Tree-ring variables as proxy-climate indicators: Problems with low-frequency signals

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Abstract

In recent years there has been a notable increase in the number of research projects engaged in building supra-long (multi-millennial) tree-ring chronologies. Together with a growing awareness of the potential for anthropogenic climate change, this work is shifting the focus of dendroclimatology. Instead of a more traditional interpretation of tree-ring data in terms of annual-to-decadal timescale climate variability the emphasis is increasingly placed on century timescale changes. We review a number of problems with the interpretation of low-frequency climate change in tree-ring derived data. Perhaps the most significant is the high-pass filtering effect of "standardization" techniques commonly used in chronology construction to remove age-related sample bias in the original tree growth measurement data. These techniques effectively remove low-frequency variability and with it the evidence of long-term climate change. Other forcings may also be 'corrupting' the climate signal in the recent period (that used for calibrating the climate signal). Differences in the origin of the samples or changes in site ecology may also impart an inhomogeneity in the response of tree growth through time, hence violating the fundamental assumption of uniformitarianism that underpins proxy climate research.

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Introduction

Significant anthropogenic modification of the atmosphere (and the terrestrial environment) has occurred over the last century with the rise in the proportion of CO_2 and other radiatively active gases accelerating greatly in the last 50 years. This is expected to increase global mean surface air temperatures, but the magnitude of this increase and the regional details of climate change patterns (including details of atmospheric circulation and moisture changes) are still largely uncertain, even controversial. Global average surface air temperatures have risen by more than 0.5°C since the middle of the 19th century, the time from which reasonable global instrumental data coverage becomes available. Climatologists seek to establish the extent to which this rise may be attributable to an enhanced greenhouse effect and so need to distinguish anthropogenic from 'natural' climate fluctuations (those that would occur without anthropogenic influences) to help them make predictions of future climate changes. Clearly the century-long instrumental record is not long enough to accomplish this. Hence tree-ring and other well-dated, high-resolution climate proxies for recent centuries and millennia (during which time Milankovitch forcing can be considered effectively constant) are correctly viewed as important; the more so where they accurately portray multi-decadal and century-timescale changes (Eddy, 1992; Bradley and Jones, 1993).

Tree rings have some claim to "special" status among so-called high-resolution proxy climate sources. This is because tree-ring data can be gathered from extensive areas of the world's land masses, and tree-ring records are both annually resolved and stretch continuously over hundreds, sometimes thousands of years.

This discussion is concerned with a particular aspect of tree-ring analysis, namely the extent to which 'long-timescale' (i.e. low-frequency) variability in climate is represented and recoverable in tree-ring chronologies and dendroclimatic reconstructions. 'Long-timescale' should be taken here to mean those slow changes occurring over periods of several decades and longer. This is, intentionally, a rather vague definition but sufficient to distinguish between the shorter timescale, interannual-to-decadal variability that characterises the large majority of dendroclimatic reconstructions.

It is now widely recognised, even outside of the dendrochronological community, that certain trees growing in regions of regular and marked seasonal climates form clear annual rings (Fritts, 1976). These trees provide data such as ring-widths or maximum latewood densities that have annual (or seasonal) resolution but also absolute calendrical dating control (Fritts, 1976; Schweingruber, 1988). By making meticulous cross comparisons between multiple, parallel measurement series (cross dating), the dendrochronologist is able to eliminate counting errors, identify 'false' rings and partially missing rings and hence maintain the integrity of the absolute dating scale in chronologies formed by averaging the data from many individual tree samples. Replicate measurement series from within individual trees, between trees from the one site, and trees at different sites also allow explicit quantification of the strength of common growth forcing and chronology confidence (Fritts, 1976; Briffa, 1995). This routine attention to dating control, replicate sampling, and statistical 'signal' quantification sets dendrochronology apart from other proxy climate disciplines.

Where chronologies are developed using data solely from living trees, their length is obviously contingent on the age of the oldest trees. Tree age varies enormously according to species, location and site disturbance history. Exceptionally, trees may grow over 1000 years old (e.g. La Marche, 1974; Stahle *et al*, 1988; Lara and Villalba, 1993) but the length of the large majority of 'modern' tree-ring chronologies is less than 400 years (Hughes *et al*, 1982). However, by using overlapping measurement series from a variety of additional wood sources such as historical structures, archaeological sites and even naturally-preserved subfossil material, extended composite chronologies can be constructed spanning many hundreds and perhaps even thousands of years (e.g. Baillie, 1982; Pilcher *et al*, 1984; Scuderi, 1990; Cook *et al*, 1992a; Kelly *et al*, 1994). What is not generally appreciated by non-dendrochronologists, however, is that the variability in long tree-ring chronologies does not necessarily represent the full range of variability that occurred in the climate parameter(s) that influenced tree growth over the same centuries or millennia.

There are biological and methodological factors that influence the extent to which long-timescale variability is manifest in long chronologies. The principal biological factors are associated with the way different tree growth variables vary simply as a function of tree ageing; long-term changes in the ecology of the site; or possible changes in the trees response to a particular climate forcing, brought about by changes in some other variable. The methodological factors relate to the ways in which particular measurements selected to represent changing tree growth are statistically manipulated during chronology construction, mostly in an attempt to mitigate the effects of the biological factors. Using regression analyses to establish the type and strength of climate forcing represented in chronologies becomes increasingly difficult as the timescale of interest increases.

Here we discuss these issues in general terms and then illustrate a number of points using specific examples of chronology development and dendroclimatic interpretation in two high-latitude Eurasian regions of northern Sweden and northwest Siberia.

'Normal' Tree-Ring Standardization

The most easily acquired measure of year-to-year tree-growth is annual ring width. This represents yearly radial expansion of the tree trunk and is assumed to be a proxy for net primary productivity or biomass increase over the growing season. Measured ring-width series display gradually declining values through time which are a function of roughly constant long-term tree productivity being distributed around an increasing tree girth. Climate variability is superimposed on this long-term decline. The other growth variable most often used in dendroclimatology is maximum latewood density. Raw measurement series for this also show a non-climate-related decline with age, though this tends to more linear than for ring width where the decline is approximately exponential (Bräker, 1981). If all ages of trees (as measured from the pith) were well represented at all times throughout the span of the chronology of which they form part, and their general overall growth rates were roughly similar, simply averaging the raw measurement data would remove age-related bias in the final chronology. However, few, if any, collections of tree-ring samples meet these criteria. Many chronologies are produced using data from roughly equally-aged (often the oldest) trees. Averaging these raw measurements would certainly preserve significant long-term non-climate variability.

In dendroclimatic research, it has therefore become common practise to 'standardize' tree-ring data series before averaging them into chronologies. The standardization involves fitting some linear or simple curvilinear function to the measurement time series (both ring width and maximum density) for each tree and expressing the original measurements as anomalies from this fitted line (Fritts, 1976). This transforms the measurements to quasi stationary indices about a common mean. Beside removing the age trend, the rescaling is generally justified on the grounds that it allows data from trees with different overall growth rates (assumed to be the result of intra-site-related differences) to be averaged without biasing the chronology. Were it possible from theory to define the precise reduction in ring-width or density as a function of tree age it would be a simple matter to remove the effect without loss of climate information. In reality, no such theoretical curves exist. Non climate-related variance in a tree measurement series, which for the sake of convenience is often termed the 'biological' or 'age' trend, in practise, represents a number of processes that effect the tree's overall productivity and the way it is distributed within the tree through time. This is the rationale for adopting a pragmatic approach to detrending the measurements from each tree and then averaging the indices to form the chronology. A very important consequence of this is that low-frequency variance produced by climate change forcing may not be distinguished from the 'biological' effect and is simply removed with it.

