Climate
Since A.D. 1500

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20 Dendroclimatic evidence from the northern Soviet Union

D. A. Graybill and S. G. Shiyatov

20.1 Introduction

We make a reliable reconstruction of average June-July temperature for A.D. 961-1969 using tree-ring width variation of *Larix sibirica* from the north Polar Urals (Graybill and Shiyatov 1989). It is of considerable interest because it is the first millennial-aged proxy record of seasonal temperatures in the Soviet sub-arctic. Some of the longer term trends (century scale) in the reconstruction are similar in direction and timing to those found in other summer temperature proxy records from the European Arctic, Greenland and the Americas that are commonly referred to as "the Medieval Warm Epoch" and the "Little Ice Age" (Lamb 1977; Williams and Wigley 1983; Grove 1988). We cautiously note that our record is only considered one of many that will be required to test rigorously hypotheses about the spatial and temporal generality of such temperature changes.

Additionally, our reconstruction may hold information about trends and long-term variation in temperature over large areas. The tree-ring chronology was derived from an area just south of the Kara Sea, bounded by latitudes 66°45', 66°55'N and longitudes 65°15', 66°05'E (Figure 20.1) (Shiyatov 1986) The region around the Kara Sea is thought to be particularly sensitive to long-term trends and variations in temperature over the arctic and possibly the Northern Hemisphere (Kelly *et al.* 1982).

Because of the unique nature of this record, and the strong possibility that others will want to use it for various scientific purposes, much of our discussion concerns analytical procedures used in its production. We then evaluate the quality of the reconstruction from several perspectives. An understanding of this background is crucial to subsequent comparisons or interpretations that might involve this record.

20.2 Data and data pre-treatment

20.2.1 Tree-ring widths

Tree-ring samples are from various localities in a research area on the eastern slope of the Polar Ural Mountains (Figure 20.1). This is a subset of the collections that includes the longest available series. They were selected to preserve as much low frequency variance as possible in a final chronology. Forty-eight series are from different living individuals of Siberian larch (*L. sibirica*). These were growing between 150 and 300m asl., the upper elevational limit for tree growth in 1970 when most data were collected. In addition, 23

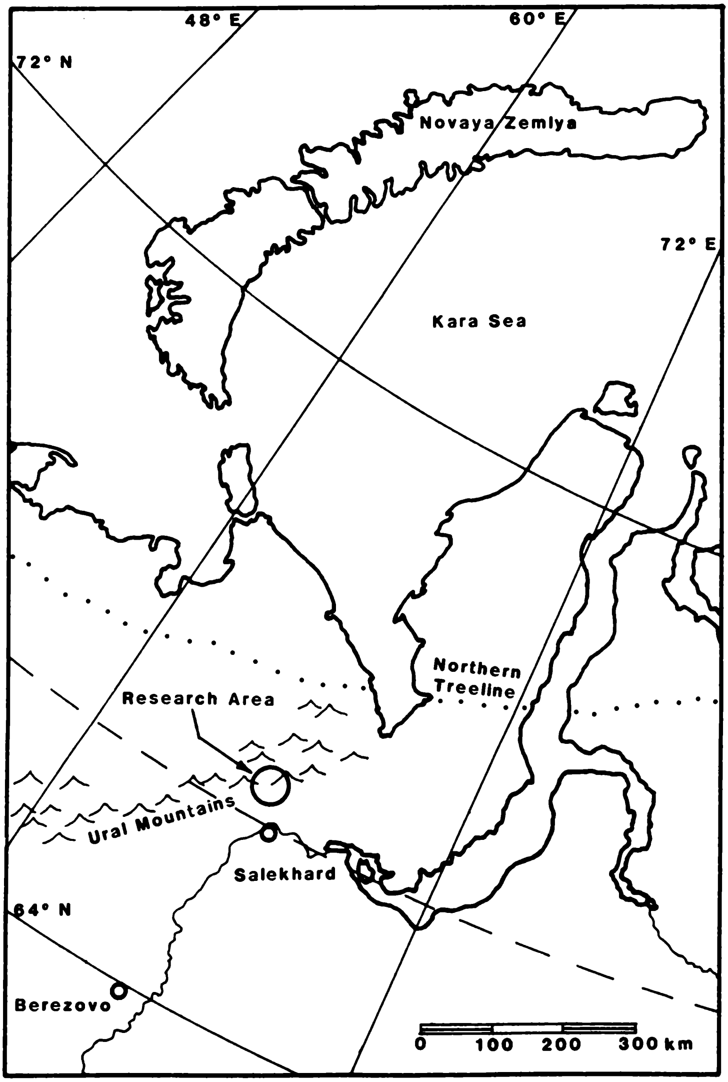

Figure 20.1 Region of research.

samples from one of the localities represent dead larch individuals found at elevations ranging up to 80m above the current treeline.

Ring width series were cross-dated with each other and then each ring was assigned a calendar year based on the known collection date of living tree samples. The total time span represented by the living series is A.D. 1541-1969. Samples from dead wood cover the time range of A.D. 960-1741 (Figure 20.2).

Inspection of time series plots of the measurements of each sample indicated that most had decaying biological growth trend that is best described as negative exponential. Removal of the biological growth trend and subsequent computation of dimensionless tree-ring indices is commonplace in dendrochronological studies (Fritts 1976; Graybill 1982; Briffa 1984; Cook

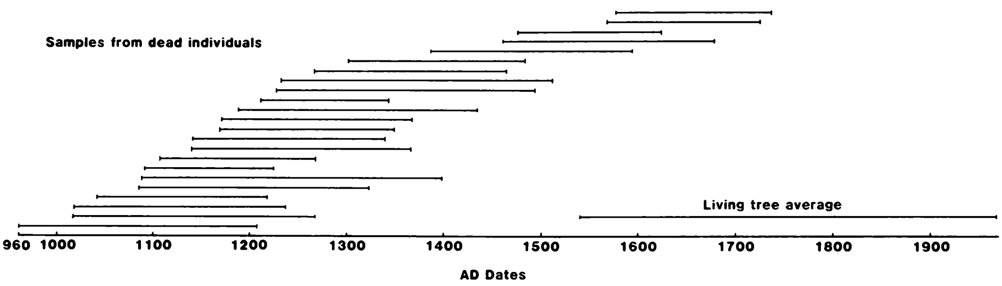

Figure 20.2 Tree-ring chronology components.

1985; Shiyatov and Mazepa 1987; Cook *et al.* 1990). A comparison of the Shiyatov 'Corridor Method' with some of the American procedures suggested that it was somewhat superior in preserving low frequency variance (Shiyatov, Fritts and Lofgren 1989). It was used with the 71 ring width series to remove age-related growth trend and to preserve other trends that appeared consistent across samples for any particular period. While the former is considered primarily biological, the latter are presumably climatic in origin. The data did not appear to have short-term (<10 years) disturbance signals that might reflect individual injuries. Because of rigorous growth conditions here, stand densities and competition are relatively low. The trees are not particularly susceptible to widespread disturbances such as fire or insect damage.

