INTERPRETATION OF TREE-RING CHRONOLOGIES

With 5 figures and 2 photos

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Zusammenfassung: Interpretation von Jahrringchronologien

Die Interpretation publizierter Jahrringchronologien und deren Verwendung in geographischen Studien setzt ein Verständnis wesentlicher Aspekte der Chronologiebildung voraus. Zahlreiche Chronologien rekonstruieren beispielsweise klimatische Variationen mit Wellenlängen von Jahren bis zu Dekaden. Längerfristige, etwa säkulare Trends sind generell schwieriger zu betonen und fehlen häufig in den Chronologien. Diese Sachverhalte zu erklären und ein grundlegendes Verständnis für die aktuellen Techniken der Dendrochronologie zu wecken, ist das Ziel des vorliegenden Beitrages. Damit soll die Interpretation von Jahrringchronologien erleichtert und das Potential dieser Methode verdeutlicht werden.

Summary: To interpret published tree-ring chronologies and to use these results for geographic studies, knowledge about essential aspects of chronology building is necessary. For example, most chronologies display climatic variation in the wavelengths of years to decades. Trends in longer time-scales, like century-scale variation, are generally more difficult to emphasize and are often missing in tree-ring chronologies. Here we aim to explain such facts and to generate a basic understanding of current dendrochronological techniques, thus allowing successful interpretation of tree-ring chronologies and the strength of this method to be understood.

1 Introduction

Knowledge about the magnitude and frequency of climatic variation patterns in pre-instrumental periods rests upon worldwide analyses of high-resolution proxy climate sources (BRIFFA 2000; CROWLEY a. Lowery 2000; ESPER et al. in prep.; JONES et al. 1998; MANN et al. 1998). Records of tree-ring variation are crucial within this research field, since they can be derived across much of the middle-to-high latitude landmasses and allow comparison of observed trends of present global warming with earlier periods that were not affected by human activities (BRIFFA et al. 1995; 1998a; 1998b; COOK et al. 1991; 1992; LARA a. VILLALBA 1993; LUCKMAN et al. 1997; SCHWEINGRUBER a. BRIFFA 1996; STAHLE et al. 1988). Because of the importance of research concerning environmental changes, the number of chronologies published over the last decade increased dramatically (Fig. 1). Chronologies are the core medium to illustrate results of dendrochronological research. Since they represent an integral of different statistical methods, the interpretation of chronologies is not trivial. Knowledge about some principle techniques of dendrochronological research is a prerequisite for the interpretation of tree-ring chronologies by geoscientists who intend to relate these results to their own work.

We intend here to explain some crucial techniques of chronology development and emphasize the potential of actual dendrochronological research. Figure 2 summarizes the knowledge necessary for effective chronology-interpretation. We first describe some principal rules, followed by current concepts of signal strength, standardization, wavelengths, and transfer. Thus, this paper is not an instruction of chronology-building steps in form of a textbook chapter, but it might enable geoscientists to interpret tree-ring chronologies better.

2 Principle Rules of Dendrochronological Studies

Climatic variation influences tree growth. The tree's metabolism and eventually the productivity of the cambium – the thin divisible tissue enveloping the stem that builds the annual rings – are limited by climatic conditions. This dependency causes synchronous growth reactions between single trees of one site and, depending on the synoptic situation, synchronous growth reactions between distinct sites. These synchronous growth reactions are the basic foundation of dendroclimatological research that allows the "crossdating"¹⁾ of trees and, for example, enables the dating of buildings (DEAN et al. 1996; DOUGLASS 1929; FRITTS 1976; SCHWEINGRUBER 1983; 1996; STOKES a. SMILEY 1968).

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¹⁾ Dendrochronological terms are explained in KAENNEL a. SCHWEINGRUBER (1995).

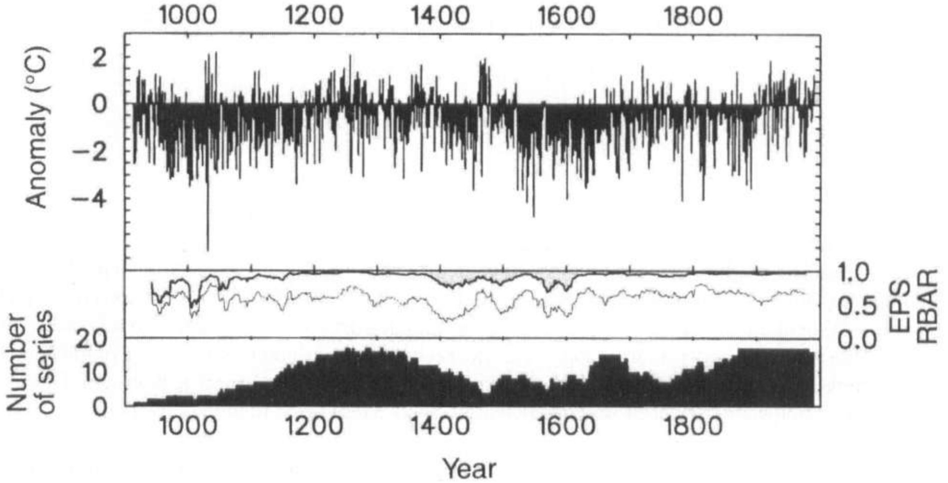

Fig. 1: Example of a widely cited summer temperature reconstruction from the Northern Urals (*Siberian larch*, ring width) shown as anomalies in °C since AD914, indicating an unusual warmth in the 20th century (BRIFFA et al. 1995). How do dendrochronologists develop such reconstructions?

