may lead to a growth-reducing effect of frost drought. On the other hand, on the assumption that high temperature during spring will remove the snow cover it will also remove the growth-reducing effect of frost drought, and one would expect a positive growth response to April temperatures. Because of these uncertainties temperature in current April was not chosen as candidate predictor.

The first three lags of ring-width indices were added as candidate predictors. No other observed tendencies in the response function analysis gave reason to select additional candidate predictors because biological evidence was missing.

The best subset multiple linear regression between each chronology and candidate climatic predictors from the neighbor meteorological station was selected, by minimizing Mallows C_p statistic (Draper and Smith 1981). Minor exceptions from this selection criterion were made when a more simple model could be chosen with a relatively small increase of the C_p-value. For example, some response functions were reduced to include only the first lag of ring-width indices instead of the first and third lags. The R-square value (explained variance) was calculated for each regression. The period of analysis was standardized in the same way as for the PC-based response function analysis. Table 5 shows the result. Three climatic variables are included in the best subset regression for chronologies from Sites 1, 3 and 5. Chronologies from Sites 2 and 6 exclude current summer temperatures, while the chronology from Site 4 excludes prior mean May–July temperature. The first lag of ring-width indices is included in all the response functions and is highly significant. Winter precipitation is the only parameter that all chronologies respond to with the highest level of significance for the chronologies that are closest to the Saranpaul station (Sites 1–3).

It is difficult to explain why some chronologies respond to only two climatic variables. One may argue that these chronologies simply have poor climatic signals because treegrowth is limited by local factors. Field observations confirm this for Site 4 as already mentioned. The same might apply to Site 2 where the competition between trees is more intense than at other sites. The weakness in the response functions selected for Site 6 (which have the lowest explained variance compared with all other chronologies) contrasts with the result of the PC-based response functions. Site six is the most southern of all sites, and the climatic response in these trees may be more complicated than the candidate variables allow for. It must also be kept in mind that all sites (especially 4–5) are far from the meteorological stations. Selected response func-

Table 5. Best subset multiple linear regression between each chronology and candidate predictors from a neighboring meteorological station selected by minimizing Mallow's C_p statistic. Candidate predictors are mean May–July temperatures prior to growth, mean June–July temperature in the current growthyear, mean July temperature in the current growthyear, total precipitation from the prior October to the current May, and the first three lags of ring-width indices (L1–L3). Explained variances (R^2) for the regressions are shown. Significances are based on the t-test.

		Temperature			Precipitation	Growth Lag			
Chronology	Meteorological Station	May–July (Prior to Growth)	June–July	July	Oct.–May (Prior to Growth)	L1	L2	L3	R^2
1	Saranpaul	X*		X*	X***	X***			0.71
2	Saranpaul	X*			X**	X***			0.67
3	Saranpaul	X†		X*	X***	X***			0.46
4	Berezovo			X**	X**	X***			0.46
5	Berezovo	X*	X*		X*	X***			0.60
6	Berezovo	X**			X*	X***			0.33

*Significant at the 5% level.
**Significant at the 1% level.
***Significant at the 1‰ level or better.
†Significant at the 14% level.

tions can be misleading simply because weather conditions are local.

RECONSTRUCTION OF THE SUM OF OCTOBER–MAY PRECIPITATION

Because winter precipitation (October–May) prior to growth was the only climatic candidate predictor to which all chronologies responded, winter precipitation was reconstructed for the Saranpaul station. The transfer function was obtained by an inverse calibration of the response function (Fritts 1976; Briffa *et al.* 1983). All six chronologies, including the first growthlag, were used as candidate predictors for the transfer function (12 candidate predictors in total). Mallow's C_p statistic (Draper and Smith 1981) was used to screen out the most promising transfer functions for the Saranpaul station. Four subset multiple linear regression models with a C_p-value close to the minimum C_p-value were selected and were subjected to a more detailed verification. The regression equations were derived over the period 1935–1964 (the calibration period) and tested over the subsequent 29 years, 1965–1993 (the verification period). Then the later period was used for calibration and the earlier for verification. The transfer function with the best verification result was calculated by using the total observation record and was then used to reconstruct total October–May precipitation for Saranpaul back to 1843 (Figure 3). The reconstruction was stopped when the chronology signal (Equation 3) in one of the predictors was reduced with more than 15% compared with that in the calibration period. The verification results for the reconstruction model are shown in Table 6. Reduction of error (Fritts *et al.* 1990), the product-moment correlation coefficient (Draper and Smith 1981), and the coefficient of efficiency (Cook *et al.* 1994) were used as verification statistics. The standard prediction error (SPE) was also used as an alternative way of testing the reconstruction model. SPE is estimated as:

$$\mathrm{SPE} = \sqrt{\frac{PRESS}{n}} \qquad (6)$$

where *PRESS* is calculated by the PRESS-procedure (Draper and Smith 1981) and *n* is the number of observations in the total lengths of the observation record. SPE is expressed in millimeters of precipitation and should as a rule of thumb be less than the standard deviation in the observations.

From Table 6 it appears that the transfer func-

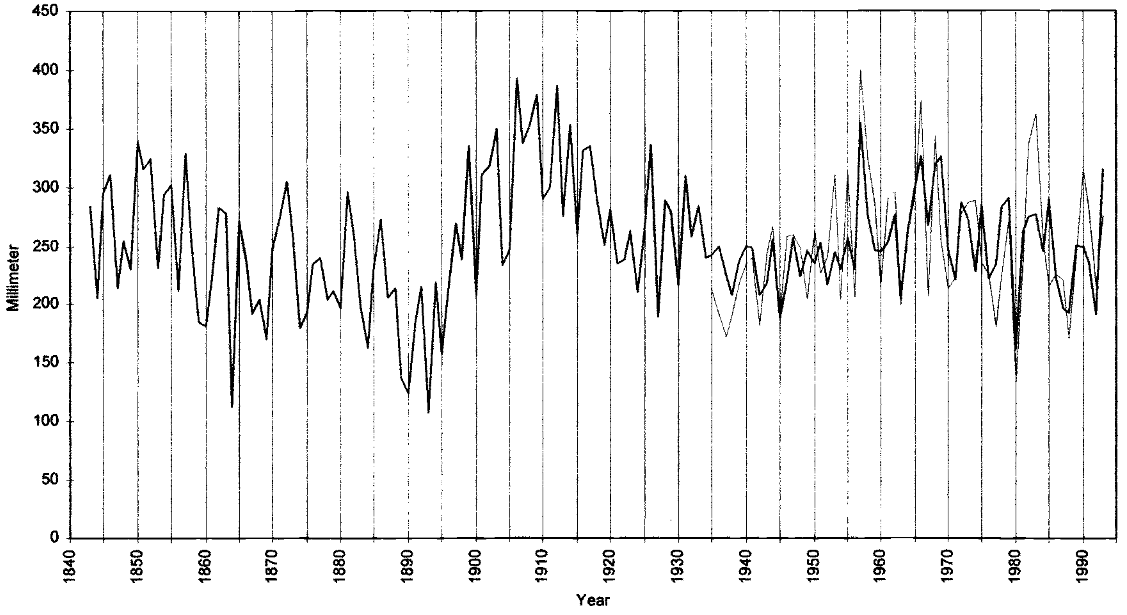


Figure 3. Reconstruction of total winter precipitation to 1843 at the Saranpaul station. "Winter" is defined as the period from the prior October to the current May (both months included). Predicted values are shown with a heavy line; instrumental records with a narrow line.

Table 6. Performance over the calibration and verification periods of the selected transfer function for reconstructing total October–May precipitation at the Saranpaul station. The F-value tests the overall regression equation. Significances of regression weights are based on the t-test.

Calibration Period:	1935–1964	1965–1993	1935–1993
Verification Period:	1965–1993	1935–1964	—
Calibration			
Variance Explained, R^2	0.63	0.45	0.48
F-Value	8.3**	3.8*	9.5**
Standard Prediction Error, SPE (mm)	—	—	42.3
Standard Deviation in Observations (mm)	—	—	53.7
Verification			
Reduction of Error, RE	0.21	0.31	—
Correlation	0.63**	0.53*	—
Coefficient of Efficiency, CE	0.18	0.28	—
Regression Weights			
Intercept	1,969.8**	2,206.1*	1,915.9**
Chronology 1	−1,754.1**	−719.6	−1,101.4*
Chronology 4	−658.5	−1,461.0	−669.8
Chronology 4 (lagged)	1,005.3*	805.6	958.0*
Chronology 5	365.3	1,022.3	383.6
Chronology 5 (lagged)	1,726.1*	725.8	1,084.0*

*Significant at the 5% level.
**Significant at the 1% level or better.