A final chronology was produced as a simple average of the 71 individual indexed series. This effectively reduced the unique error associated with each component series and maximized the common signal. Changes in the strength of the common signal in chronologies such as this are of obvious interest. As sample size per year decreases, usually near the early portion, generalizations about the reliability of a reconstruction may need to be tempered. A useful measure for consideration of this is the Subsample Signal Strength (SSS) (Wigley *et al.* 1984). This estimates the agreement between an average series made from a few samples with one made from an optimum or larger number of series. It was possible to make an estimate of SSS from 13 ring-width index series that spanned the interval of 1800-1960. When sample numbers are in the low range of two through four, a chronology derived from them explains respectively 83%, 89%, and 92% of the variance of one composed of the optimal number of series. Assuming that the living and dead trees had a relatively consistent growth response through time, these figures indicate the reliability of the early part of the record.

20.2.2 Climate data

Temperature data for 1881-1969 were selected from a gridded monthly data set for the Northern Hemisphere (Jones *et al.* 1985) at the grid point nearest the tree-ring data (65°N, 70°E). The values are expressed as departures from a 1951-1970 reference period. This grid point series represents data from two stations, Salekhard (WMO #233300) and Berezovo (WMO #236310). They are located respectively, about 75km and 350km from the center of the research area. For initial screening of climate-tree growth relationships we also used monthly precipitation totals (1883-1969) from the Salekhard records (Laboratory files, Institute of Plant and Animal Ecology, Sverdlovsk).

20.2.3 *Climate-tree growth relations*

Growing season temperature has been shown to be the dominant natural forcing function for tree growth at high latitudes, and in some cases for upper elevational treelines at mid-latitudes (Tranquilini 1979). This is reasonably well understood from physiological perspectives. In the European and North American sub-arctic it has been empirically demonstrated in many cases (Eklund 1954; Mikola 1962; Briffa *et al.* 1988; Giddings 1941; Garfinkel and Brubaker 1980; Jacoby *et al.* 1985; Jacoby and D'Arrigo 1989). Warm temperatures during the growing season, as well as through the year or so preceding growth, are found to have a positive causal effect on the width of annual growth increments. Conversely, colder periods place limitations on a variety of growth processes, resulting in diminished tree-ring widths. Evergreen genera such as spruce (*Picea sp.*) apparently integrate enough of the annual temperature variation that they can be successfully used for reconstruction of that signal (Jacoby and D'Arrigo 1989). Deciduous genera such as the larch used in this study integrate a seasonal signal. It reflects those temperatures most crucial to early initiation and maintenance of photosynthetic processes that lead to cell division. This may be for a shorter period than the actual growing season, that is, June and July *vs* June-August (Giddings 1954).

Soil moisture is also necessary for growth and can be a limiting or stressful factor. However, it has not commonly been found as limiting to growth as temperature by dendrochronologists working at high latitudes, and is not commonly reconstructed in these settings (Jacoby and Cook 1981). This disparity in response to temperature and precipitation is not so clear for tree growth at upper treeline in arid, mid-latitude settings (LaMarche 1974; Graybill 1987; Graumlich 1989; Hughes, Chapter 21, this volume).

A preliminary investigation of the relationship between climate and Polar Urals larch was undertaken. It first involved a review of simple correlations of the final index chronology with monthly temperature averages for the grid point data. Similar computations were performed using tree-ring indices and monthly precipitation totals from Salekhard. Somewhat as expected, given physiological considerations and results of similar studies cited above, there is a strong positive and significant response of tree growth to June and July temperatures (Table 20.1). There is a stronger correlation with the average for those two months ($r=0.72$, $p<0.001$). Significant correlations with temperature in the May and June of the year preceding growth probably reflect a biological dependence on stored food produced in prior years (Fritts 1976). No explanation is offered for the significance of the correlation with January temperatures. Limited but significant correlation of the index series with precipitation is present for various months as well as with a 12 month sum of July-June ($r=0.37$, $p=0.001$). The relationships with precipitation are not considered strong enough to warrant further consideration here. Continued discussion is focused on the average June-July temperature relationship to tree growth.

20.2.4 *Time-series considerations*

Time series and other statistical characteristics of the tree-ring and temperature data were evaluated to determine their suitability for use in simple linear regression. These evaluations focused on the period of common data overlap (1881-1969) as well as on the longer period of tree growth back to A.D. 960. Primary concerns were with the normality of the distributions

	Prior Growth Year								Current Growth Year							
Months	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A
Data 65°N 70°E temperature departures with prewhitened indices	.29	.37	-.14	.00	.20	.17	.04	.09	.15	.02	.00	.19	.21	.61	.67	.02
65°N 70°E temperature departures with untreated indices	.32	.55	.10	.03	.22	.20	.07	.14	.26	-.08	-.09	.21	22	.60	.56	.05
Salekhard precipitation with prewhitened indices	.01	-.08	-.19	.00	.13	.06	-.13	-.10	.05	-.01	.21	.10	.20	.07	.30	-.00
Salekhard precipitation with untreated indices	.17	.05	-.01	.09	.32	.19	.09	.16	.25	.17	.34	.26	.28	.17	.32	.11

Table 20.1 Pearson correlations of tree-ring series with monthly temperature and precipitation series (underlined value indicates $p < 0.05$).

and with the statistical independence of values in each series. Regression of series with non-normal distributions or with strong persistence can result in unreliable estimates of covariance and in problems with interpretation of the results (Wonnacott and Wonnacott 1981, Monserud 1986). Based on the results of one-sample Kolmogorov-Smirnov tests (Bradley 1968) all series are from normally-distributed populations.

Evaluation of the persistence in these series was accomplished with standard procedural software (Dixon 1985) by reviewing auto-and partial autocorrelations. If the persistence was significant then standard Box and Jenkins protocol (1976) was used to model this feature. The June-July grid point temperature series is best fit by an AR(0,2) model ($\phi_2 = 0.27$, %var. = 14.5). During the same period of 1881-1969 the best fit model for the larch indices is AR(1,2) ($\phi_1 = 0.41$, $\phi_2 = 0.34$, %var. = 47.5). The differences in the two models and the greater amount of variance in the latter model fit indicates that much of the persistence in the tree-ring indices is non-climatic in origin.

