METHODS OF DENDROCHRONOLOGY — I

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4.2 SOME NEW APPROACHES IN THE CONSTRUCTION OF MORE RELIABLE DENDROCHRONOLOGICAL SERIES AND IN THE ANALYSIS OF CYCLE COMPONENTS

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1. INTRODUCTION

Several methods have been developed in the Institute of Plant and Animal Ecology (Ural Science Center, Academy of Sciences of the USSR, Sverdlovsk) to obtain more reliable dendroclimatological series. Much attention is being given to the analysis cyclic components in them. The most important approaches are presented.

2. TREE-RING STANDARDIZATION USING THE "CORRIDOR" METHOD

Estimating the percentage of ring width deviations from the biological growth function is the most popular method for tree-ring standardization. A variety of standardization procedures are determined by the difference in the construction of growth curves. These can be obtained either by graphically or by mathematically (estimation of exponential, polynomial and other function parameters, smoothing by moving averages). As a rule, this method involves elimination of prolonged fluctuations, series shortage, unadequate estimation of the growth curve, thus reducing the accuracy of paleoecological reconstructions.

Numerous plots of annual ring widths of trees growing at the climatic range limit (upper and polar forest boundaries) show that age-specific increment trend may be more accurately evaluated if judged from maximal and minimal possible increment curves rather than from the average increment dynamics standard. To obtain such curves, one should join extreme increment values, as Fig. 1 shows. The absolute increment minimum, i.e., the missing ring, is distinctly displayed in the minimal curve. In case the widths of the narrowest rings do not exceed 0.2-0.3 mm and the probability of the missing ring is large, the minimal curve practically merges with the X-axis. Curves of maximal and minimal possible increment have been plotted subject to the following condition: they must not be wavy and must run in the same direction.

Curves of maximal and minimal possible increment generate a corridor of points illustrating annual increment fluctuations. The width of the corridor varies regularly with the age of the tree, reaching its maximum during the period of the most intensive growth. The corridor thus displays a range of increments

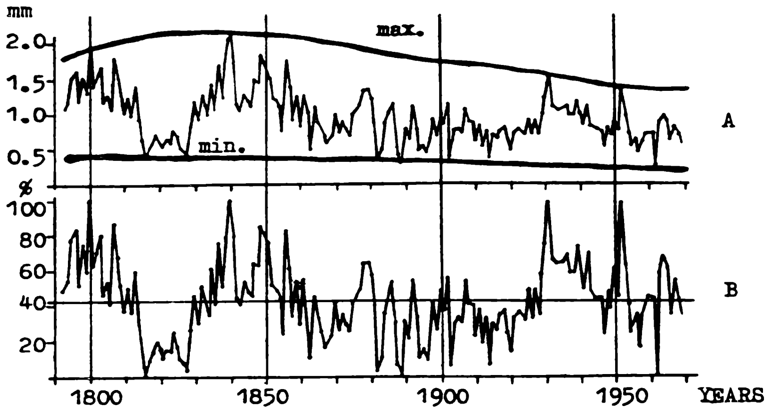

FIGURE 1 Curves of maximal and minimal increment, plotted for computing indices by the "corridor" method. A - tree-ring widths, B - tree-ring indices.

in response to environmental fluctuations in different spans of life of the tree.

In calculations of increment indices for each particular year, the width of the corridor is taken as 100% (200%), the values of the indices are computed from the formula:

$$I_t = (x_t - a_t)/(b_t - a_t)\cdot 100(200) , \quad t = \overline{1, n} \qquad (1)$$

where I_t is the increment index for the year t, x_t is the tree-ring width, a_t, b_t are the minimal and maximal possible increments accordingly for the year t (Shiyatov, 1972; 1986).

An advantage of the corridor method is its simplicity. It permits revealing long-term fluctuations, the series length remaining the same. However, a more careful technique of rings of tension and compression wood is required. Besides, a subjective factor appears. The effect of the latter can be minimized if a sufficient number of trees is used in the analysis.

In what follows we propose formulation of the problem of tree-ring standardization.

Definition. Suppose we have a time series x_t, $t = \overline{1, n}$ of absolute increment values. Suppose a_t and b_t are discrete values of continuous functions of the set of "biological growth curves" defined in the same line segment. Consider also that the values of a_t do not exceed those of x_t and the values of b_t are not less than corresponding values of x_t.

We term the discrete values of a(t) and b(t) functions the minimal and maximal possible increments, respectively, provided the area between the curves of these functions is minimal and the function humps are reached at the same t value.

The following function of the set of biological growth curves is chosen:

$$G(t) = c_1 \cdot (t + c_2)^{c_3} \cdot \exp(c_4 \cdot (t + c_2)) + c_5 \qquad (2)$$

<u>Problem statement</u>: find the minimum value of

$$\sum_{t=1}^{n} (b(t) - a(t))$$

constrained by (3)

$$b_t - x_t \geqslant 0, \quad x_t - a_t \geqslant 0 \quad \text{for all t values.}$$

3. METHOD OF COMPUTING TREE-RING INDICES FOR SEPARATE CALENDAR YEARS IN OBTAINING MEAN AND GENERALIZED SERIES

It has been established methodically that the indices of a generalized tree-ring series should be estimated by the arithmetic mean indices of the growth of individual crossdated trees for each calendar year. To this end one has to be sure that the index distribution in each year is normal or, at least, unimodal and symmetric. Analysis of histograms has shown that this condition is not always fulfilled. Consequently, the selection of the mean as a measure characterizing the growing conditions in each year should be based on index distribution at the relevant dates.

