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A "signal-free" approach to dendroclimatic standardisation

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Abstract

We describe a potential problem with the use of standardisation techniques that fit growth curves directly to measurement data. The existence of medium-frequency variance (considered here to represent timescales of decades to a century) in the common climate-related forcing of tree growth can bias the removal of supposed "non-climate" variance, leading to distortion of the external forcing signal in tree growth chronologies. This is most prevalent at the ends of the chronologies. The term "trend distortion" is used to describe this effect. The idea that the common forcing signal can be removed from multiple series of ring measurements so as not to bias the chronology standardisation process constitutes the rationale for this discussion. This simple first attempt to mitigate the trend distortion problem, using division of the common signal into the original measurement data, represents an empirical "signal-free" standardisation approach. This can reduce or remove the distortion in the expressed external forcing signal. However, as with previous data-adaptive curve-fitting approaches, this leads to the need to adjust the overall trend of the resulting chronology which has arbitrary slope after being standardised using the "signal-free" method. Hence, the use of signal-free methods will limit the preservation of long-timescale variance to that of the length of the chronology. Trend distortion is described and demonstrated using simulated and measured ring-width series. Signal-free methods are developed and are used to minimise trend distortion in chronologies produced using so-called "conservative" standardisation methods, applied here to ring-width measurements from northern Scandinavia but also to samples from Canada. Some of the limitations of using traditional standardisation and some of the potential benefits and limitations of using signal-free methods in conjunction with traditional standardisation methods are presented and discussed.

Keywords: Signal-free; Dendrochronology; Standardisation; Dendroclimatology

Introduction

In dendroclimatology, the need to separate the effects of external climatic forcing on tree growth from the natural internal variation found in tree growth measurements led to the development of specific techniques referred to as "standardisation" methods (Fritts, 1976). The natural tendency for radial ring width (and other growth measurements) to decline slowly over the life of a tree is commonly described as the age-related growth trend, which needs to be estimated and removed from measurement series in order to isolate the evidence of external, climatically driven forcing of tree growth. The age-related growth trend is thus the value of growth for each ring age that would be expected in the absence of any variation in climatic forcing. Perceived differences

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in the growth rates of trees growing in similar climatic conditions led to the practice of developing an individual age-related growth curve for each series of measurements (Fritts, 1976). The variance in tree-ring measurements due to climate-related growth forcing is generally proportional to the local mean of the measured ring width (Cook and Briffa, 1990), which is consistent with the presumption that the common forcing for each year has a similar proportional influence on the growth of each tree. Series of tree indices can, therefore, be considered as series of fractional deviations of measured growth from expected growth (Douglass, 1936). The division of measured values by the values of the age-related growth curve removes the age-related growth trend from measurements, removes the effects of overall differential tree growth rates, and results in a (quasi) stationary series of tree indices which are in a suitable state to be averaged to form a chronology (Fritts, 1976). Here we consider only this multiplicative approach to tree-ring standardisation.

A very significant problem for the resolution of long-timescale climate variability from tree rings is the high-pass filtering effect inherent in many standardisation methods, the so-called "segment length curse" (Cook et al., 1995; Briffa et al., 1996). Using traditional standardisation, an age-related growth curve for each series of ring measurements is estimated by fitting a curve to series of measurements, most commonly using deterministic methods such as least-squares-fitted sloping lines or modified negative exponential curves (Fritts et al., 1969), or data-adaptive methods such as filtering with high-pass digital filters or smoothing splines (Cook and Peters, 1981). These are referred to here as "curve-fitting" methods. They remove the slope from each series of measurements because the slope of the "fitted" expected growth curve is the same as the slope of the series of measurements. Curve-fitting methods also rescale the data series from each tree, producing indices with a mean of approximately 1.0. These two actions limit the preservation of long-timescale variance in series of tree indices and chronologies produced from them, to periods with lengths below that of the age of the trees (Cook et al., 1995).

Commonly used implementations of curve-fitting methods (e.g. Jacoby and Cook, 1981; Luckman et al., 1997; D'Arrigo et al., 2004), as implemented in programs such as INDEXA (Fritts et al., 1969) and ARSTAN (Cook, 1985), consist of finding an age-related growth curve for each series of measurements from a "hierarchy" of potential curve-fitting options. If the preferred choice cannot provide a suitable detrending curve (e.g. because values of the fitted curve approach zero) then the next choice method is tried. The so-called "conservative" methods (Jacoby and D'Arrigo, 1989; Luckman et al., 1997) as typically implemented in the ARSTAN program employ the following hierarchy of options (hereafter referred to as NEXP): modified negative exponential curve, negatively sloping straight line and horizontal line or mean. The final option in the hierarchy, i.e. of fitting a horizontal line, does not fall within the above definition of "curve-fitting" methods because the slope of the fitted line is not constrained by the slope of the measurements and is generally based on the assumption that ring widths never normally increase over the life of a tree (Fritts, 1976). Even though the magnitude of external long-term growth forcing can in theory increase or decrease, chronologies generated using these curve-fitting methods can never have a negative slope. The final chronology is constrained to have an 'arbitrary' positive (or zero) slope which depends on the proportion of measurement series fitted with a horizontal line. Dendroclimatologists generally leave the chronology slope at this "default" value.

Trend distortion

The adaptive fitting of curves to series of tree-ring measurements makes no allowance for the fact that measurements represent a mixture of the internal biological growth influence and the external (climatic) common forcing on tree growth. Variance representing the effects of climate forcing on tree growth is present in series of measurements and this variance can influence the shape of the age-related growth curves produced as statistically fitted functions. Consequently, when this fitted growth trend is removed, some of the variance of the sought after climatic forcing signal can also be removed, leading to a distortion in resulting index series. The name "trend distortion" has been used to describe this problem (Melvin, 2004, Section 4.4). When an age-related growth curve is created by calculating a least-squares-fitted sloping straight line and division is used to create tree indices, this straight line detrending sets the sum of the products of indices and distance from the centre of the series to zero (by definition producing a series with a slope of zero). Every index is changed by an amount proportional to that value's distance (in time) from the centre of the series, in effect a rotation. The "excess moment" created by a persistent trend in the external forcing of tree growth near the end of a series, will change the slope of the series and this slope is subsequently removed by adjusting every index value.

The extent of distortion created using a data-adaptive detrending curve (e.g. a modified negative exponential or smoothing spline) will be limited by the flexibility of the fitted curve. High-frequency variance in the common signal that produces little net change in slope, will not generally result in trend distortion. Variance in the common signal at frequencies lower than that of the flexibility of the detrending curve will be removed because the detrending curve can "follow" the series of measurements. When common forcing has variance on timescales representing decades to half the length of a tree and the detrending curve is inflexible, then trend distortion can occur. To create a systematic bias in a chronology the trend distortion must be common to a number of trees. In the central portions of a long chronology developed from overlapping trees, where the distortion will occur in the early, middle and late sections of tree-index series, it is likely to be reduced by the averaging process leaving little resultant distortion. The bias in a chronology created by trend distortion will be manifest mostly at the modern end of the chronology, where many series end on similar dates.

In Fig. 1a, a 20-year smoothing spline is fitted to a simulated series of tree-ring measurements describing a negative linear trend and an unusually low value at year 25. The fitted curve dips down towards this low value and as a result neighbouring index values will be higher than would be the case for a less flexible fitted curve. The distortion created by one anomalous value is relatively small and of limited consequence. Fig. 1b shows a simulated series of measurements with a linear decay which have been given an additional two-decade-long, 20% growth increase (multiplication by 1.2) near their recent end to simulate a temporary change in common

