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Trees tell of past climates: but are they speaking less clearly today?

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The annual growth of trees, as represented by a variety of ring-width, densitometric, or chemical parameters, represents a combined record of different environmental forcings, one of which is climate. Along with climate, relatively large-scale positive growth influences such as hypothesized 'fertilization' due to increased levels of atmospheric carbon dioxide or various nitrogenous compounds, or possibly deleterious effects of 'acid rain' or increased ultra-violet radiation, might all be expected to exert some influence on recent tree growth rates. Inferring the details of past climate variability from tree-ring data remains a largely empirical exercise, but one that goes hand-in-hand with the development of techniques that seek to identify and isolate the confounding influence of local and larger-scale non-climatic factors.

By judicious sampling, and the use of rigorous statistical procedures, dendroclimatology has provided unique insight into the nature of past climate variability, but most significantly at interannual, decadal, and centennial time-scales. Here, examples are shown that illustrate the reconstruction of annually resolved patterns of past summer temperature around the Northern Hemisphere, as well as some more localized reconstructions, but ones which span 1000 years or more. These data provide the means of exploring the possible role of different climate forcings; for example, they provide evidence of the large-scale effects of explosive volcanic eruptions on regional and hemispheric temperatures during the last 400 years.

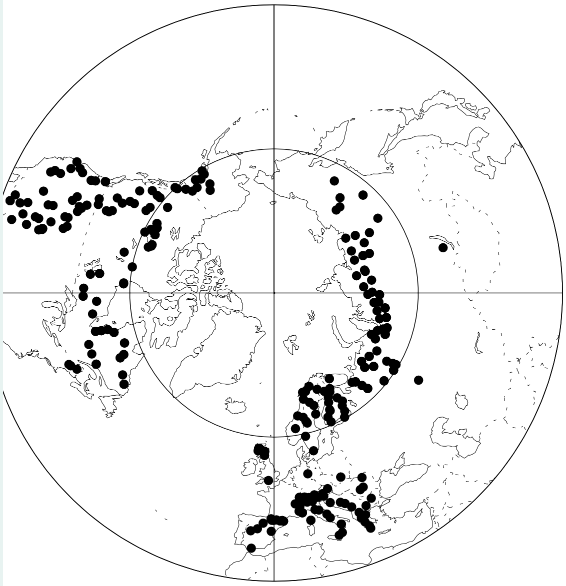
However, a dramatic change in the sensitivity of hemispheric tree-growth to temperature forcing has become apparent during recent decades, and there is additional evidence of major tree-growth (and hence, probably, ecosystem biomass) increases in the northern boreal forests, most clearly over the last century. These possibly anthropogenically related changes in the ecology of tree growth have important implications for modelling future atmospheric CO_2 concentrations. Also, where dendroclimatology is concerned to reconstruct longer (increasingly above centennial) temperature histories, such alterations of 'normal' (pre-industrial) tree-growth rates and climate–growth relationships must be accounted for in our attempts to translate the evidence of past tree growth changes.

Keywords: tree rings, climate change, volcanoes, tree biomass, fertilization

1. INTRODUCTION

The past decade has seen the steady accumulation of tree-core samples that, together, provide data on past radial growth of a variety of conifer species over a continuously expanding network of generally cool, moist sites, located at relatively high elevations in mid-northern latitudes or else at high latitudes, in the northern boreal forests of the world (figure 1). Many of these sample collections have been analysed at the Swiss Federal Institute for Forest, Snow and Landscape Research, and have yielded a range of densitometrically defined growth parameters (Schweingruber 1988), including what are, to date, the two most widely used: tree ring-width (TRW) and maximum late-wood density (MXD). TRW and MXD are both components of annual radial mass, changing throughout the life of a tree. They provide an indication of net primary production which is influenced by external climate forcing. Combining these data into site and larger regional chronologies provides continuous and annually resolved histories of past tree growth that are proxies of past temperature variability in both space and time over a large part of the Northern Hemisphere (Schweingruber & Briffa 1996).

Close attention to site selection is intended to maximize the potential sensitivity of these records to temperature variability. However, temporal records of growth parameters measured along different radii, even within the same tree, will always be, to some degree, affected by factors other than climate. The most obvious example of this is a general decline in both TRW and MXD with increasing age, as net productivity is distributed around an increasing circumference. The growth of different trees in the same stand will vary because of differing degrees of



re 1. The recent extent of the Northern Hemisphere tree- densitometric network currently under construction which s the basis of the results discussed in this paper.

petition, soil condition, micro-climates, and even tic make-up. On large regional and hemispheric s, besides climate, potential factors such as changing , O_3, and UV-B levels, and widely experienced altera- in the other atmospheric and soil balances, must be idered as possible influences on measurable tree th.

is paper describes selected aspects of the recent colla- tive work, intended to reconstruct and interpret past modern tree growth across our network: principally rms of changing climatic (temperature) variability its causes, but also in terms of anthropogenic environ- tal disturbance which, if not recognized and unted for, could lead to erroneous inferences about and future climate changes.