Using straight lines or very simple curvilinear functions to standardize very old trees, perhaps many hundreds or thousands of years old, could in theory preserve potential climate variability over centuries or millennia. Where the average length of the sample series is very much lower, standardization produces indices with variance spectra truncated at much higher frequencies, regardless of the underlying climate variability. This is illustrated schematically in Figure 1. The shorter the series, the shorter are the maximum wavelengths of climate variance preserved. This applies equally to sections of chronologies that are made up of a high proportion of short series even where the average series length may be longer. This phenomenon has been termed the 'segment-length curse' and a more detailed and clear exposition is given in Cook *et al* (1995).

The expression of the common growth variability in a mean chronology is a function of sample replication. Where between-sample common variance is low, high sample replication is necessary to ensure high chronology confidence (Briffa and Jones, 1990). A situation in which sample replication and/or low-frequency common chronology variance was low, might therefore justify a decision to remove variability on timescales significantly below the length of sample trees. For example, in closed canopy forests, the ring-width variance common among different trees may increase when measured on decreasing timescales (i.e., at higher frequencies) (Briffa, 1984). It is the interannual-to-decadal timescale variations that are registered most strongly in all of the trees. Longer timescale variations differ more because localised (tree-specific) non-climate factors such as tree architecture, light availability, soil characteristics etc., have more influence on individual tree growth rates on these timescales. Preserving longer-timescale chronology variability in such situations might decrease the accuracy of

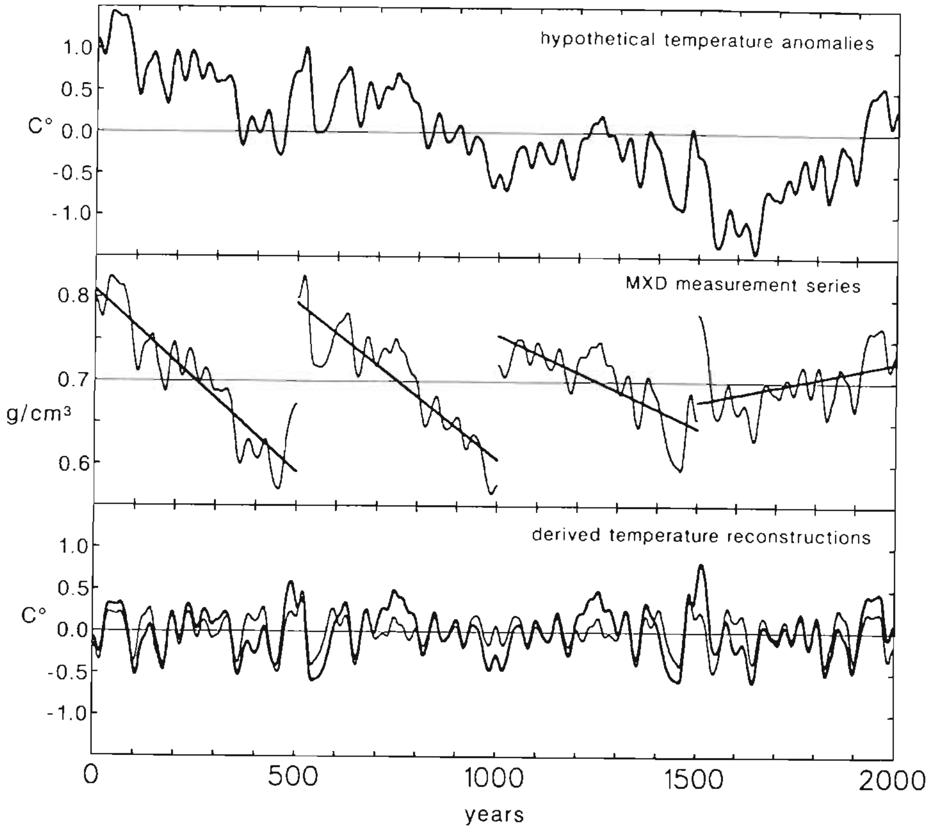

Figure 1: A simple illustration of the effects of 'standardizing' tree-ring series. The top panel shows a hypothetical 2000-year temperature series (smoothed with 50-year high-pass filter). The middle panel shows 4 500-year density series whose variability represents pure temperature forcing superimposed on a common negative linear age trend (0.0002 g/cm3 per year). The straight lines fitted to these data represent empirical standardization functions. The series shown by the thick line in the lower panel are the temperature reconstructions that would be derived from the standardized MXD indices i.e. the residuals from the straight lines fitted through the 500-year series. Note the complete loss of the negative trend in the original temperatures over the first 1500 years and the positive trend afterwards. However, even the evidence of major, century-timescale negative anomalies around 400, 1000 and 1600 years is absent in the reconstructions. The thin line in the lower panel shows equivalent reconstructions produced when the raw tree-ring series are made up of 20 100-years series, illustrating an additional loss of longer-timescale variability

the chronology and bias the climate calibration of the tree-ring data, resulting in inaccurate estimates of longer-timescale climate change. Even where common long-timescale variability is high, the dendroclimatologist might suspect the influence of some non-climate-related forcing (e.g., management or disturbance effects) and again decide to remove these directly.

In such situations, there has been an increasing use of even more flexible, or data adaptive, techniques for defining the timescales of variance removed in tree-ring standardization. The use of simple deterministic functions is frequently replaced by methods based on timeseries modelling or digital filtering of individual measurement series (Cook *et al*, 1990). This, in effect, sacrifices the potential for reconstructing climate variability on longer timescales so that more accurate reconstruction of the climate forcing on shorter timescales is achieved.

The key point here is that the variance spectra of chronologies, regardless of the characteristics of potential climate forcing, are band-limited at low frequencies to a degree that depends on the length of their constituent series; changing average sample age (i.e., length) throughout the chronology; and, crucially, how the individual measurements have been standardized (Cook and Briffa, 1990). Even chronologies constructed using data from very long-lived trees may only contain variability on much shorter timescales. Where very long-timescale variability is evident in a chronology, it will generally have wider confidence levels than variability on short timescales.

Regional Curve Standardization

Though is is not possible to construct tree growth curves on the basis of theory, it is possible to portray the general relationship between tree growth and tree age, empirically, in particular ecological situations by averaging the observed values for discreet cambial age classes, regardless of the calendar years during which the trees grew. The underlying relationship given in this way can then be expressed in terms of a simple function fit to these average 'site' data. Transforming the tree-growth measurement series for each tree, into anomalies from this function and averaging these anomalies across correct calendar years produces a series in which the age bias is removed, but the effect of long-timescale climate forcing is potentially preserved. Examples are given later in this Chapter. This approach has a long history of limited use in tree-ring research (e.g. Mitchell, 1967) though it has only recently been revised under the guise of 'Regional

Curve Standardization' (RCS), specifically in an attempt to preserve long-timescale climate variations in standardized chronologies (Briffa *et al*, 1992a).

Unfortunately, the RCS approach is far from being a general panacea for the loss of long-timescale information in dendroclimatology. Deriving an accurate RCS function requires a good distribution of different age classes, each made up of samples that grew over a wide range of climate conditions (i.e., at different times). It is not appropriate to derive an RCS curve from a near equal-aged stand of trees (the typical group of trees sampled at many locations), in which the mean growth in different age classes will be biased by common climate forcing. This can be a particular problem for the oldest age classes which may be over-represented by relatively modern samples, it being often easier to locate old trees now than in the past. If, for whatever reason, the standardization function is inappropriate spurious medium-to-long-timescale variability may be introduced in the resulting indices and chronologies.

Even where a theoretical function fit to the empirical data realistically expresses the *average* age/growth relationship over time, the validity of its use as a benchmark for calculating the degree to which tree growth was anomalous at some particular time in the past is critically dependent on whether there exists some common non-climate bias in the samples represented at that time. For example, a single linear representation of declining maximum density as a function of age based on trees that grew over a wide range of altitudes, could be inappropriate for standardizing the density measurements over a period when the available data represent a sample of trees that grew at a different elevation from the average of those used to derive the general expression (this is discussed in more detail later).

