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Comparative Analysis of the Standardization Methods of Tree-Ring Chronologies

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Many variations in tree-ring widths can be attributed to fluctuating climatic conditions, but forest stand conditions, increasing tree age and various disturbances also produce marked ring-width variations. These nonclimatic sources of variations usually produce slowly changing trends in growth through time. It is important in climatic reconstruction work that the nonclimatic trends be identified as much as possible, separated from the effects of climatic factors, and removed so that the remaining variations are faithful representations of the climatic factors.

The most popular method of ring-width standardization is to fit a curve, either graphically or mathematically, to the ring widths plotted as a function of time (Fritts, 1976). This method can be subjected to rigorous computer analysis and objective statistics can be used to describe the results. The ring widths are divided by the value of the fitted curve to obtain standardized growth indices. This method is used at the Laboratory of Tree-Ring Research, University of Arizona (programs INDEX and ARSTAN).

Program INDEX fits a negative exponential curve, a straight line or a polynomial curve to the data and then calculates the arithmetic mean of the indices to obtain the final chronology (Graybill, 1982). Program ARSTAN begins by fitting a similar exponential curve and straight line. It calculates the indices and can fit a second spline curve to the indices if there are any remaining low-frequency features. This second curve is generally a ridged spline removing 50% of the variance at periods of 2/3 the length of a ring-width record (Cook, 1985; Holmes *et al.*, 1986). In addition, ARSTAN applies ARMA modeling and uses a robust estimation of the mean to combine the indices of individual cores and trees into a single chronology.

Shiyatov (1972, 1986) proposed another method for calculating the growth indices. It uses the maximum and minimum possible range of the ring-width data, which are estimated from curves fit to these two extremes of the data. These curves form a strip or a "corridor," so it is referred to as the CORRIDOR method. The width of the corridor varies regularly with the tree age, reaching its maximum during the period of greatest growth. The corridor displays a range of growth in response to environmental fluctuations at different times throughout the life span of the tree. The location of the actual growth for each year within the corridor is taken into account by subtracting the minimum curve from the ring width, multiplying by 2 (for a range of 0 to 200) and dividing the result by the difference between the curves for the maximum and minimum. Until now, plots of ring widths were estimated using human judgment, and the maximum and minimum possible curves were drawn by hand. The technique also has a mathematical solution.

If tree ring chronologies from the US and the USSR were to be compared or used jointly in project 02.03-21, "Air Pollution Effects on Vegetation," it was necessary to evaluate any differences in the methodology. While Shiyatov was visiting the Laboratory of Tree-Ring Research in 1987, we carefully examined and compared these three methods of standardization. The ring-width data came from Siberian larch (*Larix sibirica* Lbd.) growing at the upper timberline in various provinces of the Ural Mountains (Polar, Subpolar, North and South Urals), but all grew on relatively moist sites (with running water). The mean chronology indices (Table 1) basically reflect the thermal conditions of the summer months (Shiyatov, 1986).

The three methods were used to generate three chronologies from each of the four sites (Table 2). The spline stiffness used in the second detrending of ARSTAN was 100% of the series length so maximum low frequency information was retained in these chronologies.

A visual comparison of the plots of indices, an analysis of the main chronology statistics, and a power and cross-power spectrum analysis (Blackman and Tukey, 1958) were used to evaluate the similarities and dissimilarities between the tree-ring chronologies.

The signal-to-noise ratio (the chronology variance/error variance) (Table 2) is approximately the same (from 22.9 to 29.2) for the three chronologies from the Polar, Subpolar and North Urals. The ratio was only 8.9 for the chronology from the South Urals. This difference in signal-to-noise ratio allowed us to evaluate the effects of standardization techniques on chronologies with varying amounts of climatic variation.

One can see from Table 2 that the chronologies developed by the CORRIDOR method have a little higher mean sensitivity and standard deviation as compared with the chronologies developed by the INDEX and ARSTAN programs. This difference is connected with the fact that the lower limits of the CORRIDOR method must pass through the minimum values, which are zero or positive values, while the lower limits for INDEX and ARSTAN are always

Table 1. Characteristics of the mean tree-ring chronologies

Series Code	Province	Latitude North	Longitude East	Altitude meters	Trees sampled	Chronology time span
S01	Polar Urals	66°50'	65°30'	150-300	21	1541-1968
S08	Subpolar Urals	64°40'	59°50'	550-700	20	1691-1969
S11	North Urals	59°35'	59°10'	800-950	25	1590-1969
S29	South Urals	54°30'	58°50'	1000-1100	11	1770-1972

Table 2. Statistics of the mean chronologies developed by the various standardization methods (C-CORRIDOR, I-INDEX, A-ARSTAN)

Series Code	Standardization Method	Mean Sensitivity	Standard Deviation	Autocorrelation Order1	Signal-to-Noise Ratio
S01	C	0.41	0.42	0.43	-
	I	0.40	0.42	0.46	-
	A	0.40	0.42	0.47	22.8
S08	C	0.39	0.43	0.45	-
	I	0.35	0.40	0.45	-
	A	0.36	0.39	0.39	27.3
S11	C	0.35	0.38	0.47	-
	I	0.33	0.37	0.48	-
	A	0.35	0.36	0.39	29.2
S29	C	0.31	0.37	0.52	-
	I	0.24	0.29	0.50	-
	A	0.24	0.28	0.45	8.9

zero. Thus, the divisor used for the index of the CORRIDOR method is smaller making the range of variability larger. The chronology with the weakest climatic signal (South Urals) has the greatest differences in mean sensitivity and standard deviation.

