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A new parameter to evaluate temporal signal strength of tree-ring chronologies

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Abstract

In most dendroclimatological studies standardized, individual tree-ring width series from a single site are averaged to a mean chronology to enhance the common underlying signal. The strength of this signal is frequently estimated by calculating parameters based on correlation coefficients between the individual series. We here introduce a new parameter *NET* by combining the coefficient of variation *v* and the Gleichläufigkeit *G* for each single year *j* of a mean chronology:

$NET_j = v_j + (1\text{-}G_j)$

vj denotes the coefficient of variation over single series for year *j*. G_j denotes the percentage of synchronous trends between single series for each interval *j-1* to *j*, and ($1\text{-}G_j$) is therefore an annual measurement of the inverse proportion of synchronous changes (Gegenläufigkeit). Consequently, if NET_j takes on high values, the signal strength of a chronology in year *j* is low, and vice versa. NET_j can then be averaged over defined periods (NET_{period}) or over the entire length of a mean chronology (*NET*).

NET is tested with ring width data from the Alps and the Karakorum. Both data sets are standardized using negative exponential curves to preserve low frequency variation in the resulting chronologies. The fitted growth curves (negative exponential) are better adapted to the Alp data set, and *NET* shows differences in signal strength between the Alps and the Karakorum, and in particular periods of each chronology.

Keywords: dendrochronology, coefficient of variation *v*, Gleichläufigkeit *G*, signal strength parameter *NET*

Introduction

Mean chronologies generally represent an average of standardized ring width measurements from individual trees of a single sampling site. Chronologies are widely used in dendroclimatology for reconstructing climatic variability over centuries (overview in Dean et al. 1996; Schweingruber 1983, 1996; Stokes, Smiley 1968). The signal strength, or quality of these chronologies changes from sampling site to sampling site, and from period to period (Cook, Kairiukstis 1990; Fritts 1976). Chronologies from two sites located in the same valley do not necessarily have the same reconstructive skill, nor does the same chronology for the late 19th century and the early 20th century, for example (e.g., Esper 2000; Esper et al. 2000), nor even for consecutive years (e.g., Schweingruber et al. 1991).

There already exist several parameters, like RBAR and EPS statistics (Briffa, Jones 1990; Wigley et al. 1984), to quantify changing signal strength within and amongst mean chronologies. Since most parameters rest on Pearson's correlation coefficient (Briffa, Jones 1990; Cropper 1982; Graybill 1982; La Marche 1974; Wigley et al. 1984), they are affected by the statistical properties of this coefficient. For example, cross-correlation calculations are more strongly influenced by the high frequency, interannual variability of single series than their low frequency trends and changing levels and variance. This is of importance when low frequency variation is emphasized in mean chronologies (Cook et al. 1995; Cook, Peters 1997). In this case the variability amongst the individual, to be

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averaged series is generally increased, and non-synchronous low frequency trends play an important role (Briffa et al. 1996), determining the lack of signal strength of mean chronologies. Also the significance of parameters based on correlation coefficients is related to the number of individual series entering the calculation. This sample depth generally declines in early parts of mean chronologies from living trees, changing the statistical significance of correlation calculations. That's why cross-correlations are usually calculated for selected periods with no or only slight variation in sample depth. Estimates of signal strength with interannual resolution are not possible with cross-correlation techniques.

We here introduce a new parameter *NET* to estimate signal strength of mean tree-ring chronologies with annual resolution. *NET* is a simple combination of the coefficient of variation *v* and the Gleichläufigkeit *G*, both of which widely known in dendrochronological and statistical literature (e.g., Bahrenberg, Giese 1975; Eckstein, Bauch 1969). We define *v* and *G* and argue the benefits of a combination of these parameters in detail. The performance of *NET* is then tested using ring width data sets from the Alps and the Karakorum. Both, the Alp and the Karakorum data set are standardized in the same way, with a commonly used technique to emphasize low frequency variation in the resulting mean chronologies. We will discuss the performance of *NET* with both chronologies, and show that the chosen technique is better adapted to the Alp data set.

Derivation of *NET*

NET is the sum of *v* and *1-G*. We first discuss *v* by deriving it from the standard deviation *s* and the mean $\bar{x}$. *G* is then introduced, and finally the combination of $v + (1\text{-}G)$ is discussed.

