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Annual climate variability in the Holocene: interpreting the message of ancient trees

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Abstract

Over vast areas of the world's landmasses, where climate beats out a strong seasonal rhythm, tree growth keeps unerring time. In their rings, trees record many climate melodies, played in different places and different eras. Recent years have seen a consolidation and expansion of tree-ring sample collections across the traditional research areas of North America and Europe, and the start of major developments in many new areas of Eurasia, South America and Australasia. From such collections are produced networks of precisely dated chronologies; records of various aspects of tree growth, registered continuously, year by year across many centuries. Their sensitivities to different climate parameters are now translated into ever more detailed histories of temperature and moisture variability across expanding dimensions of time and space. With their extensive coverage, high temporal resolution and rigid dating control, dendroclimatic reconstructions contribute significantly to our knowledge of late Holocene climates, most importantly on timescales ranging from 1 to 100 years. In special areas of the world, where trees live for thousands of years or where subfossil remnants of long dead specimens are preserved, work building chronologies covering many millennia continues apace. Very recently, trees have provided important new information about major modes of general circulation dynamics linked to the El Niño/Southern Oscillation and the North Atlantic Oscillation, and about the effect of large volcanic eruptions. As for assessing the significance of 20th century global warming, the evidence from dendroclimatology in general, supports the notion that the last 100 years have been unusually warm, at least within a context of the last two millennia. However, this evidence should not be considered equivocal. The activities of humans may well be impacting on the 'natural' growth of trees in different ways, making the task of isolating a clear climate message subtly difficult.

1. Introduction

These days, it hardly seems necessary to begin a survey of recent developments in dendroclimatology by stressing the value of palaeoclimate records that possess the attributes of firm dating control and highly resolved climate response. In recent years, there has been a virtual revolution in the general appreciation of the need to piece together accurate details of the earth's recent climate variability and identify the factors that have influenced it during recent millennia. The vagaries surrounding such issues as 'detection' and 'attribution' of anthropogenic climate change within the general global warming arena, reinforce the scientific motivation, and give increasing impetus to political demands, for a clarification of the roles of 'natural' versus anthropogenic drivers of climate change. Hence, the PAGES Stream 1 programme has evolved because of a real need to promote the development and recognition of 'good' high-resolution proxies. 'Good' in this context can be viewed as those that are interpretable, with little ambiguity, as evidence of specific climate variability, within a rigid dating framework.

The extensive coverage, precise dating, and highly resolved climate responsiveness of many tree-ring data provide a rich source of recoverable information about past climate variability: for a range of timescales encompassing yearly to centennial, and perhaps even longer; and, depending on the location and concomitant strength of climate response, for many different primary (e.g. mean summer temperature, total annual precipitation) or derived (e.g. available soil moisture) climate variables. Groups or networks of tree-ring series, not necessarily with the same climate sensitivity, provide the means of reconstructing spatially explicit patterns of climate changes: over the regions represented by the tree-ring data, and by virtue of the large-scale organisation of climate systems, even over remote regions. The

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interrelationships between large-scale patterns of temperature, precipitation and atmospheric pressure variability also mean that networks of climate sensitive tree-ring chronologies can be used to make statistical inferences about the past behaviour of circulation patterns or important circulation indices.

Progress in the methodology, theory and application of dendroclimatology, and the wider field of dendroecology, has been rapid over recent decades (Fritts, 1976; Hughes et al., 1982; Schweingruber, 1988,1996; Cook and Kairiukstis, 1990; Dean et al., 1996). The limited space available here is used to review some recent dendroclimatic research with more immediate relevance for 'global change' studies. That is taken to mean work concerned with new 'long' series; research in 'new' regions; work developing new large spatial data sets and interpreting them in a context of large-scale climate dynamics or forcings. The material presented is limited to the last two millennia.