First order autocorrelation values are practically the same in the chronologies developed by the CORRIDOR and INDEX methods. These statistics are lower for three of the ARSTAN chronologies and higher for one chronology. These differences probably reflect the fact that ARSTAN removes the autocorrelation as it prewhitens the individual tree data, averages the prewhitened data and then adds the average autocorrelation for the trees to obtain the ARSTAN chronology while the other two methods ignore the autocorrelation.

The correlations between the developed chronologies are very high (from 0.917 to 0.981) (Table 3). This indicates that the tree-ring chronologies developed by the three standardization methods are very similar. The differences between the correlations of the CORRIDOR

Table 3. Correlation coefficient values between the tree-ring chronologies developed by various standardization methods

Province	Polar Urals		Subpolar Urals		North Urals		South Urals	
Series Code	S01		S08		S11		S29	
Standardization Method	INDEX	ARSTAN	INDEX	ARSTAN	INDEX	ARSTAN	INDEX	ARSTAN
CORRIDOR	0.960	0.965	0.950	0.937	0.955	0.932	0.917	0.928
INDEX	-	0.951	-	0.966	-	0.965	-	0.981

chronologies with the other two methods decrease slightly in the direction from the Polar to South Urals. However, the correlations between the INDEX and ARSTAN chronologies increase in this direction. A visual comparison of the index plots also shows the high degree of similarity between all chronologies.

The power spectra of the twelve mean chronologies are plotted in Figures 1-4. Each spectrum was computed from 100 lags of the autocorrelation function. The spectral estimates at each wavelength are expressed as percent total variance, and as a continuous distribution of wavelengths throughout the entire spectrum. The spectrum estimates can show the degree of similarity in variance of chronologies at different wavelengths.

The spectra of the Polar Urals chronologies (S01) are almost identical at all frequencies. The INDEX chronology has slightly more variance at the lowest frequencies and the ARSTAN chronology has slightly more variance around 0.05 cycles per year.

The spectra of the Subpolar Urals chronology (S08) show more differences, although they are very similar especially for the INDEX and CORRIDOR chronologies. The ARSTAN method appears to have removed more variance at very low frequencies.

The spectra of the North Urals chronologies (Fig. 3) are also similar with some variations at low frequencies. Somewhat different peaks are significant and the CORRIDOR chronology has the highest variance of the three at 0.005 cycles per year. Fig. 4 for the South Urals shows the same significant peaks, but as noted in Fig. 3, the CORRIDOR chronology had the most variance at the very lowest frequencies.

The three standardizing methods produce chronologies with very similar spectra. Differences can be noted only at frequencies of 0.05 cycles per year or less. Sometimes the CORRIDOR method preserves somewhat more low-frequency variation, but the differences may not be large enough to be significant. This difference seemed to be more apparent in the chronologies that contained a weak climatic signal (S29).

The coherence spectra estimate the similarities in variance of two chronologies expressed as the percent agreement (coherence square) at different frequencies (Figs. 5-8). All spectra confirm the high agreement among the chronologies at all frequencies. Most of the estimates exceed the 95% significance level (coherency = 0.93). Occasionally, some estimates at higher frequencies were markedly low and insignificant (Figs. 5-7) due to chance or to a small percent variance in the estimate at that particular frequency (Fig. 1-3).

As was noted for the power spectra, the greatest differences were at the lowest frequencies. The coherence at low frequencies for the Polar Urals is highest for the CORRIDOR-ARSTAN comparison (Fig. 5); it is not so high for the other three areas, but the lack of agreement is often at frequencies with little variance (Figs. 2-4). The phase angle plots for all series indicated that there is no evidence of any lag problems with these data.

We conclude that the tree-ring chronologies developed by the CORRIDOR method and the INDEX and ARSTAN programs are very similar and statistically indistinguishable. Any of the three methods can be used and the results compared to the others without restandardizing. If it is necessary to preserve the very lowest frequencies, the CORRIDOR method may be superior. The ARSTAN method may be the most practical method to use because it can be altered to remove the variance at different frequencies.

However, the ARSTAN program is rather complex and it should be used with care as the available options allow one to alter the frequency distribution markedly. The INDEX program is less flexible, simpler to operate, and tends to have more variance at low frequencies than the ARSTAN program. This may arise from the fact that the exponential function estimated by the INDEX program is better fit to the early portions of the chronology with the most ring-width variability than to the late portions. This creates more error variance and low-frequency trends in the outer part of the chronology. This low-frequency error can be reduced to some extent by the double detrending option of ARSTAN (Holmes et al., 1986). A follow-up study of this phenomenon has been conducted by Fritts and Holmes but this will be the topic of another paper.