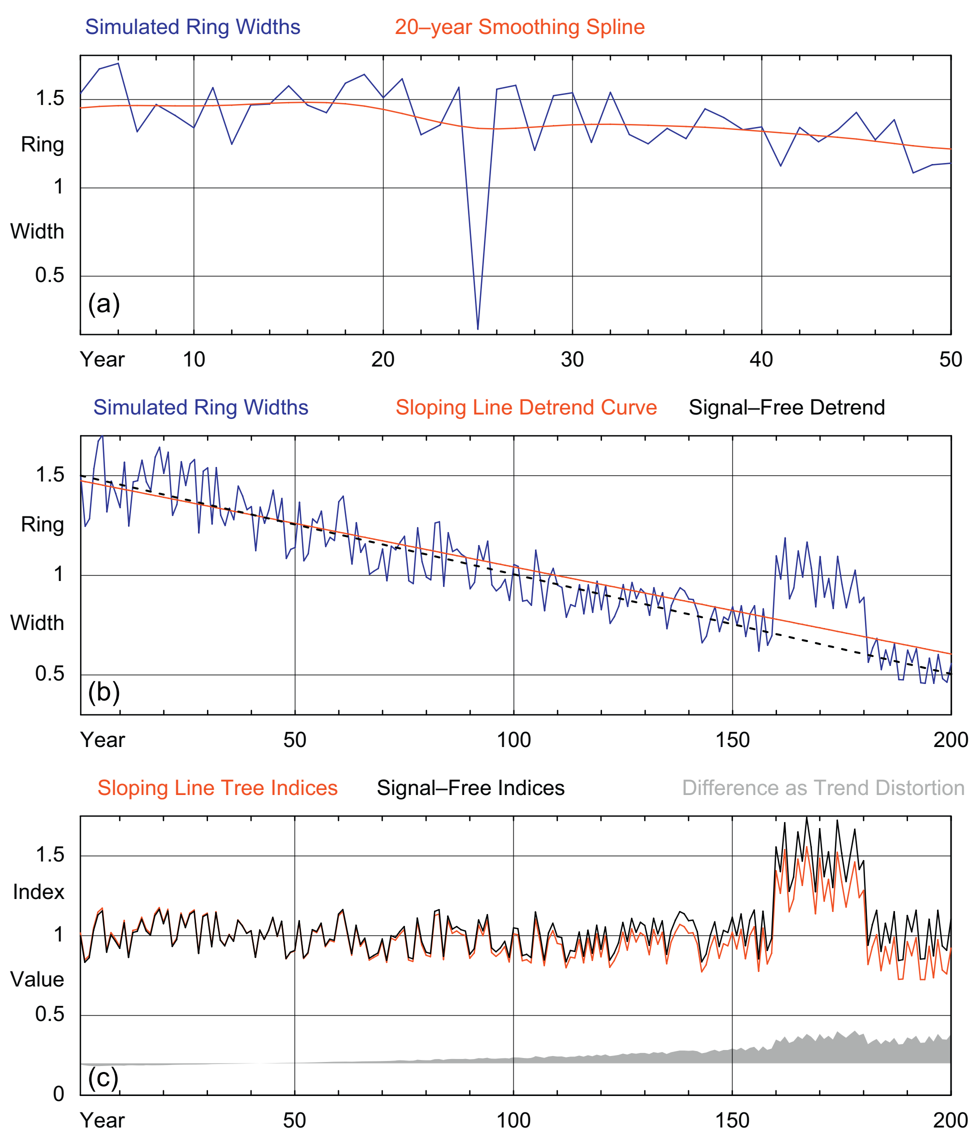

Fig. 1. Illustration of trend distortion: (a) the effect of a single low value on a fitted 20-year smoothing spline, (b) the effect of a 20-year-long growth increase on age-related growth curves (least-squares-fitted sloping straight lines) developed alternatively by: fitting to simulated measures while ignoring the "known" growth increase (dashed black line); and fitting to the data with the growth increase (solid red line). The series of indices generated from these alternative growth curves are shown as the black and red curves in (c) and the difference (grey shaded area) represents the extent of trend distortion.

climate-related forcing (blue line). The difference in straight line fits to these series, with (red) and without (black) the growth increase represents the extent of trend distortion (plotted as a grey wedge, Fig. 1c) of the underlying climate signal represented in the index series. The growth increase over a 20-year period (simulating a climatic forcing event) has modified the slope of the age-related growth curve and distorted the resulting tree-ring indices so that, in this case, the mean values of indices after year 180 (red line of Fig. 1c) are below the values of 1.0 expected from ring measurements with a linear decay. The length of the "wedge" of trend distortion is set by the flexibility (period of "rotation") of the detrending curve and the magnitude of the distortion of each index value is proportional to both the distance of that index from the centre of rotation and the index value.

The concept of "signal-free" standardisation of tree-ring measurements

The commonly used dendroclimatic, *multiplicative* model of tree growth described in detail by Melvin (2004, pp. 53–56) is used here, where for each tree ring:

$$\text{Tree index} = \frac{\text{Ring width}}{\text{Expected growth}} \quad (1)$$

Expected growth for each year is the value of the curve, an estimate of the age-related growth trend, fitted to each measurement series. Tree indices are thus "fractional deviations" from expected growth and chronology index values, calculated as the arithmetic mean of all tree indices for a year, are also fractional deviations. An error term for each ring (Error), which is proportional to the chronology index value and is thus consistent with the observation that the standard deviation of chronology indices is generally proportional to the chronology index value (Melvin, 2004, Fig. 6.3.4c), is introduced to explain the difference between chronology-index values and tree-index values as follows:

$$\text{Chronology index} = \frac{\text{Tree index}}{\text{Error}} \quad (2)$$

From (1) and (2) then for each ring

$$\text{Ring width} = \text{Chronology index} \times \text{Expected growth} \times \text{Error} \quad (3)$$

Chronology indices, created as the average of tree-index series, are fractional deviations implying that chronology signals can be added to or removed from series of tree measurements by multiplication and division. If a ring measurement is divided by the chronology index value then the resulting value will be an "estimate" of the amount of growth that would have occurred if the chronology index had a value of 1.0, i.e. the amount of growth that might have occurred in an "average" growth year. The term "signal-free" is adopted here to describe the series resulting from the division of measurements by chronology indices

$$\text{Signal-free measurement} = \frac{\text{Ring width}}{\text{Chronology index}} \quad (4)$$

A series of signal-free measurements is thus an estimate of the tree growth that would have occurred in an unvarying, mean climate but includes the age-related growth curve and the medium- to high-frequency noise or Error (Eq. (5)) found in tree measurements.

$$\text{Signal-free measurement} = \text{Expected growth} \times \text{Error} \quad (5)$$

Fitting a smoothly varying curve to a series of signal-free measurements (to reduce the error term of Eq. (5)) will result in the generation of a smoothly varying age-related growth trend for that series whose shape is independent of the effects of the common growth forcing signal (e.g. dashed line of Fig. 1b) and thus will enable a better representation of the underlying growth curve. If the common forcing signal is removed from each series of measurements then standardisation of the resulting signal-free series should produce a chronology with no variance. The ability to "remove" the common variance found in tree growth measurements (caused by common growth forcing at a site) can form the basis of a test of the performance of standardisation.

Division of measurement series by "an estimated chronology signal" and subsequent standardisation of signal-free series can be independent processes. Any residual common signal resulting after the standardisation of signal-free measurement series will indicate that the common signal has not been completely removed from the series of measurements and leads to the possibility of using this "signal-free residual" to remove this residual bias, assumed to have been created by trend distortion. An initial chronology, created by standardisation, can be used to create signal-free measurements. A signal-free chronology, developed by standardising signal-free measurements, will then give an estimate of the amount of bias due to trend distortion in the initial chronology. As chronology indices are fractional deviations, multiplying the initial chronology by the residual chronology will "correct" the bias of the initial chronology. In theory, this process can be repeated iteratively while residual (signal-free) chronology indices continue to converge to 1.0. This is the basis of the signal-free method proposed here.

In practice it is necessary to allow for the following limitations in curve-fitting detrending methods:

1. When using automated curve-fitting it is necessary to ensure fitted curves do not approach or go below zero.

2. When using hierarchical curve-fitting methods small changes to the signal-free measurements can produce large changes in tree-index series (e.g. in NEXP, described below, by fitting a horizontal line instead of a modified negative exponential curve) and iterative convergence may not occur.
3. Because curve-fitting methods remove the low-frequency variance in creating a chronology, there are an infinite number of chronologies (all with common medium- to high-frequency variance but differing in their low-frequency content) which can produce a null signal-free chronology. This problem is circumvented here by ignoring the low-frequency variance that cannot be resolved using curve-fitting standardisation methods and reverting to a test for convergence of the "high-pass filtered residual" being negligible, i.e. subsequent iterations are unchanging.
4. Using curve-fitting methods tree-index series have a mean of 1.0 but standardising series of measurements using curves fitted to series of signal-free measurements can produce tree-index series with means that are not 1.0. This can introduce low-frequency variance in the resulting chronology, i.e. variance created because the means and lengths of tree-index series vary. To avoid this problem when using curve-fitting methods, the mean of each signal-free measurement series can be set equal to the mean of the measured ring-width series.
5. Division to remove the chronology signal fails where sample counts are 1 or less.