2. Long tree-ring records

2.1. General background to chronology production

In this review, we are interested in what long tree-ring records can tell us about the variability of past climates over recent millennia and about how observations of 20th century climates compare with this extended background. Many tree-ring chronologies do not exceed 250 years in length. This simply reflects the restricted age, or preservation of heart wood, in most of the living trees that are studied for a multitude of ecological purposes in the extratropical regions of the world. The likelihood of finding older trees increases as one moves to more ecologically marginal areas. Nearer to the limits of tree distributions, where climate stress is increased, tree growth rates are slower, and tree longevity generally higher. Trees in regions with, for example, very cool or very dry climates are also subject to less interspecies competition and their relative growth rates (over a range of timescales) tend to be a stronger and less ambiguous reflection of the variability of local climate, such as for example, mean growing-season temperature or precipitation, than is seen in trees growing in more 'favourable' areas (Fritts, 1976).

In striving to construct long chronologies, dendrochronologists depend on locating unusually long-lived trees, or else they must extend records extracted from younger trees by piecing together other overlapping records from sources of earlier wood, e.g., archaeological, historical, or naturally preserved (subfossil) remnants. Underpinning the construction of all tree-ring chronologies is a meticulous process of cross-comparison of multiple annual growth series to identify locally absent rings and to ensure parallel alignment and hence absolute dating of all the samples, and hence the final chronology. This 'cross-dating' is performed giving particular attention to interannual and other high-frequency variations in ring properties because it is in the very high-frequency variance range that the common growth-forcing signal is generally registered with least ambiguity. Time series of measured tree-ring growth parameters, from whatever wood samples, almost invariably contain some trend or variance on multidecadal and longer timescales that does not represent climate forcing, but is merely a product of tree geometry and ageing (Fritts, 1976).

Building a tree-ring chronology is therefore a two-stage process. In the first, strongly detrended series are used to achieve correct dating of all sample series. In the second, the original measurement data, now firmly dated, are combined, but after some means of detrending has been applied to remove the biasing effect of changing average sample age through time. Different statistical detrending approaches are used at this stage, many with the inevitable consequence that some long-timescale climate information will also be lost. How much depends on the length of individual samples, and the detrending methods applied. Some statistical approaches aim to reduce sample ageing bias in chronologies, while preserving long-term climate signals, but these make assumptions about the temporal stability of the underlying age/growth functions in trees and they are dependent on having large sample replication throughout the length of the chronology to reduce the uncertainty on long timescales (for reviews of this topic see Cook et al., 1995; Briffa et al., 1996). Hence, different tree-ring chronologies, or reconstructions based on them, may have very different capabilities as regards reproducing long-timescale climate changes, regardless of their length. In the following review, reference will be made to this fact, where appropriate.

2.2. Northern 'High' Latitudes.

Fig. 1 shows a selection of tree-ring chronologies or dendroclimatic temperature reconstructions for a range of locations circling the globe. These examples are all based on work where attention was explicitly focussed on preserving long-timescale variability. All of the series are plotted here as 50-year-filtered versions of the original data after normalisation over the period from A.D. 1. The top panel (a) is a Siberian pine ring-width chronology from west central Mongolia, at 2500 m elevation (Jacoby et al. (1996a); Note that, even though the whole series is plotted here, the authors considers replication to be too poor before 1550 to be reliable). This is interpreted as evidence of annual (August–July average) temperature forcing and shows very warm conditions in the 20th century, unusual even in comparison to the warm 18th and possibly (much less certain) 16th centuries. There are notably cool periods around 1600 and especially in the