By convention, two types of distributions were distinguished from analysis of over 300 histograms: unimodal (single peak) and polymodal (multiple peaks). In our view, the differences in distribution patterns of the same model trees in different calendar years result from the sensitivity of limiting factors. As a rule, during unfavorable years (cold summer, water shortage) the indices on the histogram were closely grouped about a small value and were almost normally distributed, while, in contrast, the range of indices was rather large during years favorable for growth. In the latter case, their distribution may be both unimodal and polymodal. In practice, a strong emphasis is being placed on bimodal ones, because the estimation of parameters with more components in the mixture of distributions on amount of sampling 30-50 model trees would not be strict enough.

The existence of bimodal distributions in a particular year may be attributed to the fact that part of the model trees were influenced by specific limiting factors which enhanced the decrease in their annual increment compared to other models. The increment in the latter is limited mostly

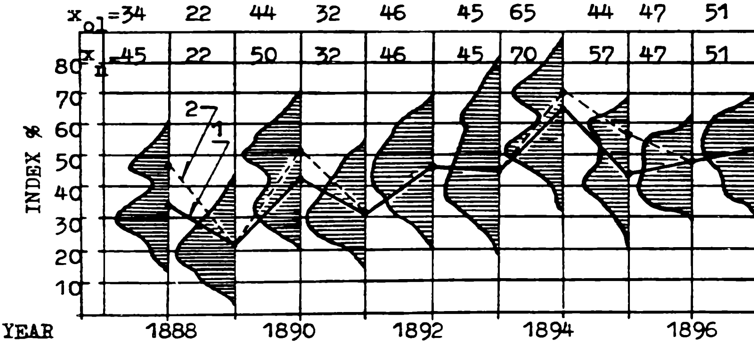

FIGURE 2 Illustration of the proposed method for computing values of generalized tree-ring series (x_{ol} is the old value, x_n is the new value). 1) series segment (1888–1897) computed using typical method; 2) series segment computed using proposed method.

by climatic factors. Partial factors such as fruit bearing, pest outbreaks, fungal colonization, etc., will act selectively.

Based on these theses, a new procedure of computing values of a generalized series was developed (Mazepa 1982). A histogram of increment indices of individual model trees is constructed for each year, and the statistical hypothesis is verified as to its membership in the class of normal distributions. If the hypothesis is not rejected, the mean is a measure of relative wood growth. An alternative hypothesis should be that indices of individual models for a given year form a mixture of two or more normal distributions. Then it is necessary to compute the mean value of the maximal grouping and to use it as an estimate of the index of the generalized dendroclimatological series. Thus, the effect of specific constraints is disregarded and the role of general climatic factors is revealed.

As a formal model of the increment index distribution for each year the following model of a mixture of fixed number normal distributions was adopted:

$$F(x) = \sum_{j=1}^{k} \alpha_j \cdot F_j(x) , \quad 0 \leqslant \alpha_j \leqslant 1 , \ \sum_{j=1}^{k} \alpha_j = 1, \qquad (4)$$

where $F_j(x) \sim N(\mu_j, \sigma_j)$, k is known, $\mu_j, \sigma_j, \alpha_j$ are unknown. The task is to estimate the parameters $\mu_j, \sigma_j, \alpha_j$ from the sample $\{x_i\}$, $i = \overline{1, n}$. There is a good review on the methods for estimating the parameters (Holgersson, Jorner 1978).

Figure 2 illustrates the proposed method for computing the values of a generalized series of Larix sibirica that

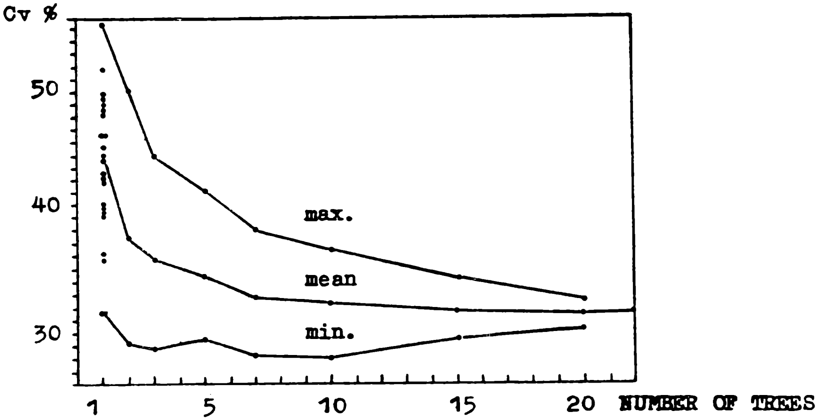

FIGURE 3 The variation coefficients of tree-ring chronologies obtained from different number of trees.

grows within the West-Siberian forest-tundra. The correlation coefficient between generalized series whose indices are computed by the method proposed, and a series of July temperatures (for 89 years) proved to be considerably higher than in the case of using the typical method. The coefficients changed from 0.49-0.59 to 0.65-0.75. We consider, therefore, that improved series reflect temperature fluctuations better.

Analysis of increment index histograms for each year may be used to reconstruct partial limiting factors such as fruit bearing, tree defoliation by insects and fires, etc.

We are aware that further development of the proposed method is necessary. In particular, one should take into account the effects of increments for preceeding years on the increment of a current year.

4. ELIMINATION OF DISPERSION HETEROGENEITY IN THE SEGMENTS OF DENDROCHRONOLOGICAL SERIES SUPPLIED WITH INSUFFICIENT AND UNEQUAL NUMBER OF MODEL TREES

To obtain the mean chronology, model trees of different age are commonly used. Therefore, different time segments are often supplied with an unequal number of model trees. Averaging gives dispersion heterogeneity in the series, which so far has practically been neglected. Almost all dendrochronological series obtained to date have this disadvantage.