The procedure proposed here for use with curve-fitting standardisation is based on iteratively improving the estimates of the values of fitted curves and using these curves, fitted to the original measurements, to generate chronologies with progressively less trend distortion but with arbitrary slopes. The steps of the procedure are:

1. Create a chronology by standardising series of ring-width measurements.
2. Divide each series of measurements by their respective chronology indices to create series of signal-free measurements.
3. Rescale the mean of each series of signal-free measurements to equal the mean of the original measurement series.
4. Replace individual signal-free measurement values for years in which the chronology sample count is one with the original measurement values.
5. Create detrending curves by fitting curves to the series of signal-free measurements.
6. Divide each original series of measurements by the curve obtained by fitting to the signal-free measurements (5), thus creating tree indices.
7. Average the tree-index series to create a chronology.
8. Repeat (2) through (6) until one of the following:
   (a) If using hierarchical options to create a chronology (i.e. the NEXP option of ARSTAN), iterate only to a degree depending on replication (e.g. two times for only 20 trees and up to six times for 100 trees).
   (b) Again if using hierarchical curve-fitting options, fit a smoothly varying curve (e.g. 2/3 length spline) to all series whose curve-fit option changes during iteration and then rerun the procedure until (c).
   (c) If using smoothly varying detrending options, then cease when convergence is achieved. This is assessed using the filtered absolute difference between chronologies generated by consecutive iterations. High-pass filter the series formed as the difference between indices of consecutively generated chronologies with a filter stiffness at or longer than the length of the tree-index series (here we use a variable length spline (Melvin et al., 2007) of stiffness in each year set to the mean length of series contributing to that chronology year) and cease iterating when the mean of the absolute values of this high-pass filtered series is less than 0.0005.

Simulated examples: the problem and a potential solution

The so-called modified negative exponential method of standardisation or NEXP, as originally implemented in the program INDEXA (Fritts et al., 1969) and later in ARSTAN (Cook, 1985) is used here as an example of the general implementation of a curve-fitting approach to standardisation. This standardises measurement series by using one of a hierarchy of possible curve-fitting techniques: firstly a modified negative exponential curve; secondly a negatively sloping line; and lastly a horizontal line. Here tree indices are created by division and chronology indices are created as the simple arithmetic means of tree indices.

The effects of the segment length curse and trend distortion are demonstrated using simulated series of measurements with known climate signals. Series of tree measurements were created to simulate ring-width values extracted from uneven-aged, living trees. This was achieved by generating 101 measurement series representing trees with successive pith dates at every even year from 1700 to 1900, with all series finishing at year 2000. To simulate linear ring-width decay, the first ring of each series was given a value of 1.2 mm with a random increment of ±20% and the final ring width was set to half the initial value with a random increment of ±20% in order to create series with varying slopes.

Intermediate ring widths were set by linear interpolation between the initial and final values. To simulate exponential ring-width decay, annual values were set using the following formula:

$$\text{Value}(i) = A \times \text{EXP}\left(-\frac{i}{B}\right) + 0.1$$

where for each series, "i" is the ring age, constant "A" is 1.2 plus a randomly selected increment between ± 0.2, and time constant "B" is the series length plus a randomly selected increment between $\pm$half the series length. The linearly sloping (or exponentially sloping) series generated in this way are considered to represent the data that could be extracted from a number of trees with no common external forcing signal. Where high-frequency noise was needed, a series of random numbers with mean of 1.0 and range between 0.8 and 1.2 were generated and these were applied to all rings by multiplication.

Some simple time-varying chronology signals were produced to represent various types of "known" common forcing of tree growth and the ring widths of the generated trees were multiplied by the corresponding yearly values to produce sets of ring-width measurements representing the data that would be acquired under these different forcing histories. Three forcing histories were chosen. These included a sine wave of period 40 years, a mean of 1.0 and amplitude ± 0.1; a step increase created by increasing the ring-width values from 1950 to 2000 by 20%; and a linear increase created by increasing the ring-width values from 1900 to 2000 linearly by 0–20% in steps of 0.2%. These artificially generated expected chronology signals were rescaled to set their means to 1.0 and are plotted as dashed black lines in Fig. 2. The chronologies resulting from standardisation, using the NEXP option in ARSTAN, of the exponentially decaying series with added chronology signals are plotted as solid red lines. The negative slope of these generated measurement series was deliberately selected to be sufficiently large to ensure that the NEXP would not fit a horizontal line fit to any series.

Fig. 2a shows that the sine wave is clearly reproduced with the correct phase and amplitude. The mean of the last two decades of the sine wave chronology is above 1.0 and this leads to the observed low-amplitude trend distortion in the final decades of the sine wave chronology where indices are below their expected value. In Fig. 2b the "step increase" signal is not recognisable in the generated chronology. Indices prior to 1900 are approximately 1.0 and are not distorted. The trend introduced by the step increase has been removed by reducing the values of chronology indices from 1900 onwards by progressively larger amounts to leave a chronology with a slope of zero. The abrupt step at 1950 has been qualitatively reproduced but with some distortion in the signal leading up to it. However, this is followed by a major distortion with the chronology displaying continuous decline, down to below average values, despite the fact that forcing remained anom-

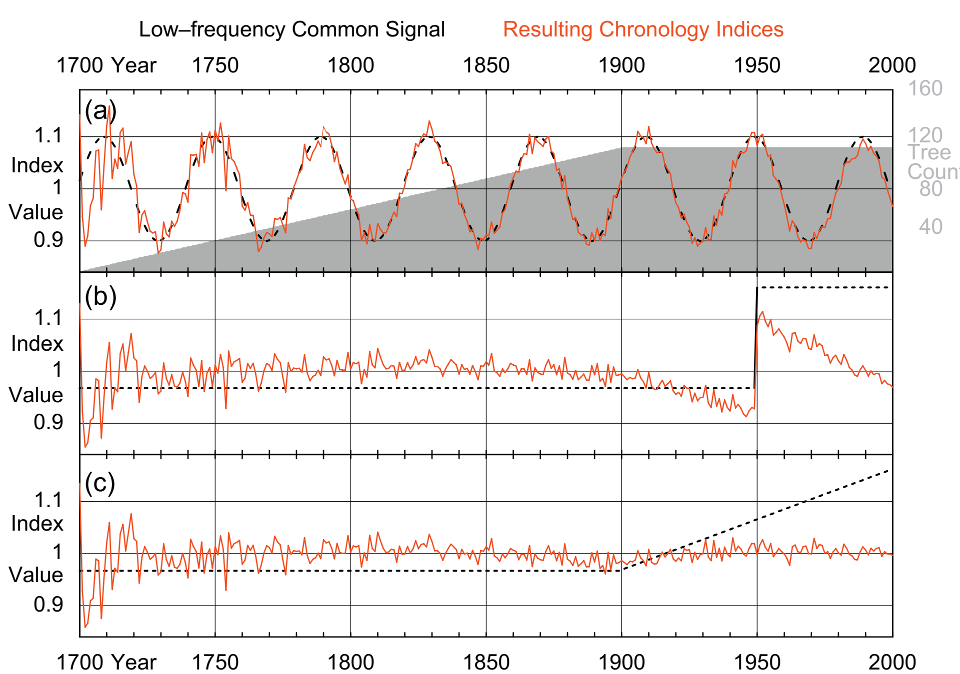

Fig. 2. Chronologies built from artificially generated ring-width series with exponentially decaying slope and high-frequency noise, with added common signals (dashed black lines), standardised using NEXP: (a) a sine wave chronology and tree counts (same for all three cases), (b) a step increase chronology, and (c) a linear increase chronology.

alously high. The low-frequency "linear increase" signal (Fig. 2c) is removed entirely from the chronology leaving indices which are approximately 1.0 for the full length of the chronology, demonstrating that this linear increase over 100 years is at a frequency sufficiently low to be removed by this "conservative" detrending method, in this case using trees of between 100 and 300 years old. Hence, the selected artificial signals that have positive slope (Figs. 2b and c) cannot be recovered using the NEXP standardisation option.