Let n_j denote the number of tree-ring width measurements x_{ij} that are available for year *j*. The mean

$$\bar{x}_j = \frac{1}{n_j} \sum_{i=1}^{n_j} x_{ij} \tag{1}$$

and the standard deviation

$$s_j = \sqrt{\frac{\sum_{i=1}^{n_j} (x_{ij} - \bar{x}_j)^2}{n_j - 1}} \tag{2}$$

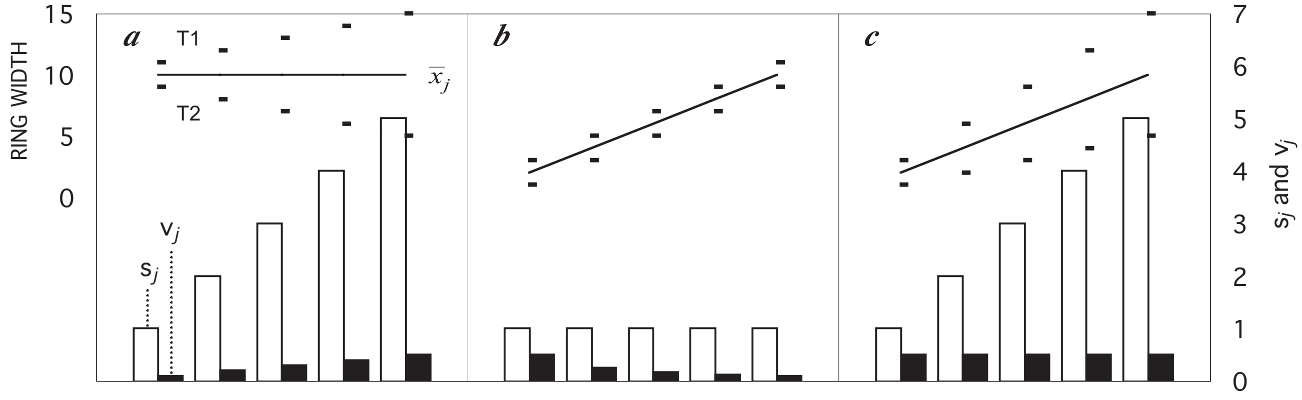
are the measures of level and spread respectively. Notice that the spread s_j is measured about the level $\bar{x}_j$, which minimizes it. These two statistics are most appropriate for Gaussian random variables. Tree-ring widths have properties that limit the usefulness of $\bar{x}_j$ and s_j. Their histograms are usually skewed toward higher values. This skew by itself can induce a dependency of spread on level (see Cook, Peters 1997), but in addition there seems to be another source of spread versus level dependency that operates even when the ring width values are systematically distributed about their mean level. It is easy to see that these properties can complicate the interpretation of s_j as a measure of signal strength. The same specific value of s_j can correspond to a weak signal if $\bar{x}_j$ is small, and a strong signal if $\bar{x}_j$ is large.

If we assume that $s_j = v_j \bar{x}_j$,

$$v_j = \frac{s_j}{\bar{x}_j} \tag{3}$$

might be interpreted as a measure of signal strength. In the statistical literature a ratio of the standard deviation to the mean about which it is computed is called a coefficient of variation when multiplied by 100 (e.g., Bahrenberg, Giese 1975). Fig. 1 shows graphically the relation between the absolute parameter s_j and the relative parameter v_j.

The second parameter entering *NET*, the Gleichläufigkeit *G*, is a simple sign test of synchronous year-to-year changes amongst single series (Eckstein, Bauch 1969; Hollstein 1980; Riemer 1994; Schweingruber 1983). The annual Gleichläufigkeit G_j, used here, calculates the proportion of synchronous increasing (positive) and decreasing (negative) changes for each year *j* amongst the single series.



	a					b					c				
T1	9	8	7	6	5	1	3	5	7	9	1	2	3	4	5
T2	11	12	13	14	15	3	5	7	9	11	3	6	9	12	15
$\bar{x}_j$	10	10	10	10	10	2	4	6	8	10	2	4	6	8	10
s_j	1	2	3	4	5	1	1	1	1	1	1	2	3	4	5
v_j	0.1	0.2	0.3	0.4	0.5	0.5	0.25	0.17	0.13	0.1	0.5	0.5	0.5	0.5	0.5

v_j without "Besselsche Korrektur" (Bahrenberg, Giese 1975:95) for small sample depths (here $n = 2$)

Fig. 1 - Standard deviation s_j and coefficient of variation v_j calculated for two single ring width series (T1 and T2) together with the resulting average ($\bar{x}_j$). ***a***, The variance of T1 and T2 increases, but the arithmetic mean stays the same. ⇒ Both s_j and v_j increase proportionally. ***b***, The variance of T1 and T2 remains constant, while $\bar{x}_j$ increases. ⇒ The absolute parameter s_j does not react. The relative parameter v_j (related to $\bar{x}_j$) decreases. ***c***, The variance of T1 and T2, and $\bar{x}_j$ increase proportionally. ⇒ s_j increases and v_j stays the same. This example demonstrates that the relative variance parameter v_j provides straightly comparable results for different mean chronology levels.