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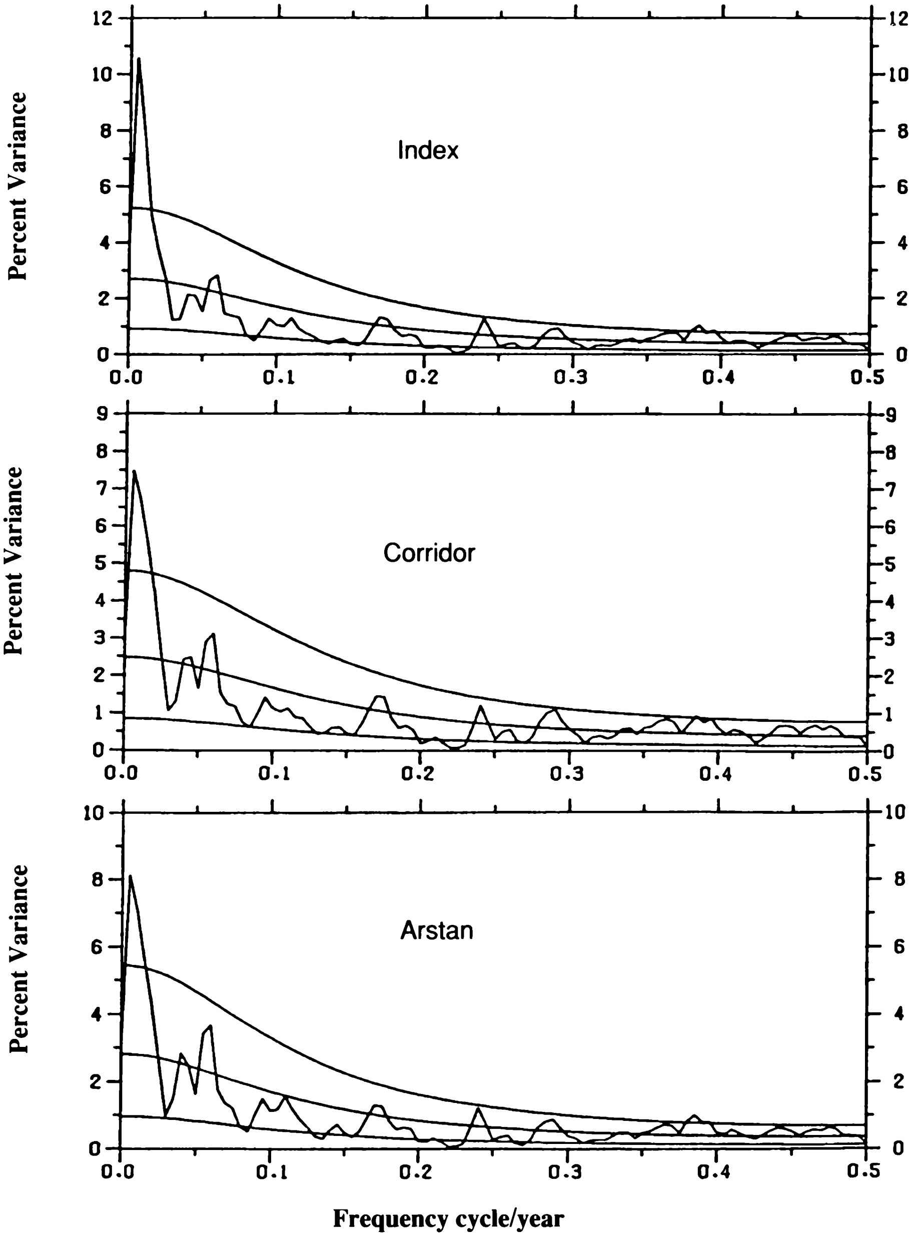

Figure 1. Polar Urals Chronology S01 Comparison of Percent Variance, Period: 1550 to 1968 with 100 Lags