At this stage of decision making we do not find widespread agreement on all of the analytical processes that should follow in developing a reconstruction. Part of this stems from the fact that while autocorrelation in tree-ring series is normally recognized and pretreated before regression, or handled in other fashions during regression, autocorrelation in temporally correspondent climate series has not been so commonly discussed. Recent exceptions include the reconstruction of a regional drought index (Stahle and others 1988) and a study on methods of reconstruction (Meko 1981). The latter author suggests one approach where significant autocorrelation is removed from both climatic and tree-ring series. This is accomplished by pre-whitening each series after best fit ARMA models are found for their period of common overlap. Regression procedures are then used with the pre-whitened residual series and the climatic persistence is later added back into the reconstruction. One problem here is that the climate of the instrumented period may be somewhat unique or different from that of preceding centuries. If so, the persistence structure of either or both the climate and tree-ring series for that period may not be a good realization or estimate of longer term climatic processes. This does in fact appear to be the case with the larch tree-ring indices and is discussed further below. If this is true with respect to a climate series then spurious variation may be introduced into a reconstruction by reddening it with a model based on data from the past century. The obvious dilemma here is that increased understanding of centennial to millennial scale climatic processes can only be obtained from multiple and relatively consistent reconstructions by proxy records from the same or neighboring regions. These do not presently exist in the North Polar Urals. In the absence of such information we thus proceed to obtain what is possible with the current data and techniques.

In developing a time series model for the 1009 year larch chronology we considered the possibility that the model fitting results might be affected by changes in sample depth during the early years. Several trials were made. The beginning point for the modelling procedure was stepped along the points in the chronology where sample depth increased progressively from one to nine series. Dates for these points range from A.D. 960 to 1141. In all cases an ARMA(1,1) model was the best fit and the model coefficients were stable. The AR coefficients only ranged from 0.77-0.78 and the MA coefficients from 0.44-0.45. The amount of variance associated with the fits ranged from 21.4 to 22.2%. The second most parsimonious and best fit model in these trials was AR(1,2). Those coefficients were also stable with ϕ_1 ranging from 0.34-0.35 and ϕ_2 from 0.20-0.21. The amount of variance ranged from 21.2 to

22.0%. Following discussion above, it is notable that the coefficients for the AR processes are somewhat less in the longer term models than in those for 1881-1969. Also, the variance associated with the longer term fits is less than half that for the more recent period. The increasingly upward trend in growth from 1881 to 1923 (Figure 20.3) and the lack of such a predominant trend over the longer period (Figure 20.4) are at least partially responsible for these differences.

One concern that surfaces in these circumstances is whether the use of time series models for pre-whitening tree-ring data actually removes trends that are assumedly or demonstrably driven by a climatic factor (Jacoby and D'Arrigo 1989:45). We do not have an immediate reference but personal experience indicates that this procedure is sometimes referred to in jargon as 'detrending'. There may be a semantic problem here in addition to the statistical issues. We suggest that the term 'detrending' should be expunged from these discussions. However, to examine this issue in more detail, we developed reconstructions of June-July temperature using both untreated and pre-whitened tree-ring indices. The ARMA (1,1)

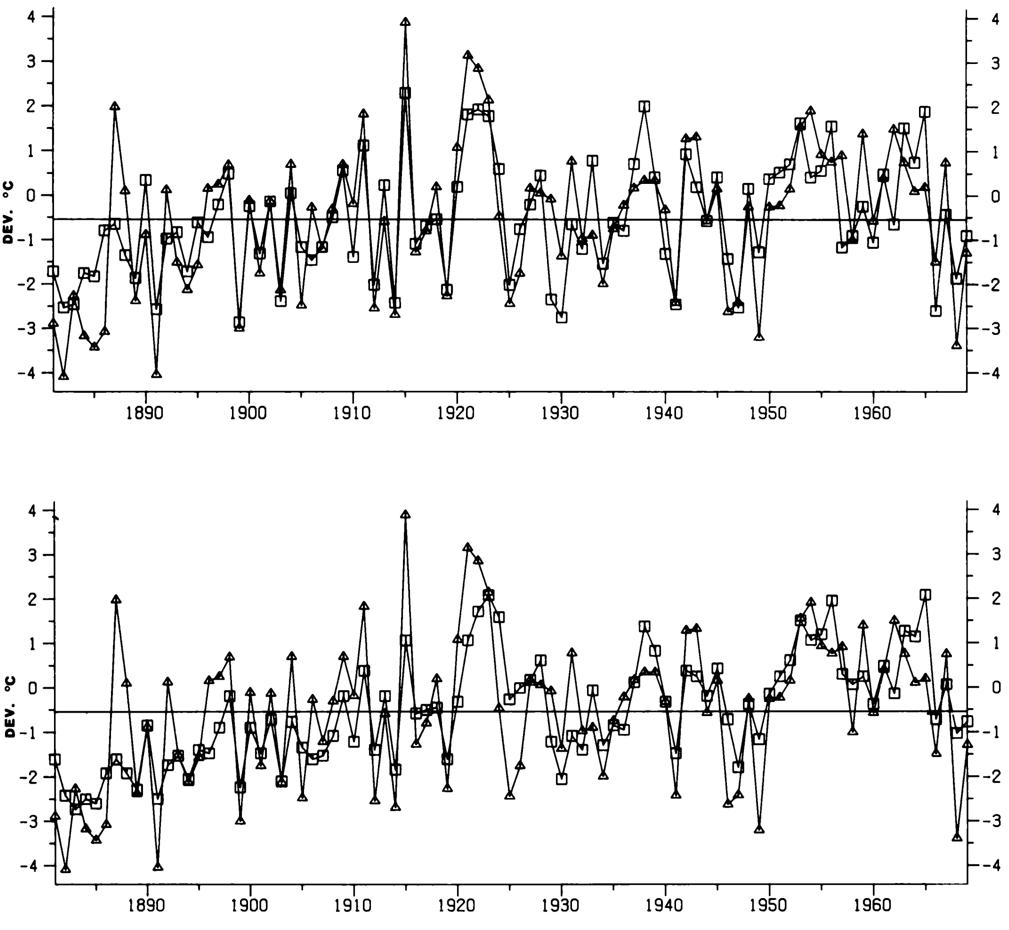

Figure 20.3 Actual and reconstructed average June-July temperature series for the Polar Urals region. (a. Reconstructed from pre-whitened tree-ring indices, b. reconstructed from untreated tree-ring indices.)