Beispiel einer wichtigen Rekonstruktion der Sommertemperaturen des nördlichen Urals (*Larix sibirica*, ring width), dargestellt als Anomalien in °C seit AD914. Die wärmsten Dekaden bezogen auf die Gesamtlänge wurden im 20. Jh. rekonstruiert (BRIFFA et al. 1995). Wie werden derartige Chronologien erstellt?

A sequence of tree-rings does not reflect a one-to-one measurement of climatic variables, however. The degree of influence on the metabolism and thus the portion of climatic information in tree-ring sequences depend on a complex combination of biological and environmental factors (COOK 1990; FRITTS 1976, 226ff). The strength of climatic signals can be increased by careful site selection. Sampling sites located near a natural forest boundary, where particular species grow near the edge of their ecological range (e. g. upper timberline) enables the reconstruction of temperature variation with a high statistical certainty, for example (Photos 1 a and b).

A careful sampling strategy also considers the tree selection. In principle, dendroclimatological studies try to minimize the individuality of trees sampled. Trees that are disturbed by site dynamics (e. g. soil erosion, rockfall, etc.) or by human impact (e. g. irrigation, grazing, etc.) are unsuitable for climatic studies. On the other hand, studies aiming to reconstruct geomorphic processes, for example, follow the rule of maximizing individuality when sampling trees. Damaged trees with scars or crooked stems showing "reaction wood" are of particular interest to date geomorphic events (GÄRTNER et al. 2001; SCHWEINGRUBER 1996; SHRODER 1980).

To achieve valid results about past climatic variability, a chronology should average ten or more trees per site (SCHWEINGRUBER et al. 1992). However, the total number of imperative sample depth ("replication") depends on the aim of a study and cannot be answered in general. A principal rule can be derived only from the synchronicity of tree-ring variation between the individual measurements. If the variances between different radii within a tree and between different trees of a site are highly common, fewer samples are needed to reconstruct climatic variation, and vice versa.

It is important to know that at least in distinct periods subsets of trees deviate from common trends recorded in a particular site. Such biased series represent a characteristic feature in the process of chronology building. Leaving these trees in the pool of series to calculate a mean site curve would result in a biased chronology, as well. However, if the variance between the majorities of trees in a site is common, the biased individual series can be excluded from further investigation steps. This is generally done, even if the reasons for uncommon growth reactions are unknown.

These principle rules are valid for several parameters that can be measured from slices or cores taken from investigated trees. The traditional and still most often illustrated parameter by chronologies is the tree-ring width (TRW). Measurements of TRW generally integrate a wide spectrum of environmental factors and thus these records strongly depend on the ecological conditions of a sampled site. Classic examples are the *bristlecone pine* TRW records from the White Mountains in California. Along a vertical gradient, those records respond to temperature at sites near the upper timberline and to precipitation near the lower timberline (La Marche 1974). Measurements of maximum latewood density (MXD)[2] and, recently, of stable isotopes are becoming more important. Compared to TRW, these parameters are more selectively limited by a single climatic factor. For example, Briffa et al. (1998 b) used MXD records from more than 300 circumpolar sites distributed over the Northern Hemisphere to reconstruct summer temperature variation only, and $\delta^{13}C$, a stable isotope extracted from tree-rings, principally reflects precipitation variation (Schleser 1995).

3 Tree-ring Chronologies

A tree-ring chronology is the average expression of standardized single time series, calculated with the arithmetic or robust mean. The single time series represent records of measured parameters (TRW, MXD, etc.) of individual trees or radii of trees. They have a certain synchronicity (to each other), contain some noise and signal, contain different wavelengths of variation, and can be transferred to climate estimates.

3.1 Signal strength

"Signal strength" describes the quality of a chronology for the purpose of reconstructing climatic variation patterns. It depends on the sample depth and the synchronicity between individual series combined to a mean chronology. The signal strength generally varies through time and between different chronologies.

When working with living trees only, the sample depth declines in the early periods of a chronology. Sample depth also varies if a chronology is built with living and older, dead material. Since one tree from a particular site is older then all others, every chronology starts with a sample depth of one tree. Because the variation of only one series cannot be validated, the earliest periods are generally truncated and published chronologies start with a sample depth of three or more trees. Changing sample depth through time, and particularly in the early periods, when sample size approaches its minimum, affects the quality of chronologies. That means, the signal strength is positively correlated with the number of series combined to a mean chronology, and the sample depth curve, as a function of time, should be known for the interpretation. The entire information is given, if the individual series are shown together with the resulting mean chronology.