If x_{ij} is the radial growth of the *i*-th tree in the *j*-th year, then $\Delta_{ij} = (x_{ij} - x_{i,j-1})$ and

$$G_{ij} = \begin{cases} G_{ij}^{>0} := +1/n_j \quad for\ \Delta_j > 0 \\ G_{ij}^{=0} := 0 \qquad for\ \Delta_j = 0 \quad \text{for each tree } (i=1,...n_j) \text{ in each year } (j=2,...t). \\ G_{ij}^{<0} := -1/n_j \quad for\ \Delta_j < 0 \end{cases}$$

$$G_j = max\left(\sum_{i=1}^{n_j} \left| G_{ij}^{<0} \right|, \sum_{i=1}^{n_j} G_{ij}^{>0} \right) \tag{4}$$

is the Gleichläufigkeit for the year *j* over all n_j trees.

v_j and G_j measure the relative standard deviation and the proportion of synchronous changes amongst all given series for each year *j* of a mean chronology. It is then possible to average v_j and G_j over defined periods or the entire length of the chronology (v and G).
The sum of v_j and $1\text{-}G_j$ defines NET_j.

$$NET_j = v_j + (1\text{-}G_j) \tag{5}$$

The average of NET_j over the entire chronology length *t* is

$$NET = \frac{1}{t-1} \sum_{j=2}^{t} NET_j \tag{6}$$

NET represents the sum of two error parameters. The signal strength of a mean chronology in year *j* is high, if the variance measured by v_j and the Gegenläufigkeit measured by ($1\text{-}G_j$) are small. The minimum value of NET_j is 0. It is attained only, if all single series in year *j* have exactly the same ring width value (then $v_j = 0$), and all changes have the

	ALP		KAK	
Species	*Picea abies* Karst.		*Juniperus turkestanica* Kom.	
Latitude/Longitude	46°26'N/07°49'E		36°10'N/75°30'E	
Elev. [m]/Exp.[°]/Incl.[°]	2000/150/40		3700/180/45	
No. Trees	17		17	
Max. Age	AD1714		AD736	
Average Age [yr.]	203		731	
	RAW	INDEX	RAW	INDEX
Average Width	0.96 mm	109.4	0.28 mm	115.2
Min./Max. Chronology	0.35/2.11 mm	52/152	0.05/0.64 mm	22/195
Autocorrelation (Lag 1/10)	0.88/0.66	0.61/0.2	0.57/0.31	0.48/0.2

Tab. 1 - Site characteristics and mean chronology statistics of the ring width data sets from the Alps and the Karakorum.

same sign (then $G_j = 1$). The amplitude of G_j ranges theoretically from 0 to 1, with 0.5 = "coincidence" and 1 = "all changes are synchronous". Values less than 0.5 occur only if some changes are zero ($\Delta_{ij} = 0$). Since v_j can reach extremely high values, when dividing s_j by extremely small chronology values $\bar{x}_j$ ("negative pointer years" Schweingruber et al. 1990a), there exists no upper limit for NET_j. These different ranges and variances of v_j and G_j can bias the simple combination of the parameters, and operators, willing to use NET_j, might therefore weight v_j and G_j differently before combining them to NET_j.

Establishing threshold values for NET_j might be useful, even if no exact theoretical derivation of NET_j and thus for the threshold values exists. A critical value of NET_j is 1, which might result from $v_j = 0.5$ and $G_j = 0.5$. $v_j = 0.5$ if s_j is half of the related $\bar{x}_j$, and $G_j = 0.5$ if 50% of all trees had increasing and 50% had decreasing changes. In this case the mean chronology has low signal strength. NET_j values of 0.8 might result from $v_j = 0.4$ and $G_j = 0.6$. At this threshold value the variance, as well as the sign test indicate some common signal. The signal gets stronger if NET_j decreases and reaches its maximum at 0.

The strength of NET_j results from the combination of two parameters measuring independently the performance of a mean chronology. NET_j enables the calculation of interannual signal strength, and averaging NET_j over defined periods or smoothing NET_j with a low-pass filter can be done additionally, as shown below. v_j is strongly influenced by the chosen standardization technique, and is of importance if low frequency, centennial variation is emphasized (Briffa et al. 1996). Since v_j does not consider the interannual crossdating of single series, this component of a chronology's signal strength is covered by G_j.