The crucial factor, as so often in dendroclimatology (and other palaeoclimate proxies), is replication. High replication will reduce the probability of significant sample bias; both in the mean standardization curve and in sections of the chronology produced using it, provided the data are drawn from a similar geographical/ecological site. In general, much larger sample replication is necessary to achieve an accurate estimate of long-timescale variability in chronologies than is required to represent short-timescale variability. Correspondingly, the statistical confidence associated with long-timescale fluctuations in RCS tree-ring chronologies is likely to be significantly less than that for the shorter timescales.

In some situations, however, this greater uncertainty is an acceptable cost for gaining some insight into long-timescale climate variability, especially where more generally applied standardization applied to short tree-ring samples would preclude the reconstruction of all but annual-to-decadal variability. Our limited experience (see later examples) suggests that the RCS approach may be more easily applied in the case of conifer ring-density (maximum latewood density), with its simple, almost linear decline with increasing age. Ring-width growth trends are more complex and appear to vary more from tree to tree, even when contemporary series are compared.

Empirical Tree-growth/Climate Relationships

Attempts at interpreting tree-ring chronologies in terms of climate (or any other) forcing, must respect the simple fact that biological systems are very complicated. Though temperature and moisture availability may strongly affect tree growth, trees are not thermometers or rainguages. The influence of numerous climate-related parameters on growth is registered only indirectly as part of a complex ecology involving the integration of many biochemical processes occurring on different timescales in many parts of the tree and influenced by factors other than climate. Hence, whatever measure of tree growth the dendrochronologist chooses to use, it can only be climatically interpreted under simplifying assumptions. While dendrochronologists might wish to extract information on some specific climate variable from a single chronology or a network, they must accept that this may exert only a partial influence on the variability represented in the data. The same is true of specific seasonal and spatial tree-growth responses. In some cases, tree growth might respond non-linearly to a change in some particular forcing or may exhibit a response only above or below some climate threshold. In order to reconstruct past climate, these relationships are generally expressed linearly. A major aspect of dendroclimatic research therefore involves trying to construct tree-ring chronologies that best represent the climate variability of interest and establishing a rigorous framework within which they can be realistically interpreted as evidence of that climate forcing.

Careful sampling strategies, such as collecting data from trees growing near the limits of their distributions, for example, at high latitudes and elevations or in semi arid areas, can greatly improve the potential for recovering largely unambiguous and reliable information on particular climate or climate-related parameters such as mean summer temperature, rainfall or soil moisture. Ultimately, however, whatever climate forcing is expected, the practical basis of most dendrochronological reconstruction work is empirical. Regression equations based on the overlap between chronology and climate series are used to derive statistical relationships between them, and to provide some quantitative basis for the interpretation of the past tree-growth data in terms of climate variability (Fritts *et al*, 1971, 1990; Fritts, 1976; Guiot *et al*, 1982; Briffa *et al*, 1986; Guiot, 1990; Cook *et al*, 1994). As with all regression-based relationships, the interpretations are valid only in as much as the general limitations of statistical regression are respected and, even then, only within the context of the range of climate variability represented in the regression comparison (Draper and Smith, 1981).

A valuable lesson that has been well demonstrated in dendroclimatic studies is that standard measures of the goodness of fit of multiple regression equations, even those apparently adjusted to take account of the number of predictors, frequently overestimate the likely strength of the derived association, as is demonstrated when this is tested outside of the fitting (or calibration) period (Rencher and Pun, 1980; Cramer, 1987). High levels of explained variance are easily achieved when using multiple predictors, perhaps representing numerous chronologies each with several lagged variables (Lanzante, 1984). Where there is significant autocorrelation in the dependent variable, similar persistence in the predictors can also produce highly inflated measures of the real tree-growth/climate association. For this reason, it has long been normal practice in dendroclimatology to test (or verify) calibrated relationships by withholding some climate data from the calibration to compare with the regression-based estimate. By applying a range of statistical tests in these independent comparisons, a much more realistic impression of the true predictive (or retrodictive) power of regression equations is gleaned than any based on calibration statistics alone (e.g. Fritts *et al*, 1990; Fritts, 1991; Briffa *et al*, 1986, 1992b; Cook, 1992; Cook *et al*, 1994).

However, it should be apparent that the timescales over which verification comparisons are feasible are strictly limited by the length of the verification climate data. This also applies to the range of high-frequency variability. Some long European climate series can stretch over 200 years. In other areas of the world, they are typically 100 years in length. In some more-recently-developed areas such as Tibet, they only span a number of decades (Wu, 1992). Given the necessity of withholding climate data for verification, climate and tree-growth series can only be directly compared on timescales up to a century at best, and in the large majority of situations, only up to several decades. Hence, dendroclimatic calibration is generally on high-frequency variability. The longer the timescale of interest, the more difficult it becomes to calibrate and verify regression equations. If there is little significant persistence or evidence of long-timescale variability in the recent period, low-frequency variability arising in reconstructed data may represent extrapolations beyond the range of the calibration data (Graumlich and Brubaker, 1986). Again, the same is true of very large high-frequency extremes. Where there is significant trend in both tree-ring and climate series, any regression is severely limited by the low degrees of freedom. This is not to say that both situations cannot yield accurate reconstructions on long timescales, merely that in either case, it is not possible to formally verify the long-timescale variability.

It would not be wise to assume that a regression fitted primarily on high-frequency variability (or mainly on low-frequency variability) will always be equally valid for estimating low-frequency (or higher-frequency) forcing. To illustrate this, envisage trees growing in a stable maritime climate. Short climate anomalies, such as a range of occasional moderate dry summers, may be clearly registered as high-to-medium frequency disruptions in tree growth (as an appropriate range of narrow rings). The rapid resumption of 'normal' conditions following these dry summers allows the trees to recover quickly, with no protracted effect on long-term growth patterns. However, if the magnitude and/or duration of the anomalous conditions become much more pronounced, such as in a very severe drought, the trees' response to this high-frequency forcing may be disrupted. Die back in some branches, even death of a major part of the crown (e.g. the typical 'stag-headed' oaks seen in southern Britain) could reduce the photosynthetic potential of the trees, perhaps for years. This could even lead to the growth of epicormic branches (i.e. low lateral branches), changing the architecture (and hence the local distribution of wood biomass) and the apparent long-timescale patterns of ring growth. The low-frequency variability apparent in the tree-ring data will persist well beyond the end of the climate anomaly. Another example would be subalpine environments, where tree growth is strongly influenced by temperature. The response to high-frequency extremes, such as very cold summers, could be moderated by the general 'background' state of the climate. Near the tree line, general tree vitality is dependent on cumulative temperatures over several years and tree-ring timeseries display strong year-to-year persistence. A run of cool summers will place trees under increasing stress and an extreme cold summer during such a period will have a much more marked effect on growth than a similar extreme occurring during a much warmer period.

Awareness of the possibility of frequency-related problems in dendroclimatic regression is reflected in the development of various methodological techniques. A large body of work, particularly in the southwest United States, aimed at reconstructing moisture-related parameters using relatively old trees growing in the semi-arid areas, is based on auto regressive moving average (ARMA) modelling of the tree-ring data. Pre-whitened ring-width series frequently display strong affinity with the generally high-to-medium frequency variability observed in hydrologic data such as rainfall, riverflow or the Palmer Drought Severity Index (see Cook *et al*, 1992b and references therein). Guiot (1985) developed a spectral canonical regression technique in which the predictand data are decomposed into different frequency bands and separate calibration equations used to estimate the variance in each. More usual regression exercises sometimes calculate calibration and verification statistics for high-pass and low-pass data separately.

The potential for modelling, and for testing the modelling of long-timescale climate variability by all of these approaches, is dependent on how well it is represented in the observational data.

Anthropogenic Influences Compound the Problems

Ironically, probably the main reason behind the growing interest in reconstructing multidecadal and longer-timescale climate variability in the late Holocene, i.e. anthropogenic modification of the environment, may also prove to be a major complicating factor in our attempts to produce accurate climate reconstructions using biological and dendrochronolgical data, most particularly on longer timescales.