Analysis of the mean chronology shows that when the number of sampling decreases, the increment indices become more variable in the corresponding time segment. Figure 3 shows changes in the variation coefficient of the increment indices against the number of the models used. The 22 model trees of *Larix sibirica* from 170 to 290 years old were used to construct the

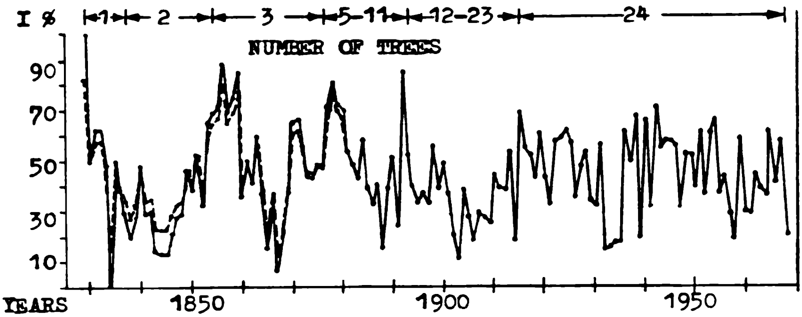

FIGURE 4 Mean chronology with series segments obtained from a different number of trees (from 1 to 24). Solid line stands for the indices averaged for each year to obtain chronology, dotted line for improved ones.

plot. The figure gives the mean, maximal and minimal variation coefficient values, obtained by exhaustive search of these models. These variation changes are most significant on the left hand side of the plot, when the number of models was not great (1-10 sp.). As the amount of sampling increases, the variation coefficient diminishes and reaches a certain stable level.

Further calculations of the index variation as a function of the number of models used were carried out on constructing more than 100 mean chronologies of Larix sibirica, Picea obovata, Pinus sibirica that grow at the upper and polar forest boundaries. In most of the series, significant changes in the variation coefficients are observed only when less than 7-10 models used. Poorly supplied series segments have an index variation of 20-35% over the standard. Heterogeneity is a significant limitation of many dendrochronology series published. A wrong conclusion may be drawn if one disregards this especially if one reconstructs climatic conditions and finds similarity measures between the series. Heterogeneity may be overcome by excluding those series segments for which the number of models is inadequate. As a rule, the most ancient and valuable series segments, which contain less accurate but very important information about the ecological changes in the past, are sacrificed. Therefore, this method is not always acceptable. A new method, aimed at avoiding heterogeneity in tree-ring series through corrections in increment indices, has been proposed (Shiyatov 1980).

The method consists in reducting those series segments which are insufficiently supplied with model trees to a level of variability that is typical of well-supplied segments (over 10 sp., as a rule). To introduce corrections, the following procedures are carried out. The dependence of the increment index variation coefficient on the number of model trees used is determined for each series. The mean value of the variation coefficient, obtained for the series segment supplied with over 10-12 model trees, is taken as a standard. Thereupon the increment indices for the time segments, provided with few models, are multiplied by the coefficient of contraction which is equal to the ratio of the standard variation coefficient to the variation coefficient, typical of the above-mentioned time segments. The computational formula is:

$$I_t^{cor} = (I_t^{ol} - I)\cdot k + I \,, \qquad t = \overline{t_i, t_j} \qquad (5)$$

where I_t^{cor} is the corrected value of the increment index, I_t^{ol} is the old value of the increment index, I is the average value of the increment indices for the series, k is the coefficient of contraction.

Figure 4 shows actual (solid line) and corrected (dashed line) increment indices for Picea obovata from the lower Pechora river. The increment indices for this series are calculated graphically by the corridor method.

5. SPECTRAL APPROACH TO INVESTIGATE THE CYCLIC DYNAMICS

Dendrochronologists are aware of the fundamental possibility to split tree-ring series into cyclic components. Thus, these series are often represented as a trend plus cycles plus random error. However, the terms used are not well-defined. Widely spread methods of smoothing do not permit statistically admissible terms to be worked out.

Our approach to the analysis of the cyclic components in increment dynamics is based on a spectral presentation of random stationary process. One of the main practical results of the spectral theory is the following: any jump of the spectral function is interpreted as an increased contribution of the corresponding frequency band to the total variation of the series. Most practical problems are solved when neither the type of spectral function, nor the class of parametric model is known a priori. Therefore, estimates of the spectral function are used. Estimates may be good or bad in the sense of their proximity to the estimated function of the process, statistical properties of this estimate, ease of calculation, etc. But that falls into the line of practical spectral analysis (Kay, Marple 1981). Two methods of spectral density estimation were used in computer experiments: the Blackman-Tukey method and the maximum entropy method. The results were as follows:

the spectra of ring-width indices for individual trees growing in homogeneous ecological and extreme abiotic conditions of the same climatic region are similar. The spectra calculated from time series segments of 200-1010 years do not change significantly within the period of 300 to 500 years (Fig. 5);

spectral analysis shows the existence of important narrow frequency bands with fluctuation amplitudes much higher than those of the neighbouring ones. Their widths are about 0.02-0.05 cycles a year.

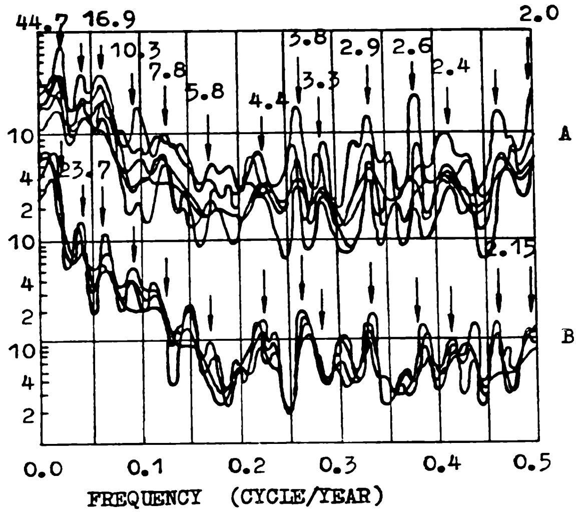

FIGURE 5 The maximum entropy power spectrum of the single tree-ring series coming into use for generalized series. A - spectra for the series within the period XVII-XX cc; B - spectra for the series within the period XII-XVII cc.