Application of *NET*

Data

We use two ring width data sets from the Central Alps (Alp, *Picea abies* Karst.) and the NW-Karakorum (Kak, *Juniperus turkestanica* Kom.), both consisting of 17 trees, to test *NET* (Esper 2000; Esper et al. 1995, 2000; Neuwirth 1998; Treydte 1998). The trees were sampled near the local upper timberlines in phytosociologically homogeneous plots following the criteria of Schweingruber et al. (1990b). Both samplings were executed within larger programs to reconstruct climatic variation over longer time-scales. Analyses of the site characteristics indicate that trees from the Alps grow faster and are significantly younger than those from the Karakorum (Tab. 1).

Fig. 2 shows the single raw (*a*) and standardized (*b*) ring width series from Alp and Kak. The series were standardized using negative exponential curves. These growth curve models are useful to estimate age-related trends in ring width series.

Calculating ratios from the fitted curves is generally suitable to emphasize low frequency variation of the wavelength of decades and longer (Bräker 1981; Cook, Briffa 1990; Cook et al. 1990; Fritts 1976).

The raw ring width series (Fig. 2a) clearly demonstrate that only the Alp data set contains age-related trends. The slow growing *Juniper* trees show no such long-term trends in the raw data (details in Esper 2000; Esper et al. 2000). Since the chosen standardization technique is adapted to data sets containing age-trends, the changes caused by standardization vary strongly between Alp and Kak. Standardization reduces the autocorrelation of the Alp mean chronology from 0.66 (raw) to 0.2 (index) at lag = 10. The difference in autocorrelation of the Kak mean chronology, before and after standardization (from 0.31 to 0.2), is only 0.11 (Tab. 1).

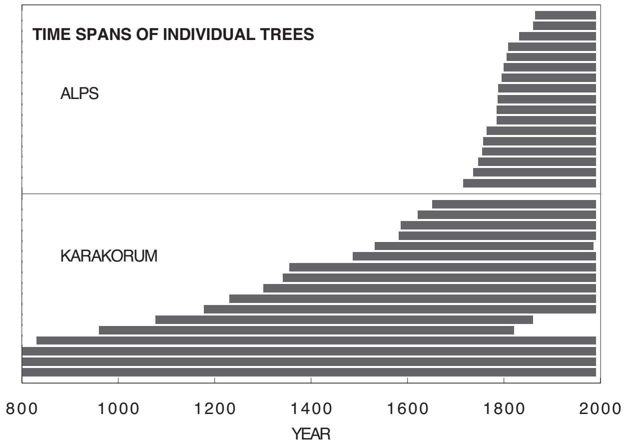


Fig. 3 - Time spans of the 17 ring width series from the Alps and the Karakorum.

The variance of the single ring width series, before and after standardization, indicates additional differences between Alp and Kak. Standardizing the raw ring width series into dimensionless indices