We refer here firstly to the possible 'fertilization' effect of increasing atmospheric CO_2 levels on tree growth. Controlled experiments on various plant species grown under elevated CO_2 levels demonstrate the potential for increased plant productivity: through higher photosynthetic rates, reduced respiration, more efficient use of limiting resources such as nitrogen, and through greater water use efficiency (e.g. Lemon, 1983; Strain and Cure, 1985). However, these experiments were conducted using small, often short-lived plants growing under strictly controlled conditions so that generalizing from their results to infer changes in the growth of natural tree populations is highly uncertain.

Comparatively few experiments have been carried out using trees or seedlings grown in 'natural' conditions or run over more than a few years. Those experiments that have been run have provided contradictory evidence of the net assimilation of carbon in trees grown under high levels of CO_2 (e.g. Idso, 1991; Norby *et al*, 1992). Nevertheless there is observational evidence of increased tree growth over the last century in widely reported regions, though mostly at high elevation or high altitude (La Marche *et al*, 1984; Innes, 1991). The extent to which this may be directly attributable to rising CO_2 levels is highly uncertain (Wigley *et al*, 1984; Cooper, 1986; Gale, 1986; La Marche *et al*, 1986; Kienast and Luxmore, 1988). Some growth increases have been ascribed to climate forcing (Graumlich *et al*, 1989; Becker, 1989). Some may be the result of increased nitrogen supply, some perhaps both (Briffa, 1990; Becker *et al*, 1995). However, we must acknowledge the possibility that the unprecedented (at least as regards the Holocene) CO_2 levels of the present century could have affected tree growth directly or through their effect on other growth limiting relationships.

Besides enhanced CO_2 and nitrogen levels, anthropogenic pollution of the environment by other chemical species has increased greatly throughout the present century. In some regions, heavy metals, nitrogen, sulphur compounds and the general acidity of the atmosphere, precipitation and some soils have all increased. Some pollutants are restricted to small, near-source regions whereas others are distributed over much larger, even continental areas. There have also been increases in the levels of UV radiation reaching the earth's surface, mostly at high latitudes, because of damage to the ozone layer. All of these can be expected to have some effect on tree growth, at individual tree, site, and larger ecosystem levels. Any of them might, in theory, bias calibration of tree-growth series with contemporary climate data and lead to systematic inaccurate retrodiction of climate. In practise, different factors will be of varying regional significance and their effects will be moderated by specific site ecology. Therefore our knowledge of their likely individual effects is limited and our expectation of the possible cumulative effects even more so. Ideally, future work will aim to quantify the roles of these factors as a prerequisite for isolating the role of climate forcing (Wigley *et al*, 1987). This will require a combination of theoretical, laboratory and field approaches. In the meantime we should at least bear in mind that the period over which we have the best climate data for establishing climate/growth relationships is the same period in which the most persistent contamination of the natural environment has occurred.

The Value of Independent Comparisons

One of the strongest indications of long-timescale fidelity in dendroclimatic reconstructions is likely to come simply through comparisons with independent palaeoclimate evidence, either from other tree-ring records or alternative proxy climate sources. However, the value of such comparisons will depend on a realistic appreciation of the limitations of the different records: the dating accuracy and resolution; the type, strength and frequency limitations in their inherent climate signals, the response times; and especially the likely extent of their geographic representativeness. All proxy data are limited to some degree in each of these areas, but provided this is recognised, bringing together and reconciling the evidence from diverse proxy sources offers an exciting challenge in palaeoclimatology.

When making comparisons of different regional climate series it is necessary to lay particular stress on the geographical, seasonal and even conceptual limits to the feasibility of interpreting the comparisons as supporting or questioning the validity of the series. We know that the coherence between different instrumental climate series varies according to the distance between them and the timescale of comparison (Briffa and Jones, 1993 and Jones and Briffa, this volume). Our expectations are dependent on our understanding of the regional climate change mechanisms operating on these timescales. However, that understanding is largely framed through the development of theories and modelling experiments which must themselves be influenced by our appreciation of past climate variability on the appropriate timescales.

The dating control and resolution of tree-ring-derived reconstructions offer good prospects of making rigorous interseries comparisons. Where there is some a priori basis for expecting them, long-timescale similarities in the reconstructed climates derived from different proxies could provide mutual support of their veracity. Differences particularly in 'adjacent' reconstructions, however, must cast doubt on one or more of them.

Insurmountable Problems?

It may be the case, that even given unlimited homogeneous tree-ring samples, there will be some timescale above which changing climate conditions are not represented

in measured tree-growth parameters. This might be considered more probable than possible when one remembers that contemporaneous trees of the same species are known to exhibit physiological adaptations to different climates. For example, trees at different altitudes (hence growing under different climate conditions) are capable of acclimation by virtue of differences in, for example, rates of respiration, photosynthetic capacity, sensitivity to frost, photosynthetic dormancy and susceptibility to dessication (for references see Tranquillini, 1979). On millennial timescales, particularly if the life span of the trees is relatively short, they may also exhibit genetic adaptation to changed climates. At present, little work has been done to explore the diversity or possible rates of change in the genetic makeup of tree populations but the technology is certainly available. Some exploratory research in this area seems justified. In Holocene studies, especially those based on long-lived trees, genetic change is unlikely to be of significance. The significance of adaptive responses, however, may prove to be much more so.

Selected Regional Examples

Now we turn to some illustrative examples of the problems of portraying long-timescale climate variability from tree-ring data; in this instance summer temperature variability in high-latitude ring-width and densities. The examples are based on ongoing work in northwest Sweden and northwest Siberia.

The Swedish data are derived from collections of *Pinus sylvestris*: living-tree cores, dead standing and fallen logs surviving above ground and sub-aquatic samples preserved in small lakes near the northern and southern shores of the main Lake Torneträsk, northwest Sweden (68°13'N; 19°43'E). The Russian data are from *Larix sibirica*: a mixture of living trees and remnant surface samples on the upper eastern slopes of the Ural Mountains near 66°50'N; 65°40'E (Sob River site). At both locations it is possible to compare tree-ring width data with densitometric data. Continuous chronologies for these variables already extend back more than 1000 years from the present, constructed mostly from relatively short series (<400 years). These data have been used to explore alternative approaches to standardization, one where the principal aim is to preserve low-frequency variability in the composite chronologies. At each location there are also plentiful sub-fossil data which will eventually enable continuous multimillennial (7-8,000 years) chronologies to be constructed. The initial results of this continuing work illustrate the problems of extrapolating the results of temperature regressions based on very short instrumental data to infer temperature changes on long timescales.

The sample collections from both the Torneträsk and Polar Urals regions are described in a number of prior publications. The locations of the material and much of the background to the research projects that are ongoing in both these regions can be found in Bartholin and Karlén (1983); Bartholin (1987) and Schweingruber *et al* (1988) for the Torneträsk data, and Shiyatov (1979, 1986, 1993) for the Urals data. Descriptions of climate calibrations of both ring-width and maximum-latewood-density chronologies, and reconstructions of different summer temperature series made using these, include, for Sweden, Aniol and Eckstein (1984); Briffa *et al* (1990, 1992a), and for the Russian data, Graybill and Shiyatov (1992) and Briffa *et al* (1995). Here we give detailed information on the sample make up in order to illustrate the implications and specific problems for long-timescale climate interpretation that arise in standardization and chronology construction using these data.

Figure 2 illustrates the annual replication and changing mean ring age of all samples through time. There are large differences in the makeup of the sample groups. The Swedish ring-width data (STRW) are made up of numerous series (over 420) but only a selected subset (65 series) containing the longest series, has been densitometrically analysed. The Russian data are from the same samples (93 series) for both ring-width and density (RMXD and RTRW).

Annual replication in STRW is between 10 and 20 samples most of the time after A.D. 200 and more than 50 samples for each year after 700. The SMXD replication is lower but still reasonably high (10-20 series) and fairly constant during the whole period following 550. The Russian data (RMXD and RTRW) are notably less well-replicated than the Swedish data, below 10 series prior to 1150 and between ~ 1450 and 1630 and between ~ 1720 and 1780. Replication for the other periods, is in the range 10 and 20 series.