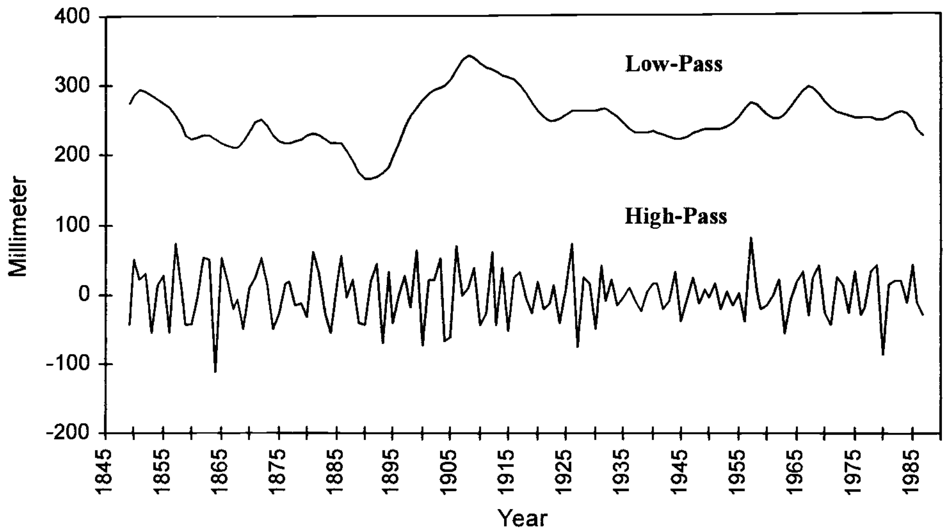


Figure 4. Reconstructed winter precipitation at Saranpaul station filtered with two reciprocal filters which pass variance with approximate wavelengths <8 years (high-pass) and >8 years (low-pass), respectively.

tion for the Saranpaul station shows moderate results in both verification periods. The positive RE-values (0.21 and 0.31) indicate that the model is better than using the average of the calibration period, but these RE-values are not high. The correlations (0.63 and 0.53) show that the model is rather good at estimating the temporal patterns in the observations, but CE-values clearly indicate that a relatively small proportion (18% and 28%) of the variance in the observations is reduced by the model. The regression weights are relatively unstable in time.

The reconstruction was filtered with two reciprocal filters which pass variance at opposite extremes of the frequency spectrum (Fritts 1976). The high-pass filter transmits variance with approximate wavelengths <8 years, while the low-pass filter passes variance with approximate wavelengths >8 years. Figure 4 shows the reconstruction after the filters have been applied. It appears that both low- and high-frequency variance exist in the reconstruction. 47% of the unfiltered variance is passed as high-frequency variance, while 43% is passed as low-frequency variance (10% of the variance is not passed by the filters).

Extreme individual winter precipitation predictions along with extreme mean values of longer periods appears from Table 7. All values are shown as anomalies with respect to the 1951–1970 period. Of the extreme individual winters, five are reconstructed to have lower amounts of precipitation, and three to have higher amounts, than the reconstructed extremes (1957 and 1980) during the calibration period. Compared with the instrumental extremes (1957 and 1980), three winters are reconstructed to have lower amounts, but none higher. The mean value of the 1847–1896 period is below average, while the mean value of the 1897–1946 period is above average, but significant variance on shorter time-scales exists within the latter. For example, 1899–1918 and 1957–1976 were above average, while 1877–1896 and 1937–1956 were below. A spectral analysis revealed a significant 30-year cycle in the reconstruction. This is confirmed by Table 7c which shows that since 1867 the mean value of the winter precipitation has changed from low to high and vice versa in 30-year periods.

DISCUSSION OF RESULTS

This reconstruction of winter precipitation from high latitudes is the first reported in the tree-ring literature. However, the verification of the precip-

Table 7. Extreme individual winter precipitation predictions along with the extreme mean values from among all 20-year, 30-year, and 50-year periods. Amounts of precipitation are shown as anomalies with respect to the 1951–1970 period. Only values for non-overlapping periods are shown. "Year" refers to the winter starting in October of the previous year.