When important for the majority of the tree-ring chronologies in the area investigated, these frequency bands may be used as characteristics in studies of wood increment dynamics. Thus, by a cycle we mean a tree-ring series component which corresponds to a certain important narrow frequency band.

This concept is methodically convenient. Purposeful narrow band-pass filtration with a prescribed transfer function becomes possible. When extracted, the important frequency bands can be analysed by choosing a corresponding filter. In our work we used a filter with coefficients that are truncated Fourier series coefficients of the Π-shaped function. Good results are obtained with optimum (in the minimax sense) finit impulse response linear phase digital filters: in designing such filters, the Chebyshev approximation problem is used (McClellan, Parks 1973). Using this filter, an explorer may control the magnitude and position of unwanted fluctuations in the transfer function. This enables one to extract a certain frequency band by means of a filter of a given length with minimal risk of contaminating the outgoing series by spectral components that belong to some other frequency bands.

WEST-SIBERIAN FOREST-TUNDRA

$N = 14$; $r = 0.56$; $K_s = 68\%$; $S = 29\%$

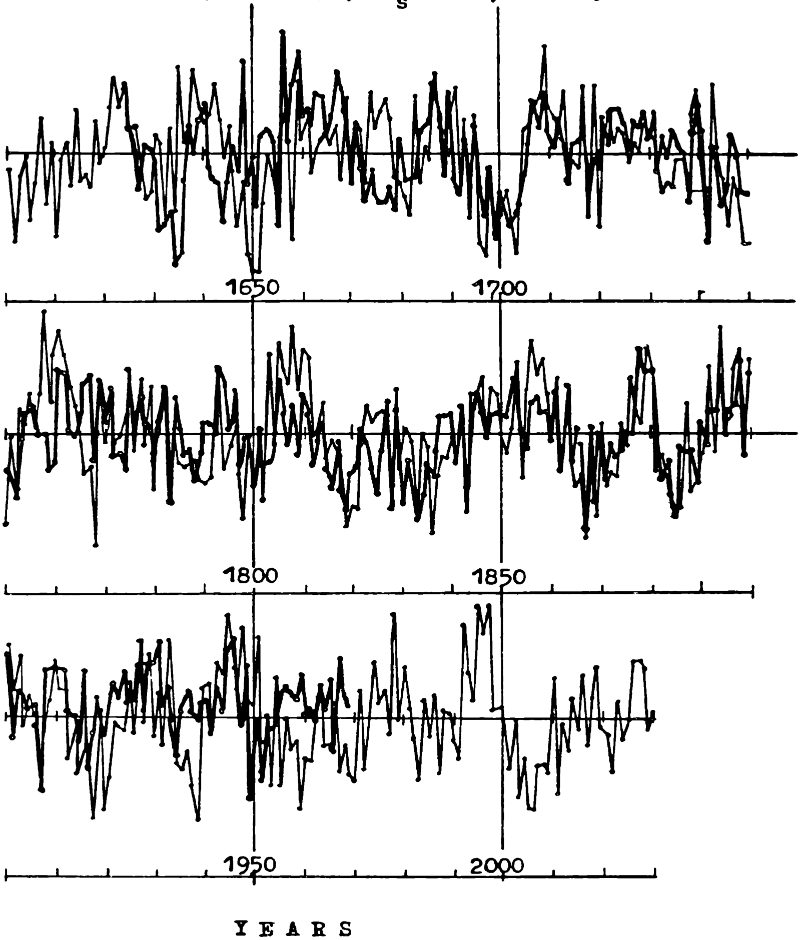

FIGURE 6 Tree-ring chronology (thick line), its approximation and extrapolation by sinusoids (thin line). N is the number of sinusoids in the approximation, r the correlation coefficient, K_s synchronization coefficient, S the mean-root-square error.

6. APPROXIMATION AND EXTRAPOLATION OF A TREE-RING CHRONOLOGY BY A SUM OF SINUSOIDS WITH UNDIVISIBLE FREQUENCIES

One of the practical purposes of analysing the cyclic components in tree-ring series is the forecast the woody plants increment dynamics due to climate.

Our experience of computer experiments has shown that, if one employs a reasonably narrow band-pass filtration of tree-ring series, the outgoing series may be quite accurately approximated by a sinusoid with a frequency belonging to a spectral band over many periods. It stands to reason that outgoing series will not be strictly periodic even if the band is very narrow. Sinusoids approximating such components are to have different amplitudes and phases in various time segments. However, the changes in them, in particular phases ones, are quite slow to succesfully approximate the filtered component by a sinusoid.

Based on this, we used narrow band-pass filtration aiming at extraction of only those frequency bands which give increased spectral density estimates. The extracted components were then approximated by a sinusoid and the forecasting series of increment due to climate was represented as a sum of sinusoids.

Amplitudes and phases were estimated by the least squares method. Frequencies were evaluated by exhaustive-search in the extracted bands.

The approximation is specified by several quantities: correlation coefficient, synchronization coefficient and mean-root-square error of approximation. Correlation coefficient between the original and approximated series was 0.5-0.8, synchronization was 65-75%, the mean-root-square error was not more than 20-30%.

Figure 7 gives an example of approximating and extrapolating the mean tree-ring chronology, obtained for *Larix sibirica* growing in West-Siberia forest-tundra.