Between A.D. 500 and the present, the mean age of the STRW series is about 100 ($\bar{x}$ = 105.1 years σ = 37.4) and about 150 years ($\bar{x}$ = 155.2, σ = 59.4) for SMXD. Both Swedish data sets show a similar pattern of sample age bias in different periods: predominantly younger trees before 800 and for much of the time between 1200 and 1600, and older trees from 800 to 1200, and after 1600, with a very strong increasing

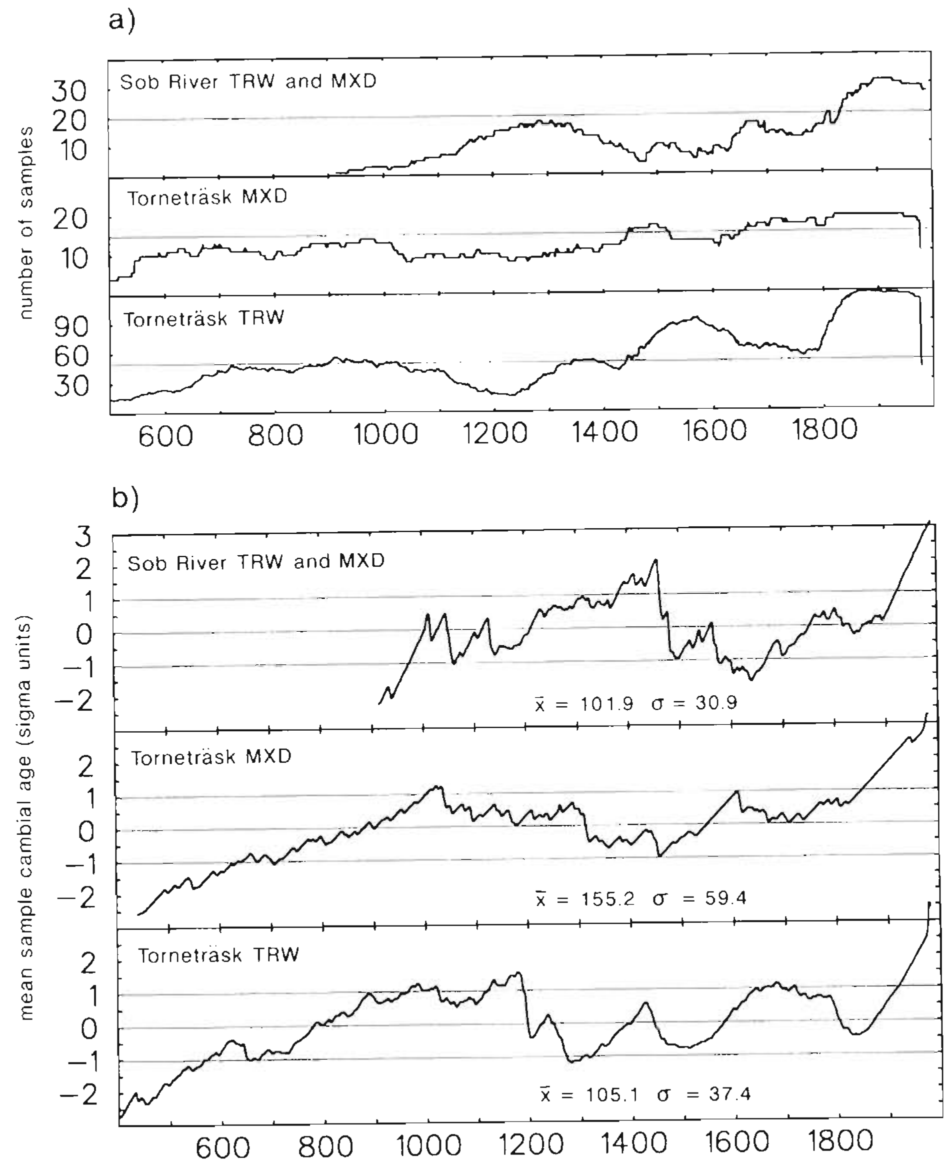

Figure 2: **(a) Series replication in the Russian, Sob River and Swedish, Torneträsk ring-width (TRW) and maximum-latewood-density (MXD) chronologies (b) The cambial age of the same data averaged over all samples in each year. These data are plotted as standardized departures.**

bias towards greater mean age (up to 200 years) after 1900. This recent bias is due to the deliberate selection of old trees when developing a modern chronology from living individuals. Variations in mean age remain generally within a range of plus or minus one sigma (with only very minor exceptions) for both the Swedish chronologies except at the early (the juvenile stage of the earliest samples) and the recent ends (referred to above). The mean age of the samples in the Russian data sets show greater variation through time. The overall mean is about 100 years ($\bar{x} = 101.9$ years $\sigma = 30.9$). Again there is the early bias towards young samples (before 950) and the recent bias towards older samples (after 1900). However, sample age is relatively high between 1200 and 1450, particularly so (above 1 σ) between $\sim$1390 and 1460, and low between 1460 and 1640, particularly 1600-1650. There is a rapid change from old to young samples during the second half of the 15th century.

Figure 3 shows the general relationships between tree growth (TRW and MXD) and tree age, for the Torneträsk pine and the Sob River larch. These functions represent RCS curves that could potentially be used to remove the sample age bias when constructing chronologies with low-frequency variability preserved, as described in an earlier section. The curves shown in the upper two panels are based on all available data at each site. The general rates of declining growth shown in these, are similar between the sites but the Russian larch clearly form systematically smaller and denser rings. The curves in the lower two panels show the curves for the Sob River data divided into subfossil (approx. pre 1750) and modern (post 1635) samples. The elevation of the two sets of samples overlap, but the mean height of the subfossils is higher: the subfossil sample range is 200-380 m a.s.l., whereas the modern trees were mostly sampled between 200-250 m (see Fig. 4). The similarity in the two straight line fits to the separate density sets implies that there is no systematic bias between these data that might have arisen because of the average height difference (see later discussion). However, there is a noticeable difference in the ring-width functions. The 'modern' rings are wider in youth and reduce more rapidly with age than the subfossil rings. This could indicate greater stand density in the modern data (with greater competition as the trees develop). Standardizing with an RCS curve based on the average (i.e. a mixture of subfossil and modern) ring-width data could produce systematic over- (producing negative bias) and under- (positive bias) fitting of the various raw data curves. Figures 5-8 illustrate the pronounced differences in the low-frequency appearance of the Swedish and Russian