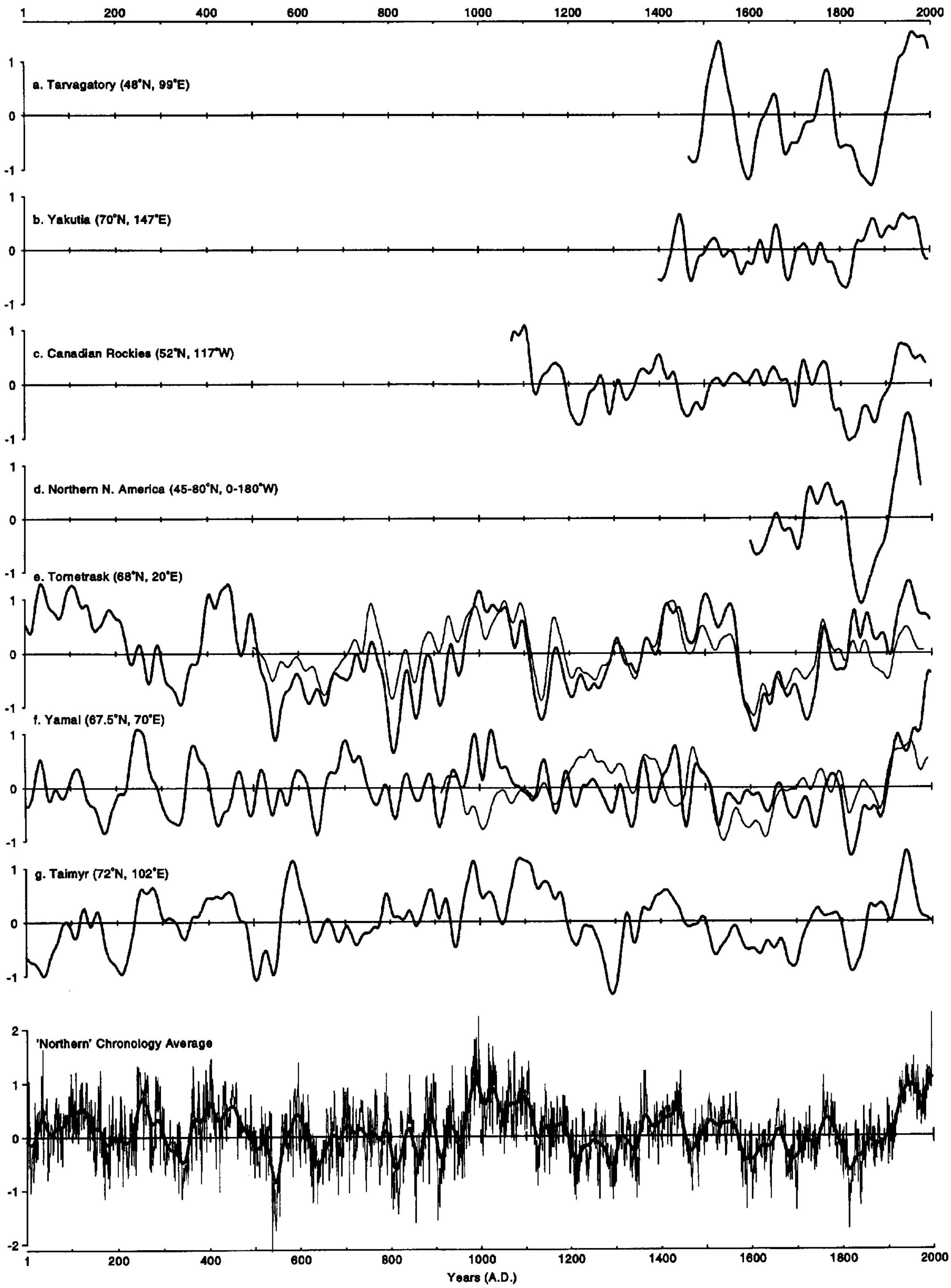

Fig. 1. Northern 'high-latitude' temperature changes over the last 2000 years. The curves show selected reconstructions of summer (annual series a + d) temperatures or temperature-sensitive tree-ring chronologies: (a) Mongolia (Jacoby et al., 1996a); (b) Eastern Siberia (Hughes et al., 1999); (c) eastern Canada (Luckman et al., 1997); (d) North American tree line (D'Arrigo et al., 1992); (e) Northern Sweden (Grudd et al., 1999) with a shorter density-based temperature series superimposed as thin line (Briffa et al., 1992); (f) western Siberia (Hantemirov, 1998reprocessed) with a nearby density-based temperature series for the northern Urals (Briffa et al., 1995); (g) Central Siberia (Naurzbaev and Vaganov, 1999). All series are plotted as normalised values smoothed with a 50-year low-pass filter. The bottom curve is the average of the other data sets after rescaling to give equal mean and variance (over the common period 1601–1974), also plotted as 50-year smoothed values.