Fig. 3a shows the example of the artificial step increase signal (solid line) but with the slope set to zero by division by a least-squares-fitted straight line (dotted line), which forms the best possible signal that can be recovered within the limitation of the segment length curse, i.e. the artificial signal with an arbitrary slope. To illustrate the differences in indices generated by standardisation and the values that the series would require for their arithmetic means to generate the expected signal chronology, we have selected sample series (numbers 1, 26, 51, 76, and 101) with ages ranging from 301 years to 101 years in steps of 50 years from the linearly sloping chronology (without random noise). The chronology has been detrended using sloping straight lines. Each series of indices and the corresponding sections of the expected chronology signal have been replaced, either by their mean values (red horizontal lines) in Fig. 3b, or by their slopes (least-squares-fitted straight lines shown in red) in Fig. 3c. The tree indices have means of 1.0 and slopes of approximately zero. These can be compared with the mean values and slopes (shown as dotted lines) that these indices would require for the signal to be recovered. Much of the distortion of the step increase chronology (Fig. 2b) is a direct result of tree-index series having different lengths, arbitrary slopes of zero, and means of 1.0. The averaging together

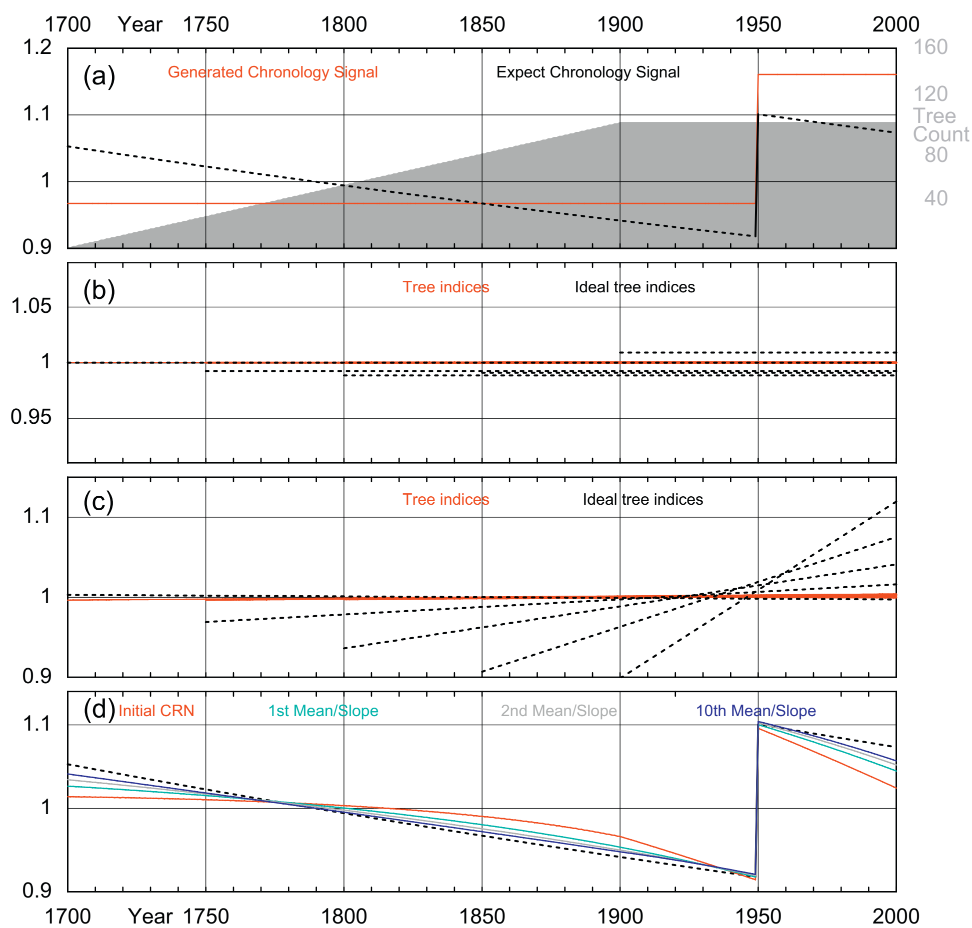

Fig. 3. (a) The artificial step increase signal (solid red) and this signal after division by a fitted trend line to remove slope (dashed black). A comparison of index series for sample series (numbers 1, 26, 51, 76, and 101), generated by standardisation of linearly sloping series (without high-frequency noise) using sloping straight lines, (solid red lines) and the expected chronology values for the common period of each (dashed black lines) with each series replaced by the series mean value (b) and secondly with each series replaced by the series least-squares-fitted straight line (c). (d) The artificial signal with zero slope (black dotted), the initial chronology (red), and the 1st (cyan), 2nd (grey) and 10th (blue) iterations of chronologies, created as the arithmetic means of index series, after setting the means and slopes of each index series to the mean and slope of the chronology (from the previous iteration) over their common periods.

of these tree indices cannot produce the expected chronology. This is the essence of the segment length curse.

The result of iteratively resetting the means and slopes of each series of indices to the means and slopes of the chronology over their common period is illustrated in Fig. 3d. Here we presume that the chronology signal (black dotted line) is not known so we start with the chronology (red) created by standardising all the linearly sloping measurement series with sloping straight lines. The means and slopes of each series were set to those of the chronology over their common period and then indices were averaged to produce a 1st "mean and slope-adjusted" (Mean/Slope) chronology (cyan). The process was repeated iteratively to produce a 2nd Mean/Slope chronology (magenta) and finally a 10th Mean/Slope chronology, by which time chronology indices had ceased to change. The 10th Mean/Slope chronology is an improvement on the initial chronology but still fails to reproduce the horizontal version of the artificial chronology signal contained by these trees.

Examination of Fig. 3d shows that the chronologies are curved. Division of a sloping straight line (e.g. linearly reducing ring-width data) by a sloping straight line with a different slope (e.g. due to a step increase) will produce a series of residuals that are curved. Where distance is measured from the centre of a series and is zero and changes sign at the centre, the last term of the product of two straight lines (slope multiplied by slope multiplied by distance squared) produces curvature and although the slopes are small this becomes noticeable at the ends of series when distances are large as can be seen in Fig. 3d.

$$(1.0 + \text{slope1} \times \text{distance}) \times (1.0 + \text{slope2} \times \text{distance}) = 1.0 + (\text{slope1} + \text{slope2}) \times \text{distance} + \text{slope1} \times \text{slope2} \times \text{distance}^2$$

The arithmetic mean of series which include high-frequency noise will be offset toward higher values (relative to normally distributed indices). Any common systematic bias in the fit of standardisation curves to series of measurements will be manifest within the chronology (e.g. if negative exponential curves are fitted to linearly sloping series of measurements or if sloping straight lines are fitted to exponentially decaying series of measurements), then there will be residual systematic bias in the final chronologies. For series of measurements detrended with fitted lines, potential solutions must involve adjusting the slope of the fitted line, e.g. the slopes of series of indices can be adjusted by changing the slope of the line fitted to the measurement series (Melvin, 2004, Section 5.5.7), but this is not pursued here using curve-fitting methods limited by the segment length curse.

In the general application of standardisation techniques, of course, the underlying chronology signal is not perfectly known. In the approaches discussed below, the assumption is always made that the initial chronology created by standardising the available tree-ring data is a partial representation of the undistorted chronology. This does not rely on any prior knowledge of the underlying common signal, other than assuming it is, within sampling error, held in common by the different tree series (as shown by the examples in Fig. 4). Fig. 4 shows samples of randomly generated ring-width series with a step increase at 1950, fitted detrending lines, and tree indices created from them by division. The distortion of the step increase signal can be seen to depend on the series length. The distortion of the linearly sloping series (Figs. 4a and b) could be removed by changing the slopes (rotation) of the fitted curves. In the examples of Figs. 4c and d where series of exponentially sloping measurements (blue) with a step increase common signal are detrended using a fitted negative exponential curve (red), rotation is not practical. In practice, the fitted curve closely follows the series of measurements for the first part of the series and the distortion created by fitting through the step increase is concentrated in the second half of the series. Rotation might correct the second half of the series but would result in a misfit in the first half. Hence, the methods involving resetting slopes, described above cannot be applied in situations where the curve used for detrending can "bend" to fit series of measurements. The solution explored here is to use the signal-free method to remove the common signal from all series of measurements and to generate expected growth curves by fitting to series of signal-free measurements, thus removing (or reducing) the source of distortion.