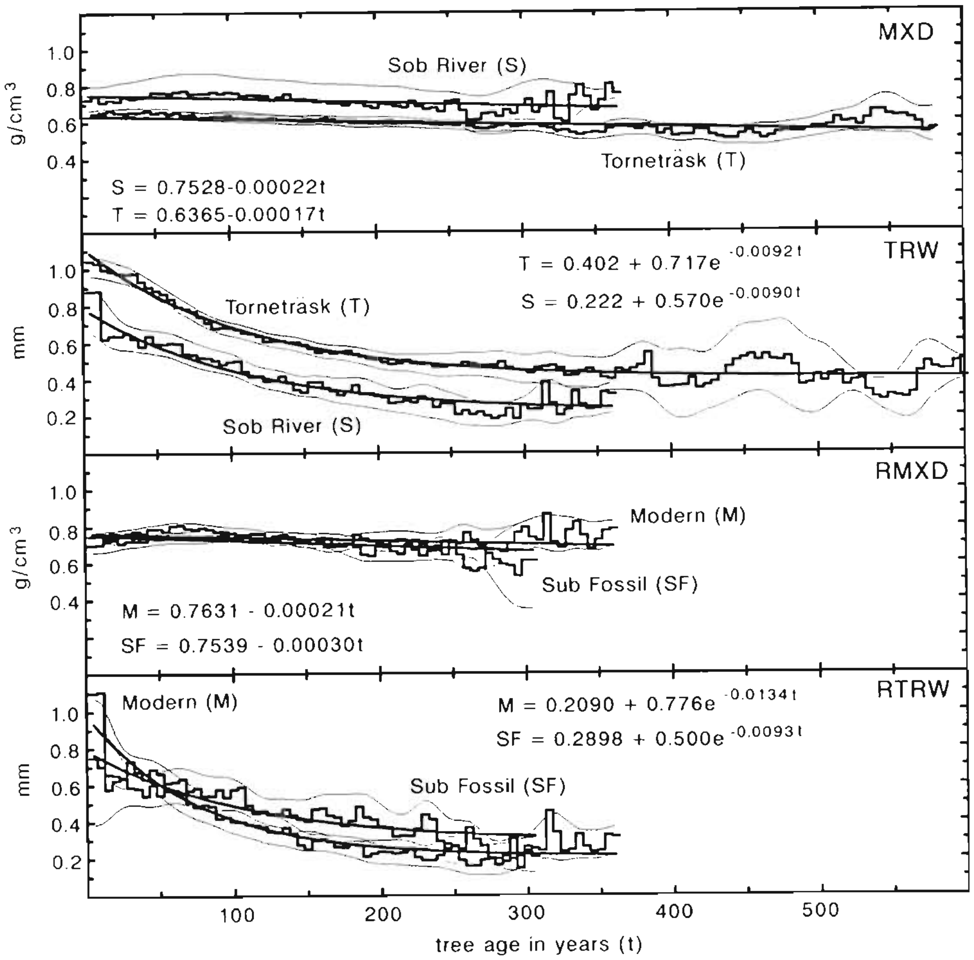

Figure 3: **Regional Curve Standardization (RCS) functions for the Swedish and Russian data. Histograms are 5-year age-class growth averages. Thin lines are their smoothed one standard error confidence limits. Thick lines are linear or negative exponential functions fit through the age-class data. The upper panels show the RCS curves derived using all available (i.e. living-tree and subfossil) data. The lower panels show RCS curves derived separately from the Russian, living and sub-fossil data**

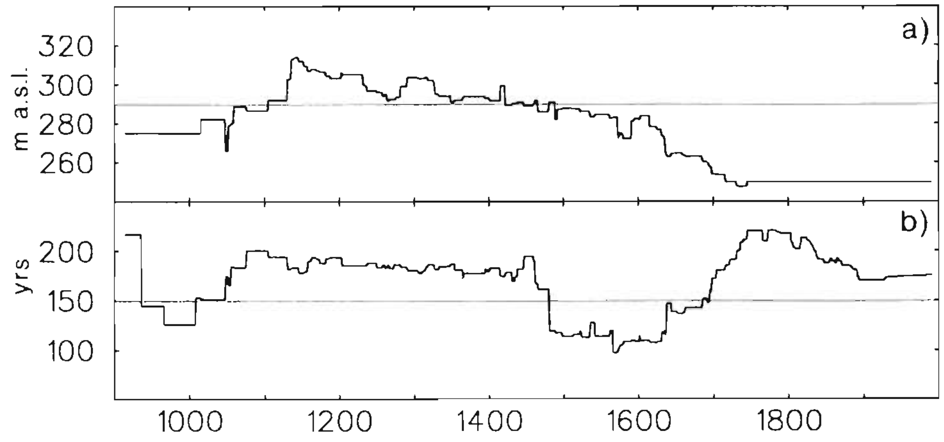

Figure 4: (a) Mean elevation through time of the Russian, Sob River subfossil samples. The living-tree data are plotted at a constant elevation of 250 m a.s.l. as their precise elevations are not known (see text) (b) The mean length of all sample series represented in any particular year. This shows a marked bias towards shorter series between the late 1400s and the late 1600s

TRW and MXD data when they are standardized in different ways. Raw data averages are shown above chronologies standardized using first, individual splines tailored to preserve long-timescale variance in each sample series in proportion to the series length (i.e., 50 per cent amplitude preservation of a cycle two thirds the length of the series; Cook *et al*, 1990); and second, using the RCS curves shown in the upper half of Figure 3.

The curves shown here have been filtered to suppress variations or timescales below 25 years. Note the multi-century-timescale changes in the RCS chronologies, lost in the spline-standardized series. The alternative chronologies reconstruct the same high-to-medium frequency variability of climate, but the relatively short length of many of the constituent series in these areas restricts the low-frequency variance captured by

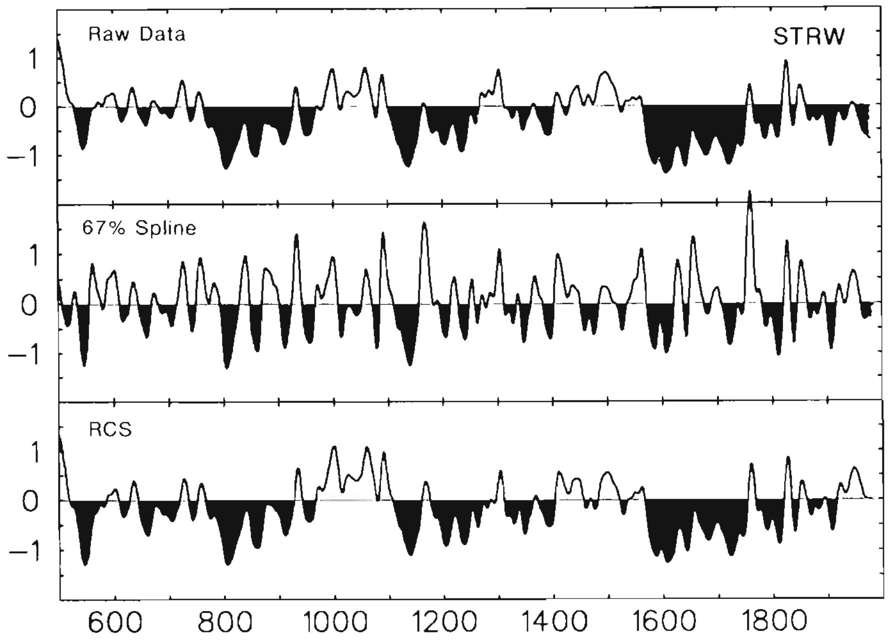

Figure 5: The Swedish, Torneträsk ring-width (TRW) chronologies after standardizing the raw measurements using two different methods: the 'conservative' spline and the RCS function (see discussion in text). Note that the data are plotted as standardized departures from the mean of the overall series and have been smoothed with a 25-year low-pass filter

these data. Where replication is high, as in the Torneträsk data much of this variability is apparently correctly preserved even in the raw data averages, but even very high replication in recent centuries cannot overcome the negative growth bias associated with reduced growth in old-age samples. Note also the good general agreement between the MXD and TRW RCS chronologies at Torneträsk. In the Russian data (where the general levels of replication are poorer) the raw and RCS MXD series are very similar but there are differences between the RCS TRW and MXD chronologies, in particular the high