HRONOLOGY PRODUCTION METHODS IMPOSE IGNAL' TIME-SCALE DEPENDENCE

uch of the non-climate-related variability in year-to- growth of trees at a site is unique among individuals. simple expedient of averaging a number of precisely d and correctly aligned measured records at the tree or site level will, therefore, reveal the underlying mon forcing or 'signal' (Fritts 1976; Wigley *et al.* 1984; a & Jones 1990). The efficiency with which non- mon 'noise' cancels out is, however, time-scale depen- , so that interannual and decadal variability in raw etrended) average chronologies is invariably more rately represented than longer time-scale variability. sured TRW and MXD records invariably show g age-related trends, and in typical sample collec- the distribution of mean tree age over time is always rom even. Therefore, to eliminate what would clearly purious (i.e. related to mean tree age rather than nally forced) trends in tree-ring chronologies, roclimatologists long ago adopted 'standardization' as an almost ubiquitous stage in chronology development (Fritts 1976).

This, simply expressed, involves detrending each measured series prior to its incorporation within a mean site chronology. Because it is not possible to develop a generally applicable theoretical basis for defining the 'expected' age trends in various trees, a range of techniques has been used. The dendroclimatologist's obsession with this aspect of tree-ring research is shown by the extensive literature on the philosophy, techniques and applications of various tree-ring standardization approaches (Cook *et al.* 1990). The simple message of relevance here is that standardization removes 'long time-scale' information because it involves the use of dimensionless tree-ring indices that are the residuals from a curve tailored to fit the original measured time-series from individual trees. The more data-adaptive or 'flexible' the tailoring, or where measured series length is short, the threshold for the loss of low-frequency chronology variance occurs on a correspondingly short time-scale, even if overlapping series are combined to form a very long chronology (Cook *et al.* 1995; Briffa *et al.* 1996). Temperature reconstructions based on standardized chronologies should not, therefore, be interpreted as necessarily illustrative of all time-scales of variance, but rather as potentially high-pass filtered series where the low-frequency variance 'cut-off' is dependent on the distribution of different sample lengths through time: the flexibility of the detrending option used, and changing sample replication.

Figure 2 illustrates one example of the effect of different standardization when applied to the same chronology data to produce alternative temperature reconstructions (Briffa *et al.* 1996).

The two curves show 25-year smoothed changes in mean summer temperatures over the last 1000 years in the Northern Urals region of north-western Siberia. Both curves are plotted as °C anomalies from the mean of 1951–70, and were derived from linear regression of the modern tree-growth data against parallel instrumental temperatures recorded over the last century. These regressions (based on annual data) were repeated over various subsections of the tree-growth/temperature overlap, and produced stable and similar regression coefficients (Briffa *et al.* 1995). The tree-ring data have around 70% variance in common with the temperature data, even when measured against independent (of the fitting period) data. Hence, interannual (not shown here) and multidecadal variability in past temperatures is represented with high fidelity in both curves. However, the top (thin line) curve in figure 2 is based on chronologies that were 'standardized' by removing an individually tailored trend from each tree-ring series prior to its being pieced together with all the other similarly detrended series to form the long chronology. The bold curve is based on MXD series, each of which was detrended by taking residuals from a single (fixed parameter) straight line, defined as the average growth function of all measurement series after they had been aligned with respect to common tree age (i.e. regardless of their calendrical year of growth). It can be seen that this alternative ('regional curve standardization', or RCS) approach preserved much more long time-scale variation in the final chronology, after the rescaled series were then realigned according to the correct date of growth and

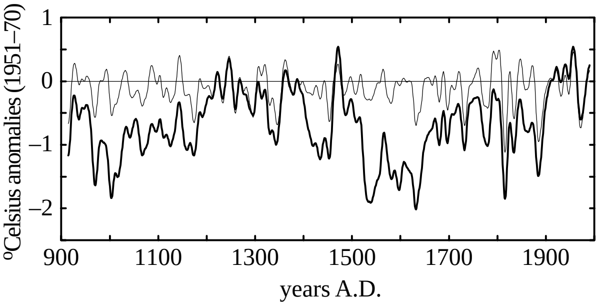


Figure 2. Differences in the long time-scale temperature information (25-year filtered) reconstructed in northern Fennoscandia using the same tree-ring data, but processed using different techniques to remove localized age bias in the constituent measurement series. The graph shows Northern Urals mean summer (May–September) temperatures.

averaged. The RCS method potentially provides much more information on century-to-century time-scale changes in temperatures than the previous approach, but the lack of very long temperature data means that it is simply not possible to verify this centennial time-scale information without reference to other evidence (Briffa *et al*. 1995).

Tree rings (TRW and MXD data) provide demonstrably accurate information on interannual and decadal time-scales, but it is clear that as we try to deduce centennial and longer scales of information, the reconstructions are subject to increasing levels of uncertainty. Nevertheless, where good data replication exists, especially if many samples from a wide range of tree ages are available over long periods, the single RCS approach can be used to attempt to capture long, as well as short, time-scale information.