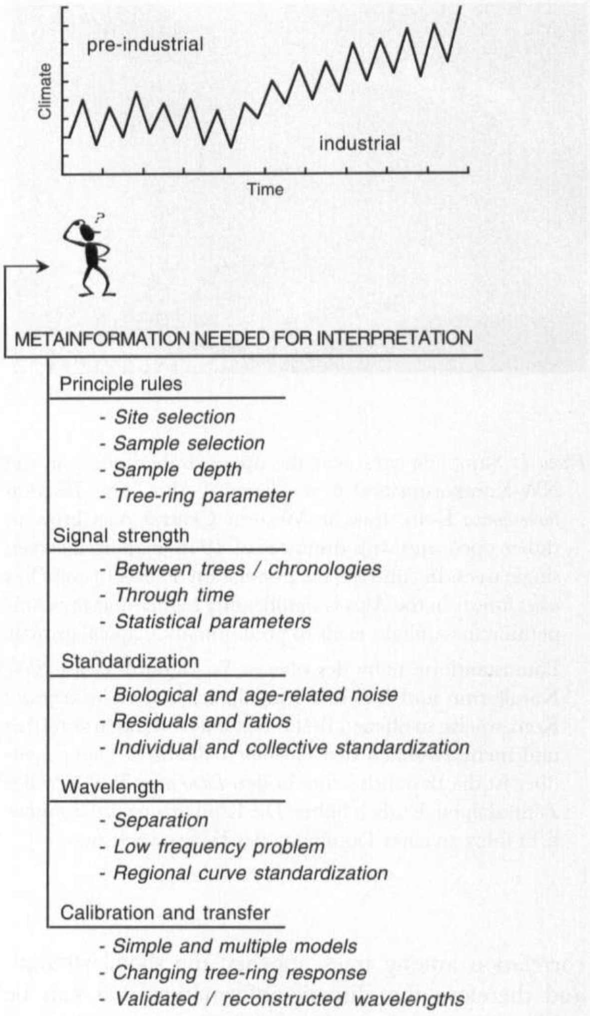

Fig. 2: Metainformation needed for the interpretation of tree-ring chronologies
Notwendige Metainformation für die Interpretation von Jahrringchronologien

Many studies have shown (e. g. Esper et al. 2000 b) that the response to temperature variation, for example, is higher at a site located near the upper timberline than several hundred meters below. In addition, a cold year in a given area will limit tree growth more severely than a normal year. In years or at sites where the limitation is strong, high values of common variance between the individual series are recorded. If a high

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[2] Latewood is the dense and often dark outside zone of a tree-ring, produced in the later part of the growing season. In gymnosperms, small, flat and thick-walled cells characterize it. The maximum density of the latewood can be quantified by the use of X–ray films (Schweingruber et al. 1978).

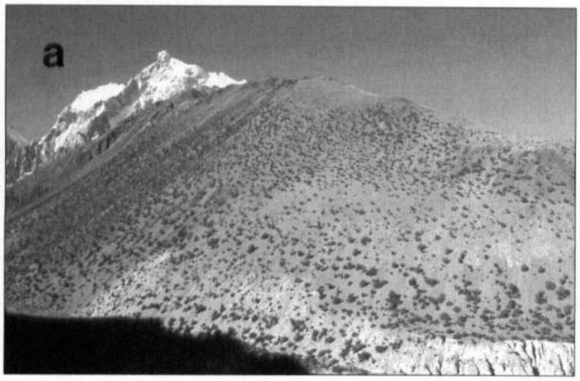


Photo 1: Sampling sites near the upper timberlines *a*, in the NW-Karakorum and *b*, the Central Alps. The *Juniperus turkestanica* Kom. trees in Western Central Asia grow in rather open sites with distances of 10 m or more between single trees. In contrast, the population density of the *Picea abies* forests in the Alps is significantly higher and the competition for sunlight leads to predominantly apical growth

Baumstandorte nahe der oberen Waldgrenze *a*, im NW-Karakorum und *b*, den Zentralalpen. *Juniperus turkestanica* Kom. wächst in offenen Beständen mit Abständen von 10 m und mehr zwischen den einzelnen Bäumen. Demgegenüber ist die Bestandsdichte in den *Picea abies* Wäldern der Zentralalpen deutlich höher. Die Konkurrenz um Sonnenlicht führt zu einer Dominanz des Höhenwachstums

correlation among trees appears, the signal strength and therefore the climatic information that can be expected from a chronology are high.[3)]

Figure 3 shows an example of changing signal strength of a mean site chronology (Fig. 3 a) by illustrating the individual series (Fig. 3b). Even if the sample depth is almost constant over the entire 20th century, a shift from 15 trees AD1900–69 to 14 trees AD1970–90 occurred (for details see ESPER 2000a; 2000b), and causes a slight decrease of signal strength in the most recent period of the resulting chronology. In addition, the temporally varying synchronicity between the individual series causes some significant changes of chronology signal strength, too. Highest signal strength is reached when all or almost all series react synchronously with increasing or decreasing TRW. These "pointer years" (SCHWEINGRUBER et al. 1990), like AD1911, AD1928 (negative) and AD1921 (positive), originate from anomalous climatic conditions that are not given in other years of the sequence. The single measurements also demonstrate periods when the vertical spread is enhanced, like AD1937–43, or reduced, like AD1975–80. The signal strength of the mean chronology is again related to this individual behavior. It is decreased around AD1940 and increased in the late 1970s. Note that the changes described are not recognizable by analyzing the chronology only.

Changing signal strength along a chronology and between them can be calculated with the „*Gleichläufigkeit*" (e. g. CROPPER 1979; RIEMER 1994; SCHWEINGRUBER et al. 1990) or in combination with the coefficient of variation (ESPER et al. 2001 b). The *Gleichläufigkeit* compares the ratio of increasing and decreasing intervals between two consecutive years.[4)] The coefficient of variation quantifies the distances between the series while considering the absolute levels.[5)] More complex but widely used statistics rest on PEARSON's correlation coefficient, like RBAR (BRIFFA a. JONES 1990; WIGLEY

[3)] Many publications (still) also discuss the "mean sensitivity" (MS) underlying a chronology. MS measures the interannual variance of tree-ring series relative to the growth speed, and is frequently interpreted as an expression of the suitability to record climatic variation. Though this rating cannot be disputed in general, we refute MS-results as a proof of signal strength of a chronology.