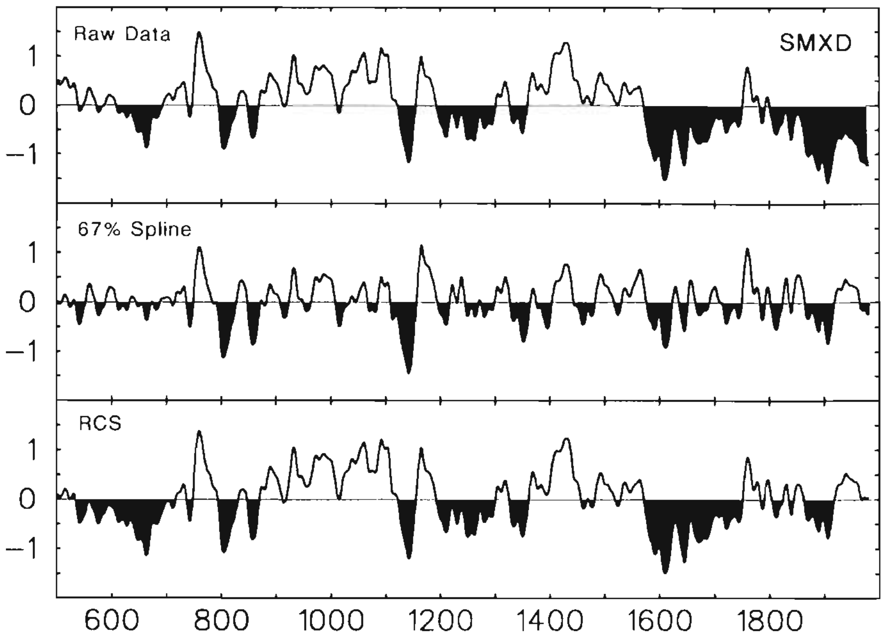

Figure 6: **The Swedish, Torneträsk maximum-latewood-density (MXD) chronologies after standardizing the raw measurements using the same alternative approaches shown in Figure 5 and discussed in the text. Note that in this case the RCS data have been adjusted in the recent period (see Briffa *et al*, 1992a)**

positive growth values in the 16th century in the RTRW data. This may indicate a standardization problem due to the relatively low replication, a bias of relatively short and very young samples (c.f. Figs. 2 and 4) and perhaps an inappropriate standardization curve, referred to earlier in the context of Figure 3.

Figure 9 illustrates the practical effect of the different standardization experiments as they are reflected in alternate reconstructions of mean summer temperature in Northern Fennoscandia and northwest Siberia, in both cases using TRW and MXD predictors (Briffa *et al*, 1992a; 1995), but in the case of Russian reconstruction, using only spline

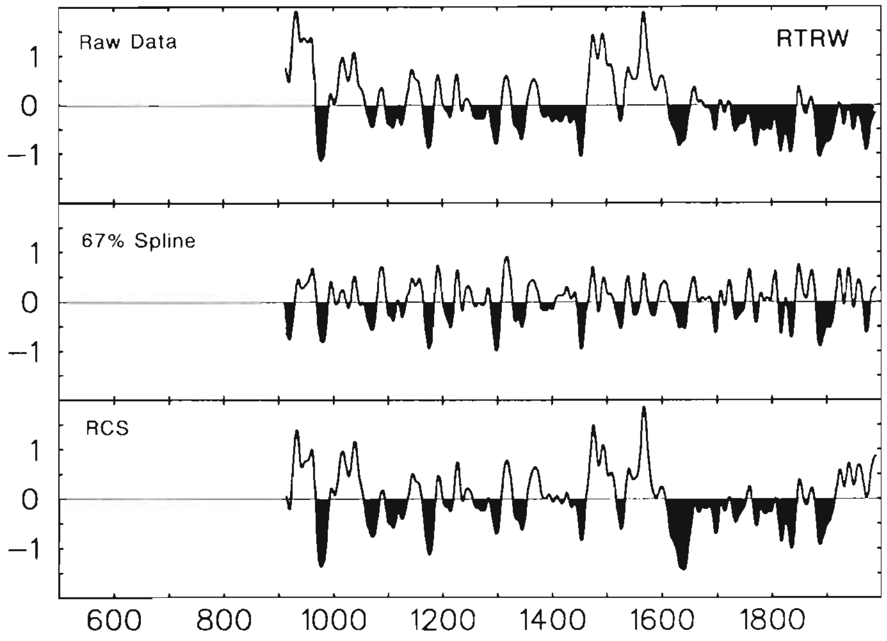

Figure 7: **The Russian, Sob River ring-width chronologies standardized with alternative methods. See the legend to Figure 5 and text for more details**

standardized data for the reasons described above. Again only the long-timescale components of the reconstructions are shown here. The additional presentation of long-period variability achieved by RCS standardization is much greater in the Russian as opposed to the Swedish data. In both reconstructions, the 20th century, overall, is warm in the context of the last millennium. However, the relative warmth is apparently far greater in the Russian series. In fact, the mean for the 90 year period 1901-1990 is higher in this reconstruction than any consecutive period of the same length (Briffa *et al*, 1995). Empirical modelling of the relationships between summer temperature and tree growth variability produce similarly good results regardless of whether

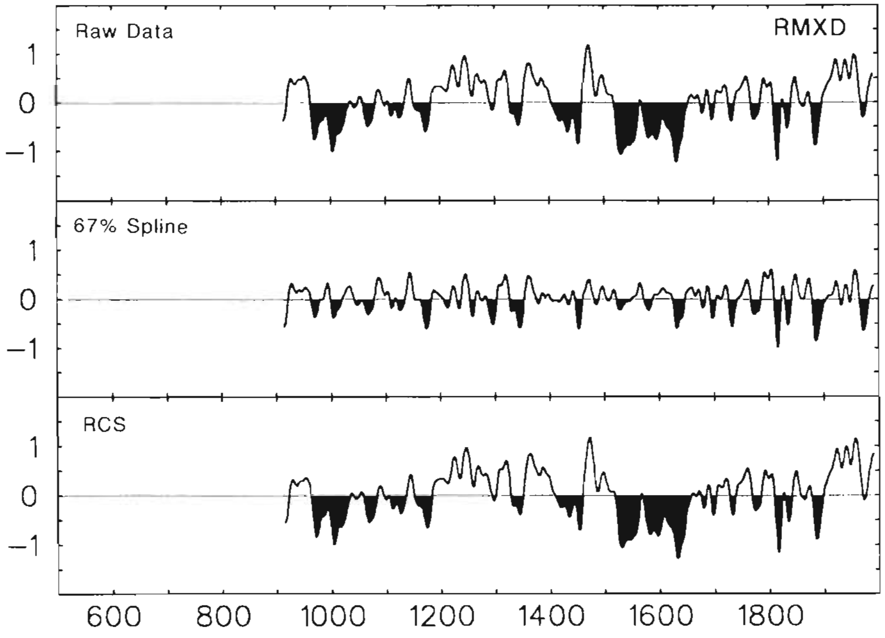

Figure 8: **The Russian, Sob River maximum-latewood-density chronologies standardized with alternative methods. See the legend to Figure 5 and text for further details**

spline-standardized or RCS data are used (Table 1). It is worth stressing that the instrumental record cannot help us to resolve the question of which chronologies produce the most realistic picture of past summer temperature change in this region. The alternatively-standardized chronologies are basically the same during the period of overlap between climate and tree-growth data. Therefore the results of any calibration/verification scheme using these data give essentially similar results. In reality, the spline-standardized data in this particular instance, are likely under-representing what are, very likely, genuine long term climate changes. However, given variable (sometimes low) replication and little control over the homogeneity of the sample data through time,