3. EXAMPLES OF TEMPERATURE RECONSTRUCTIONS IN TIME AND SPACE

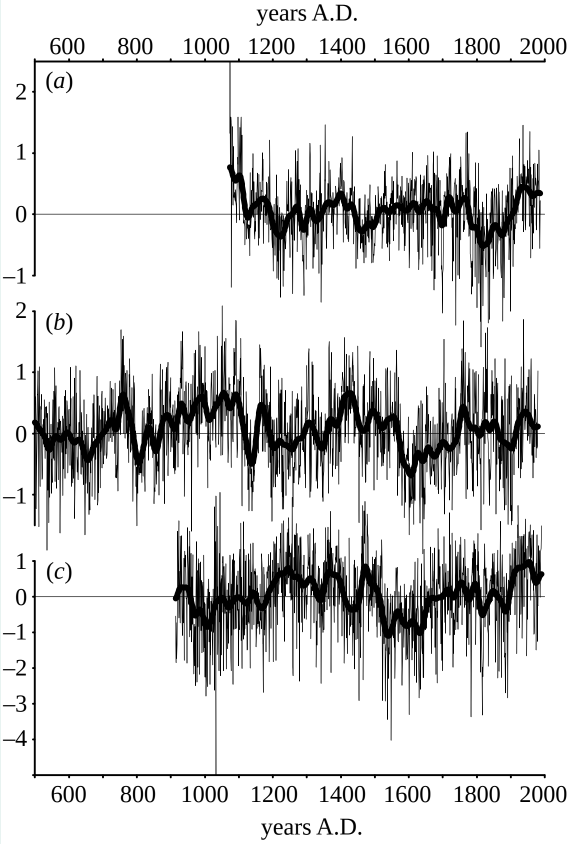
Dendroclimatology has pioneered the development of techniques for ensuring absolute dating accuracy of tree-ring time-series, and realistic assessment of the quality of statistically derived climate inferences (Fritts 1976; Cook & Kairiukstis 1990). Replication of tree-ring series, by multiple sampling within and between trees at a site, allows routine quantification of chronology confidence, while the rigid annually resolved scale facilitates rigorous use of temporal regression against observed climate time-series (Briffa 1995). Derived expressions for estimating climate as a function of growth at one or many sites (often using multiple parameter time-series, e.g. MXD and TRW) are routinely 'verified' by comparison with independent climate data, specifically reserved for the purpose. This guards against the possibility of accepting inflated estimates of common variance that are invariably achieved when calibrating regressions with only short predictand series and numerous predictor series. Regression equations are calibrated over various periods, regression coefficients are compared, and verification statistics are calculated to gain insight into the likely strength and weaknesses of early climate estimates.

Reconstructions, usually derived using principal component regression (Fritts 1976; Cook *et al*. 1994), have been produced for single sites or directly over networks of sites such as across western North America, or Western Europe (Schweingruber *et al*. 1991; Schweingruber & Briffa 1996). Figure 3 illustrates several reconstructions of mean summer temperatures, all estimated as a function of both TRW and MXD predictors (Briffa *et al*. 1992, 1995; Luckman *et al*. 1997). These tree-ring data were all 'standardized' in order to preserve century, as well as decadal and annual, variability. Taken together, they show the sort of reconstructed climate detail that tree-ring records can provide. Very large interannual variability, characteristic of high latitudes, is superimposed on prominent long time-scale fluctuations. Perhaps one of the most notable features is that the extended relative warm and cool departures are rarely, if ever, synchronous at all locations. The prominent cool conditions of the seventeenth century in Sweden are seen in the Russian series, but they began earlier there and amelioration was earlier. In western Canada, however, conditions remained close to 'normal', or even somewhat warmer, during this time. The apparent warmth of the tenth and eleventh centuries in northern Sweden was matched by relative cold in Russia. However, note that in all areas, the early twentieth century was warm. In the Canadian and Russian series, the present century is the warmest (just) of the respective records. There are only three records, and they extend only to about 1000–2000 years. Work is underway to extend them, perhaps to cover the last 7000–8000 years, and to develop similar long records in other high-latitude areas of Fennoscandia and Russia (Briffa 1994; Zetterberg *et al*. 1994; Shiyatov *et al*. 1997; Vaganov *et al*. 1997).

Figure 4 illustrates the spatial dimension of climate reconstruction more explicitly. It shows the extent and level of detail that is now becoming feasible as the density and spread of the tree-ring densitometric network develops. Examples of simple contoured anomalies of MXD are shown (interpretable as relative temperature maps) at each of more than 300 sites. Such maps now allow the characterization or classification of large-scale temperature patterns for each of the last 400 years.