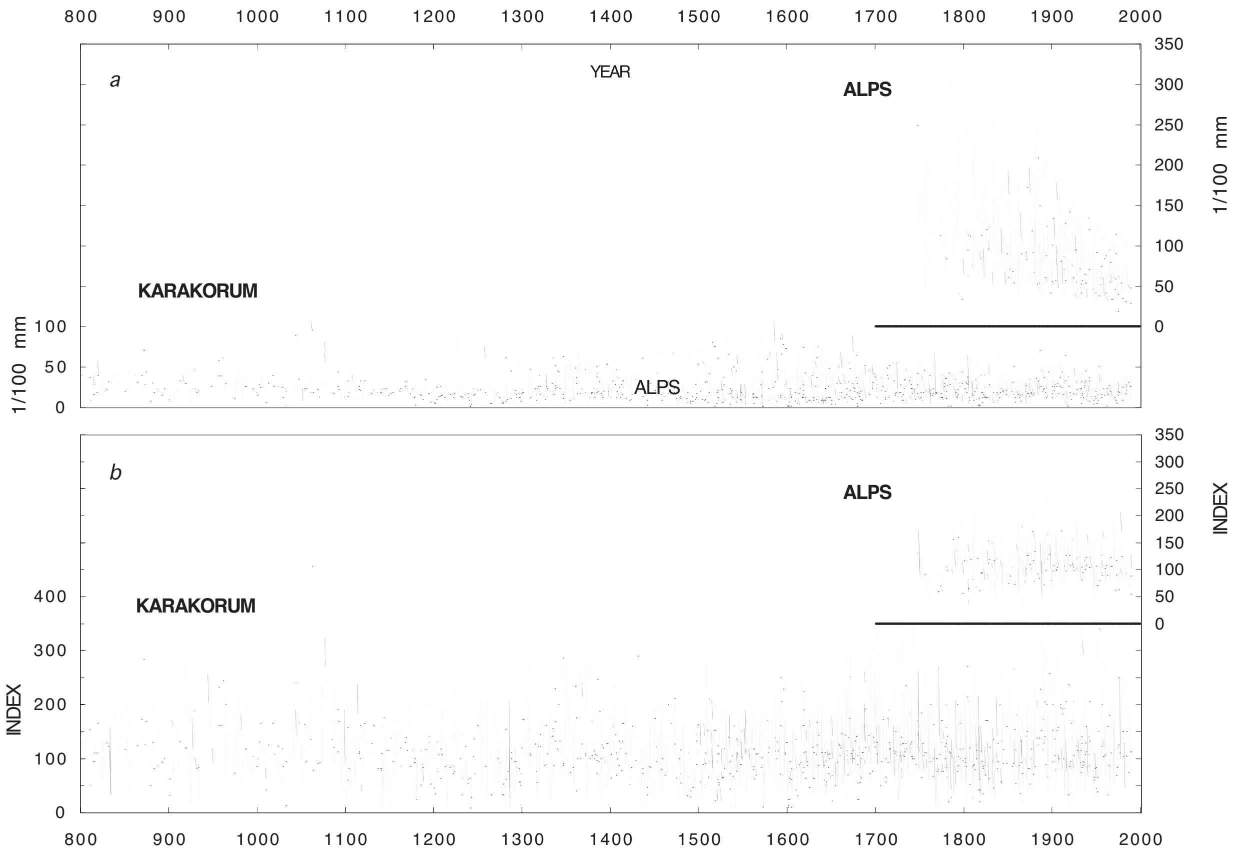
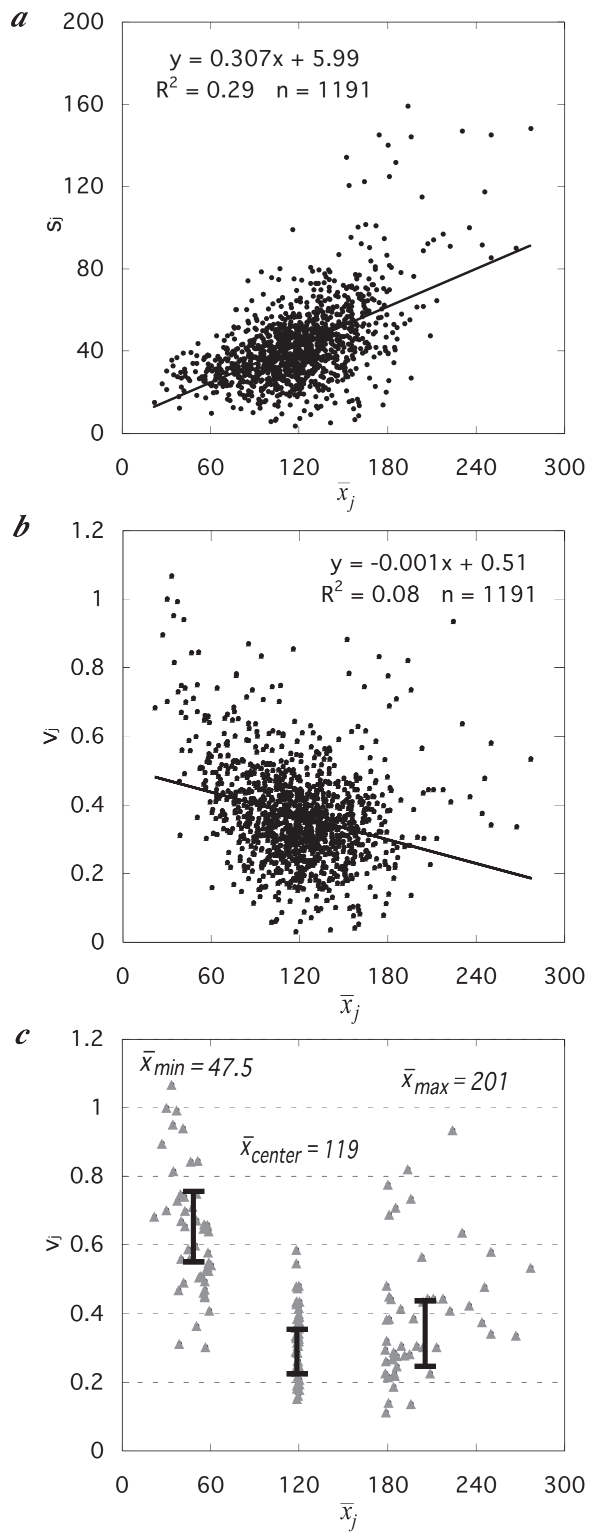


Fig. 2 - 17 raw (a) and (b) standardized ring width series from sampling sites in the Alps and the Karakorum.



with average values around 100 (see Tab. 1: Average Width) changes the variance of Alp and Kak differently. The variance of the raw Alp data set was significantly larger than of the Kak data set before standardization (Fig. 2a). Standardization decreased the variance of Alp and increased the variance of Kak (Fig. 2b). These visible changes will be important for the discussion of *NET*.