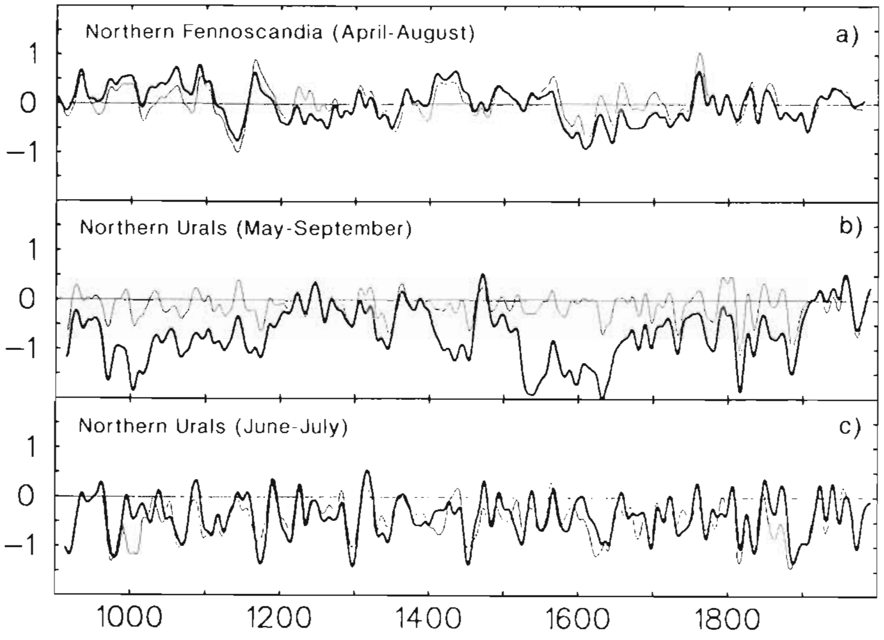

Figure 9: **Different reconstructions of 'summer' temperature. (a) April-August mean temperatures over Northern Fennoscandia using RCS TRW and MXD chronologies from Torneträsk (thick line) and using the same chronologies standardized with 67% splines (thin line). (b) May-August mean temperature over the Northern Urals region reconstructed using RCS MXD and spline-standardized TRW from the Sob River site (thick line). (c) June-July mean temperatures over the Northern Urals reconstructed using spline-standardized TRW and MXD (thick line) and the earlier reconstruction for the same 'season' based on TRW data only standardized using the 'corridor' method (Graybill and Shiyatov, 1992). All data are shown as °C anomalies from the 1951-70 mean and are smoothed with a 25-year low-pass filter**

Table 1: **Selected statistics illustrating the goodness of fit and fidelity, over the calibration and independent verification periods, of regression models relating summer temperature to maximum-latewood-density (MXD) and ring-width (TRW) chronologies produced using alternative standardization techniques. See the text and Figures 5-9 for further details and discussion**

Northern Fennoscandia (April-Aug. mean)

Predictands: MXD and TRW standardized with 'conservative' splines

Calibration Period		1876-1925	1926-1975
Verification Period		1926-1975	1876-1925
Calibrated Variance		0.49	0.44
Verification	r^2	0.42	0.46
	RE	0.56	0.59
	CE	0.33	0.43

Predictands: MXD and TRW standardized with RCS functions

Calibration Period		1876-1925	1926-1975
Verification Period		1926-1975	1876-1925
Calibrated Variance		0.51	0.56
Verification	r^2	0.50	0.46
	RE	0.62	0.51
	CE	0.42	0.32

Northern Urals (May-Sept. mean)

Predictands: spline-standardized MXD and TRW

Calibration Period		1882-1935	1936-1990
Verification Period		1936-1990	1882-1935
Calibrated Variance		0.70	0.64
Verification	r^2	0.62	0.69
	RE	0.64	0.70
	CE	0.61	0.68

Predictands: RCS MXD and spline-standardized TRW

Calibration Period		1882-1935	1936-1990
Verification Period		1936-1990	1882-1935
Calibrated Variance		0.70	0.66
Verification	r^2	0.65	0.69
	RE	0.67	0.70
	CE	0.65	0.68

there must be some uncertainty attaching to the accuracy of the lowest timescales of variations represented in the RCS reconstructions.

However, in this context, we have explored two potential sources of bias in this reconstruction. The first is the possibility of temporal bias in the results that might arise due to changes in the elevation of the samples. The second is the possibility that some anthropogenic influence may be producing enhanced tree growth in the recent part of the record.

We do not have details of the elevations for the living trees sampled, except that they grew between 200 and 250 m a.s.l. The elevations of the subfossil data are known precisely, however, and changes in average deviation through time are illustrated in Figure 4. We examined the evidence for a time-dependent sample elevation bias in the reconstruction by regressing mean MXD against mean sample elevation for different age classes of trees (i.e., 1-50 year old, 51-100 etc.). These results (shown in Table 2) indicate no significant elevational influence on mean density, at least over the range of elevations involved in these calculations.

Table 2: **Correlations between the mean maximum-latewood-density of different age classes of the Sob River samples and their elevations above sea level. The density data in each age class are averaged over different time periods so that effects of climate variability should hopefully largely cancel out. Two sets of correlations are shown: one based only on the subfossil series and the other including the living tree material whose precise elevations are not known and have been set here to a constant elevation of 250 m a.s.l. None of the correlations is significant indicating that there is little evidence for an elevation influence on ring density and hence little age-dependent bias in the temperature reconstruction arising out of the differences in sample heights shown in Figure 4**

Age Class	**Mean MXD (subfossil only)**	**Mean MXD (all samples)**
1-50	0.09 (37)*	-0.07 (62)
51-100	0.05 (49)	-0.12 (90)
101-150	0.10 (40)	-0.05 (71)
151-200	-0.20 (17)	-0.07 (39)
201-250	0.10 (8)	0.22 (18)
251-300	-0.25 (3)	-0.08 (9)

* The number of cases involved for each correlation is shown in parentheses

Neither is there evidence that anthropogenic fertilization may be amplifying the apparent warmth of the 20th century. Details of nitrogen deposition in this remote region of the northern Urals is, largely unknown, but any increases are likely to have been relatively small and will be greatest over recent decades. Similarly global CO_2 levels increased by less than 10 per cent above pre-industrial levels by about 1960. The increase has accelerated markedly after that time. The empirical relationships that we have derived between summer temperature and tree-growth (c.f. Table 1) appear strong and stable when calculated over different periods and there is no trend in the regression residuals that might suggest the increasing influence of some alternative growth forcing factor.

None of this proves unequivocally that the long-timescale variability illustrated in the RCS reconstructions is real. However, the results do indicate the important potential for recovering significant long-timescale variability, that could be lost depending on how the data are processed.

It has been our intention to make clear that there remain problems associated with such work and that there is scope for experimenting with new approaches to recovering long-term climate change in tree-ring data. However, in common with all proxy-data analysis, equal emphasis must be placed on establishing the veracity of any long-timescale information indicated.

Conclusions

This paper has discussed general issues relating to the preservation and interpretation of long-timescale variance in tree-ring chronologies. Our main intention has been to alert the non-dendrochronologist to the existence of potential problems and to caution against viewing published dendroclimatic timeseries as necessarily representing all timescales of climate variability with equal accuracy. Even when the limitations of specific dendroclimatic reconstructions are explicitly stated or clearly implicit in the description of the work, they can be overlooked in subsequent use or interpretation of the data by others.

We have focused on specific examples, drawn from our own work, to illustrate the uncertainty that accompanies attempts to reconstruct progressively longer timescales of climate variation. While these problems are real, their specific nature should not be generalized to all dendroclimatic situations. As well as considering the problems and

limitations associated with regression-based climate calibrations of tree-ring data, apparent long-timescale climate signals in chronologies may, to some extent, be affected by changes in sample site homogeneity; tree age (series length); tree growth form and population density; and series replication. The apparent long-timescale variations will be modified by chronology construction methods. These must all be considered when viewing the likely reality of inferred climate variability on long timescales. The relevance of each of them will vary greatly according to the study.

Our discussion of these problems should not be interpreted as detracting from the very real strengths of the main body of dendroclimatological output: providing easily the bulk of genuine absolutely-dated, annually-resolved, pre-instrumental climate information across much of the middle-to-high latitude landmasses. Other high-resolution proxy sources are rapidly becoming more widely exploited and will increasingly provide valuable information in areas devoid of dendroclimatically-suitable trees (particularly coral and various ice-core data e.g., see Cole this volume and Thompson, this volume). However, compared to dendroclimatology, analyses of these data sources still have some way to go towards adopting the same rigorous approach to routine dating and quantification of climate expression even on interannual-to-multidecadal timescales. Our observations on the need to demonstrate the replication of long-timescale variability in proxy data and the problems of formal climate calibration (and verification) of this variability are as relevant to these other palaeoclimate sources as they are to tree-ring data.

Despite the problems, working towards the successful exploitation of long-timescale climate information in all of these records is clearly worthwhile. A knowledge of climate change on timescales from one to several hundred years, especially during the recent millennia is of crucial importance for providing a context within which to analyse the climate variability that has been observed during the last century. Well-dated palaeoclimate information on timescales centred on about 100-years, remains largely elusive. Recognising the problems associated with attempts to recover this information is a step forward.

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