4. LARGE REGIONAL TEMPERATURE SIGNALS: THE VOLCANIC EFFECT

In the light of the strong local summer temperature signals expressed by selected tree-ring chronologies, we can consider constructing amalgamated chronologies in order to represent large regional, and even high-latitude, circum-hemispheric temperatures. Figure 5 illustrates just such a series, made up of MXD chronologies from all of the locations shown in figure 1 (with some variance adjustment to allow for reduced numbers of series at the start and very end of the series). Like the maps shown earlier (figure 4), these series should be considered representative of interannual-to-centennial time-scales of MXD variability. The data in figure 5 (and other large regional series not shown here) are strongly correlated with a 'real' summer temperature series made up of similarly averaged instrumental records from all of the regions represented by the trees. The simple correlation over the period 1881–1975 is 0.70. Figure 5 therefore represents



re 3. Summer temperature reconstructions for three high-ude regions of the Northern Hemisphere. Annual values onger-term (50-year low-pass) variations are shown. rence from 1100–1900 mean. (*a*) Canadian Rocky Moun-, 52° N, 117° W. (*b*) Northern Sweden, 68° N, 20° E. (*c*) Mountains, 67° N, 66° E.

of the best available proxies for summer temperature ability around the northern high latitudes over the last years (Briffa *et al.* 1998).

n important feature of these data is the prominence of ral pronounced negative growth anomalies: both indi- al years and distinct groups of years. These point to important influence of volcanoes (Jones *et al.* 1995; kin & Siebert 1994). The groups of apparently cool ners include the early 1640s, the end of the 1690s, the 1810s. The 1640s and the 1810s are associated with d volcanic eruptions: 1640 and 1641 in Japan and the ppines, an ‘unidentified’ mid-latitude eruption in , and another eruption of Tambora, Indonesia, in One of two cool summers in 1666 and 1675 is likely e associated with the large Long Island eruption in a New Guinea that is believed to have occurred at t this time, but is not otherwise precisely dated. r important single-year volcanic signals occur in (Novarupta, Alaska), 1883 (Krakatau, Indonesia— rent in 1884), 1783 (Skaftareldahraun, Iceland) and (Pinatubo, Philippines—apparent in 1992). ever, by far the most extreme negative signal in our occurs in 1601. This either indicates that the eruption uaynaputina (Peru in 1600) was considerably larger has previously been thought or else at least one

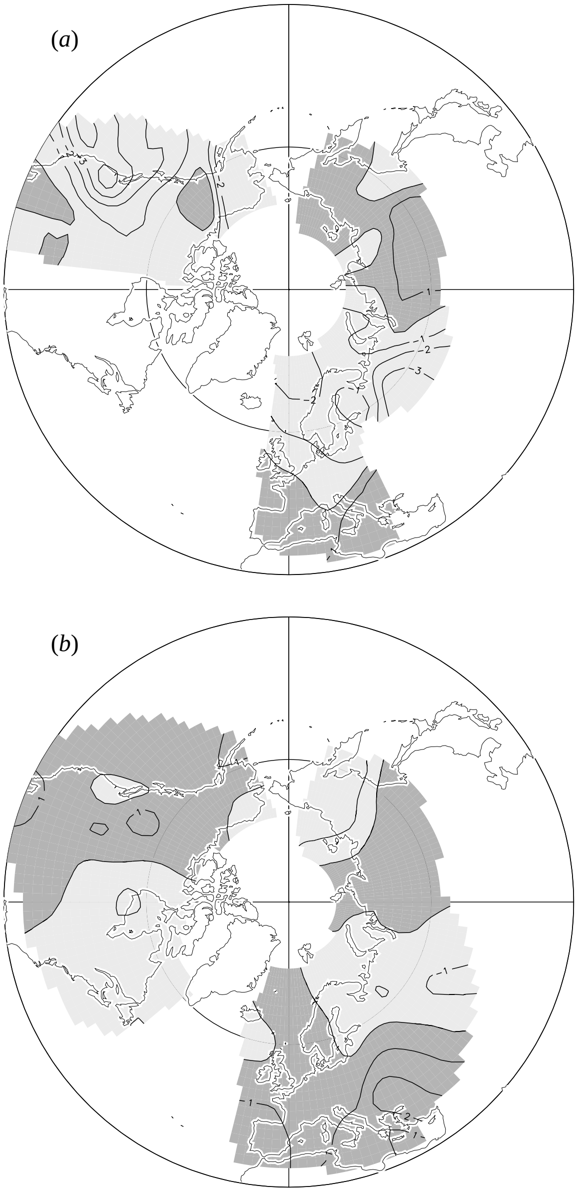


Figure 4. Examples of contoured tree-ring-density anomalies, interpretable as relative summer temperatures across much of the Northern Hemisphere. Lighter shading indicates relatively cool areas, darker shaded areas are warm. (*a*) 1612; (*b*) 1724.

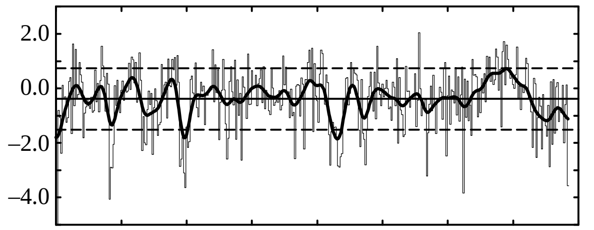


Figure 5. Series of annual and decadally smoothed standardized anomalies (1901–70 base) of tree-ring density averaged across all sites shown in figure 1. The dotted lines are ±1 s.d. about the long-term mean. The extreme negative departures often coincide with the eruption dates of known explosive volcanoes.

other, as yet unidentified, major volcano erupted in 1600 or 1601.