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Stepan G. Shiyatov, Valeriy S. Mazepa

1. INTRODUCTION

Several methods have been developed in the Institute of Plant and Animal Ecology (Ural Science Center, Academy of Sciences of the USSR, Sverdlovsk) to obtain more reliable dendroclimatological series. Much attention is being given to the analysis cyclic components in them. The most important approaches are presented.

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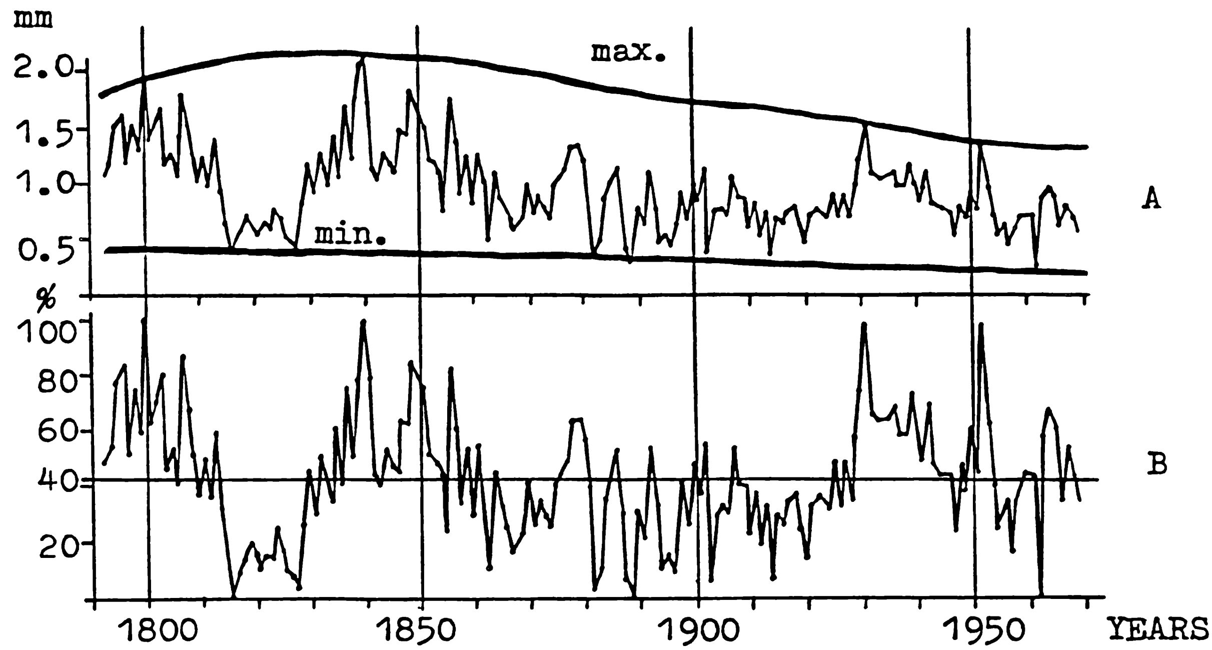

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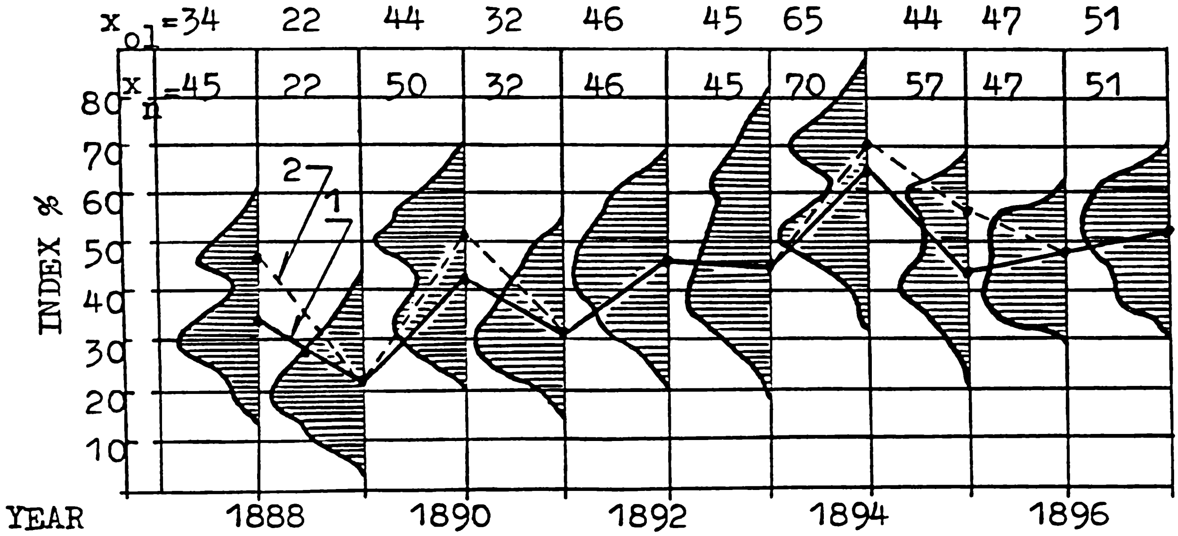