(a) Individual Winters:

Lowest		Highest	
Year	Anomaly (mm)	Year	Anomaly (mm)
1893	−159.2	1906	126.4
1864	−154.2	1912	119.9
1890	−143.3	1909	112.0
1889	−129.9	1957	87.3
1895	−108.7	1914	87.1
1980	−105.6	1908	86.4

(b) 20-Year Mean Periods:

Lowest		Highest	
Years	Anomaly (mm)	Years	Anomaly (mm)
1877–1896	−64.1	1899–1918	47.5
1937–1956	−34.1	1957–1976	4.3

(c) 30-Year Mean Periods:

Lowest		Highest	
Years	Anomaly (mm)	Years	Anomaly (mm)
1867–1896	−56.3	1897–1926	29.0
1927–1956	−26.5	1957–1986	−1.1

(d) 50-Year Mean Periods:

Lowest		Highest	
Years	Anomaly (mm)	Years	Anomaly (mm)
1847–1896	−39.2	1897–1946	7.0

itation reconstruction shows moderate results compared with the verification of other reconstructions from high latitudes, for example the reconstruction of summer temperatures in Scandinavia (Briffa *et al.* 1990) and Siberia (Graybill and Shiyatov 1992; Briffa *et al.* 1995b). This result is ambiguous because of the short verification periods, but the relatively low R-square values in the final regressions used for reconstruction indicate that the models in this study have relatively low predictive value. However, if precipitation is a more local phenomenon than temperature, the reconstruction model may be more unstable than the growth-climatic link gives cause for. That is, in some years, October–May precipitation at selected sites may have differed substantially from that of the meteorological station 50–150 kilometers away. This may especially apply to sites in the mountains where weather conditions can change from one valley to another because of changing topography and wind conditions. The low predictive value of the reconstruction model may also be explained by a possible time-varying climatic signal in the Siberian Scots pine. For instance, the response to winter precipitation may be real only in years when the amount of precipitation reaches a specific level. Below this level, snow has no influence on tree-growth in the coming summer because it has disappeared by the beginning of the growing season. In such years, tree-growth responds to summer temperatures, but in other years when winter precipitation exceeds the threshold, summer temperatures have less or no influence on treegrowth. However, a visual inspection of the reconstruction in the calibration period (Figure 3) does not confirm this theory. On the contrary it seems to show that years with high and low amounts of winter precipitation are reconstructed with an equal degree of skill. Another interesting aspect about reconstruction confidence is the possibility that the reconstruction model gets stronger and more stable if some kind of density parameter is included as predictor. This is an unsolved question that should be cleared up in future work.

The rather short length of this reconstruction makes it difficult to compare it with the millennium-aged reconstructions of summer temperatures from *Larix sibirica* in the Polar Urals (Graybill and Shiyatov 1992; Briffa *et al.* 1995b). Briffa *et al.* (1995) reports that the mean summer (May–September) temperatures of the twentieth century (1901–1990) is higher than during any similar period since A.D. 914. Correspondingly, the result of the present study shows that the mean value of winter precipitation in the 1901–1990 period was higher with 32.3 mm compared to the mean value of the early part of the reconstruction (1843–1900). Also, the extremes of individual winters, with high amounts of precipitation, are all found in the 20th century. However, to determine if this increase in recent winter precipitation is unusual in a long context, similar to the rise in summer temperatures, clearly implies a longer precipitation reconstruction. None of the two temperature reconstructions reports of any 30-year cycle similar to that found in the reconstruction of winter precipitation.

CONCLUSIONS AND RECOMMENDATIONS

The results presented here show that the Scots pine, growing at its upper and northern limits of its distribution in the northwestern Siberian Plain and subpolar Ural Mountains, has a complex climatic signal. The response function analysis reveals a significant negative response to total winter precipitation (October–May) in all chronologies. Most chronologies have a positive response to mean May–July temperature of the year prior to growth and the mean July temperature of the current year of growth, but these responses are weaker than the response to winter precipitation.

The multiple linear regression model used here to estimate the winter precipitation for northern Urals, provides a reconstruction back to A.D. 1843. This reconstruction contains almost equal amounts of high-frequency (<8 years) and low-frequency (>8 years) variations, among them a significant 30-year variation. There are, however, important limitations of this reconstruction as the reconstruction model passed the verification with only moderate results. For example, only about 28% to 40% of the dependent climate variance has been retrieved. Apart from reflecting an unstable and time-varying growth-climatic link, this result may partly be due to problems with short verification periods.