Collectively, these MXD data clearly identify volcanic forcing as a very significant large-scale temperature influence on extreme interannual and even decadal timescales—more so on the decadal scale than has been indicated by previous volcanic/instrumental data comparisons (Sear *et al*. 1987) and simple climate modelling studies.

5. A RECENT CHANGE IN TEMPERATURE SENSITIVITY

In §4, we referred to a notable correspondence between 'hemispheric' MXD series (averaged over all sites) and an equivalent 'hemispheric' instrumental temperature series. Despite their having 50% common variance measured over the last century, it is apparent that in recent decades the MXD series shows a decline, whereas we know that summer temperatures over the same area increased. Closer examination reveals that while year-to-year (i.e. mutually ten-year high-pass filtered) correlations are consistently high between tree-growth and temperature (*ca*. 0.7 for 1881–1981), the correlations based on decadally smoothed data fall from 0.89, when calculated over the period 1881–1960, to 0.64 when the comparison period is extended to 1881–1981. This is illustrated in figure 6, which shows that decadal trends in both large-scale-average TRW and MXD increasingly diverge from the course of decadal temperature variation after about 1950 or 1960. This phenomenon is also apparent when similar comparisons are made between smoothed tree growth and equivalent-area temperature series averaged over various sub-continental scale regions of the network (Briffa *et al*. 1997). It seems clear that a major, wide-scale change has occurred in the ecology of Northern Hemisphere tree-growth and temperature. As yet, the cause is not understood, but a number of factors such as increasing atmospheric CO_2, higher levels of pollutant (i.e. nitrates or phosphates) transport, other changes in soil chemistry or increased UV-B levels might be involved. There is also evidence that increasing atmospheric opacity has resulted in a notable reduction in the amount of solar radiation reaching the earth's surface since the middle of this century (Bradley & Jones 1992). Several factors could be acting together, and possibly interacting with changes in climate itself.

The implications of this phenomenon are important. Long-term alteration in the response of tree growth to climate forcing must, at least to some extent, negate the underlying assumption of uniformitarianism which underlies the use of twentieth century-derived tree growth–climate equations for retrodiction of earlier climates. At present, further work is required to explore the detailed nature of this changing growth–climate relationship (with regard to species, region, and time dependence). It is possible that it has already contributed to some degree of overestimation in published reconstructed temperature means—more likely only those that attempt to reconstruct long time-scale information. However, in various earlier work, we either made empirical correction for apparently reducing recent MXD (Briffa *et al*. 1992), or undertook detailed analysis of regression weight-stability and calibration and verification-period regression residuals when fitting regressions over earlier and recent data (Briffa *et al*. 1995). These analyses did not indicate the likelihood of a bias in these reconstructions, but future reconstruction work must either find a satisfactory means of correcting for any recent (non-climatic) tree-growth bias or be calibrated against data that do not include it. However, by further reducing the overlap between instrumental temperatures and tree-growth records, the opportunities for independent verification of the low-frequency (multi-decadal and longer) component of temperature reconstructions are also further reduced.