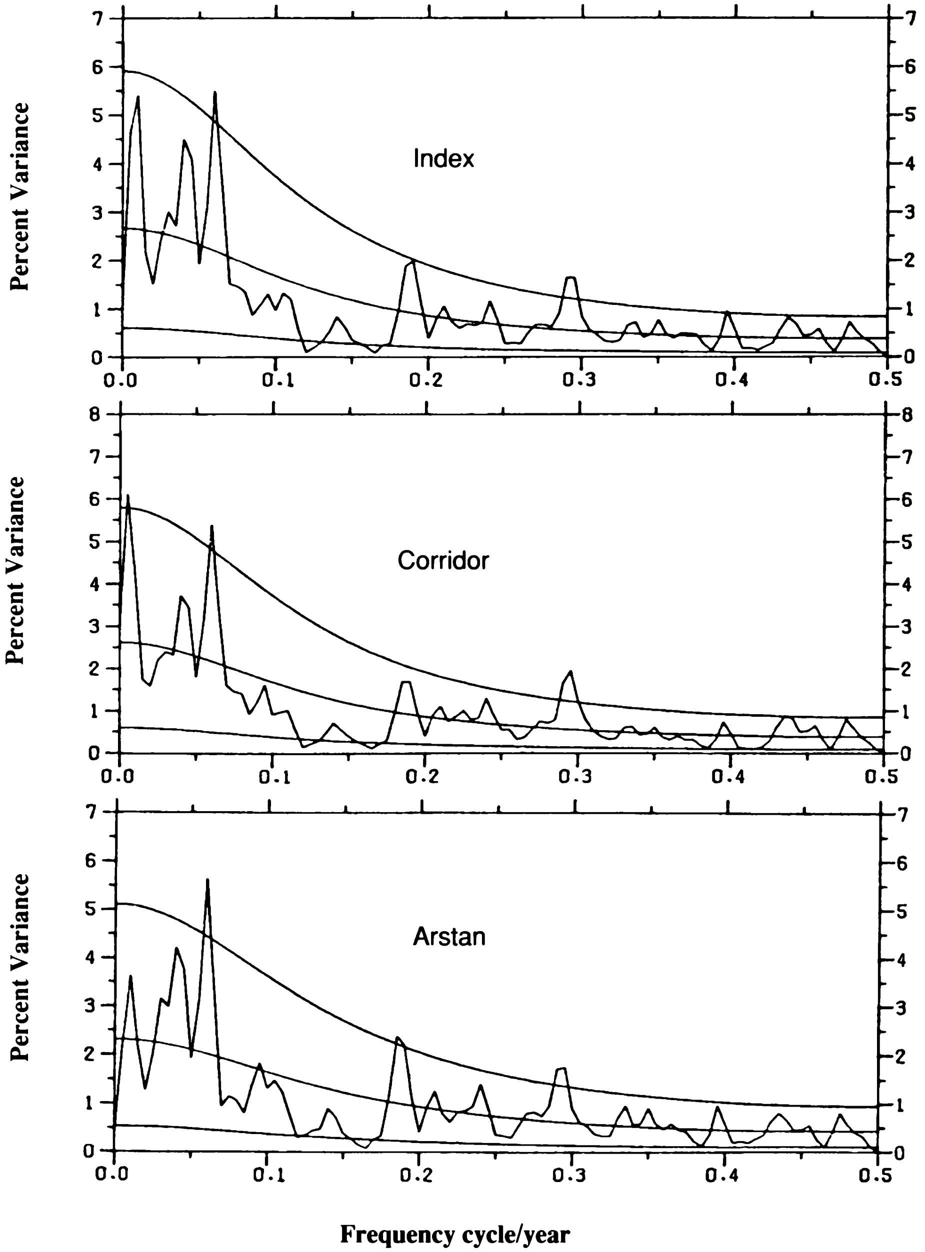

Figure 2. Subpolar Urals Chronology S08, Comparison of Percent Variance, Period: 1691 to 1968 with 100 Lags