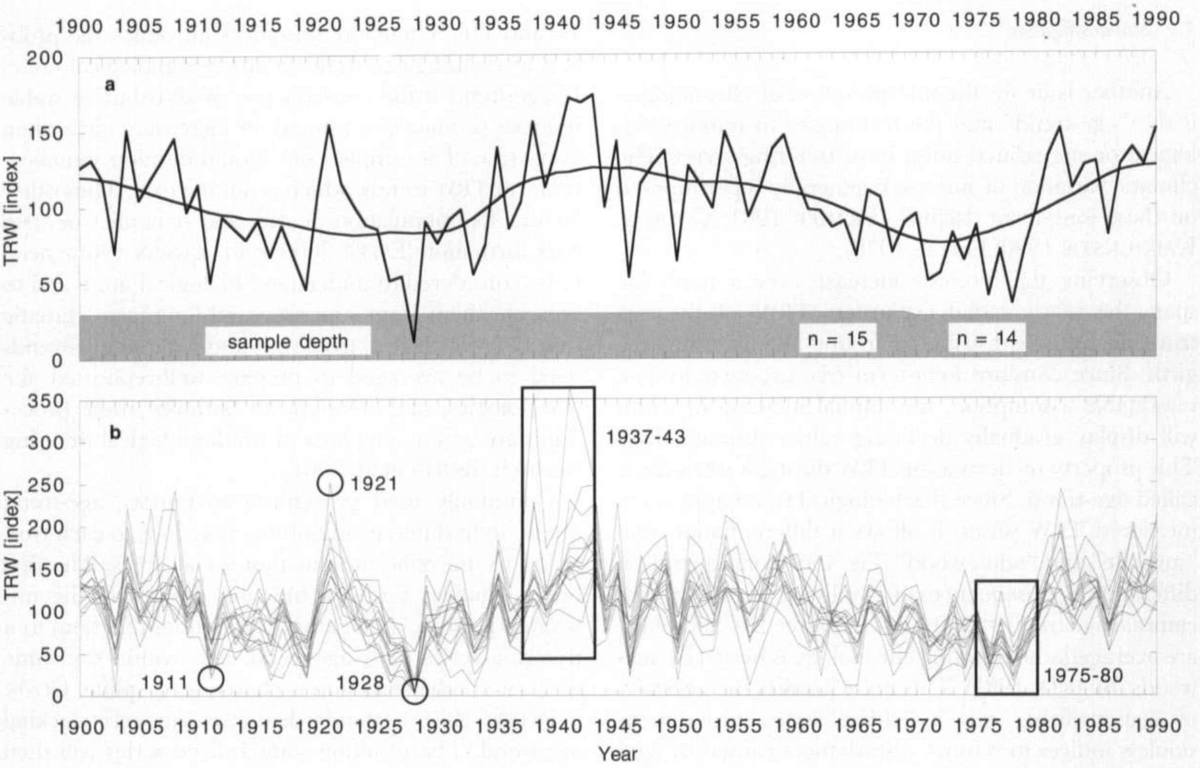

Fig. 3: a, Recent period (AD1900–90) of a millennial long chronology with a digital low-pass filter and the sample depth (ESPER 2000b). *b*, Single ring width series that have been averaged to the site chronology. Rectangles indicate periods with different vertical spread. Circles indicate pointer years. The term "TRW [index]" on the Y-axis will be explained in *3.2*

a, Jüngster Ausschnitt (AD1900–90) einer 1000-jährigen Chronologie mit low-pass Filter und Belegungsdichte (ESPER 2000b). *b*, Einzelserien der Jahrringbreite, die zur Chronologie gemittelt wurden. Die Rechtecke kennzeichnen Perioden unterschiedlicher vertikaler Streuung. Die Kreise kennzeichnen Weiserjahre. Der Begriff "TRW [index]" an der Y-Achse wird in *3.2* erläutert

et al. 1984) (see Fig. 1, thin curve). The idea of these statistics is to quantify some between-tree signal, defined as the "mean interseries correlation". RBAR, for example, calculates the mean correlation between all possible pairs of individual series for a number of overlapping time intervals, such as 50-year segments, through the entire length of a chronology ("windowing-procedure"). In fact, there exist several preconditions, like the similarity of sample depth, to make the results between different chronologies or distinct periods of one chronology exactly comparable (ESPER et al. 2001b). Consequently, many studies calculate RBAR in defined time-windows (e. g. the 19th century), where sample depth does not change significantly. The "expressed population signal" (EPS, see Fig. 1, thick curve), developed by WIGLEY et al. (1984), takes some of these preconditions into consideration. A benefit of this commonly used parameter is the relation of cross-correlation results to the time dependent changes in sample depth (for details see WIGLEY et al. 1984).

These techniques are quite important, since they evaluate the portions of common variance carried by a chronology and express the potential to reconstruct past climate conditions. "A dendrochronologist who selects cores from trees with the best crossdating and the highest sensitivity is simultaneously selecting for high percent variance in the group chronology, for high correlation among trees, and for a high proportion of climatic information in the chronology of the site" (FRITTS 1976, 295).

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[4] In AD1928 (interval AD1927–28) 14 trees experience a negative and one tree a positive interval. This ratio results in a *Gleichläufigkeit* of 93,3%, where 100% represents the maximum and 50% no signal strength. Chronologies with a mean *Gleichläufigkeit* of less than ca 60% over the entire length possess a low potential to reconstruct past climatic variation.