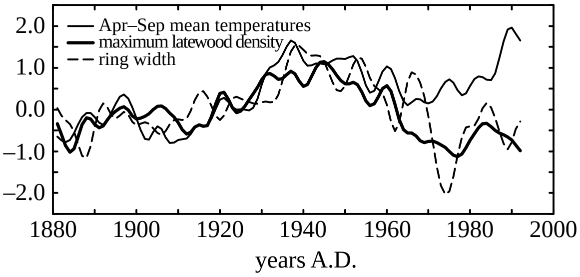


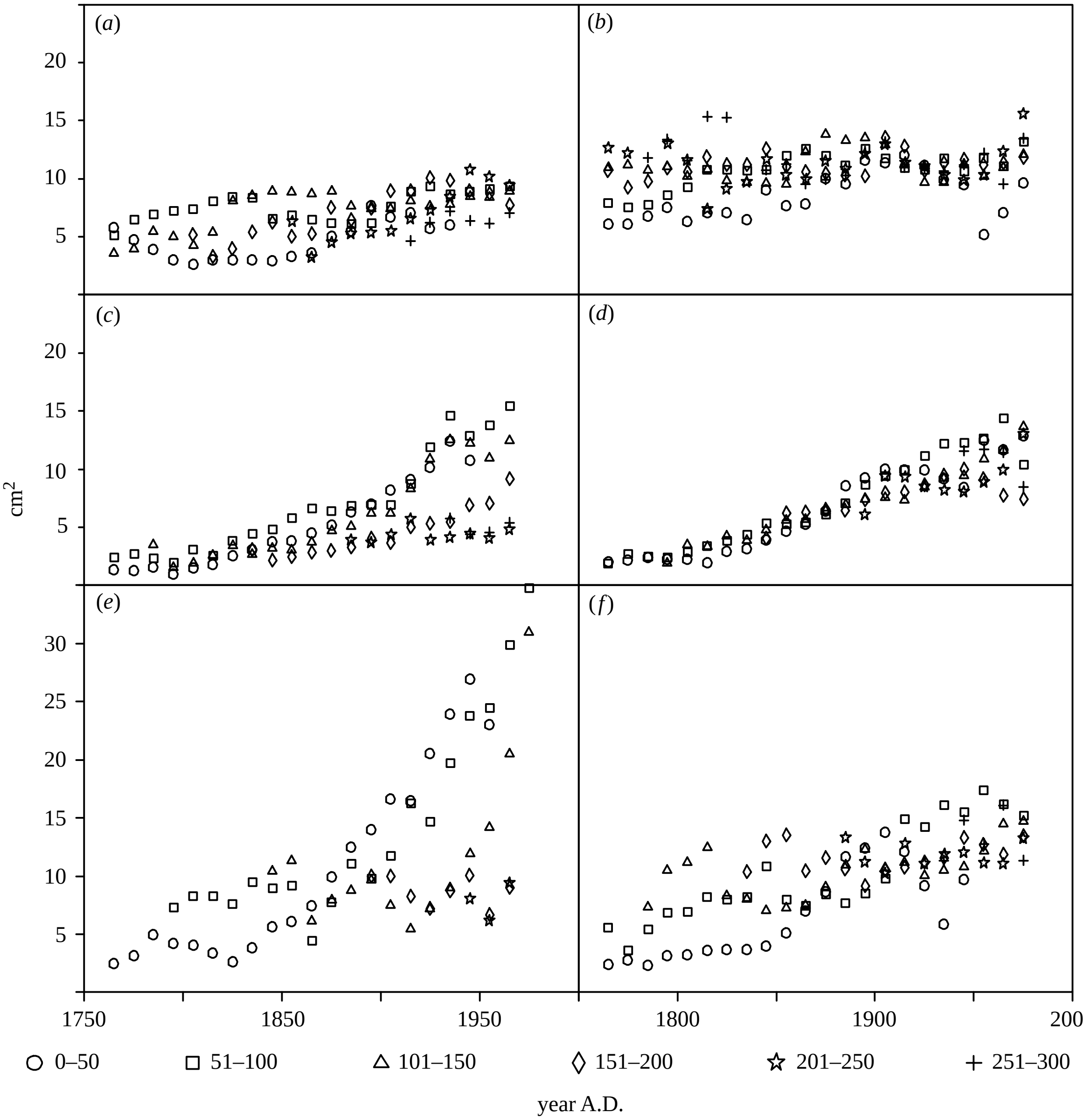
Figure 6. Twenty-year smoothed plots of averaged ring-width (dashed) and tree-ring density (thin solid line), averaged across all sites in figure 1, and shown as standardized anomalies from a common base (1881–1940), and compared with equivalent-area averages of mean April–September temperature anomalies (thick line).

6. POSSIBLE LONG-TERM ANTHROPOGENIC CHANGES IN TREE GROWTH

Now, we make reference to some previous and recent analyses, further exploring the evidence for possible anthropogenic influences on tree growth rates in the pre- and post-industrial eras. In an earlier analysis, stimulated by an ongoing debate about the reality and causes of increasing tree growth in various parts of the world (Briffa 1992), ring-width measurements from a group of European tree-ring site collections were converted into basal area increment (BAI) values and stratified according to time and tree age. In other words, the mean BAIs for particular tree genera in particular regions of Europe were calculated separately for pre-selected age bands of trees, and compared decade-by-decade from 1760 to 1980 (figure 7). This age stratification overcomes the age-related bias that confuses attempts to compare changing absolute growth rates where the data are made up of different aged trees through time.

The general conclusion to be drawn from this analysis is that BAI, at least in Europe, when averaged across all age bands of trees, has increased steadily over recent centuries. The increase is detectable in all areas and genera, although it may be (i) greater in spruce and fir than in pine; (ii) greater in central and southern regions than in the north; and (iii) more apparent in younger, compared to older, trees.

Recently, we have been taking the same approach to investigate whether similar growth increases occur over larger and widely separated regions of the current densitometric network. Figure 8 illustrates two selected examples



re 7. Changes in basal area increment for different age classes of trees (shown as different symbols) over the last 200 years. The shown are the averages from a number of European sites, arbitrarily divided into northern, central and southern groupings. orthern pine; (*b*) southern pine; (*c*) northern spruce; (*d*) central spruce; (*e*) southern spruce; (*f*) southern fir.

ear-by-year changes in BAI over the period 1700– . These examples illustrate extreme differences in ion (northern North America and Eastern Siberia) species (*Picea glauca* and *Larix dahurica*). Yet they also a very similar picture of increasing growth over than a century, which is associated mostly with a linear increase between about 1850 and 1940. It is clear that since about 1940 or 1950, the trend in BAI levelled-off in both data sets. Note also that the valent maximum density data show no overall trends, he declining trend since about 1950 or 1960 (cf. §5) is ly visible.

nese data demonstrate clear century time-scale ases in overall radial tree growth, and are strongly estive of increases in overall net tree productivity and, aps even of total biomass in the boreal forest ystem—up until about 1950. Other researchers working in Europe and elsewhere have also come to similar conclusions (Innes 1991; Becker *et al.* 1995; Spiecker *et al.* 1996*a*). Schadeur (1996) demonstrated a 24% increase in current annual increment since 1961 in Austrian forests. Zingg (1996) came to virtually the same conclusions regarding forests in Switzerland. In a study of the carbon budget of European forests, Kauppi *et al.* (1992) provide evidence for an increase in the stock of standing timber (especially stem volume) from Sweden to Switzerland. They report an increasing trend between 1940 and 1990, and estimate that there was a 25% greater stock in the most recent year compared with 1971. More recent work shows that the increase is not equally distributed, being more evident in central than in northern Europe, and not detectable in Norway or Finland (Spiecker *et al.* 1996*b*).