The signal-free method was used on randomly generated chronologies with a selection of specified common forcing signals in order to demonstrate such problems. Data sets representing randomly generated ring-width series with linearly reducing ring-width values (Figs. 5a–d) and added chronology signals comprising (a) a step increase at 1950, (b) a linear increase from 1900, (c) a step decrease at 1950, and (d) a linear decrease from 1900, were standardised using least-squares-fitted sloping straight lines. The "expected" common signal (dashed black line) created by dividing the added artificial signal by a count-weighted least-squares-fitted straight line, the initial chronology (red line) generated by the first iteration of standardisation and the final chronology (blue line) after six signal-free iterations are shown in each case. The distortion in the initial chronologies is marked and the chronologies generated by the signal-free method closely resemble the expected artificial chronologies after 1800 in Figs. 5a and b. The curvature after 1980 in Figs. 5c and d is more marked because indices have lower values than those of

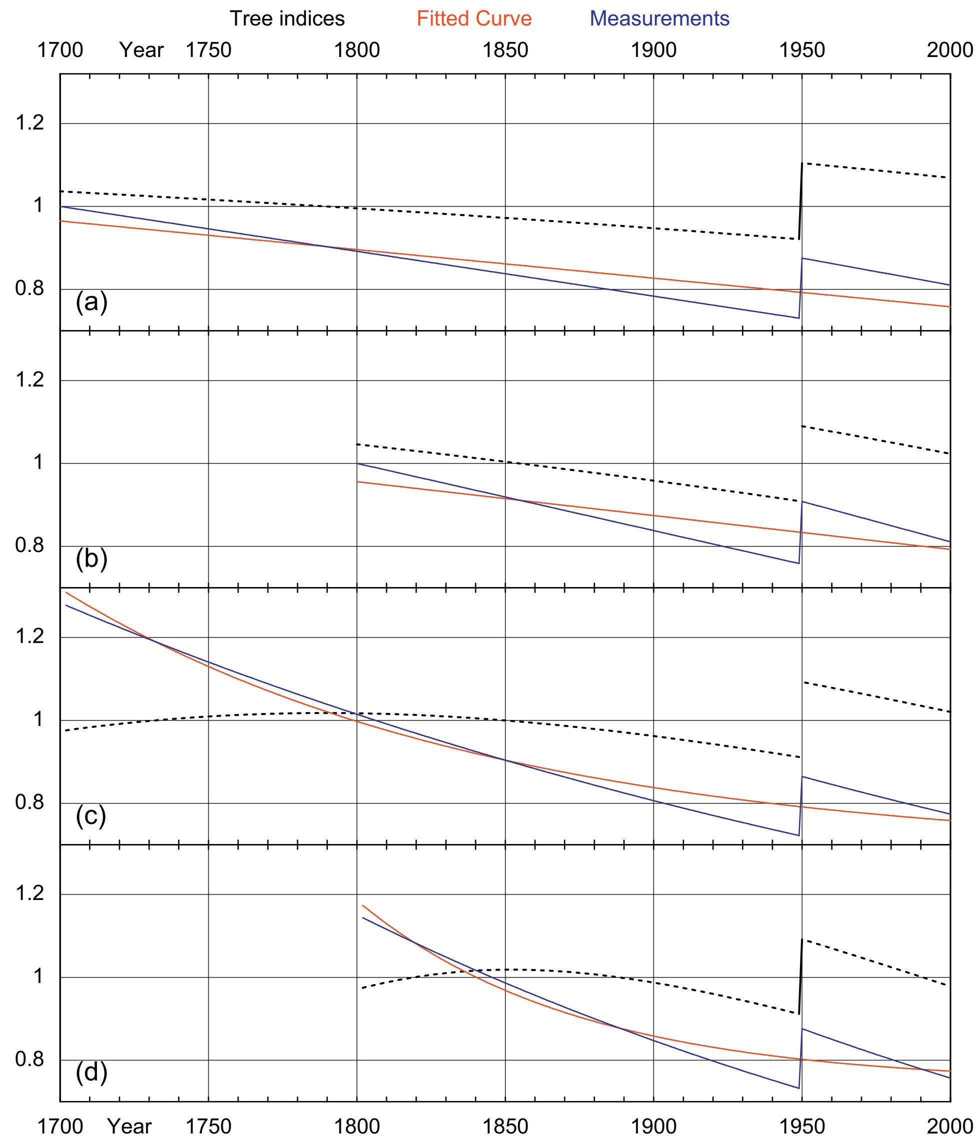

Fig. 4. Samples of randomly generated ring-width series all with a step increase signal from 1950, showing series of measurements (blue), fitted detrending curves (red), and tree indices (dashed black). For clarity, growth series do not contain high-frequency variability. 300 year (a) and 200 year (b) linearly sloping series detrended using least-squares-fitted sloping straight lines and 300 year (c), and 200 year (d) exponentially sloping series detrended using fitted negative exponential curves.

Figs. 5a and b. The pre 1800 periods of all four signal-free chronologies (blue), although not capturing as much of the input signal as during the later period, represent a general improvement over the single detrending using sloping lines.

Figs. 5e–h are similar to Figs. 5a–d except that the generated measurement series exhibit exponentially decaying slopes and each series has been detrended using a negative exponential curve. The initial chronologies (red) are seriously distorted relative to the expected common signals (dashed black) and signal-free chronologies (blue) are not an improvement. The problem is systematic bias; in Figs. 5e and f chronologies curve downwards relative to the expected signal because the fitted curves have lower decay rates than the decay rates of the simulated ring-width measurements (shown clearly in Figs. 4c and d) and in Figs. 5g and h, chronologies curve upwards relative to the expected signal because the fitted curves have higher decay rates than the decay rates of the simulated ring-width measurements.

Tree measurements and added artificial forcing

Demonstrating the effects of trend distortion with 'real' ring-width measurements is, of course, problematic, given that the precise nature of the external common forcing signal is not known. However, to demonstrate the potential of signal-free methods using

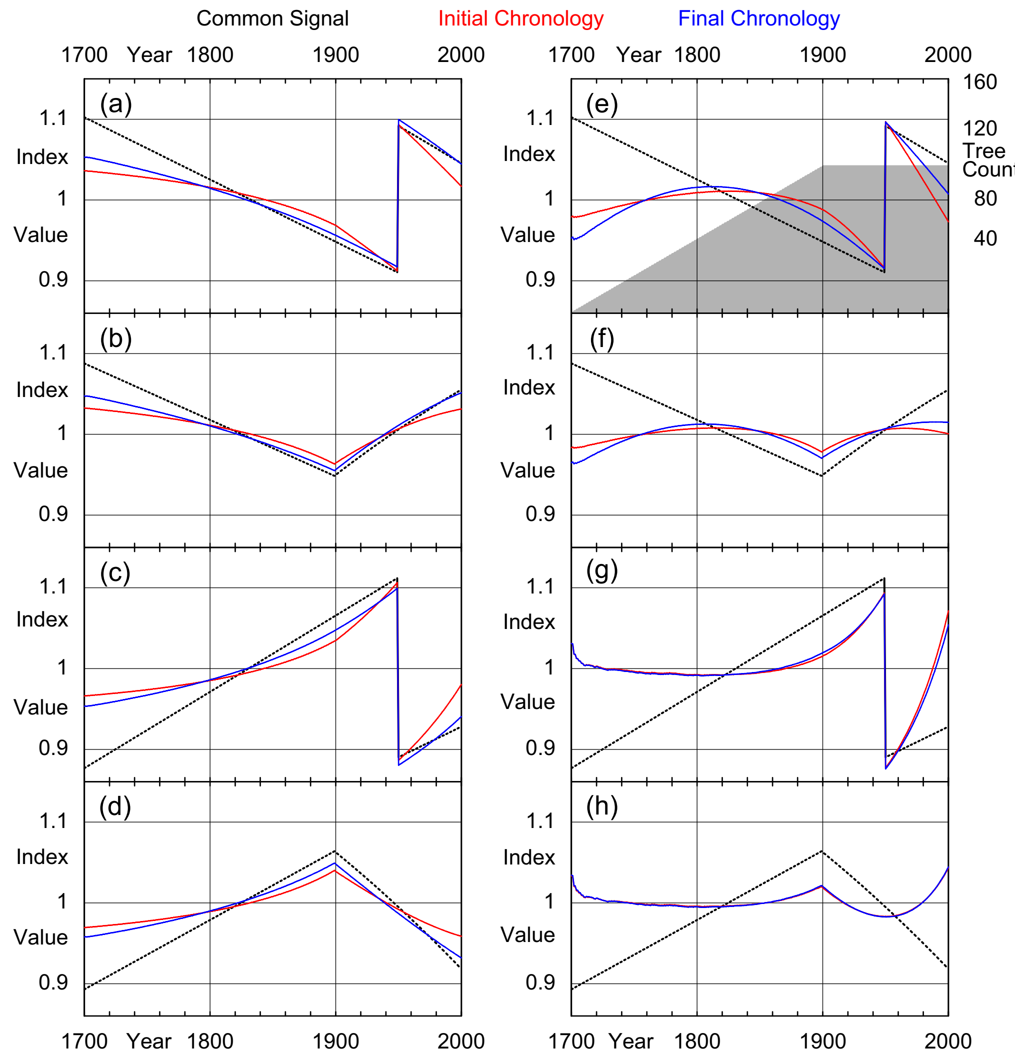

Fig. 5. Chronologies built from randomly generated ring-width series with linear slopes (a–d) and exponential slopes (e–h) with added chronology signals of a step increase from 1950 (a and e), a linear increase from 1900 (b and f), a step decrease from 1950 (c and g), and a linear decrease from 1900 (d and h). The data are detrended using least-squares-fitted sloping straight lines (a–d) or modified negative exponential curves (e–h). The "expected" common signal (dashed black line) created by dividing the added artificial signal by a count-weighted least-squares-fitted straight line, the initial chronology (red line), and the final chronology (blue line) after six signal-free iterations are shown for each generated-signal case.