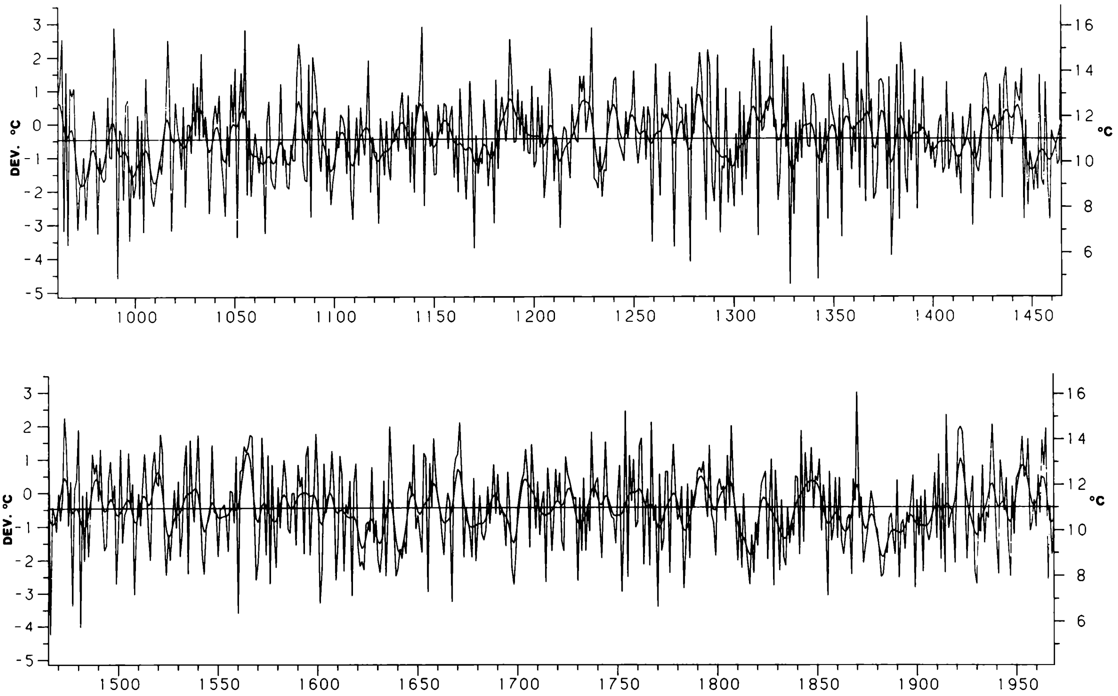

Figure 20.4 Reconstructed average June-July temperature from pre-whitened tree-ring series. (Scales on the left are for deviations from the 1951-1970 normal period at 65°N 70°E and scales on the right are for actual °C at Salekhard.)

model coefficients used for pre-whitening were 0.78 and 0.45 respectively. Pearson correlations were again computed between the pre-whitened indices and the same monthly climate data discussed above (Table 20.1). Note that the correlations with precipitation are decreased from those with the indices and that the correlation with January temperature is low and not significant. The strongest relationship of tree growth to monthly climate remains with the temperatures for the current June and July, and to a lesser degree with those of the prior May and June. The correlation with the current June-July temperature average is 0.78 ($p < 0.001$).

20.3 Calibration and verification procedures

Several calibration and verification procedures were conducted to evaluate the stability of the temperature-tree growth relationships at different times (Table 20.2). In each calibration either the pre-whitened tree ring series, or the untreated index series, was used as the independent variable in linear regression with the June-July temperature average. The equations derived from these regressions were used to reconstruct temperature values during the corresponding verification periods. Each reconstruction was then compared with the actual temperature values. Evaluation of the calibration regressions utilized standard goodness-of-fit criteria (Draper and Smith 1981). Comparison and evaluation of the recon-

	Periods		r^2a	r^2	S_d	S_m	T	W	F_c	RV_c	F_v	RV_v	RE	CE
	cal.	ver.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
I	1926-1969	1881-1925	.40	.76	a	a	a	a	r	.42	r	.20	.57	.41
	1881-1925	1926-1969	.75	.42	a	a	a	a	a	.76	a	1.54	.18	.05
	1881-1969		.60						r	.60				
II	1926-1969	1881-1925	.44	.59	a	a	a	a	r	.45	r	.29	.53	.50
	1881-1925	1926-1969	.58	.45					r	.59	a	.89	.16	.04
	1881-1969		.51						r					
III	1912-1969	1883-1911	.58	.56	a	a	a	a	r	.59	r	.30	.61	.51
	1883-1911, 1941-1969	1912-1940	.54	.66	a	a	a	a	r	.55	a	.74	.65	.55
	1883-1940	1941-1969	.62	.51	a	a	a	a	r	.62	a	.76	.52	.48
	1881-1969		.59						r					
IV	1912-1969	1883-1911	.50	.59	a	a	r	r	r	.51	r	.26	.45	.30
	1883-1911, 1941-1969	1912-1940	.49	.49	a	a	a	a	r	.50	r	.40	.51	.48
	1883-1940	1941-1969	.50	.56	a	a	a	r	r	.50	r	.45	.44	.39
	1881-1969		.49						r					

1. Calibration period regression covariance adjusted for degrees of freedom, alpha = .01.
2. Covariance of independent and dependent series during the verification period, alpha = .01.
3. Sign test of first differences, see text, alpha = .01.
4. Sign test of direction from mean, see text, alpha = .01.
5. Students T-test, alpha = .05.
6. Wilcoxon matched pairs signed ranks test, alpha = .05.
7. F test for equality of variances, actual and reconstructed temperature, calibration period, alpha = .05.
8. Ratio of reconstructed to instrumented temperature variance, calibration period.
9. F test for equality of variances, actual and reconstructed temperature, verification period, alpha = .05.
10. Ratio of reconstructed to instrumented temperature variance, verificationb period.
11. Reduction of Error.
12. Coefficient of Efficiency.

a = null hypothesis accepted

r = null hypothesis rejected

Table 20.2 Results of calibration and verification procedures of tree-ring data with June-July temperature departures from 65°N 70°E (I, III used pre-whitened larch indices; II, IV used untreated larch indices).

structed and actual temperature values utilized standard parametric and non-parametric statistics. Other not-so-standard statistics (CE, RE) that are sometimes found in the hydrologic and dendroclimatic literature were also included in the analyses (Nash and Sutcliffe 1971; Fritts 1976; Gordon and LeDuc 1981).

In the first set of trials the data were divided into two equal and sequential halves that were alternatively used for calibration and verification. There is nothing particularly sacrosanct about this kind of data division although it is simple and is common practice. One kind of problem that can occur in this circumstance, and did with this data set, is that one or more of the basic distributional characteristics of the climate or tree-ring data may actually change from one time period to the next. This makes comparison of the actual and reconstructed series during the verification period somewhat difficult. A notable change of this nature is a decrease in the variance of the temperature data. It is about 50% less in the post-1925 period than in earlier years. The tree-ring indices exhibit this to a lesser extent with a decrease in variance near 30% over the same periods. The pre-whitened series show only limited change in that value. Other grid point temperature data in the region bounded by 50°N, 65°N and 50°E, 90°E were reviewed to see if they had similar temporal patterns of change in average June-July temperature variance. This pattern is restricted to the northeastern sector of that region, appearing in grid point series along the meridian at 70°E from 55°N to 65°N and at 65°N, 90°E. Grid point data along the meridian at 80°E are too limited in length for these considerations. This kind of change appears to correspond temporally with a shift from more meridional to more zonal flow in the Northern Hemisphere. The former period was more continental and cooler than the latter (Lamb and Johnson 1959, 1961; Dzerdzeevskii 1962). Sometime near 1960 there appears again to be a shift to meridional flow and higher variance in the same sector just described. This was apparent in our computations (1881-1984) and is also indicated for much of the Soviet Union by Borisenkov (Chapter 9, this volume).