Greater twentieth-century tree growth is likely to have been driven by a combination of factors. Undoubtedly,

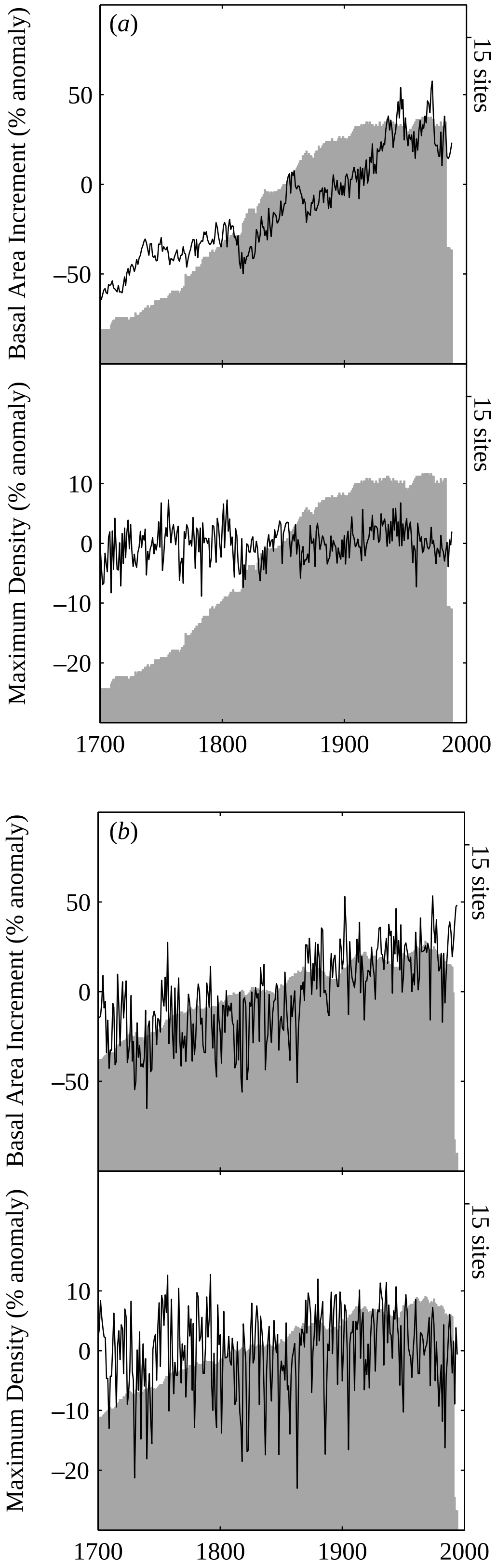


Figure 8. Annual changes in basal area increment and latewood maximum density for two example species, averaged across a number of sites (shown as shading in relation to the right-hand *y*-axis). The curves shown are the mean changes calculated as per cent anomalies (with respect to the period 1700–1990) averaged across various age-stratified bands of growth data, similar to those shown in figure 7. (*a*) *Picea glauca* in northern North America; (*b*) *Larix dahurica* in north-eastern Eurasia.

twentieth-century temperature rise is a contributor, but it is notable that growth seemingly rose even before 1800 and certainly strongly after 1850, well before the recorded warming in the first half of the twentieth century, and rising CO_2 levels and distant transport of nitrates are also likely to have played some part in this. Our ongoing analyses, incorporating many different species, provide general widespread confirmation of these results.

There are several implications that we may touch on here. First, in the context of long-term (multicentury and above) dendroclimatic reconstruction, this partial non-climatic enhancement of twentieth-century tree growth, particularly if it acts in tandem with temperature forcing, will bias the coefficients in any regression-based equation estimating tree growth as a function of recent measured temperatures. Hence, the magnitude of modern warming might be overestimated in the context of earlier reconstructed variability. Second, as regards carbon cycle modelling, our results (along with those of other workers) support the theory that mid- and higher-latitude forests represent at least part of the 'missing' carbon sink, increasingly so after about 1850. However, the increasing extent of carbon sequestration, implied by figures 7 and 8, ceased around 1950, even though these regions experienced subsequent warming. Carbon cycle models that assume a constant CO_2 take up by mid-latitude forest systems over past and future centuries may underestimate future CO_2 levels, and thereby rates of future temperature increase (Wigley 1993).