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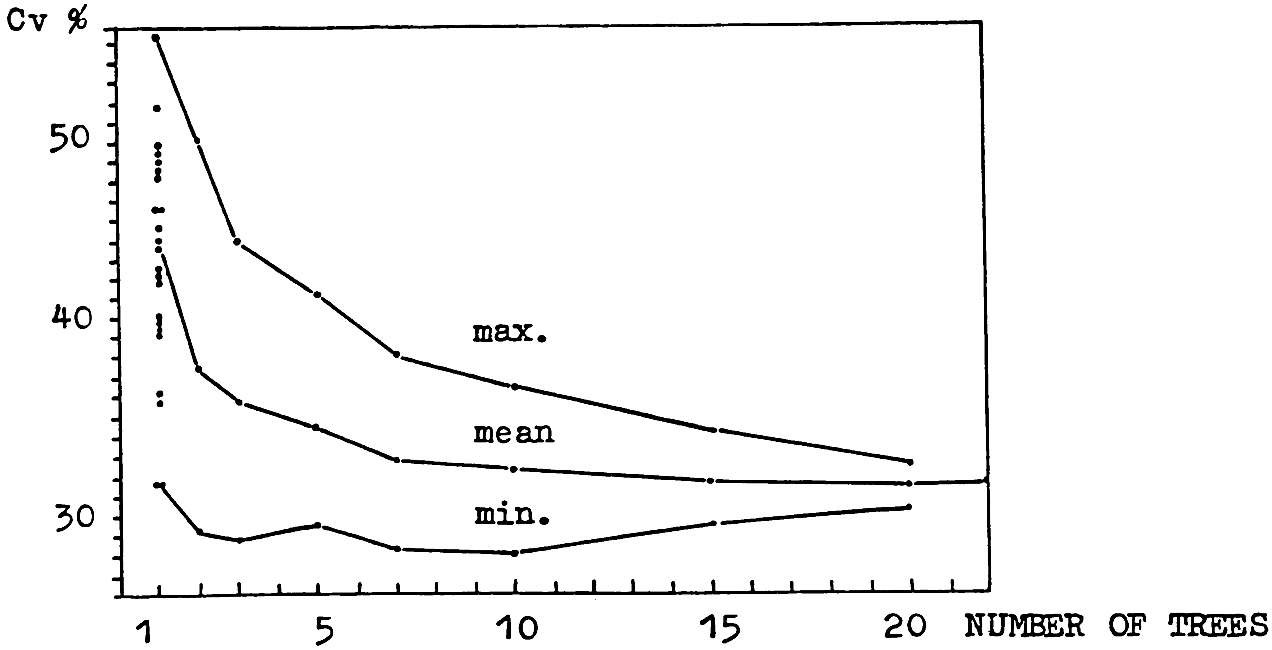

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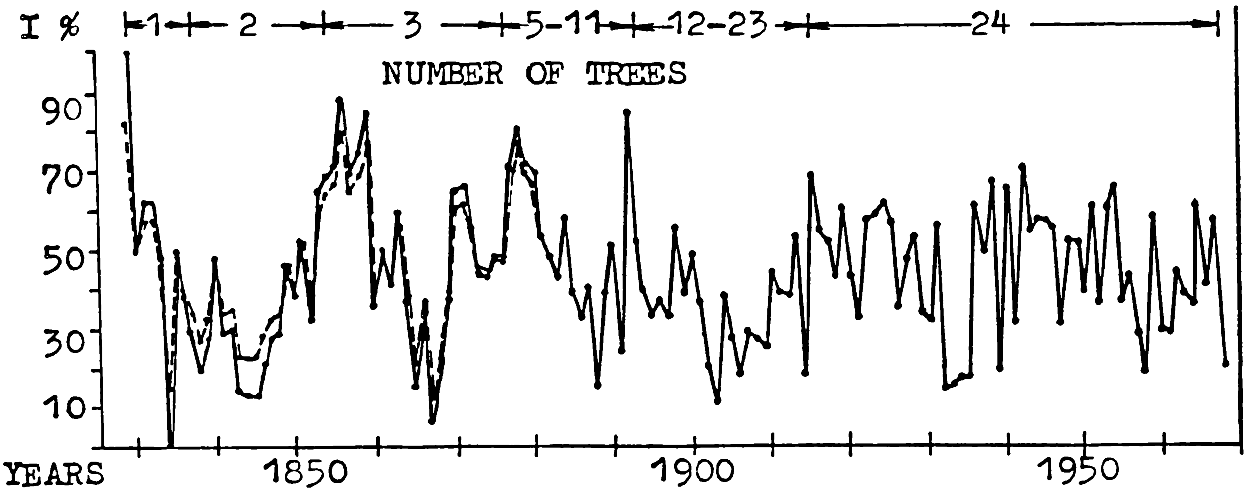


FIGURE 4 Mean chronology with series segments obtained from a different number of trees (from 1 to 24). Solid line stands for the indices averaged for each year to obtain chronology, dotted line for improved ones.

plot. The figure gives the mean, maximal and minimal variation coefficient values, obtained by exhaustive search of these models. These variation changes are most significant on the left hand side of the plot, when the number of models was not great (1-10 sp.). As the amount of sampling increases, the variation coefficient diminishes and reaches a certain stable level.

Further calculations of the index variation as a function of the number of models used were carried out on constructing more than 100 mean chronologies of Larix sibirica, Picea obovata, Pinus sibirica that grow at the upper and polar forest boundaries. In most of the series, significant changes in the variation coefficients are observed only when less than 7-10 models used. Poorly supplied series segments have an index variation of 20-35% over the standard. Heterogeneity is a significant limitation of many dendrochronology series published. A wrong conclusion may be drawn if one disregards this especially if one reconstructs climatic conditions and finds similarity measures between the series. Heterogeneity may be overcome by excluding those series segments for which the number of models is inadequate. As a rule, the most ancient and valuable series segments, which contain less accurate but very important information about the ecological changes in the past, are sacrificed. Therefore, this method is not always acceptable. A new method, aimed at avoiding heterogeneity in tree-ring series through corrections in increment indices, has been proposed (Shiyatov 1980).