Given this situation a second series of calibration-verification trials was undertaken to try to avoid such potentially dichotomous results. Three trials successively used the first, middle, and final two-thirds of the data for calibration and the remaining portion for verification. In reviewing the results of these exercises (Table 20.2) the highest amount of calibration variance in common between tree-growth and temperature is found in early periods that are the coldest and have the highest climate variance. The converse is also true, particularly in the analyses where the data are only split into two parts. However, all correlations (and by extension-covariances) are highly significant with associated probabilities being less than 0.001. Similar kinds of results were reported for conifers in the North American sub-Arctic which were being used to reconstruct annual temperatures from 1880-1973 (Jacoby and D'Arrigo 1989:46). Calibration period covariance was highest during the earlier and colder portion of the temperature record. They infer, as we do, that the warmer temperatures of the mid to late 20th century were not as limiting to growth as cooler temperatures of earlier years. As those earlier stresses decreased, other factors (noise at this time) have recently intervened, which somewhat obscure the growth response.

Other information presented in Table 20.2 provides further perspectives on the quality of the Polar Urals tree-ring data for reconstruction purposes. A basic consideration is how well the mean temperature of the verification period data is reproduced. To evaluate this, the non-parametric Wilcoxon matched-pairs signed-ranks test (Bradley 1968) was used in addition to the T-test because some of the tripartite schemes involved limited sample sizes. In most cases the mean values were reconstructed, although the Wilcoxon test resulted in two more rejections than the T-test. Models based on regression using the residual white noise series only failed to reconstruct one of the means. Models based on untreated indices could not do this in four cases, given results of the Wilcoxon test.

Results of F tests for the equality of variances in the actual and reconstructed climate series (F_c, F_v) are not commonly included in these exercises. To speculate, this may be due to the fact that not all of the variance in a climate series can normally be reconstructed; a large and significant F value is commonplace, and may not therefore be of interest. Even with an alpha level of 0.05, it is apparent that rejection of the hypothesis of equal variances is more common than acceptance. However, in a few of the calibrations and several of the verifications this is not the case. Another consideration is how the amount of variance in the reconstructed temperature values, relative to that of the actual values, varies from the calibration to the verification periods. Those ratios are labelled RV_c and RV_v in Table 20.2. One would commonly hope to find limited differences, assuming at least some stationarity in the mean and the variance of both series. Given discussion above, the largest differences in those ratios are expected to be found where the calibration is based on the least variable temperature data and the verification on the most variable temperature data. Differences in those ratios are somewhat diminished in other trials where the temperature variances of the two periods are not so dissimilar. These patterns are similar for both the pre-whitened and untreated larch indices.

Two of the other results in Table 20.2 (S_m, S_d) are from non-parametric sign tests designed to evaluate two hypotheses. (1) The locations of the annual values of the reconstructed and dependent series either above or below the mean of the dependent series are not significantly different (S_m). (2) the first differences of the actual and reconstructed values do not differ significantly in sign (S_d). In all cases these hypotheses could not be rejected at the 0.001 alpha level. Values for the reduction of error (RE) and coefficient of efficiency (CE) are also reported in Table 20.2. A discussion of the similarities and differences in these can be found in Briffa *et al.* (1988). The RE statistic was originally designed for evaluation of errors in predictions of the distributional characteristics of short-term changes (hours, days) in weather (Lorenz 1956). Its applicability to longer-term phenomena can be questioned, and there are no significance tests associated with either the RE or CE statistic. Their inclusion here is solely for comparative purposes because they are now presented frequently in literature on climatic reconstruction. Values of the two statistics can range from negative infinity to 1.0. Any positive values are considered a reflection of good calibration model performance. Given those criteria, all the calibration models developed here were successful to varying degrees. The lowest RE and CE values are from trials where the data were split into two portions and the calibrations were performed on the sector of temperature data with the highest variance. The highest values are found with some of the threefold data divisions where the differences in temperature variance are smallest.

Final calibrations of the pre-whitened tree-ring indices and the untreated indices with the June-July temperature record used the full span of available data to obtain the fullest sample of covariation in each series. Tree-ring covariation with the temperature series was highest for the pre-whitened indices (Table 20.2). These linear regressions provided equations that were used to compute reconstructions (R_1, R_2). The data sets and derived equations are:

(1) Pre-whitened tree-ring indices (PI) grid point average June-July temperature departures

$$R_1 = (PI * 3.6858) - 0.4633$$

(2) Untreated tree-ring indices (UI) grid point average June-July temperature departures

$$R_2 = (UI * 2.6143) - 2.9914$$

20.4 Comparison of reconstructions

Although the quality of these reconstructions can to some degree be judged by reference to Table 20.2 and the discussion above, it is pertinent to consider other aspects of them. The following discussion compares the two reconstructions, indicating various strengths and weaknesses of each.

One of the first exercises we undertake upon completion of a reconstruction is to consider the distributional characteristics of the actual and reconstructed data during their period of overlap, and of the longer period reconstruction. A lack of similarity in the moments of the instrumented and reconstructed series can signal various limitations on inferences that might be drawn from the reconstruction. This is aided by reference to Table 20.3 and to time series plots for some of the values (Figures 20.3-6). An eight year low pass filter was used to produce the smooothed line through the central portion of Figures 20.4-6. The temperature scale on the left of the long period reconstructions is departure values derived from the grid point reconstructions. On the right side, this axis is annotated with temperature values for the June-July season at Salekhard. This was included in anticipation of physiological and ecological research in the region that might require estimates of instrumented values rather than deviations. To reduce the visual dominance of high frequency variation in Figure 20.4, and to aid in recognition of other important trends and patterns, we computed 20 year non-overlapping averages of the reconstructed values (Figure 20.6a). They were positioned such

Table 20.3 Statistics for actual and reconstructed June-July temperature data, grid point 65°N 70°E (I. – from pre-whitened larch indices; II – from untreated larch indices).

I.	Actual	Reconstructed	
Dates	1881-1969	1881-1969	1061-1969
Mean	-.54	-.54	-.46
Std. dev.	1.66	1.29	1.35
Skewness	.01	.21	-.15
Kurtosis	2.76	2.31	2.80
II.			
Mean	-.54	-.54	-.39
Std. dev.	1.66	1.19	1.08
Skewness	.01	.30	.08
Kurtosis	2.76	2.38	2.57