At present, further speculations must await more detailed investigations of our, and other, tree-ring collections. The net effect on biomass and actual ecosystem carbon must be quantified, taking account of species-specific radial size and densitometric changes, as well as regional and age-dependent factors. Ideally, more extensive, more appropriate (with a better distribution of age classes), and up-to-date collections of tree-ring samples would aid this work.

7. CONCLUSIONS

Long, continuous, and absolutely dated tree-ring chronologies are powerful tools for monitoring past tree growth and, by inference, tree-growth forcings. By judicious sampling and a rigorous statistical approach to the calibration and independent verification of climate–growth models, dendroclimatology can provide unique insight into the nature of past climate variability. However, the statistical characteristics of the sample data, allied with the chronology construction techniques, can impart variable time-scale dependence in the reliability of derived reconstructions. On annual, decadal, and probably even centennial time-scales, tree-ring data are demonstrably reliable palaeoclimate indicators, but where the focus of attention shifts to inferences on century and longer time-scales, the veracity of inferred change is difficult to establish. Furthermore, recent analyses of large regional-scale growth patterns and absolute tree growth changes over recent centuries strongly suggest that anthropogenic influences are increasingly challenging our assumptions of uniformitarianism in tree growth–climate responses. While this clearly represents a problem in interpretation, it also provides challenging opportunities for disentangling different tree-growth signals.

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DISCUSSION

J. COWIE (*Concatenation Science, Erith, Kent, UK*). You mentioned that there was a global gap in the data *ca.* 350 BC. What do you think happened?

K. R. BRIFFA. This question refers to ongoing work, constructing a 7000–8000-year tree-ring chronology in Torneträsk, N. Sweden. The 'gap' arises because of our inability, as yet, to join an early, approximately 5000-year continuous chronology (based on subfossil wood recovered from lakes) to our absolutely dated chronology (based on subfossil and living-tree material) which stretches from 350 BC to the present. Radiocarbon dates on a number of the early chronology wood samples indicate that the two chronologies should virtually overlap, but we have not been able to find samples that positively bridge the two series. I believe it likely that we have some samples that date to around this period—say *ca.* 450–300 BC and the ring patterns show some short tentative matches with the existing chronologies. However, the ring widths are very narrow and often distorted by 'reaction wood'—probably caused by tilting or disturbance of the trees. A rapid rise in water levels on the margins of original lakes may have inundated the trees, perhaps only for a decade or so, but enough to disrupt the ring growth sufficiently to prevent cross-matching of the samples. This is speculation, but the existence of a similar gap at precisely this time (*ca.* 400 BC) in independent work to build a long chronology in northern Finland, and less precisely dated evidence for wetter conditions in other Fennoscandian regions, all point to a likely severe, possible short-lived environmental perturbation at this time.

J. COWIE (*Concatenation Science, Erith, Kent, UK*). Your idea that the decrease in wood density after about 1950 might be attributable to increased UV due to the ozone hole. Is it possible, has it been considered, that this decrease in density is due to a synergistic effect of both increased CO_2 as well as increased temperature?

K. R. BRIFFA. At this time, we do not know why maximum late-wood density declines in relation to large-scale changes (recent warming) in temperature. Further work needs to be done to investigate the regional and species-specific extent of this phenomenon. However, its widespread and apparently synchronous manifestation, N. America, Europe and Siberia, suggests one or more hemispheric-scale factors. Higher UV-B was suggested as an example of one such influence. Some synergistic interaction between different factors is certainly possible, in fact probable. One could reasonably speculate that CO_2 and temperature are implicated, but no more so (given our current knowledge of tree physiology and what experimental work has been done) than, say, higher nitrate levels or perhaps tropospheric ozone. It is salient to note that relative tree-ring width, and basal area increment, also show a relative decline and divergence from the temperature curve(s), arguing against the decline in density being a compensation reaction to increasing ring growth (as is seen in forestry soil fertilizing experiments). I would imagine that higher temperatures, and possibly some increasing sensitivity to lower summer soil moisture are involved, but some additional growth-limiting factor must also be implicated. Higher CO_2 would be expected to increase basal area growth, so I consider it unlikely that this is the factor.

J. COWIE (*Concatenation Science, Erith, Kent, UK*). How do you feel your work relates to that on the Huon pine published in *Science*?

K. R. BRIFFA. The Huon pine work of Ed Cook and his colleagues, building a long temperature-sensitive chronology at relatively high altitude in Tasmania, parallels our work and that of others (e.g. in western North America, Canada, South America, Mongolia and eastern Russia) in that we are all striving to define the characteristics of past climate variability prior to the very short period of instrumental records. Interestingly, some of these other workers, as well as ours and Cook's results, show apparently 'unprecedented' warmth in the twentieth century, compared to that seen over hundreds or even thousands of years. We all face similar statistical problems in constructing long chronologies, and are increasingly aware of possible anthropogenic influences on modern tree growth. However, at this time, the consensus is probably that the twentieth century was unusually warm—perhaps the more so when one realizes that these long records point to significant differences in regional climates on the decadal and century time-scale during almost all of the last millenium. Even the so-called Medieval Warm Period and Little Ice Age are shown not to be ubiquitous.