The precipitation signal in Siberian Scots pine is interesting because it may add an important aspect to the work of reconstructing paleoclimatic fluctuations in the northern hemisphere. The temperature signal is less interesting because it is reconstructed more accurately with *Larix sibirica* in the same area. If the work with the Scots pine in northern Siberia is continued, attempts must be made to improve its quality as a precipitation reconstruction. This may be possible by sampling trees closer to meteorological stations with long records (to eliminate the problem that precipitation and snow accumulation may be local phenomena) and from sites where topography favors snow accumulation. Also, inclusion of a density parameter as predictor may possible improve the reconstruction. The possibility of finding old living trees and subfossil wood is another major and unanswered question that may influence the potential of future dendroclimatological studies of Scots pine in this area.

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REFERENCES CITED

Anonymous
1956 *Climatological Reference Book for the USSR,* Issue no. 17, parts 1 and 2. [*Klimatologitjeskij spravotjnik SSSR,* Vypusk 17. Tjast 1 i 2. In Russian.] Gidrometeoizdat, Leningrad, 154 pp.

Briffa, K. R., and E. R. Cook
1990 Methods of response function analysis. In *Methods of Dendrochronology: Applications in the Environmental Sciences,* edited by E. R. Cook, and L. A. Kairiukstis, Kluwer Academic Publishers, Dordrecht; pp. 240–247

Briffa, K. R., P. D. Jones, and M. L. Wigley
1983 Climate reconstruction from tree rings. Part 1, Basic methodology and preliminary results for England. *Journal of Climatology* 3:233–242.

Briffa, K. R., T. M. L. Wigley, and P. D. Jones
1987 Towards an objective approach to standardization. In *Methods of Dendrochronology—1. Proceedings of the Task Force Meeting on Methodology of Dendrochronology: East/West Approaches, Kraków, Poland, 2–6 June, 1986,* edited by L. A. Kairiukstis, Z. Bednarz, and E. Feliksik, pp. 69–86. International Institute for Applied Systems Analysis and Polish Academy of Sciences—Systems Research Institute, Warsaw.

Briffa, K. R., T. S. Bartholin, D. Eckstein, P. D. Jones, W. Karlén, F. H. Schweingruber, and P. Zetterberg
1990 A 1,400-year tree-ring record of summer temperatures in Fennoscandia. *Nature* 346:434–439.

Briffa, K. R., P. D. Jones, F. H. Schweingruber, W. Karlén, T. S. Bartholin, S. G. Shiyatov, E. A. Vaganov, P. Zetterberg, and M. Eronen
1995a Regional temperature patterns across Northern Eurasia: tree-ring reconstructions over centuries and millennia. In *Proceedings, International Conference on Past, Present and Future Climate,* edited by P. Heikinheimo, pp. 115–118. Academy of Finland (Suomen akatemian julkaisuja) no. 6.

Briffa, K. R., P. D. Jones, F. H. Schweingruber, S. G. Shiyatov, and E. R. Cook
1995b Unusual twentieth-century summer warmth in a 1,000-year temperature record from Siberia. *Nature* 376:156–159.

Briffa, K. R., P. D. Jones, F. H. Schweingruber, W. Karlén, and S. G. Shiyatov
1996a Tree-ring variables as proxy-climate indicators: problems with low-frequency signals. In *Climatic Variations and Forcing Mechanisms of the Last 2000 Years,* edited by P. D. Jones, R. S. Bradley, and J. Jouzel, pp. 9–41. NATO ASI Series. Series I: Global Environmental Change, Volume 41.

Briffa, K. R., P. D. Jones, F. H. Schweingruber, S. G. Shiyatov, and E. A. Vaganov
1996b Development of a North Eurasian chronology network: rationale and preliminary results of comparative ring-width and densitometric analysis in northern Russia. In *Tree Rings, Environment, and Humanity. Proceedings of the International Conference, Tucson, Arizona, 17–21 May 1994,* edited by J. S. Dean, D. M. Meko, and T. W. Swetnam, pp. 25–41. RADIOCARBON. Department of Geosciences, The University of Arizona, Tucson.