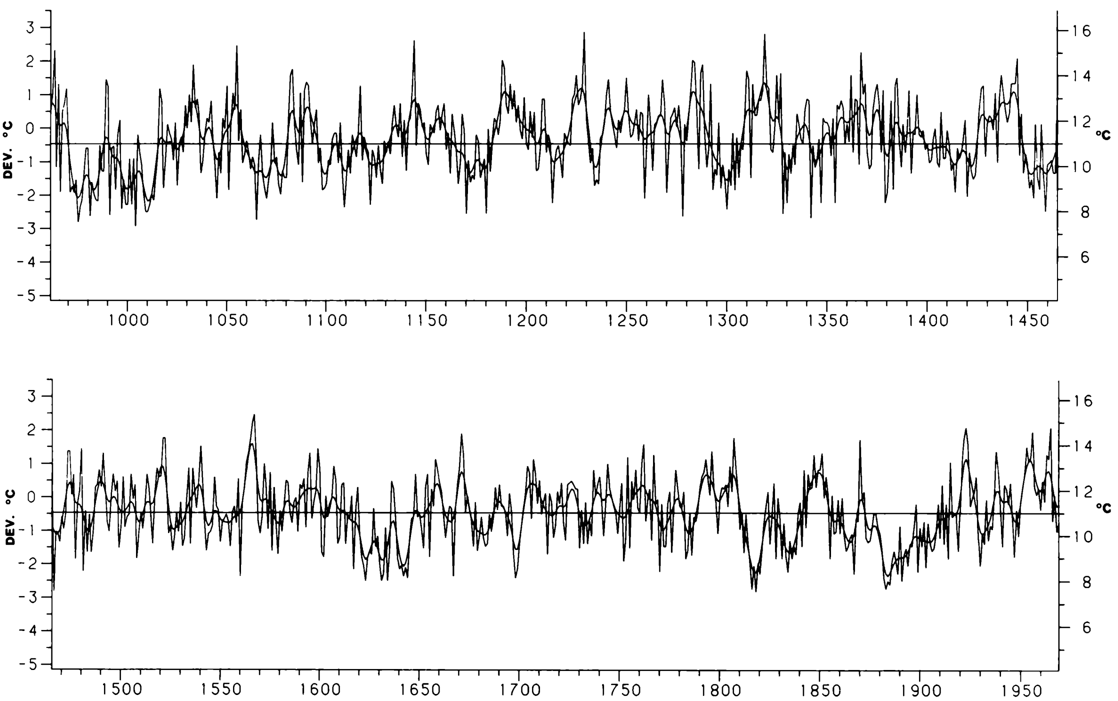

Figure 20.5 Reconstructed average June-July temperature from untreated tree-ring series. (Scales on the left are for deviations from the 1951-1970 normal period at 65°N 70°E and scales on the right are for actual °C at Salekhard.)

that the final period includes the last 20 years of data (1950-1969). The first eight years of the reconstruction were not used.

During the full calibration period the mean values of the actual and reconstructed series are the same, by definition of the regression process. The slightly warmer long-term mean values are somewhat a product of the higher values through the period of about A.D. 1120-1450 (Figures 20.4 and 20.6a). The variance of the actual temperature data is best reconstructed by the pre-whitened index series. The relatively high amount of variance in the long period reconstruction from the pre-whitened index series is partially due to higher variance from the late 1200s to the mid-1400s (Figure 20.4). This is more apparent in a plot of 20 year non-overlapping averages of the sums of absolute first differences (Figure 20.6b). These values were used instead of variance to avoid any scale dependence on either local or global means.

Skewness of the temperature values is near the expected value in a normal distribution and is best reconstructed by the pre-whitened indices. The slight negative skew of the long period reconstruction from pre-whitened indices is probably due in part to the presence of many extreme low values in the period of about A.D. 1250-1390. The kurtosis values for the actual and reconstructed series are not remarkably different from each other or from an expected value of 3.0 in a normal distribution.

We now consider the question of whether the quality of reconstruction is somewhat different for low and high climatic values. It is commonly found that lower values are best

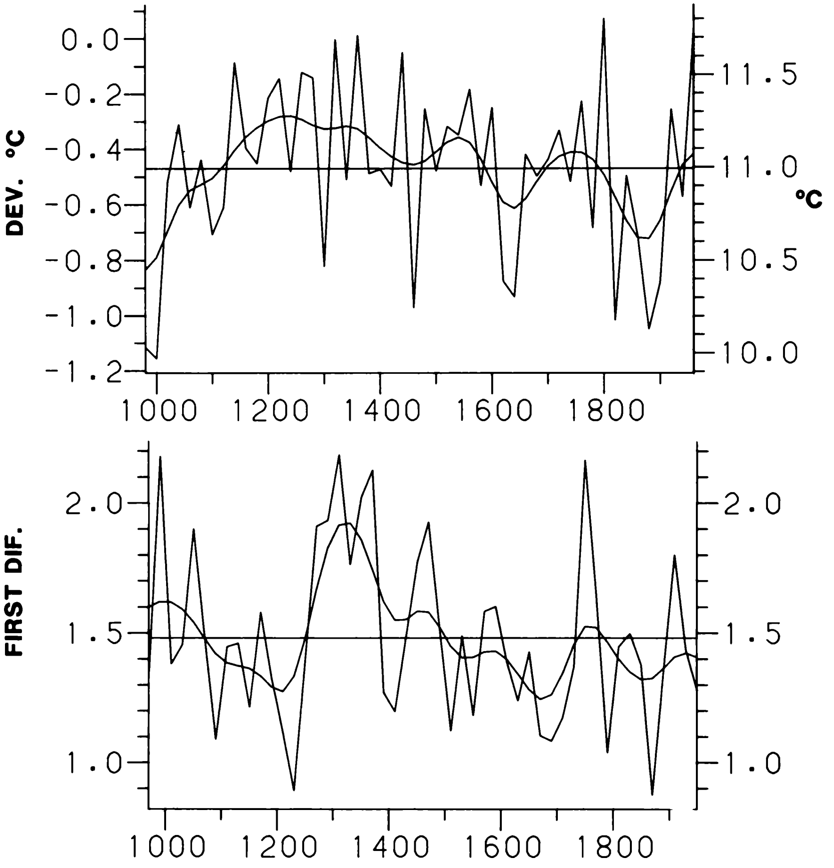

Figure 20.6 Twenty year averages of (a) reconstructed average June-July temperature and (b) of absolute first differences of average June-July temperature. (The scale on the left of (a) is for deviations from the 1951-1970 normal period at 65°N 70°E and the scale on the right of (a) is for actual °C at Salekhard.)

reconstructed because they represent conditions of highest biological stress. Most trees from a stand will respond in a more similar fashion under these conditions and in a less similar fashion when stress is not so strong (Fritts 1976; Graybill 1989). In review of this issue, two linear regressions of tree-ring data and June-July temperature series were conducted using (1) values above the means, and (2) values below the means of the actual temperature data sets (Table 20.4). In all cases the lower values were better explained than the higher. Covariances of the pre-whitened indices and untreated indices with values below the mean of the grid point data are about the same. In general, the untreated indices do the poorest job of reconstructing high temperature values as well as the full range of values (Table 20.2). This is also visually apparent in Figure 20.3. These findings suggest that generalizations about the highest temperatures that may be represented in the reconstructions must be limited in nature and made with recognition that the highest reconstructed values are likely underestimations.

Although no accurate statistical generalizations can be made about the probable amounts of actual temperature underestimations in times prior to instrumented records, we did

Table 20.4 Regressions of tree-ring series with temperature data above and below mean levels. Data sets are: I grid point June-July temperature, pre-whitened indices, II grid point June-July temperature, untreated indices.