19th century. The latter part of this series is remarkably similar to the shorter record (also calibrated against mean annual temperatures) for northern North America from 1601, based on seven, mostly spruce, chronologies (D'Arrigo and Jacoby, 1992) and shown here as Series (d).

Panel (b) shows a 'high summer' (June–July) temperature reconstruction derived from larch ring widths in the Indigurka coastal lowlands of eastern Siberia (Hughes et al., 1999) from 1400 on. The authors of this work again stress the 'unusual' nature of the apparent 20th century warmth. The same is true of the (ring-width and ring-density based) reconstruction of April–August temperatures in the Canadian Rockies, spanning over 1000 years, from 1073 (Luckman et al., 1997); panel (c). In this, the 1961–1990 period is warmer than any other of equivalent length, except for a period at the end of the 11th century that is, again, based on few samples.

The other three regional series in Fig. 1 (e–g), all represent continuous 2000-yr series of ring-width data, all from near-tree-line regions in northern Eurasia, and here all reprocessed in a consistent fashion to preserve maximum long-timescale changes. The Torneträsk series (e), represents the 'recent' northern Swedish part of a 7500-yr Fennoscandian pine series currently under construction in northern Sweden (e.g. see also Grudd et al., 1999; Zetterberg et al., 1994; Eronen et al., 1999). The Yamal (Shiyatov et al., 1996; Hantemirov, 1998) and the Taimyr (Vaganov et al., 1996; Naurzbaev and Vaganov, 1999) data are both constructed from Siberian larch and again form part of ongoing much longer chronology construction projects (Briffa et al., 1999a). These three series extend over more than 80° of longitude. They do not correlate significantly on very high (interannual) timescales, yet they display distinct low-frequency similarities between different pairs for some periods: such as between (f) and (g) in 100–300 and 1700–1900, and between 800 and 1000 for (e) and (f). They all seem to show distinct warmth near A.D. 1000; in the 15th century; and most dramatically, as with the other high-latitude series, in the 20th century. For series (e) and (f), other, slightly shorter (densitometric-based) estimates of past summer temperatures have been previously published (Briffa et al., 1992, 1995). These are superimposed in Fig. 1 on the ring-width curves. It is notable that these density-based reconstructions fail to emulate the magnitude of the positive growth anomalies (and inferred warming) seen in the 20th century ring-width series. We shall return to this point later.

After renormalization, to scale the original variance of all series over a common base (1601–1974), simple averaging of series (a–g) provides an indication of relative temperature changes (a mixture of predominantly summer and some annual signal) at high latitudes (mostly ~ 60–70°N) throughout all of the last 2000 years. This, exclusively tree-ring based, 'Northern Chronology Average' series clearly shows the very high 20th century growth rates, but also only marginally less high rates in the late 10th and 11th centuries.

Other relatively long chronologies exist in northern high latitudes but they are not included in Fig. 1 because they either have ambiguous climate responses (e.g. Jacoby et al., 1996b) or have limited (or ambiguous) low-frequency variability. One of these spans just over 1000 years; a 'northern Alaskan' composite white spruce chronology of living trees and driftwood from the Noatak River, combined with older tree core samples and archaeological wood collected in the 1940s (Jacoby et al., 1996b). Unfortunately, this series is poorly replicated in (early) parts, but it does also show evidence for unusual (maximum) warmth in the 20th century and warm conditions in the 11th century. It also shows notable cool periods in the second half of the 16th, much of the 17th and in the early 19th centuries. Another, very recently produced, millennial length chronology (Barclay et al., 1999), again assembled from living and subfossil tree remains, from near Prince William Sound in southern Alaska, indicates warm summers around A.D. 1300, 1440 and 1820, but no anomalous warming in the 20th century or around 1000, compared to these earlier episodes. However, this series certainly does lack low-frequency variance that may be recoverable with additional samples and different processing methods (Barclay et al., 1999).