The method consists in reducting those series segments which are insufficiently supplied with model trees to a level of variability that is typical of well-supplied segments (over 10 sp., as a rule). To introduce corrections, the following procedures are carried out. The dependence of the increment index variation coefficient on the number of model trees used is determined for each series. The mean value of the variation coefficient, obtained for the series segment supplied with over 10-12 model trees, is taken as a standard. Thereupon the increment indices for the time segments, provided with few models, are multiplied by the coefficient of contraction which is equal to the ratio of the variation coefficient, typical of the afore-mentioned time segments, to the standard. The computational formula is

$$I_t^{cor} = (I_t^{ol} - I)\cdot k + I , \qquad t = \overline{t_i, t_j} \qquad (5)$$

where I_t^{cor} is the corrected value of the increment index, I_t^{ol} is the old value of the increment index, I is the average value of the increment indices for the series, k is the coefficient of contraction.

Figure 4 shows actual (solid line) and corrected (dashed line) increment indices for Picea obovata from the lower Pechora river. The increment indices for this series are calculated graphically by the corridor method.

5. SPECTRAL APPROACH TO INVESTIGATE THE CYCLIC DYNAMICS

Dendrochronologists are aware of the fundamental possibility to split tree-ring series into cyclic components. Thus, these series are often represented as a trend plus cycles plus random error. However, the terms used are not well-defined. Widely spread methods of smoothing do not permit statistically admissible terms to be worked out.

Our approach to the analysis of the cyclic components in increment dynamics is based on a spectral presentation of random stationary process. One of the main practical results of the spectral theory is the following: any jump of the spectral function is interpreted as an increased contribution of the corresponding frequency band to the total variation of the series. Most practical problems are solved when neither the type of spectral function, nor the class of parametric model is known a priori. Therefore, estimates of the spectral function are used. Estimates may be good or bad in the sense of their proximity to the estimated function of the process, statistical properties of this estimate, ease of calculation, etc. But that falls into the line of practical spectral analysis (Kay, Marple 1981). Two methods of spectral density estimation were used in computer experiments: the Blackman-Tukey method and the maximum entropy method. The results were as follows:

the spectra of ring-width indices for individual trees growing in homogeneous ecological and extreme abiotic conditions of the same climatic region are similar. The spectra calculated from time series segments of 200-1010 years do not change significantly within the period of 300 to 500 years (Fig. 5);

spectral analysis shows the existence of important narrow frequency bands with fluctuation amplitudes much higher than those of the neighbouring ones. Their widths are about 0.02-0.05 cycles a year.