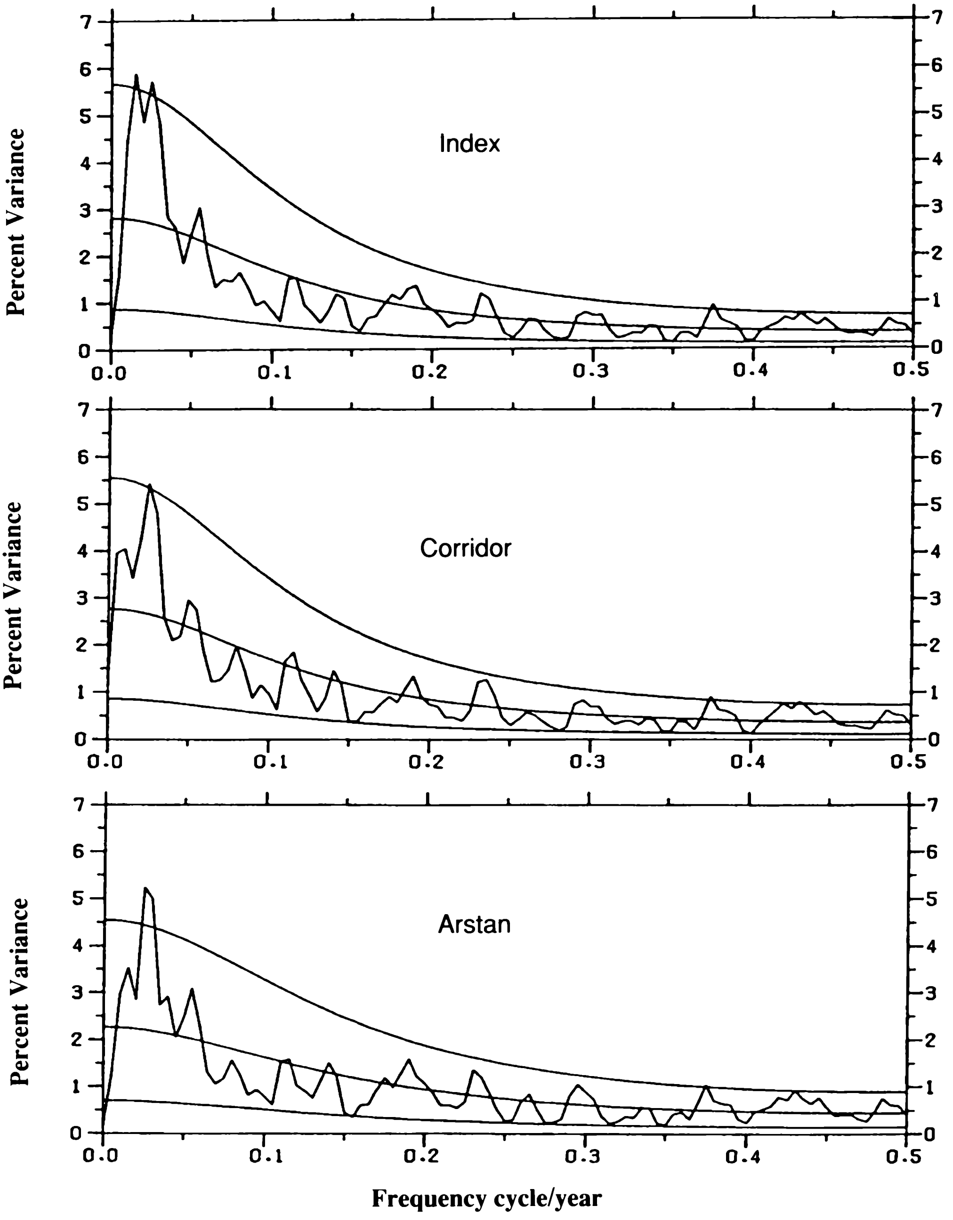

Figure 3. North Urals Chronology S11, Comparison of Percent Variance, Period: 1590 to 1969 with 100 Lags

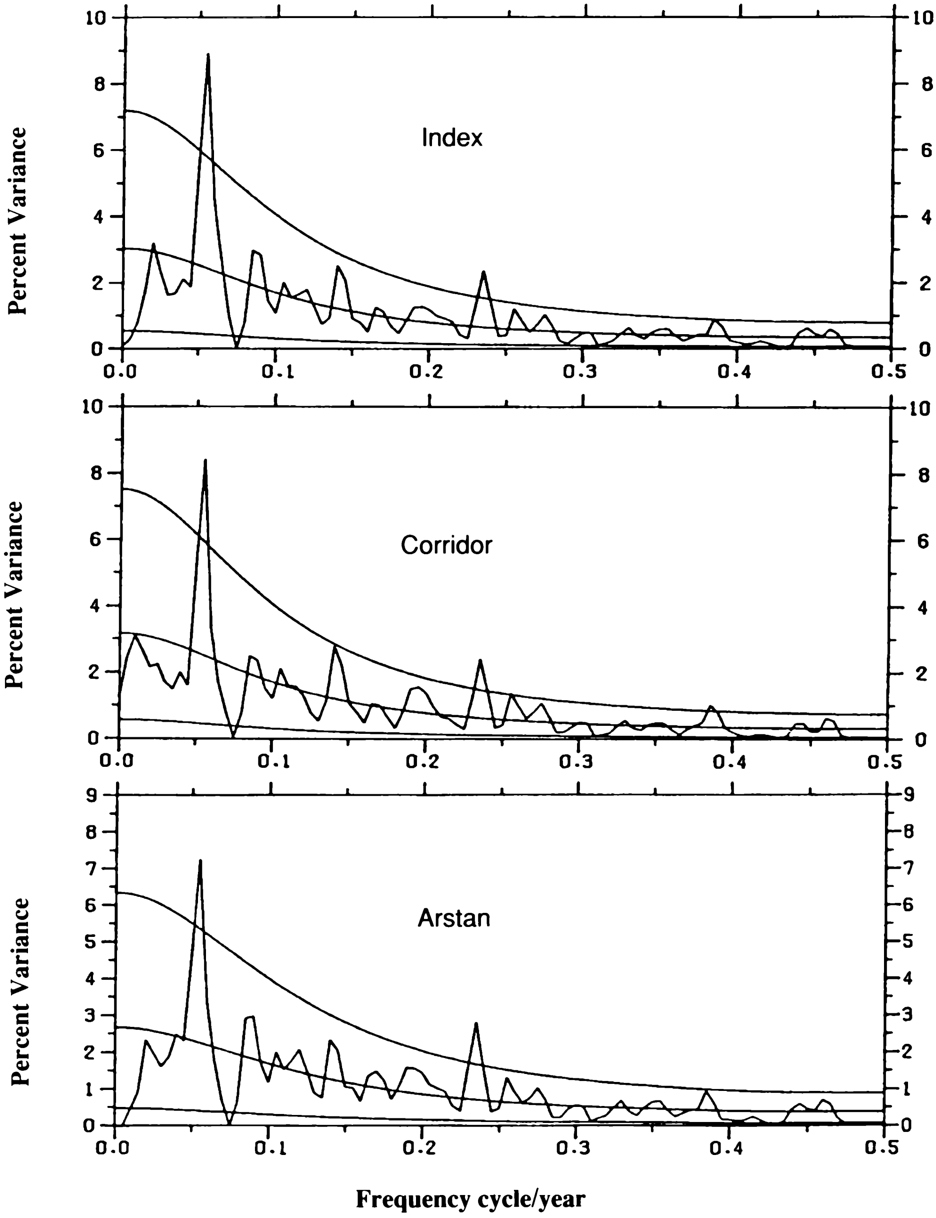

Figure 4. South Urals Chronology S29, Comparison of Percent Variance, Period: 1770 to 1972 with 100 Lags