[5] For details especially concerning the "problematic nature of small values" see ESPER et al. 2001b.

3.2 Standardization

Another issue for the interpretation of chronologies is the "age-trend" and the techniques to remove biological or site-related noise from tree-ring series. The climatic variation of interest is generally superimposed on these long-term declines (BRÄKER 1981; COOK a. KAIRIUKSTIS 1990; FRITTS 1976).

Observing the biomass increase over a tree's life span, the yearly radial expansion (TRW) of the tree trunk needs to be distributed around an increasing tree girth. Since constant long-term tree productivity is a reasonable assumption, the annual increase in width will display gradually declining values through time. This property of decreasing TRW during a tree's life is called age-trend. Since this biological trend appears in measured TRW series, it allows a differentiation into "juvenile" and "adult wood" (Fig. 4 a). Consequently, if differently aged sequences of two living trees (e. g. with cambial age tree 1 = 200 years, and tree 2 = 300 years) are averaged, the resulting chronology is biased by age-trends (BRÄKER 1981). This noise justifies the necessity of standardizing raw individual series into dimensionless indices to remove disturbances caused by age-trend. Standardization also aims to make different TRW sequences, e.g. from a slow and a fast growing tree, comparable.

Figure 4 shows a schematic example of standardizing two even-aged trees with different growth rates (T1 fast, and T2 slow growing). Both form idealized age-trends that can be removed by calculating residuals (Fig. 4b) or ratios (Fig. 4c) from "expected growth curves" (Fig. 4 a, 5-year digital filters, GASSER a. MÜLLER 1984). And, in both original series the inter-annual variance (spread) is related to the TRW values (level). Calculating residuals removes age-trend, but does not change the variance structure of the series. Yet ratios also stabilize the variances, so that T1 and T2 behave almost similar through time. These differently standardized series might emphasize again the meaning of signal strength. Stabilizing the variance through time and increasing the variance in common are principal aims of the chronology-building process (COOK a. KAIRIUKSTIS 1990; COOK a. PETERS 1997; FRITTS 1976; SCHWEINGRUBER 1983).⁶⁾

There are, nevertheless, some relevant limitations regarding the age-trend concept, when analysing different trees and different sites. First, not all trees of a given site develop comparable age-trends, as in the Alps (NEUWIRTH et al. 2001; TREYDTE et al. 2001), and second, trees exist where age-related noise is absent in almost all TRW series, like the old *Juniper* series from the Karakorum (ESPER 2000 b; ESPER et al. 2001 c) (Photos 1a and 1b). These circumstances introduce the problem of defining age-trend as inherent biological noise. If age-trend is the consequence of distributing stable biomass productivity around an increasing girth, then every tree of a sampled site should develop somehow uniform TRW trends, which is not the case. Thus other factors, like population density and dynamics or strip bark formation (ESPER 2000 a; FERGUSON 1968), need to be considered to understand biological noise and to separate them from superimposed long-term climatic trends. Nevertheless, trees with and without age-trends need to be averaged to prepare well-replicated site chronologies, and solutions to optimize these procedures are an ongoing area of methodological tree-ring research (BRIFFA et al. 2001).

Commonly used procedures to remove age-trend are, *(i)* to fit different smoothing functions to each tree, or *(ii)* to use only one function for all trees. The first option enables fitting a function describing the unwanted noise (e. g. negative exponential function) to a tree-ring series with age-trend, and within the same data set another function is chosen (e. g. spline, COOK a. PETERS 1981) to standardize a tree-ring series lacking age-trend. The resulting standardized series will then experience a rise of common signals and enable the calculation of a chronology reflecting climatic variation.

Both of the methods have weaknesses, however. The first procedure greatly depends on the individually fitted growth curves chosen by the operator. Since the second variant uses only one function, it does not distinguish precisely between differently biased sequences. This procedure leads generally to standardized individual series with a lowered degree of common variance. To be clear, the resulting chronology will average individual series with a wider vertical spread to each other.

This brief discussion on current standardization procedures might indicate that the variance of chronologies greatly depends on the techniques an operator applies.⁷⁾ Note that almost all published chronologies average standardized individual series, and that the

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⁶⁾ In the current dendrochronological literature a trend towards calculating residuals together with a prior power transformation (to stabilize the variance) is evident. This technique has some advantages compared to the calculation of ratios, when stiff splines or filters or negative exponential functions or linear curves are fitted to the raw series. For details especially on the "end effect problem" see COOK a. PETERS (1997).

⁷⁾ In this example we would prefer the second technique. Even if the resulting chronology might possess lower degrees of common variance, the statistical procedure appears to be more intelligible.