	Location Relative to Temperature Mean					
	Below			Above		
	r^2_a (1)	dif_b (2)	n (3)	r^2_a (1)	dif_a (2)	n (3)
I	.38	.65	40	.25	.67	49
II	.42	.75	40	.14	.78	49

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1. Regression covariance adjusted for degrees of freedom.
2. Average value of underestimated temperature departures (I,II).
3. Number of cases in computation of 2.

compute those values for the instrumental period. When temperature values were both above the mean and also underestimated by the reconstructions, the differences were summed and averaged (dif_a, Table 20.4, these equate to about 1.4-1.2°C at Salekhard). Since some observers may also be interested in the average underestimate of values below the mean, this value was also computed (dif_b, Table 20.4, these equate to about 1°C at Salekhard). It represents the average of differences for only those years where the actual temperature values were less than the estimates from the tree-ring data.

Another consideration of the two reconstructions is focused on their ability to reproduce the increasing temperature trend from the late 19th into the early quarter of the 20th century. Trends over this period were computed by simple linear regression of incremental annual values with the June-July data of the climate series and with the reconstructions from the tree-ring data (Table 20.5). The trends represented by these slopes are indistinguishable statistically given the range of the standard errors of the regression coefficients. This indicates that other trends of at least this length (45 years) and of similar slope may be reasonably well represented throughout all sectors of the reconstructions.

One other aspect of the records concerns their ability to reproduce the autocorrelation pattern in the temperature series. It will be recalled that this exhibits higher autocorrelation at lag two than one (0.19, 0.24) and the second value is significant at the 0.05 level. During the instrumental period, both the pattern and amount of autocorrelation in the reconstruction from the pre-whitened indices are similar to that of the temperature data (0.15, 0.30). The untreated index series reconstruct their own pattern of changes and levels in those lag values and do not adequately model the persistence in the temperature series. The lag one and two values in this reconstruction are respectively 0.50 and 0.48, and both values are highly significant ($p<0.001$).

A cross-spectral analysis (Jenkins and Watts 1968) of the temperature data and the reconstruction based on pre-whitened indices indicated strong coherence at most periods less than the 20 year frequency range. These 89 year records are somewhat limited for high resolution of spectral densities but there are some significant similarities at periods of about

2.0-2.1 and 2.8 years. We do not speculate on possible reasons for these periodicities. Spectral analysis of the reconstruction based on untreated indices is not appropriate given the high amounts of autocorrelation present (Chatfield 1980).

Because of the results of the comparisons and analyses presented here, we think that the most reliable generalizations will be based on use of the temperature reconstruction from the pre-whitened index series. Further discussion below is accordingly restricted. This decision, as well as the discussion above, should not however be construed as polemics. Seldom have the relative merits of these kinds of approaches to data manipulation been discussed or compared in detail with full presentation of results in the professional literature. Continuing investigation of these issues is fully warranted in dendroclimatic research. We also look forward to similar, detailed examination of the quality of climatic reconstructions from other proxy sources by our colleagues in disciplines such as palynology and ice core studies. Only when this is accomplished can we collectively attempt to make reliable generalizations about long-term regional, hemispheric and global patterns and processes of climate variability.

20.5 Variation in the reconstruction

Our time series plots (Figures 20.4 and 20.5) of the reconstruction extend back to A.D. 961 as a matter of completeness of record. However, comments here will be restricted to variation in that record after A.D. 1086 when five or more component tree-ring series are usually present. The overall similarity of longer term trends to those found in many other summer temperature proxy records outside of this region was earlier noted. Somewhat warmer than normal temperatures in medieval times are followed by a general decline into the late 1800s, with an obvious increase again into the 20th century. Now, most of the constituent series forming the chronology are from about 220-400 years in length, although a few are somewhat shorter. Given this, and the fact that standardization can remove trends that are the same or greater length than each series, the ability of this reconstruction to mirror some of these longer term trends may be questioned. There are, however, important field observations that bear on this issue. Series from the dead individuals were found at elevations up to 80m above the current treeline, although the majority were found in the first 20 to 40m of that incline. All the dead series that were living in the early to mid-1600s, a period of inferred temperature decrease, experienced dramatic growth decline at that time. Their demise occurred then or shortly thereafter. This is also the time period when many of the oldest living trees found near the current elevational treeline germinated, although some date to the mid-1500s. Therefore, it is possible that the longer term trends in temperature are at least reasonably estimated. The two different elevational groupings of trees provided continuous monitors of temperature variation at their respective locations and sequentially their records may have captured those trends.

Early medieval times from about A.D. 1100-1250 experienced warming above the long term mean and stable interannual variation (Figures 20.4 to 20.6). June-July average temperatures generally remained above that mean until the late 1500s, with two major exceptions. They are cool periods centered on A.D. 1300 and 1460 that represent two of the three most rapid temperature decreases between adjacent 20 year periods (1° and 1.4°C at Salekhard). On even shorter time scales there are some remarkable changes in the variability of reconstructed temperatures as measured by absolute first differences (Figures 20.4 and 20.6b). This is particularly evident through later medieval times from A.D. 1259 to 1379. It is not thought to be an artefact of sample depth because one of us (SGS) noted extensive variability in the ring widths of most samples from these times. Overall, this 121 year period is relatively warm and contains five of the twelve years that are greater than two standard deviations above the long term mean. However, it also contains nine of the seventeen years with values that are more than two standard deviations below the mean, as well as the only two values that are more than three standard deviations in either direction (below the mean, in 1328 and 1342).

The predominant trend of decreasing temperature from the late 1500s to 1880 is primarily due to three periods with one or more strong excursions below the long-term mean. These are from about 1610-1640, 1810-1820 and 1850-1880. The relatively warm recent period of 1950-1969 (11.74°C) is only exceeded by that of 1790-1809 (11.80°C). The decline from the 20 year period centered on 1800 to that centered on 1820 is the greatest in the reconstruction (1.62°C). In terms of possible arguments about volcanic forcing of tree growth in this time period, via restrictions of sunlight from aerosols, it is noted that tree growth began to decline after 1807, reaching a low in 1818. Increases in growth are found from 1819-1824. Whether the eruption of Tambora in Indonesia, April of 1815, may have had some or any cooling effect on summer temperatures at this high latitude, thereby limiting tree growth in that or subsequent years, is a difficult issue to resolve (Sear *et al.* 1987; Bradley 1988).

Reconstructed interannual temperature variation after A.D. 1500 is highest from 1750-1769, with a lesser peak again in the late 19th and early 20th century. Changes in circulation types that were noted above, in connection with variance changes in the instrumental record, may also have been involved at earlier times. The extreme nature of most of these, as well as the duration of high values in medieval times, are clearly outside the range of variation during the instrumental period. Improved understanding of the spatial pattern of such changes, and of the changes themselves, will require a larger spatial array of reconstructions than is now available.