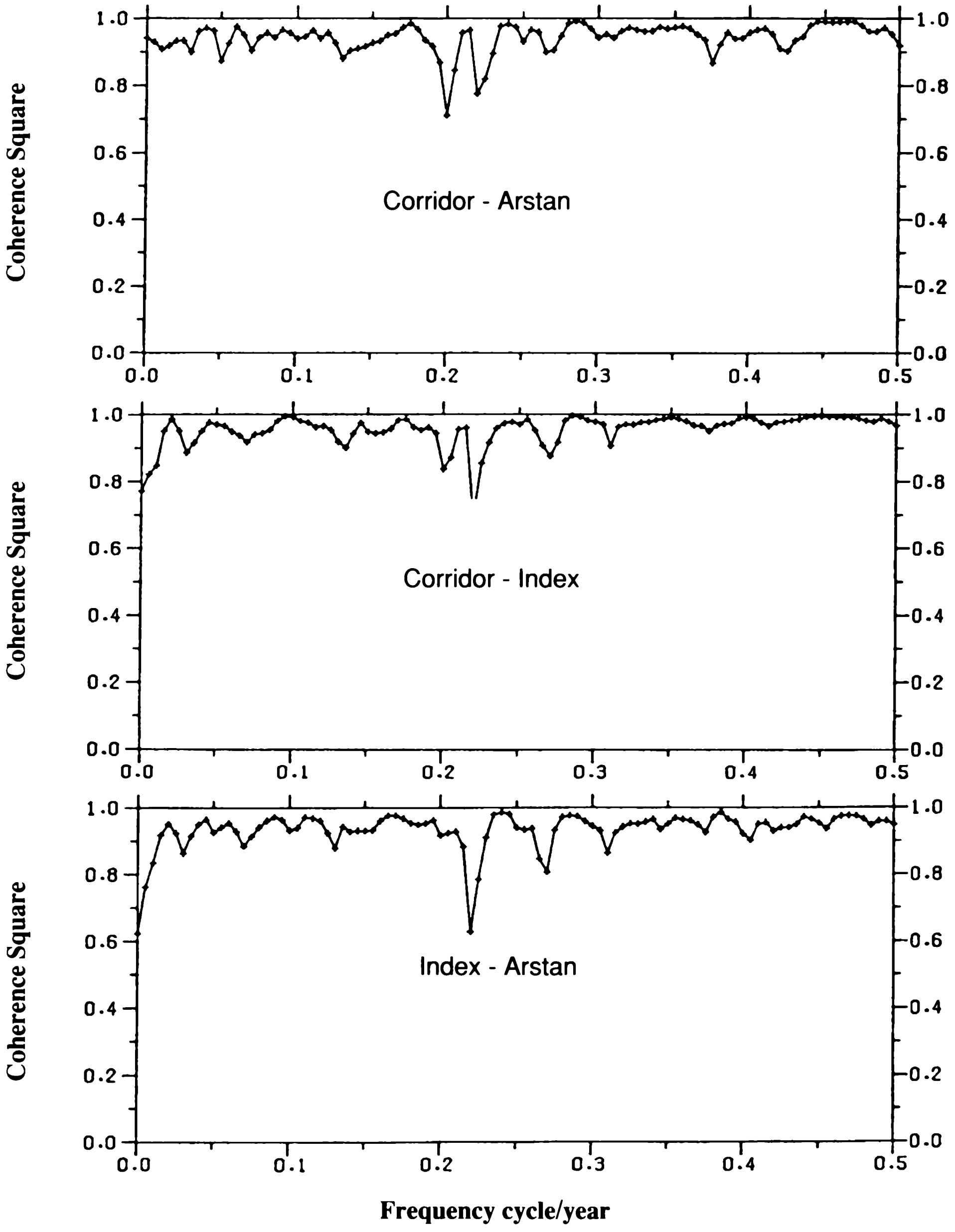

Figure 5. Polar Urals Chronology S01, Comparison of Coherence Square, Period: 1550 to 1968 with 100 Lags