non-simulated data, a set of ring-width measurements are used and additional sets are created from these measurements by systematically applying known artificial changes to them. The 100 series of ring-width measurements (mean of all cores for each tree) of living *Pinus sylvestris* trees from Luosto, north Finland (Melvin, 2004, Section 3) covering the last five centuries and with a mean length of 270 years were selected as an example of a well replicated set of ring-width data. Tree counts over time are shown in Fig. 6d. Two alternative artificial sets of ring-width measurements simulating differing growth regimes were created by the multiplication of the measured values after 1920, in one case by a constant factor of 0.7 to represent a "30% decrease chronology" and for the other case by 0.5 to give a "50% decrease chronology". The mean ring width over time is plotted for the Luosto chronology (black), the 30% decrease chronology (red) and the 50% decrease chronology (blue) in Fig. 6a and the chronologies generated by standardising these three sets of ring-width measurements using the NEXP method (smoothed for display purposes) are plotted in Fig. 6b. In the most recent 30 years Fig. 6a shows a twofold difference in mean ring width while over the same period there is little difference in the magnitude of chronology indices of Fig. 6b. The high-frequency signal is preserved in all chronologies (not shown) whilst at decadal-plus time scales the chronologies do not retain the differences in ring-width magnitude known to have been applied to the measurements. The combined effects of the segment

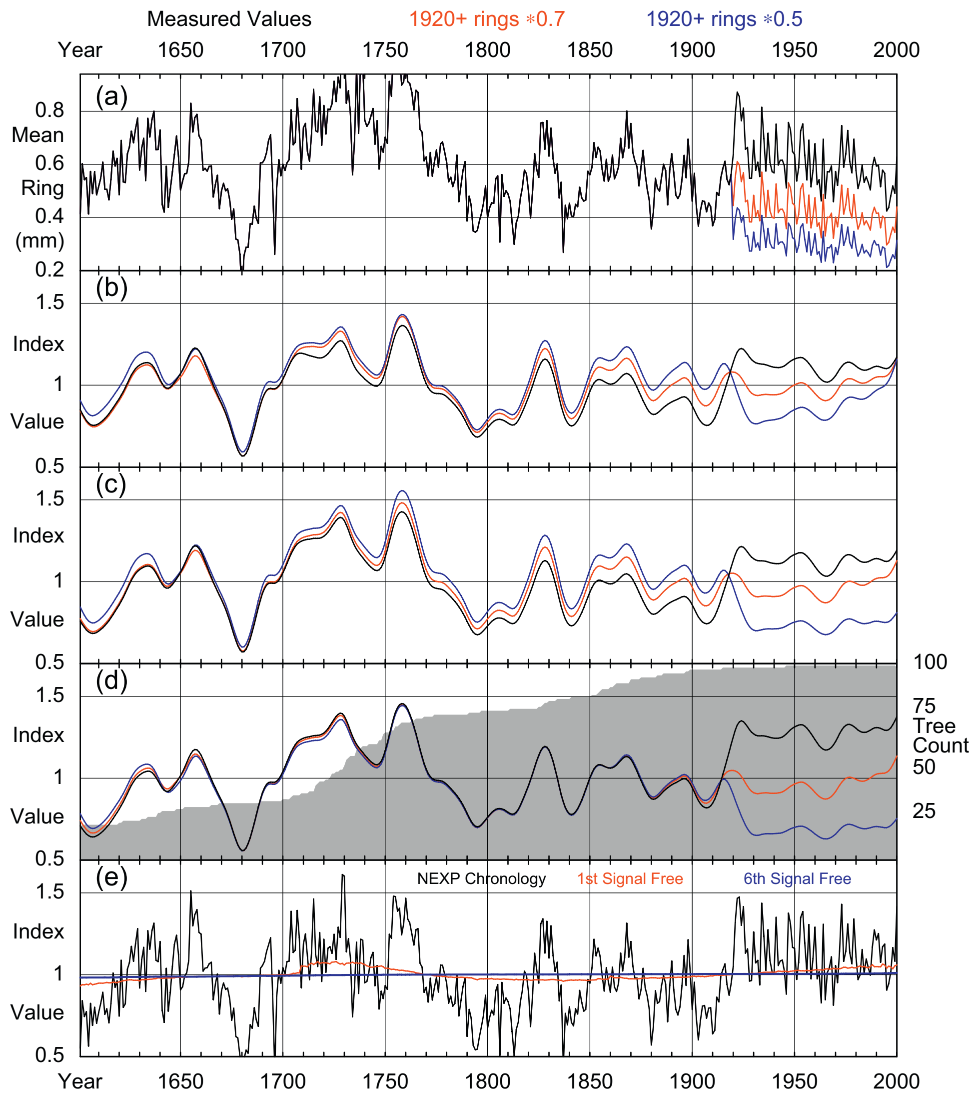

Fig. 6. A chronology of mean unstandardised ring-width data (a) and chronologies generated from the same data using the NEXP method as in ARSTAN (b), signal-free NEXP chronologies (c), and signal-free NEXP chronologies with slope set to zero and mean set to 1.0 for period prior to 1900 (d). The chronology constructed from actual data from Luosto, Finland (black) is shown along with chronologies using measurements with ring measurements after 1920 reduced by 30% (red), and ring measurements after 1920 reduced by 50% (blue). The grey shading in (d) shows tree count through time for all chronologies and chronologies in b, c and d have been 20-year low-pass filtered for display. The progressive removal of the common signal from the actual Luosto chronology by signal-free methods is shown in (e) with the standard NEXP chronology shown in black, the first signal-free chronology in red, and the sixth iteration (final) chronology in blue.

length curse and trend distortion on these chronologies, standardised using what are considered to be conservative standardisation methods is clearly seen to be a serious problem. The chronology based on measured values (Fig. 6b black) has a positive slope because a number of the series have been fitted with a horizontal line; this is because the increase in ring-width increment after 1920 resulted in some series of measurements having a positive slope.

The Luosto measurement series with and without the artificially added signals were standardised using six iterations of the signal-free method, NEXP detrending, and arithmetic means to generate chronologies. The chronologies (smoothed) are displayed in Fig. 6c. There is a clear difference in the magnitudes of chronology indices after 1920 which demonstrates how the known artificial differences in measurements have been largely preserved in the chronologies without excessive distortion. The standardisation has produced chronologies with arbitrary slopes and because of the different mean values of indices after 1920 the earlier sections of all three chronologies have differing slopes. For display purposes only, the three chronologies (not individual series) were rotated by detrending with a straight line to set each of their slopes to zero over the pre-1900 period and rescaled to have means of 1.0 over the pre-1900 period. The resulting slope-adjusted chronologies are shown in Fig. 6d. The pre-1900 sections of these chronologies are similar and Fig. 6d demonstrates clearly that the relative magnitudes of the artificially added step changes after 1900 have been recovered from the measurements using signal-free methods, although the overall chronology slopes are arbitrary.

Because signal-free methods reduce or remove trend distortion, it is reasonable to infer that if standard and signal-free chronologies are similar then there has not been a distorting trend (e.g. step increase or decrease). The 30% decrease chronologies, red lines in Figs. 6b–d, are very similar and, because removing trend distortion (6c) produces a similar result as not removing trend distortion (6b), this strongly suggests an absence of any substantial change in ring-width indices in the 30% decrease chronology which implies that the ring-width series of the Luosto chronology likely display evidence of a large growth increase in northern Finland trees after 1920.