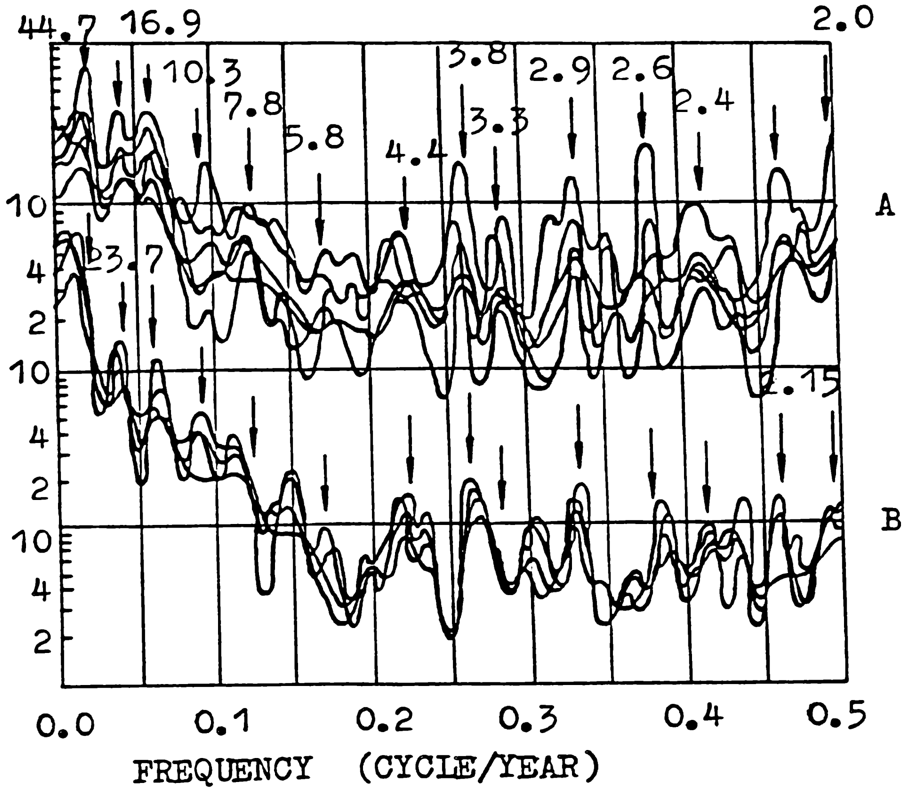


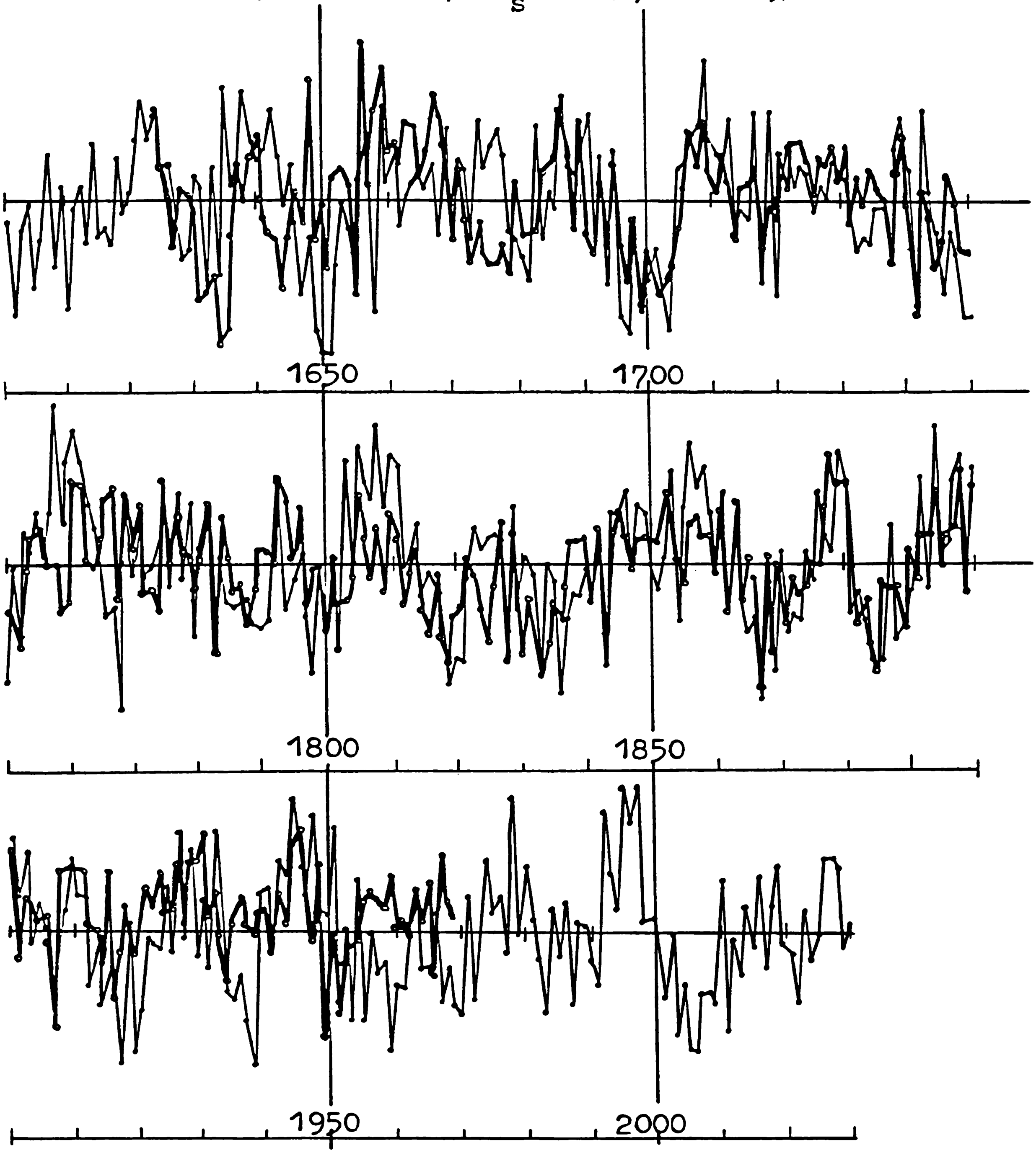
FIGURE 5 The maximum entropy power spectrum of the single tree-ring series coming into use for generalized series. A - spectra for the series within the period XVII-XX cc; B - spectra for the series within the period XII-XVII cc.

When important for the majority of the tree-ring chronologies in the area investigated, these frequency bands may be used as characteristics in studies of wood increment dynamics. Thus, by a cycle we mean a tree-ring series component which corresponds to a certain important narrow frequency band.

This concept is methodically convenient. Purposeful narrow band-pass filtration with a prescribed transfer function becomes possible. When extracted, the important frequency bands can be analysed by choosing a corresponding filter. In our work we used a filter with coefficients that are truncated Fourier series coefficients of the Π-shaped function. Good results are obtained with optimum (in the minimax sense) finit impulse response linear phase digital filters: in designing such filters, the Chebyshev approximation problem is used (McClellan, Parks 1973). Using this filter, an explorer may control the magnitude and position of unwanted fluctuations in the transfer function. This enables one to extract a certain frequency band by means of a filter of a given length with minimal risk of contaminating the outgoing series by spectral components that belong to some other frequency bands.

WEST-SIBERIAN FOREST-TUNDRA

$N = 14; \quad r = 0.56; \quad K_s = 68\%; \quad S = 29\%$



YEARS

FIGURE 6 Tree-ring chronology (thick line), its approximation and extrapolation by sinusoids (thin line). N is the number of sinusoids in the approximation, r the correlation coefficient, K_s synchronization coefficient, S the mean-root-square error.

6. APPROXIMATION AND EXTRAPOLATION OF A TREE-RING CHRONOLOGY BY A SUM OF SINUSOIDS WITH UNDIVISIBLE FREQUENCIES

One of the practical purposes of analysing the cyclic components in tree-ring series is the forecast the woody plants increment dynamics due to climate.

Our experience of computer experiments has shown that, if one employs a reasonably narrow band-pass filtration of tree-ring series, the outgoing series may be quite accurately approximated by a sinusoid with a frequency belonging to a spectral band over many periods. It stands to reason that outgoing series will not be strictly periodic even if the band is very narrow. Sinusoids approximating such components are to have different amplitudes and phases in various time segments. However, the changes in them, in particular phases ones, are quite slow to succesfully approximate the filtered component by a sinusoid.

Based on this, we used narrow band-pass filtration aiming at extraction of only those frequency bands which give increased spectral density estimates. The extracted components were then approximated by a sinusoid and the forecasting series of increment due to climate was represented as a sum of sinusoids.

Amplitudes and phases were estimated by the least squares method. Frequencies were evaluated by exhaustive-search in the extracted bands.

The approximation is specified by several quantities: correlation coefficient, synchronization coefficient and mean-root-square error of approximation. Correlation coefficient between the original and approximated series was 0.5-0.8, synchronization was 65-75%, the mean-root-square error was not more than 20-30%.

Figure 7 gives an example of approximating and extrapolating the mean tree-ring chronology, obtained for *Larix sibirica* growing in West-Siberia forest-tundra.

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