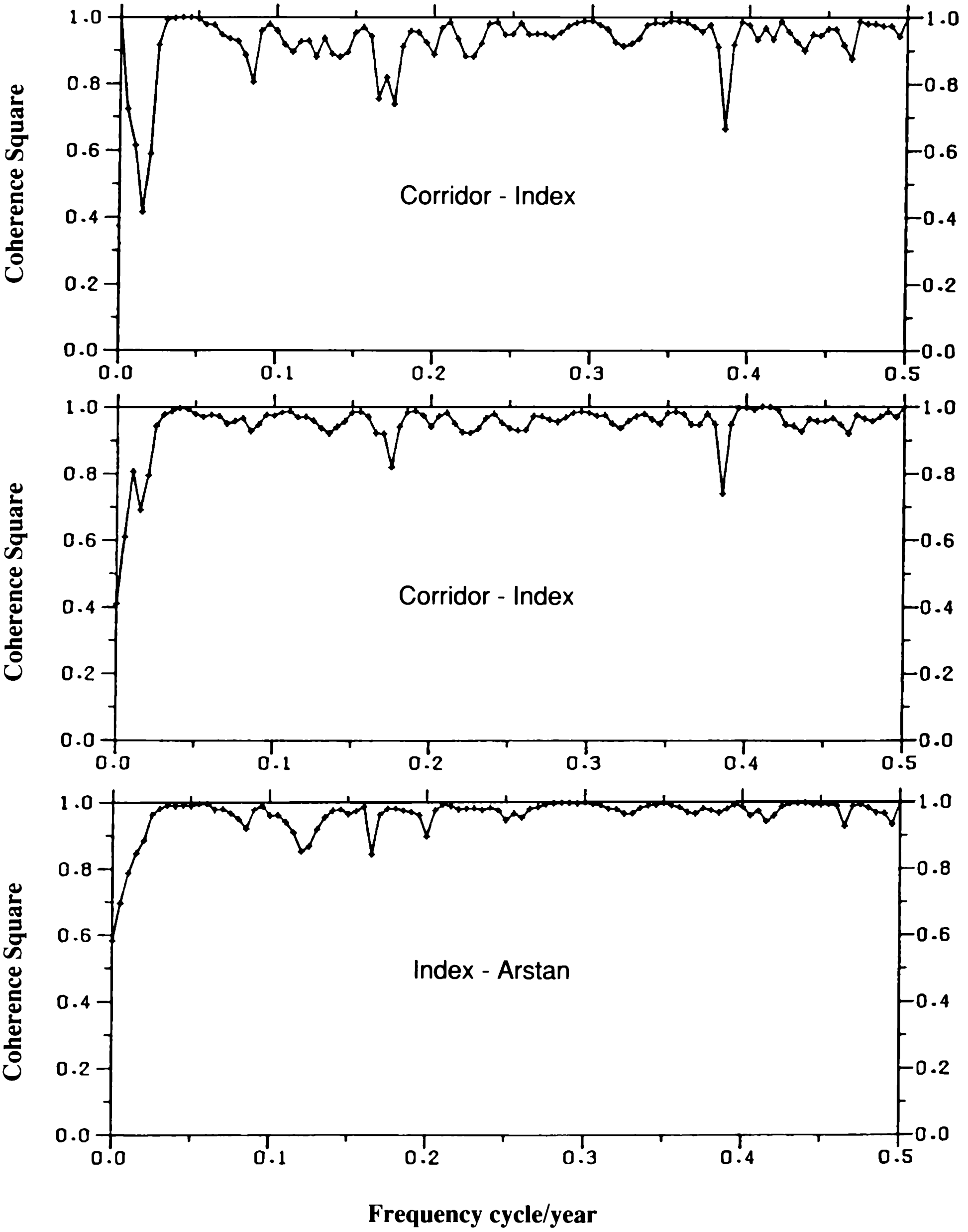

Figure 6. Subpolar Urals Chronology S08, Comparison of Coherence Square, Period: 1691 to 1968 with 100 Lags