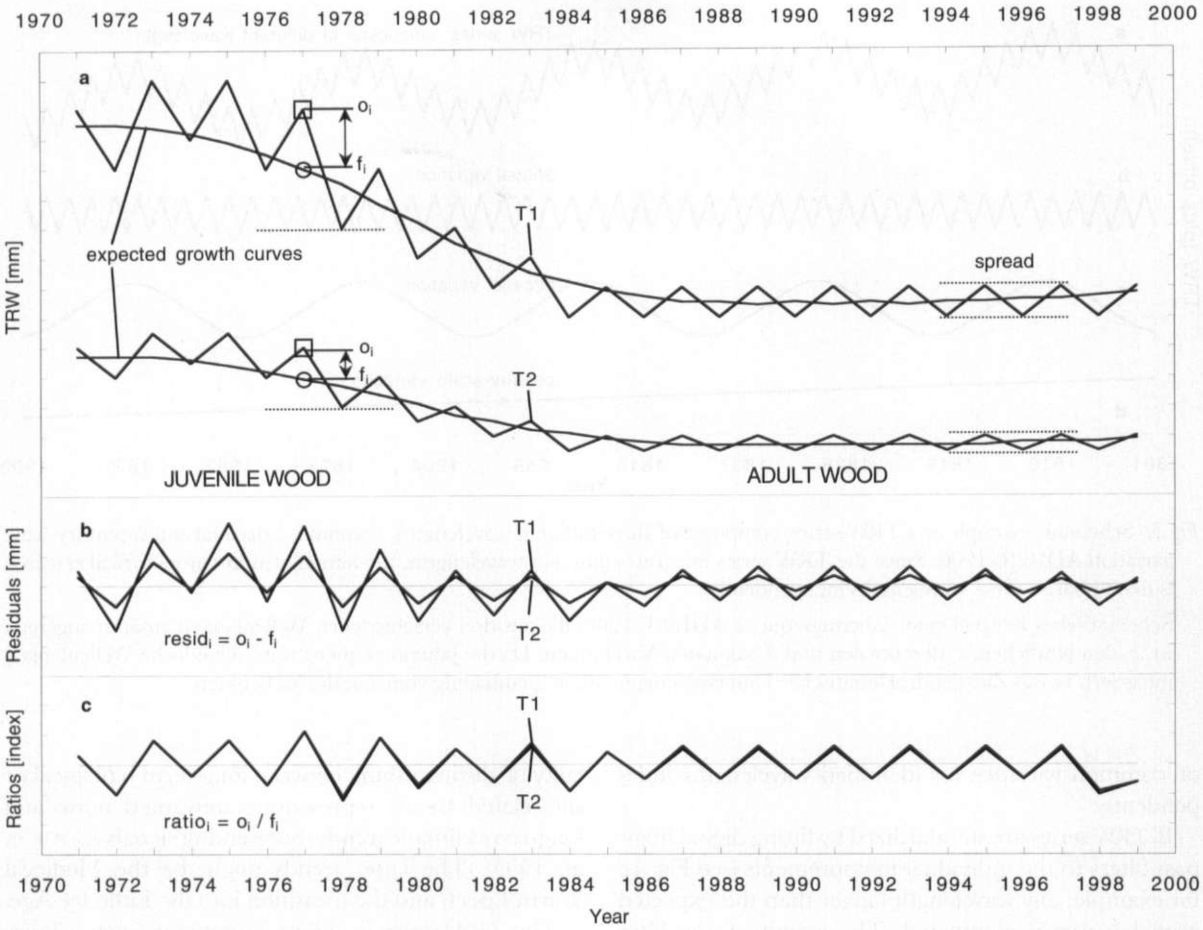

Fig. 4: Schematic example of standardization. *a*, Both trees, T1 and T2, are biased by (almost proportional) age-trends making a differentiation in "juvenile" and "adult wood" possible. T1 has wider tree-rings (in mm) than T2. The variances (dotted lines) decline through time, differ between T1 and T2, and are related to the level. Expected growth curves (5-year digital filters, *f*) describe the age-trends of the original series (*o*) for each year *i*. *b*, Calculating residuals between the original series (o_i) and the fitted function (f_i) removes any long term variation, like age-trend. However, the variances still differ between T1 and T2. *c*, Calculating ratios (o_i / f_i) considers the spread-versus-level relationship and even stabilizes the variance

Schematisches Beispiel einer Standardisierung. *a*, Beide Bäume, T1 und T2, sind durch (fast proportionale) Alterstrends gekennzeichnet, die eine Unterscheidung in „juveniles" und „adultes Holz" ermöglichen. Die Jahrringe von T1 sind breiter (in mm) als die von T2. Die Varianz (punktierte Linien) nimmt mit der Zeit ab, ist zwischen T1 und T2 unterschiedlich und korreliert mit der Jahrringbreite. Angepasste Ausgleichsfunktionen (5-jährige digitale Filter, *f*) beschreiben die Alterstrends der Rohwertkurven (*o*) für jedes Jahr *i*. *b*, Die Berechnung von Residuen zwischen den Rohwertkurven (o_i) und den Ausgleichsfunktionen (f_i) eliminiert alle langfristigen Variationen. Allerdings bleibt die unterschiedliche Varianz zwischen T1 und T2 erhalten. *c*, Die Berechnung von Quotienten (o_i / f_i) gleicht die Varianz sowohl zwischen den beiden Serien als auch entlang der Zeitachse aus

chosen techniques determine the amount of long-term trends as well as the variance of the resulting chronology.