Calculation of the Interseries Correlation IC

We calculate *IC* of the Alp and Kak mean chronologies to demonstrate the benefits and limitations of estimating signal strength from cross-correlation parameters. High *IC* values up to +1 indicate strong signal strength of the mean chronologies, and small *IC* values down to 0 indicate no signal strength. The statistical significance of *IC* depends on (*i*) the number of single series being averaged to a mean site chronology and (ii) the period length chosen to calculate *IC*.

Fig. 3 shows the changing sample depths of Alp and Kak over time. Periods with 100% sample depth (n = 17 trees) are shifted in time between Alp and Kak. Alp has 100% sample depth AD1864-1990, Kak AD1650-1820. Calculations of *IC* for these different periods would therefore not be comparable. In addition, the length of the 100% sample depth period compared to the total length of the data sets is significantly higher for Alp. Thus, a calculation of *IC* for the 100% sample depth period would represent the entire chronology much better at Alp than at Kak.

A useful, straightly comparable alternative might be the calculation of *IC* for the 20th century only. After this $IC_{1900\text{-}90}$ of the standardized data sets is 0.37 for Alp and 0.30 for Kak, indicating higher signal strength of Alp, predominantly in the high frequency domain. However, these *IC* result from 100% of all coupled values possible at Alp and only 76.6% of all coupled values possible at Kak. The

Fig. 4 - “Problematic nature of small values” here demonstrated with values of the standardized mean chronology Kak. ***a***, s_j is affected by the chronology values $\bar{x}_j$. ⇒ High $\bar{x}_j$ values provoke increased s_j values. ***b***, Calculation of the relative variance by v_j seems to be independent from $\bar{x}_j$. ***c***, v_j of the 50 smallest chronology values ($v_{j\ min}$ = 0.63) is significantly increased in comparison to the centered ($v_{j\ center}$ = 0.32) and maximum ($v_{j\ max}$ = 0.39) chronology values $\bar{x}_j$ (confidence levels are illustrated).

statistical significance of the obtained *IC* values differs.

Calculation of v_j

Before calculating NET_j the performance of v_j with extremely small mean chronology values needs to be discussed.

Fig. 4a and b show the correlation between the standardized ring width values of the Kak chronology ($\bar{x}_j$), and s_j, and v_j. Fig. 4c shows then the relationship between the 50 smallest, 50 centered, and 50 largest $\bar{x}_j$, and v_j. After this, s_j is related to the mean ring width $\bar{x}_j$, as predicted in the previous section (see Fig. 1). s_j increases with $\bar{x}_j$, testifying that the absolute variance is positively correlated with the chronology values (Fig. 4a). The scatter-plot, as well as the explained variance R^2 in figure 4b suggests that the relative variance – measured by v_j – is independent from the mean ring width $\bar{x}_j$. This observation needs to be adjusted when v_j is calculated for the 50 smallest ring width values only (Fig. 4c). v_j is systematically increased at minimal chronology values ($v_{j\ min}$ = 0.63, $v_{j\ center}$ = 0.32, $v_{j\ max}$ = 0.39). This problematic nature of small chronology values must be considered when calculating NET_j.

Calculation of NET_j and NET

NET results from averaging NET_j over the entire length of a given chronology. It is therefore appropriate to discuss first the benefits and limitations of NET_j, before calculating *NET* for Alp and Kak.

Fig. 5a shows the standardized mean chronology (thick curve) and the single series (thin curves) of Alp (a), together with G_j and v_j (b), and NET_j (c) since AD1745. The thick curves in (b) and (c) show 11-year low-pass filterings. The mean chronology and single series show some characteristic features of dendrochronological reconstructions that can be found in every tree-ring data set. First, periods of enhanced variance of single series (e.g., AD1865-1880) can be distinguished from periods of reduced variance (e.g., AD1850-1860). It is obvious that the mean chronology has higher signal strength in low-variance-periods. Second, pointer years, where most (or all) single series form a small or a large ring, can be distinguished from years with no clear signal. A good example is the negative pointer year AD1948, where 94% of all series show a negative change from AD1947 to 1948. Pointer years have the highest signal strength (Schweingruber et al. 1990a).