Fig. 6e illustrates stages of signal removal using the signal-free method on the Luosto tree-ring series. The measurement series are divided by the initial NEXP chronology (black) and standardisation of the signal-free measurements using NEXP produces the first signal-free chronology (red), which as expected has substantially less variance. The variance comprising the sixth (and final) signal-free chronology (blue) represents time scales beyond those that are detectable using the NEXP method. This supports our earlier assumption that chronology signals can be removed from series of measurements by division. Changing the value of any one chronology index will create a residual in the signal-free chronology implying that the high to medium-frequency signal isolated using the signal-free method matches that of the common signal present in the measurement data. There is a range of chronology signals, all with varying low-frequency which are beyond

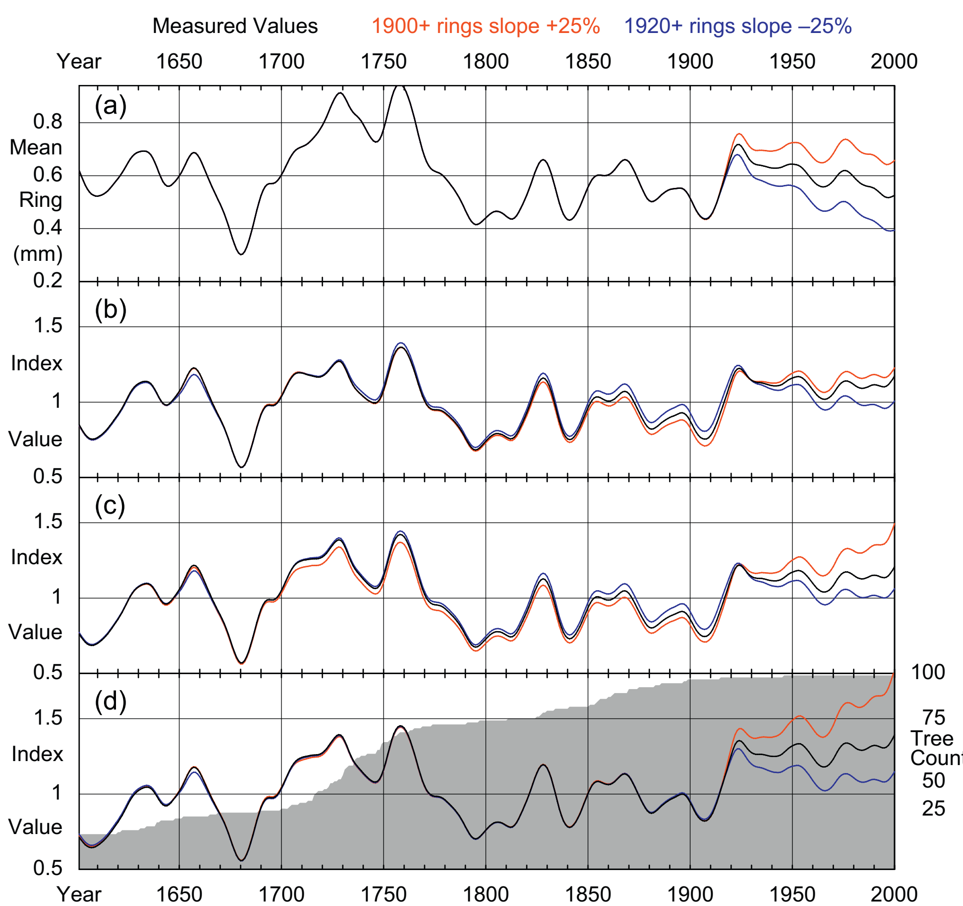

Fig. 7. A chronology of mean unstandardised ring-width data (a) and chronologies generated from the same data using the NEXP method as in ARSTAN (b), signal-free NEXP chronologies (c), and signal-free NEXP chronologies with slope set to zero and mean set to 1.0 for period prior to 1900 (d). The chronology constructed from actual data from Luosto, Finland (black) is shown along with chronologies using measurement series with ring measurements after 1900 increased linearly to 25% (red), and ring measurements after 1900 decreased linearly by 25% (blue). The grey shading in (d) shows tree count through time for all chronologies and all chronologies have been 20-year low-pass filtered.

the level detectable by the NEXP method, which can reproduce this same result, i.e. when measurements are divided by chronology signal and then standardised the result is a chronology with no variance.

The procedures used to produce Fig. 6 were repeated (Figs. 7a–d), but this time using artificial chronology signals comprising firstly, a linear increase (a 25% increase from 1900) and secondly, a linear decrease (25% decrease from 1900). In these cases, the standard NEXP method (Fig. 7b) distinguishes the three different chronologies correctly (due mainly to the fitting of horizontal lines) but fails to capture the magnitude of the artificial differences. The signal-free NEXP method captures the magnitude of the artificial changes (Fig. 7d) although the slopes of the final chronologies (Fig. 7c) vary (as for standard methods) due to the segment length curse. Repeating the processes that produced Figs. 6 and 7 using the detrending option of positively sloping straight lines instead of horizontal lines (not shown), produces similar results with the main difference being that the arbitrary slope of chronologies is closer to zero.

Fig. 8 shows the results of using the signal-free method, described earlier for use with curve-fitting standardisation, applied to measurement data from three sample sites. A smoothly changing curve-fitting method was selected where each measurement series was detrended with a smoothing spline (Cook and Peters,

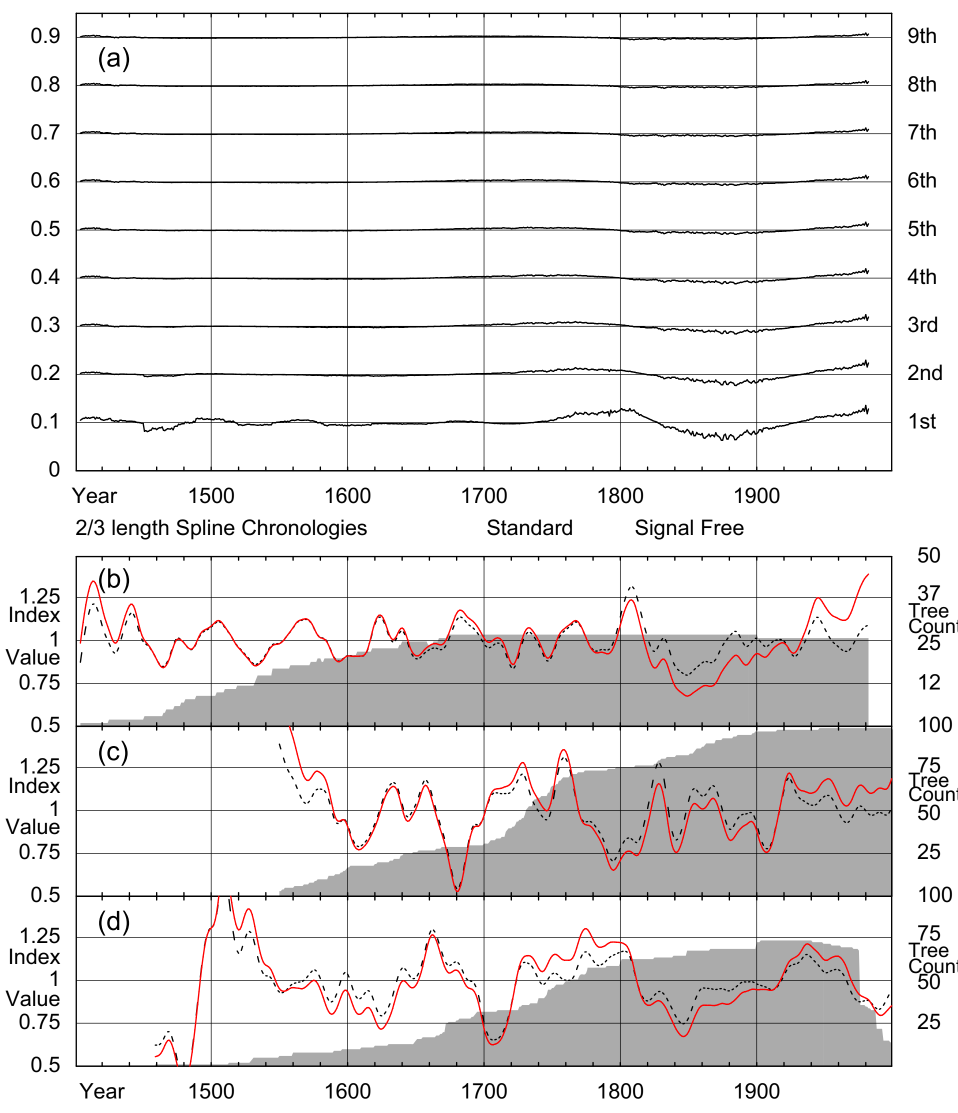

Fig. 8. Comparison of the use of normal (dashed line) and signal-free (solid red line) methods of standardisation showing chronologies created by standardisation of each series with a spline with 50% frequency cut off set at two-thirds series length for the (b) St. Annes River, (c) Luosto, and (d) TTHH site data. All chronologies were low-pass filtered with a 20-year spline for display purposes and sample counts through time are shown by shading. (a) The progressive convergence of chronologies for St. Annes River. Series of the high-pass filtered difference between current and the previous chronology for the first nine iterations of the signal-free method are plotted, using the scale shown but with each offset by 0.1 times its number for display purposes.