3.3 *Wavelength*

We here explain the concept of separating different wavelengths and focus the most questioned scale, the centennial variation. Since a TRW series is the expression of the stem's cambial activity through the tree's life span, climatic variability influences portions of the TRW series variation. And since climate and other limiting factors vary on different time-scales, a sequence of tree-rings reflects a composite of different wavelengths. Dendroclimatological research aims to isolate these wavelengths for each tree and to determine the degree

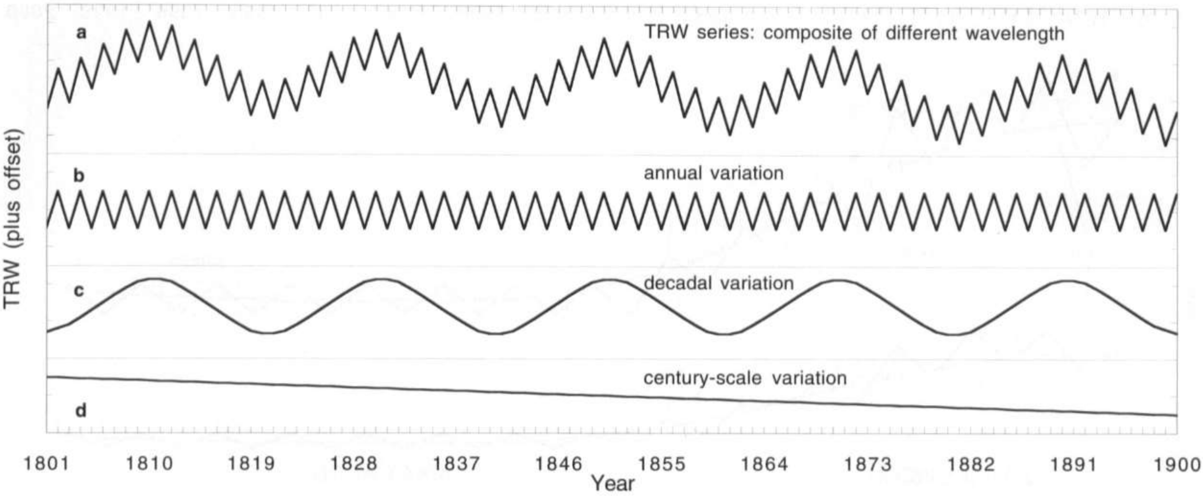

Fig. 5: Schematic example of a TRW series, composed of three different wavelengths, *b*, annual, *c*, decadal and *d*, century-scale variation AD1801–1900. Since the TRW series integrates different wavelengths, the aim of dendrochronological research is to emphasize these wavelengths independently

Schematisches Beispiel einer Jahrringsequenz AD1801–1900, die aus drei verschiedenen Wellenlängen zusammengesetzt ist, *b*, den jährlichen, *c*, dezennialen und *d*, säkularen Variationen. Da die Jahrringsequenz unterschiedliche Wellenlängen integriert, ist das Ziel dendroklimatischer Untersuchungen, diese unabhängig voneinander zu betonen

of common variance for identified wavelengths independently.

If TRW series are standardized by fitting digital high-pass filters to the individual measurements (see Fig. 4), for example, any wavelength longer than this expected growth curve is eliminated. The length of the filter fitted to the raw series determines the maximum length of TRW variation in the resulting index series. Figure 5a is a schematic example of a TRW series composed of (b) inter-annual, (c) decadal and (d) century-scale variation. If a seven year high-pass filter is fitted to the original data (a), inter-annual variation will be emphasized in the resulting standardized series (b). If an intermediate, 51-years filter is fitted to the raw series, decadal variation will be emphasized (c). Both wavelengths, inter-annual and decadal, can easily be emphasized within a data set of lets say 20 trees sampled at one site, and the common variance of both chronologies can be analysed independently.

These procedures are applied to most published chronologies. There exist plenty of useful models that may be fitted to the raw individual series to emphasize common variance up to decadal and inter-decadal wavelengths (synopses in Cook a. Kairiukstis 1990; Fritts 1976). However, preserving century-scale variation is more complicated and chronologies reconstructing climatic variation in this wavelength are still rare (e. g. Esper 2000 b; Esper et al. in prep.). The reason for this discipline-specific problem is the difficulty of distinguishing between long-term biological or site-related trends representing unwanted noise and long-term climatic trends representing signals (Cook et al. 1995). The latter trends might be the Medieval Warm Epoch and the transition into the Little Ice Age.

The TRW series in figure 5a contains such a long-term trend of decreasing values and since this persisting variation (d) is added to the shorter wavelengths (b, c), the raw measurement declines through time. An often-applied solution to emphasize long-term climatic trends is fitting different models of expected growth curves to the individual series (section 3.2). If a positive overall trend is recorded in a raw individual series, this trend is assumed – due to the geometric properties of stem growth discussed earlier – to be a climatic signal. In this case operators might avoid fitting a model with positive overall inclination to the original series (e. g. linear trend line). However, if a comparable but negative trend is recorded by a raw individual series, this trend is assumed to be biological noise. Fitting growth curves with negative slopes removes long-term trends of this kind. Note that this procedure of differently detrended individual tree-ring measurements to remove long-term, age-related noise, might overestimate 20th century positive trends in chronologies.

One of the most powerful techniques in current dendrochronological research to avoid these problems is the "regional curve standardization", (RCS; Briffa et al. 1992; Esper et al. 2001 a). RCS aligns all individual series by biological age, i. e. the series are shifted left along the X-axis, so that the first tree-ring of all (differently aged) trees of a population is equal to zero. The raw series are then averaged together and a growth curve is fitted to the mean, using a stiff spline or a negative exponential function, for example. This curve is then used to de-trend all individual series by calculating ratios or residuals. The final step is to date the (standardized) series back to calendar years. This method preserves long-term, centennial trends in tree-ring chronologies. The key is the assumption of a temporally independent noise-function ("regional curve", RC) representing an age-related, long-term trend valid for a given data set and removed from all individual series.