Does NET_j identify these changes in signal strength? If the variance of single series is increased, like in the year AD1875 or the period AD1865-1880, v_j increases too. The same is true for the early period AD1756-1772, where v_j attains the highest values (> 0.5). Note that the sample depth is low in this early period. G_j identifies 23 years when the changes of all single series are synchronous (G_j = 1). These years clearly differ from years with G_j values down to 0.5, which have no signal strength. The low-pass filtered series also display periods with higher (e.g., AD1905-1920) and lower G_j values (e.g., AD1870-1880). NET_j combines the results of v_j and (1-G_j), and benefits from the independent observations. For example, if both v_j and G_j identify low signal strength, like in the year AD1875 or the period AD1865-1880, NET_j attains high values. If v_j and G_j identify high signal strength, like AD1902-1919, NET_j attains low values. NET_j also reflects changes in signal strength in the early periods of the mean chronology, where sample depth is low. Starting with relatively low values, signal strength declines after AD1755, driven by a significantly increased variance AD1756-1772.

Important for the understanding of NET_j is the negative pointer year AD1948. Here v_j produces an extremely high value (v_{1948} = 0.41), pointing to the discussed problematic nature of small values. In contrast, *Gj* reaches an extremely high value (G_{1948} = 0.94), indicating high signal strength. Because of

	ALP	**KAK**	
	AD1745-1990	AD800-1990	AD1745-1990
v	0.26	0.37	(0.39)
G	0.74	0.73	(0.70)
NET	0.53	0.64	(0.70)

Tab. 2 - Calculation of *v*, *G*, *NET* over the entire chronology lengths of Alp (AD1745-1990) and Kak (AD800-1990), and the period AD1745-1990 of Kak.

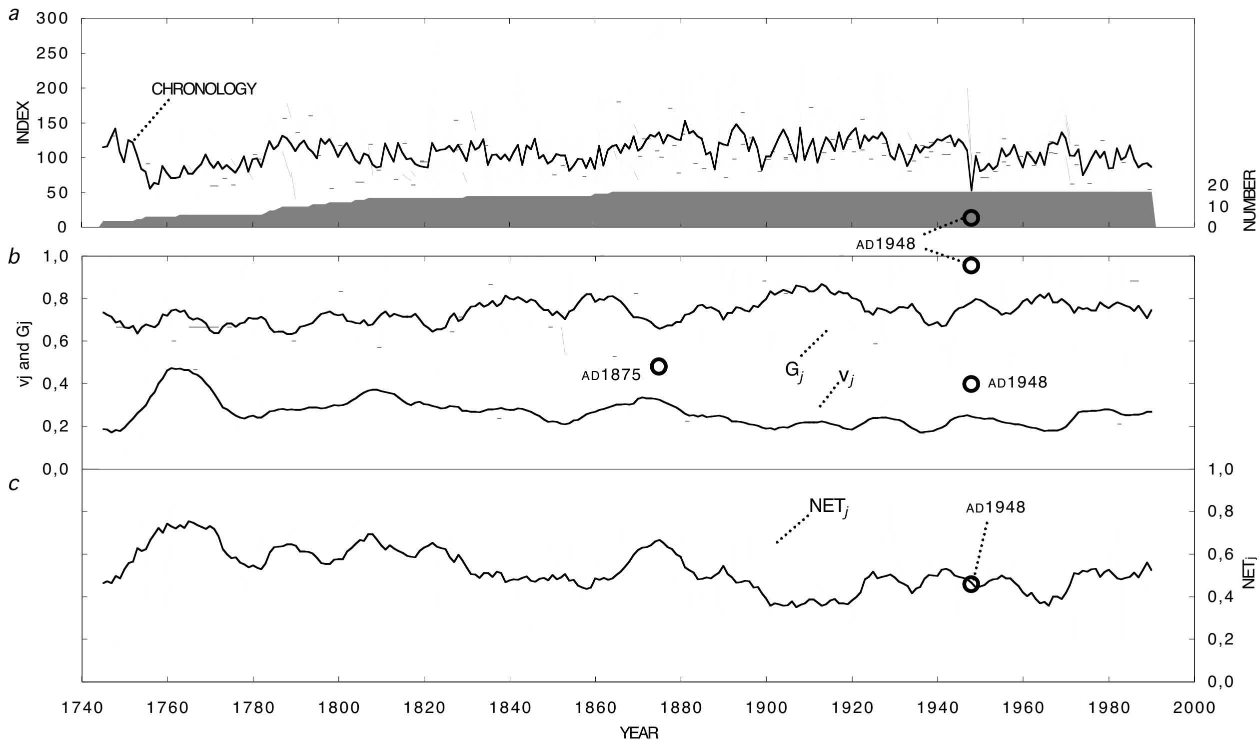


Fig. 5 - Application of NET_j to the standardized mean chronology Alp (AD1745-1990). ***a***, 17 standardized ring width series (thin curves), mean chronology (thick curve) and sample depth (colored plane) of Alp. ***b***, G_j and v_j , and ***c***, NET_j calculated for each chronology year.