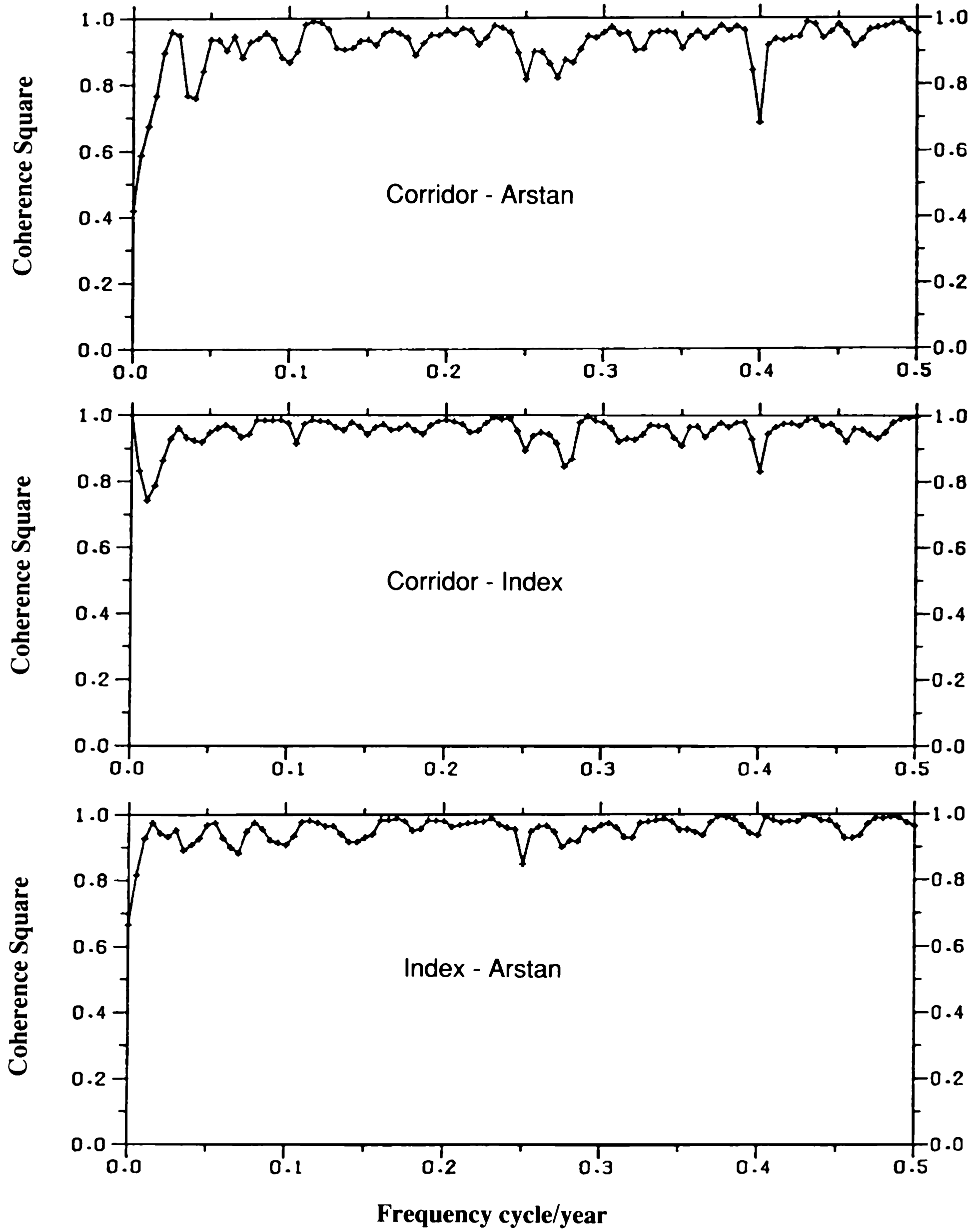

Figure 7. North Urals Chronology S11, Comparison of Coherence Square, Period: 1590 to 1969 with 100 Lags

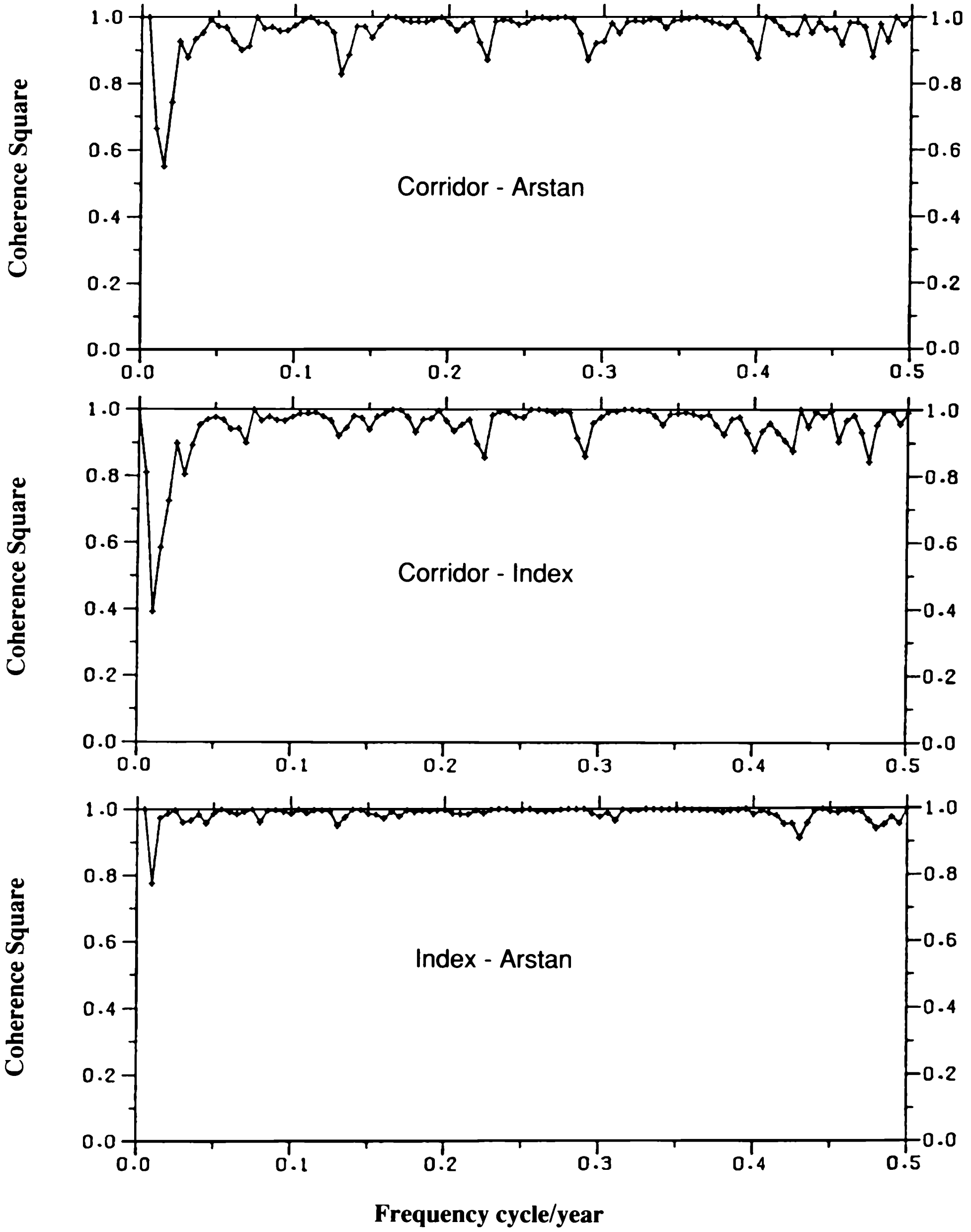

Figure 8. South Urals Chronology S29, Comparison of Coherence Square, Period: 1770 to 1972 with 100 Lags