Even though this procedure enables emphasizing low frequency variation, the result depends on the similarity of growth levels and age-trend slopes in the raw data set (BRIFFA et al. 1992). If the RC is fitted to individual series with and without age-trend, the function is less useful to remove age-related noise from a data set. In addition, huge sample depths are required to calculate robust de-trending models. Note that chronologies containing century-scale variation generally have wider confidence limits than chronologies emphasizing variation on shorter time-scales (BRIFFA et al. 1996).

3.4 Calibration and transfer

If the mentioned chronology building steps are considered, that is:

- climatically sensitive trees were sampled,
- biological and site-related noise were removed,
- different wavelengths of growth variation were emphasized and
- signal strengths were quantified,

chronologies can be calculated with the aim to reconstruct climatic fluctuations. The final step is the statistical transfer from tree-ring values into climatic variables. Therefore correlation and regression analyses, like response functions (FRITTS 1976), are calculated to quantify the tree-ring response to precipitation or temperature variation, for example. The typical process is: *(i)* Calculation of regression functions (multiple stepwise, simple linear, etc.) between tree-ring and climatic data within a defined period, *(ii)* verification of the ascertained dependency in another period, and *(iii)* reconstruction of climatic variation on the basis of a stable, time-independent, relationship between tree-rings and climatic variables. In the last step the tree-ring chronology is used as a predictor to estimate climatic variation with a quantified certainty, calibrated and verified in steps *(i)* and *(ii)*. Even if this procedure is widely accepted and undisputed, some qualities regarding multiple regressions, temporally varying responses, and validated versus reconstructed wavelengths should be known for the interpretation.

Multiple regression techniques permit quantifying tree-ring responses to a variety of climatic variables. Calibrating a tree-ring chronology against several climatic parameters generally increases the variance explained by different, perhaps orthogonal, forcings. However, when applying these techniques the selectivity of the reconstructed climatic signal as well as the ecological understanding is reduced broadly (BRÄUNING 1999). It seems to be misleading, for example, that a climatically sensitive chronology enables one to reconstruct $R^2 = 0.4$ explained variance of summer temperature, $R^2 = 0.15$ explained variance of winter precipitation, etc. Interestingly, a trend towards simple regression analysis has taken place in the current dendrochronological literature (e. g. BRIFFA et al. 1998a; 1998b). This trend might lead to a greater understanding of the results by those in other disciplines. In any case, the natural interdependencies between different climatic variables need to be considered, if transfer-functions are calculated (SCHWEINGRUBER 1996).

Another approach is the understanding of the temporally changing nature of the relationship between tree-ring parameters and climatic variables. Many studies showed that the limitation of a single climatic variable, like summer temperature, varies through time, from year-to-year (e. g. SCHWEINGRUBER et al. 1991). This finding results in the formation of pointer years (section *3.1*). Thus the calculation of dependencies by applying correlation coefficients in defined time-windows integrates strongly influenced pointer years, as well as slightly influenced years with diminished limitation by a particular climatic element. To be clear, the application of correlation and regression techniques prevents a complete understanding of the (temporally changing) tree-ring response to climate. A single-year analysis in addition to continuous calculations is therefore highly recommended.

Another restriction that may limit the interpretation of published tree-ring reconstructions is the discrimination of validated and reconstructed wavelengths in the transfer process. The tree-ring response to climate is frequently quantified in the high frequency domain only. Calibration and verification might, for example, prove that a summer temperature controls tree growth with an explained variance of $R^2 = 0.5$. Since this dependency enables the reconstruction of inter-annual summer temperature changes, it does not necessarily justify the reconstruction of long-term, multi-decadal summer temperature trends. Palaeoclimatic studies using proxy records need therefore to distinguish precisely between the emphasized wavelengths, and make clear which wavelength dominated the calibration (and verification) process and which wavelength is shown by the reconstruction.

4 Conclusion

Tree-ring chronologies are high-resolution proxy sources to reconstruct climatic variation on longer time-scales. They are highly useful to understand past climatic variability and to forecast valid trends. Even though a gap still exists in information concerning certified low frequency variation (HUGHES a. DIAZ 1994), dendroclimatological reconstructions contribute considerably to the current debate on global warming (IPCC). The integration of different tree-ring parameters like TRW, MXD and stable isotopes, is highly recommended to increase the utility of tree-ring based chronologies. The combination of numerous chronologies to comprehensive "networks" enables additional verification and regional differentiation of reconstructed climatic fluctuations. If the climatically forced, common tree-ring variation from a given region is understood, other environmental processes (e. g. mass movement) can be reconstructed by analysing individual growth reactions and comparing them with the unaffected "master-chronology".

However, there exist some chronology building steps a geoscientist should know to relate the outcome of dendrochronological research to his own work. The most important are the concept of common variance, the effects of standardization, the differentiation of distinct wavelengths, the temporally changing nature and quality of climatic response, and the coherence between calibrated and reconstructed climatic variation. These techniques are crucial for the understanding of tree-ring chronologies and they enable a rating of published results by readers from other disciplines.

Current dendroclimatological research is still dominated by the requirement to transfer tree-ring values into climatic variables. This axiom will probably be questioned in the ongoing evolution of the discipline. Since environmental changes, like the alteration of vegetation boundaries in high mountainous ecosystems, can be recorded directly, the transfer to climatic variables seems to blur the original signals covered by perennial plants. To answer questions of how forest populations respond or ecosystems adapt to climate change, reconstructions of temperature and precipitation are less informative than the data provided by the trees themselves. A recent development that might lead to fewer efforts concerning transfer functions might be the dramatically increased relevance of carbon-sequestration pools and fluxes of terrestrial ecosystems.

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