The autospectrum of the larch reconstruction has three significant peaks that occur at 2.1, 3.8 and 8.6 cycles per year. These are mentioned only for the sake of documentation. We have no strong *a priori* convictions or hypotheses to test about the physical meaning of such periodicities and they are not discussed further.

20.6 Comparisons with other temperature reconstructions

Other estimates of past summer temperatures from northern Europe and Asia have been made with ice core data from the arctic islands of Svalbard (Spitsbergen) Franz-Josef Land, Novaya Zemlya and Svernaya Zemlaya (Tarussov, Chapter 26, this volume). It is thought by Tarussov that the most reliable record of temperatures is for a seasonal period of June-August. This is based on annual melting percentage (AMP) values in a core from the Austfonna region (Spitsbergen) some 1800km to the northwest of Salekhard. The data have a temporal resolution of about 4-5 years. Some trends that are similar to those in our larch reconstruction include cooling from about 1550 to 1750, and warming events near 1780 and 1820. The sharp cooling between the latter two events that is found in the tree-ring record, and in other ice core data, is not apparent in this series. Tarussov suggests there are physical reasons for this. In some additional agreement, mid-19th century cooling and late to post-19th century warming are apparent in both records. Given the differences in temporal resolution of the ice core and tree-ring records, these are interesting coincident results. Further ice core and tree ring records from this sector of the Arctic will be needed to validate these correspondences.

Other AMP records from high north latitudes that are thought to provide summer temperature records over the past millennium are from Dye 3 in Greenland (Herron *et al.* 1981) and from Devon Island in the Canadian Arctic (Fisher and Koerner 1981). Those localities are respectively about 4300km and 4000km from Salekhard. The 1979-1980 series from Dye 3 has some correspondence with the larch reconstruction in the earlier years. Both show increases to relatively high temperatures by the first half of the 1300s. This is followed by a sudden decrease to near long-term mean values in the ice core series, while the larch series has a more gradual decline in the same succeeding five centuries. The Devon Island record indicates a warming trend from 1300 to 1450, followed by a substantial warming event in the first half of the 1500s. This is somewhat different from the Polar Urals reconstruction. The two series share an overall cooling trend in the succeeding 200 years, as well as warming events in the late 1700s, the mid-1800s, and after about 1880.

Dendroclimatic reconstruction of late summer temperatures in northern Fennoscandia (July-August, A.D.1700-1964) are presented in another chapter of this volume by Briffa and Schweingruber. The center of that study region is about 1880km west of Salekhard. The simple correlation coefficient of the Polar Urals reconstruction with theirs is relatively low and nonsignificant (r=-0.05, p=0.30). Comparison of the respective time series plots does not indicate any remarkable similarities in the estimated temperature records for single years or for short term (10-20 years) variation. It can be questioned whether temperature of the two areas would demonstrate strong synchroneity of change on short time-scales, based on studies of instrumental records in the Arctic for the period of 1881-1980 (Kelly *et al.* 1982). Briffa and Schweingruber's principal component analyses of annual and seasonal temperature variation suggest some differences in the two regions, and they note that summer temperature patterns are less well organized spatially than patterns in other seasons. Additionally, the seasonal period of strongest climatic sensitivity varies by one month, and the two genera (*Larix vs Pinus*) may be responding somewhat differently to seasonal as well as to annual temperatures due to biological differences.

20.7 Conclusions

After extensive experimentation we conclude that the highest quality dendroclimatic reconstructions of June-July average temperatures in the Polar Urals from *Larix sibirica* are best obtained by using pre-whitened tree-ring indices rather than untreated tree-ring indices. This empirical finding is only one of such studies and may not be generalizable to others, but it remains an issue for continuing investigation.

Early summer temperature variation in the Polar Urals evidences long-term trends on the scale of centuries or more that are broadly similar to changes derived from many other proxy temperature records over the past millennium from diverse areas that include the European

High Arctic, Greenland and the Americas (see especially Williams and Wigley 1983). These include warming to above long-term means from near A.D. 1000 to 1200 or 1300. Subsequently there is overall cooling until the 19th century that usually includes some regional episodes of intervening warm periods. In the Polar Urals the post-A.D. 1500 period is generally one of cooling until the early 1880's, the coldest part of the record. The relatively sustained rise in temperature from the 1880's to the 1960's has the greatest magnitude in the record for such an extended period (1.6°C difference between the 20 year periods centered on 1870 and 1960). Other extremes in the post-1500 period include the highest 20 year mean value for the period centered on 1800 (11.8°C) the greatest decrease (1.6°C) from one 20 year period to the next 1790-1810, and the second warmest value in the entire reconstruction (1870: 16.1°C).

Comparison of the larch temperature reconstruction with AMP records in ice cores from Svalbard, Devon Island and southern Greenland indicates that the greatest correspondence since 1500 is with Svalbard which is the closest and the northernmost record. This suggests that a regional signal might be forthcoming if more ice core records could be developed from the remaining archipelagos to the north of Siberia. The Polar Urals reconstruction and the two other AMP records collectively suggest that the period from about 1000-1550 was one with various regional episodes of warming well above long term means. Subsequent centuries underwent overall cooling until the late 1800s and all three records indicate a brief but obvious warming just before 1800.

Comparison of the early and late summer dendroclimatic reconstructions from the Polar Urals and Fennoscandia did not reveal strong similarities. Probable reasons for this are biological differences in the climatic responses of larch and pine as well as in the short-term climates of the two regions. A larger network of tree-ring chronologies that includes series from the intervening sector of the northwestern Soviet Union and climatic reconstruction from longer series (Schweingruber *et al.* 1988) is desirable. In conjunction with other new proxy records such as ice cores, we would then be better able to evaluate the strength, coherency, and history of climate signals across these regions.

These kinds of endeavors are important beyond the level of academic exercise. They can inform on climatic extremes or states that we have not yet experienced but which may potentially occur. The Early Medieval warm period is a strong illustration of this and contains some parallels to recent climatic history which are pertinent in this regard. Early Medieval warming was accompanied by relatively low and stable interannual summer temperature variation, much as the Polar Urals experienced from about 1930 to 1960. Although later medieval times remained relatively warm, they were characterized by a long period of exceedingly high interannual variance that is unparalleled in the rest of the record. If widespread, changes of this kind may have had important economic and social implications. For example, reliance upon subsistence agriculture in marginal environments was and still is a precarious enterprise at best. Major changes in the interannual variability of a crucial factor such as growing season temperatures at high latitudes could result in substantial decreases in crop production, which would probably also be accompanied by exhaustion of any stored reserves. Barring a set of social and political mechanisms to cope with these circumstances, famine and population displacement were not unlikely. Is it possible that some of those events during the thirteenth and fourteenth century in European Russia that are described by Borisenkov (Chapter 9, this volume) were driven by such climate changes, and, is the recently increasing variance of Soviet Arctic climate a portent of things to come?

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