2.3. Southern hemisphere temperature records

2.3.1. Tasmania

One of the few long dendroclimatic reconstructions in the Southern Hemisphere is that for Lake Johnston, in northeast Tasmania, based on living and subfossil Huon pine. The data are plotted as normalised departures in Fig. 2. To the lengthening series of papers describing the development of this multimillennial chronology, has just been added the latest (Cook et al., 1999a) that documents the most recent extension, and temperature interpretation, now back to 1600 B.C. The raw data have, for the first time, been processed using a technique designed to retain maximum low-frequency climate-related variance and the resulting warm season (November–April) temperature reconstruction explains over 45% of the local instrumental temperature variability, making it almost the longest, and probably the most reliable, of southern hemisphere tree-ring reconstructions. Other much longer Tasmanian subfossil series are available, but for lower elevations, and they do not possess a clear temperature signal. Indeed, it may be that the special, sub alpine location of the Lake Johnston trees makes them the best suited (perhaps uniquely so) for temperature interpretation in Tasmania (Buckley et al., 1997).

The Lake Johnston reconstructed temperature series (Fig. 2) shows low overall variability compared to many Northern Hemisphere reconstructions, but this is

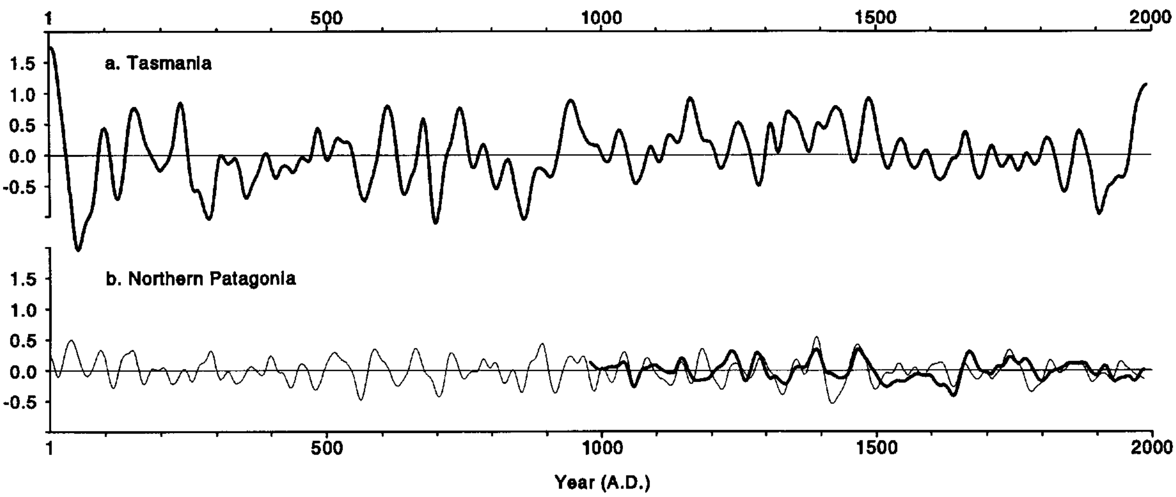

Fig. 2. Southern Hemisphere summer temperature reconstructions for Tasmania (Cook et al., 1999a) and Northern Patagonia (Lara and Villalba, 1993 — thin line; and Villalba et al., 1999a — thick line). The original data were normalised and then smoothed with a 50-year filter.