the combination of G_j with v_j , the NET_{1948} value is reduced to 0.47 indicating average signal strength. An additional reduction might result from low-pass filtering the v_j values. Note that the calculation of NET_j reduces but does not eliminate the effect of extremely small chronology values on v_j.

By averaging NET_j over the entire chronology lengths of Alp (AD1745-1990) and Kak (AD800-1990), estimates of total signal strength *NET* of these chronologies can be provided. Calculating *NET* of Kak solely over the recent period AD1745-1990 allows a straight comparison between Alp and Kak (Tab. 2).

The relative variance over the entire chronology length is v = 0.37 for Kak and only 0.26 for Alp. These results confirm the visible differences in variance shown in Fig. 2. The relative variance of Kak (0.39) is also higher than that of Alp (0.26) in the directly comparable period AD1745-1990. *G* indicates a slightly higher proportion of synchronous changes over the single series for Alp (0.74) than for Kak (0.70) over the equivalent period AD1745-1990, and similar results over the entire chronology length (Kak, $G_{800\text{-}1990}$ = 0.73). Since *NET* combines the relative variance and the proportion of synchronous changes, it indicates higher signal strength for Alp (0.53) in comparison to Kak (0.64) for the period AD1745-1990. Similar comparisons over the entire chronology lengths are not appropriate. There is no point in comparing different time windows directly without empirical verification. However, *NET* of the entire chronology at Kak (0.70) indicates that the signal strength estimated for the recent period stays fairly stable back to AD800.

Discussion

The reliability of mean tree-ring chronologies in dendroclimatology generally depends on the number of trees averaged (Fritts 1976). The signal strength is also affected by the way the single series fit together. Since these circumstances are widely

known in dendrochronology, several parameters to estimate changing signal strength of mean chronologies have been developed. Calculating the relative variance of single series together with the proportion of synchronous changes for each year of a mean chronology – as done by NET_j – might improve the estimation of signal strength. Advantages of NET_j are
(i) the ability to calculate a signal strength estimate for each year of a mean chronology,
(ii) the combination of two parameters measuring the quality of a chronology independently,
(iii) the mathematical simplicity of NET_j .

Since an estimate of the relative variance over single series gets more important when low frequency variation is emphasized, we recommend calculating NET_j for mean chronologies reconstructing decadal to centennial variation.

The application of NET_j to different tree-ring data sets, containing different species, indicated higher signal strength of the mean chronology from the Alps than the Karakorum. NET_j also showed the changing signal strength of the mean chronologies from year-to-year and period-to-period, a common characteristic of this proxy. The higher signal strength of the Alp data set results at least partly from the chosen standardization method. Calculating ratios from negative exponential curves is a useful transform for data sets containing age-related trends, which do not exist in the Kak data set. As a result, the relative variance of the standardized Kak chronology is significantly increased in comparison to Alp.

We also showed the behavior of NET_j with negative pointer years of mean chronologies. In these extreme years, when most single series formed an extraordinarily narrow ring, v_j is systematically biased to higher values. By summing v_j with $1\text{-}G_j$, the signal strength estimate calculated with NET_j attenuates this effect but does not eliminate it entirely. Modification of NET_j to resolve this effect completely might increase the mathematical complexity of the new parameter, but is being considered. Also an adjustment of the mean and variance of v_j and G_j before combining them to NET_j might be done to improve the performance of the new parameter.

Terminology

t Length of a chronology
j Subscript for j-th year
n Number of series
i Subscript for i-th time series
x Value
x_i Value of the i-th time series
x_j Value in the j-th year
x_{ij} Value of the i-th time series in the j-th year
$\bar{x}$ Average value (= mean chronology value)
$\bar{x}_j$ Average value (chronology value) in the j-th year
s Standard deviation
s_j Standard deviation in the j-th year
v Coefficient of variation
v_j Coefficient of variation in the j-th year
G Gleichläufigkeit
G_j Gleichläufigkeit in the j-th year
G_{ij} Gleichläufigkeit of the i-th time series in the j-th year

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