1981) with a 50% frequency cut off set to two-thirds the series length. The three datasets are made up from samples of white cedar, *Thuja occidentalis* L., from St. Annes River, eastern Canada (48°N 65°W) (Cook E.R., personal communication), living-tree samples of *P. sylvestris* L. from Luosto, north Finland (Melvin, 2004), and living-tree samples of white spruce, *Picea glauca* (Moench) Voss, that make up the updated TTHH chronology (D'Arrigo et al., 2004) from western Canada (65°20N, 138°20W). Convergence in the signal-free iteration procedure was judged to be achieved when the mean of the high-pass filtered absolute difference (i.e. sum of absolute differences for all years divided by the year count) between subsequent chronologies was less than 0.0005 index units. This occurred for St. Annes River, Luosto, and TTHH in 27, 11, and 14 iterations, respectively. The series of the high-pass filtered difference between consecutive chronologies for the first nine iterations of the St. Annes River site are shown in Fig. 8a. The difference reduces steadily as convergence occurs. The spline curves, fitted to each series of signal-free measurements, will change to fit the low-frequency variance of the signal-free measurement series for each iteration and thus, by fitting to and removing the low-frequency signal of the chronology, will increase the number of iterations needed to achieve convergence relative to a less flexible fitted curve. In all three examples the low-pass filtering effect of standardisation has produced chronologies with an arbitrary slope of approximately zero and it is, therefore, not possible to assess whether or not the last portion (1/2 a tree in length) of these chronologies should slope up, down or have no slope when using this standardisation method.

Discussion

In practice, a number of factors reduce the applicability of signal-free methods. Tree-ring data are often "noisy" and it is necessary to have data from sufficient trees in each year of a chronology to obtain an accurate series. Standard chronology diagnostics, such as the Expressed Population Signal (EPS) and Subsample Signal Strength (SSS), based on measurements of the strength of the common chronology signal RBar (Briffa and Jones, 1990), can be used as an indication of relatively weak sections in a chronology. There is also a need to ensure that the values of fitted expected growth curves do not go below or closely approach zero when using division (Fritts, 1976; Cook and Peters, 1997) and this requires that subjective decisions are made concerning the acceptability of age-related growth curves for each tree. In order to circumvent this problem during the use of computer based iterative techniques where manual intervention is impractical, fitted curves whose values fall below zero are rejected and fitted curves whose values fall below zero either shortly before the beginning of the series or shortly after the end of the series are also rejected. Here, a practical decision was made to define "shortly before" and "shortly after" as being within 3% of the series length beyond the ends of the series. For the specific case of fitted splines, the simple expedient of setting a minimum spline value of 0.01 (the minimum possible non-zero ring size consisting of a row of early-wood and a row of latewood cells) was applied.

There is potential for the application of signal-free methods in situations where removing the common signal from tree growth measurements could aid in the identification and isolation of the signal of interest, e.g., signals found in only a proportion of trees, such as the effects of disease, or where intra-site differences need to be examined in the absence of the common regional signal. Also, there are a number of situations where extreme externally forced annual values need to be isolated, e.g. in an analysis of the cause of pointer years of chronology indices (Schweingruber et al., 1990) or in a comparison of the relative magnitudes of volcanic signals (Briffa et al., 1998a), where the existence of the extreme values (of interest) distorts the high-pass smoothing curves used to isolate them, as in Fig. 1a. The signal-free method also has a potential application, along with Autoregressive Modelling (Cook et al., 1990), in the removal of transient disturbance related effects.

It is widely known in dendroclimatology that data-adaptive standardisation ensures that the relative magnitudes of indices in the early and late parts of a chronology have been rescaled to produce zero slope (Cook et al., 1995). Further, the use of a hierarchical series of curve-fitting options which include fitting a horizontal line, will create separate classes of tree indices, those with zero slope and those with a positive slope. Hence, it is very often inappropriate to interpret variation in a chronology, derived using curve-fitting methods and having an "arbitrary" slope, as indicative of the relative rates of growth in the earliest and most recent centuries and these problems need to be explicitly accounted for when comparing the recent end of a chronology produced using curve-fitting methods, with climatic measurements that may exhibit a slope. The signal-free method will not solve these problems. In the presence of a medium-frequency increase (or decrease) in tree growth rates, trend distortion can occur and the additional problem caused by trend distortion can be mitigated using signal-free methods. The existence of a standardisation problem has been demonstrated here using the Luosto trees and their artificial derivatives (Fig. 6b) and it has been shown that in the presence of the recent increase in tree growth rates seen in northern

Europe, the combination of the segment length curse and trend distortion restricts the value of chronologies, produced using curve-fitting methods, for comparing the magnitudes of past and current warming.

The value of signal-free methods used in conjunction with curve-fitting methods, which can only be viewed within the constraints of the existing limitations, i.e. chronologies are generated with arbitrary slopes, is shown in Fig. 6c. The difference made to these chronologies only becomes clear when the "arbitrary" slopes are set to similar values (thus temporarily removing problems related to the segment length curse) over a common, central period (Fig. 6d).

Trend distortion may be a contributory factor to the observed "sensitivity" problem (Jacoby and DArrigo, 1995; Briffa et al., 1998b; Barber et al., 2000; D'Arrigo et al., 2004, 2008; Wilmking et al., 2005). For example, Briffa et al. (1998b) found that, averaged over large geographic areas, the maximum density and ring-width chronologies generated using the Hugershoff standardisation curve (Warren, 1980), applied to data from trees specially selected because their annual growth was limited primarily by summer warmth, showed a close (particularly high-frequency) correlation with summer temperature but the relationship between decadal mean growth and temperature was seen to deteriorate in recent decades. The last two decades of chronology indices of Fig. 2b have values below the chronology mean of 1.0 and correlations between the common signal and chronology will be negative producing a marked decrease in correlations between tree growth indices and the common forcing signal in the most recent decades. The similarity between this result and the observed sensitivity change, the use of curve-fitting methods in reported cases of divergence, and the possibility of substantial growth increases in temperature-sensitive boreal forest trees due to increased temperatures in the 20th century, all suggest that trend distortion may have been a contributory factor in the sensitivity issue and that further investigation into the sensitivity problem is likely to benefit from the use of signal-free methods.

The effects of trend distortion on maximum latewood density chronologies and on chronologies created using Regional Curve Standardisation methods (Briffa et al., 1992; Melvin, 2004), both require further study and the wider applicability of signal-free methods using inflexible curves will be addressed elsewhere (Briffa and Melvin, 2008). Computer code implementing these procedures will be available as Fortran 90 subroutines on CRU website [http://www.cru.uea.ac.uk/cru/people/melvin/] and signal-free options will be implemented in program ARSTAN (Cook E.R., personal communication).This will facilitate wider exploration of its potential and hopefully lead to improved future implementation.

Conclusions

The principle, based on the properties of fractional deviations, that division can be used to remove the common signal from series of measurements has been demonstrated and this forms the basis of a test of standardisation, i.e. if the signal is removed from series of measurements, standardisation of the residuals (signal-free measurements) will result in chronology indices with no variance (within the frequency limits of standardisation). The effects of common external forcing on tree growth have been shown here to influence the generation of expected growth curves and the resultant problem is called trend distortion. The concept of chronology indices being viewed as fractional deviations has been used to develop a 'signal-free' method of standardisation in a first attempt to mitigate this distortion.

Signal-free methods can improve the resolution of medium-frequency variance from series of tree-ring measurements and comparisons of Figs. 6b with 6d and 7b with 7d provides evidence that signal-free methods provide a valuable tool for investigation. The overall limitations on the resolution of long-timescale variance using curve-fitting methods; that chronologies will have an arbitrary slope, will still apply. Even with the use of signal-free methods to reduce some of the bias, flexible-curve-fitting methods are not suitable tools for the examination of 20th century warming and alternatives (e.g. Regional Curve Standardisation) are needed. The evidence of this work points to the need for caution in the application of "curve-fitting" approaches to the standardisation of chronologies intended to provide a long-term context for measuring changes in tree growth rates, especially in the context of recent, observed warming.

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