consistent with a location where the climate is moderated by the thermal inertia of expansive surrounding ocean. Even for individual summers the vast majority (≈ 98%) of temperature estimates fall within a range of 2°C. A marked and abrupt warming is very apparent in recent decades. This warmth is matched in several early periods, e.g. in the 4th and early 1st centuries B.C., but not in any subsequent period in the following two millennia (Cook et al., 1999a). Periods of sustained cool summers occurred between 850 and 750 B.C. and an abrupt cooling in the early 1st century A.D. persisted for several decades. Cook et al. (1999a) have also explored the correlation between their Tasmanian temperature estimates and observed sea-surface temperatures. They detect significant positive decadal-timescale associations across a zonal band of the southern Indian Ocean between 30° and 40°S from the west of Tasmania as far as the coast of South Africa, and also, perhaps somewhat surprisingly, in a region of the west Pacific, to the north east of the Philippines. These results are consistent with an expansive, decadal-timescale westerly oceanic influence on Tasmania temperature, but with possible complex teleconnections further afield.

2.3.2. South America

In South America, the 'centre of action' of tree-ring studies has traditionally been Argentina and Chile, largely focussed on the Laboratorio Dendrocronologia, Mendoza, where, incidentally, the next International Tree-Ring Conference will be held in 2000. The source of very long-temperature reconstructions in these countries is the long-lived conifer *Fitzroya cupressoides*, from which 5 ring-width chronologies, spanning 2000 years and 19 longer than 1000 years have been constructed in the southern Andes (Villalba et al., 1996, 1999a). This long-lived conifer often lives in close canopy forests, so that long-term growth trends may be strongly influenced by random, non-climatic processes such as competitional interactions among the trees (Boninsegna, 1992). The interannual growth of Fitzroya also has a quite complex climate response, involving a negative association between ring width and summer warmth, primarily during the year preceding ring growth.

Fig. 2 shows the most recent 2000 years of reconstructed summer temperatures in northern Patagonia, based on a single Chilean chronology (Lenca) located on the western slopes of the southern Andes (Lara and Villalba, 1993). The method of constructing this chronology originally limited the extent of low-frequency variability. Another more recent reconstruction, based on an analyses of 17 of the new millennial-length chronologies, has now been produced (Villalba et al., 1999a). This better represents long-term temperature trends because of the way in which the chronologies have been constructed and because it expresses common variability in a number of, rather than in just one, predictor series. This new reconstruction is superimposed on the Lenca reconstruction in Fig. 2. There is a fair degree of common variability between them. The most notable feature of the curves is the period of cool summers reconstructed for the period 1500–1650 (cf. Fig. 1). Note also the absence of any major recent growth increase that might indicate anomalous warmth (cf. The Tasmanian series). The development of long tree-ring chronologies in this region is continuing apace. These may offer an ideal opportunity for experimenting with new methodologies for isolating common large-scale growth signals (not necessarily just climate) on various timescales in long tree-ring data sets.

The dramatic progress in the development of both temperature and precipitation sensitive chronology networks in South America, and their interpretation with respect to regional atmospheric circulation dynamics, is one of the major dendroclimatic success stories of the last decade (see also Villalba et al., 1997, 1998, 1999b).

2.4. United States precipitation reconstructions

The traditional heartland of dendroclimatology lies in the southwest United States and easily the greatest number of long chronologies (more than 80 longer than 1000 years) were developed at the Laboratory of Tree-Ring Research in Tucson. Hughes and Graumlich (1996) provide a review and list of numerous works that describe climate reconstructions based on many of these. Here reference is made to examples of recent reanalysis of existing data and other new reconstructions of southwest precipitation variability over past millennia.