Cook, E. R.
1985 *A Time Series Analysis Approach to Tree Ring Standardization.* Ph.D. dissertation, The University of Arizona, Tucson; 171 pp.

Cook, E. R., and K. Peters
1981 The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin* 41:45–53.

Cook, E. R., S. G. Shiyatov, and V. S. Mazepa
1990 Estimation of the mean chrononlogy. In *Methods of Dendrochronology: Applications in the Environmental Sciences,* edited by E. R. Cook, and L. A. Kairiukstis, pp. 123–132. Kluwer Academic Publishers, Dordrecht.

Cook, E. R., K. R. Briffa, and P. D. Jones
1994 Spatial regression methods in dendroclimatology: a review and comparison of two techniques. *International Journal of Climatology.* 14:379–402.

Cropper, J .P.
1982 Comment. In *Climate from Tree Rings,* edited by M. K. Hughes, P. M. Kelly, J. R. Pilcher, and V. C. LaMarche, Jr. Cambridge University Press, Cambridge; pp. 47–50.

Draper, N., and H. Smith
1981 *Applied Regression Analysis,* 2nd ed. John Wiley & Sons, New York; 709 pp.

Fritts, H. C.
1976 *Tree Rings and Climate.* Academic Press; 567 pp.

Fritts, H. C., J. Guiot, and G. A. Gordon
1990 Verification. In *Methods of Dendrochronology: Applications in the Environmental Sciences,* edited by E. R. Cook, and L. A. Kairiukstis, Kluwer Academic Publishers, Dordrecht; pp. 178–185.

Graybill, D. A., and S. G. Shiyatov
1992 Dendroclimatic evidence from the northern Soviet Union. In *Climate Since A.D. 1500,* edited by R. S. Bradley, and P. D. Jones, Routledge, London; pp. 393–414.

Jones, P. D., S. C. B. Raper, B. D. Santer, B. S. G. Cherry, C. M. Goodess, R. S. Bradley, H. F. Diaz, P. M. Kelly, and T. M. L. Wigley
1985 *A Grid Point Surface Air Temperature Data Set for the Northern Hemisphere 1851–1984.* US Department of Energy Technical Report, TR022. US Department of Energy Carbon Dioxide Division, Washington, D.C.

Kirchhefer, A. J., and K.-D. Vorren
1995 Tree rings of Scots pine, *Pinus sylvestris* L., a source of climate information in Vesteralen, northern Norway. [Årringer på furu, *Pinus sylvestris* L., som kilde for klimainformasjon i Vesterålen, Nord-Norge. In Norwegian.] *AmS-Varia* 24:79–85.

Ljung, G. M., and G. E. P. Box
1978 On a measure of lack of fit in time series models. *Biometrika* 65:297–303.

Meko, D. M.
1981 *Applications of Box-Jenkins Methods of Time Series Analysis to the Reconstruction of Drought from Tree Rings.* Ph.D. dissertation, The University of Arizona, Tucson; 149 pp.

Patterson, H. D., and R. Thompson
1971 Recovery of inter-block information when block sizes are unequal. *Biometrika* 58:545–554.

Shiyatov, S. G.
1986 *Dendrochronology of the Upper Forest Boundary in the Urals. [Dendro-chronologija verchnej granicy lesa na Urale.* In Russian.] Nauka, Moscow; 136 pp.

Tranquillini, W.
1979 *Physiological Ecology of the Alpine Timberline. Tree Existence at High Altitudes with Special Reference to the European Alps.* Springer-Verlag, Berlin-Heidelberg; 137 pp.

Vaganov, E. A., S. G. Shiyatov, and V. S. Mazepa
1996 *Dendroclimatological Investigation in the Ural-Siberian Subarctic.* [*Dendroklimatitjeskie issledovanija v Uralo-Sibirskoj Subarktike.* In Russian.] Nauka, Novosibirsk; 245 pp.

Vose, R. S., R. L. Schmoyer, P. M. Steurer, T. C. Peterson, R. Heim, T. R. Karl, and J. K. Eischeid
1992 The Global Historical Climatology Network: Long-Term Monthly Temperature, Precipitation, Sea Level Pressure, and Station Pressure Data. Data set NDP-041. Oak Ridge National Laboratory, Tennessee, USA.

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