2.4.1. Nevada

The longest absolutely dated, and annually resolved, reconstruction of any climate variable is the near 8000-year series of annual (prior July – current June total) precipitation for southwest Nevada, reconstructed by simple linear regression using a single Bristlecone pine series (Methuselah Walk) from the White Mts., California (Hughes and Graumlich, 1996; Hughes and Funkhouser, 1998). This series captures between 30 and 40% of the interannual and longer-term observed precipitation variability. The 'recent' 2000-year part of this record, smoothed to emphasise 50-year-timescale variations, is shown in Fig. 3. This is plotted along with a series representing the smoothed 1st principal component time-series of five other independent long chronologies located northeast of Methuselah Walk in southern Nevada and S.W. Utah (Hughes and Funkhouser, 1998). Comparison of these curves gives a realistic impression of the likely underlying regional signal of long-term moisture variability east of the Sierra Nevada over the last 2 millennia. There are certainly some differences in the two curves (such as in the 18th Century), and probably these reflect uncertainty in the single Methuselah-based series, but there is also much remarkable similarity between them, notably the protracted occurrence of low moisture conditions in the 10th and early 11th centuries; high precipitation around 300, 700 and 1100; and the series of multi-decadal oscillating dry and wet periods through the 14th–16th centuries. The accompanying long-term pattern of changing interannual variability (Fig. 3) also shows dramatic evidence of continuing quasi-periodic fluctuations on timescales of a century or more that would be impossible to detect without the availability of these trees.

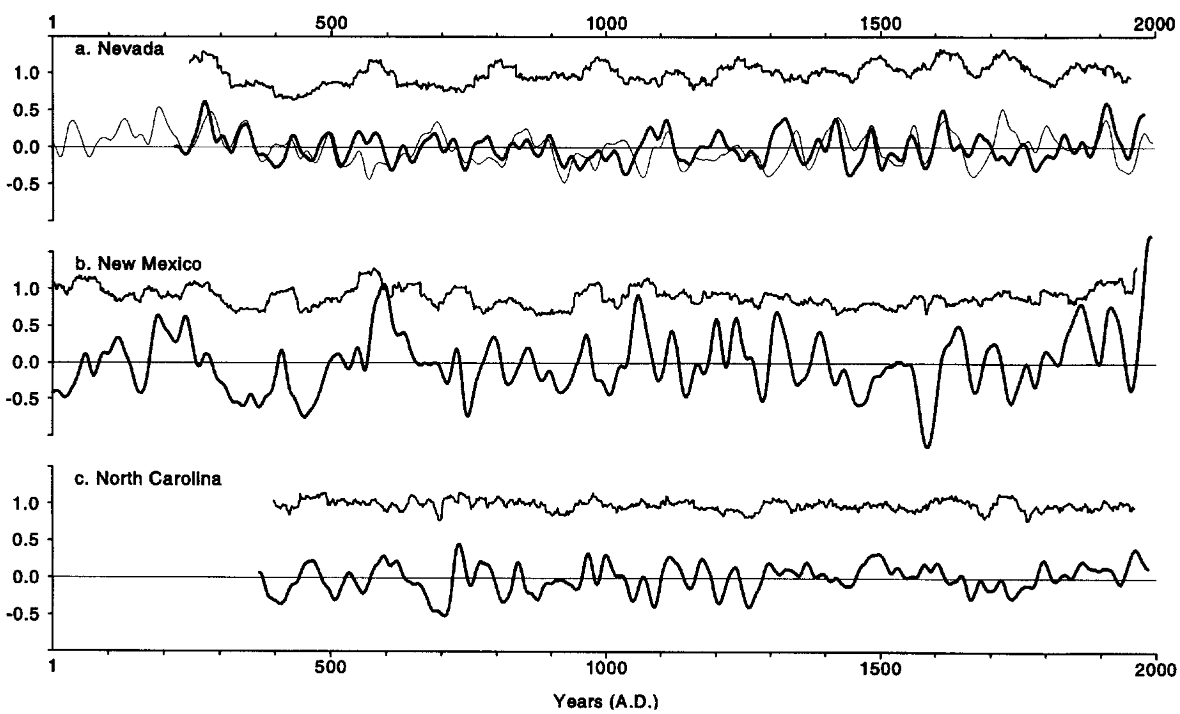

Fig. 3. Selected long reconstructions of moisture conditions in the southwestern and southeastern US. The smooth curves show 50-year timescale changes in (a) Nevada, deduced from a single chronology (Hughes and Graumlich, 1996 — thin line) and as shown in five other series (Hughes and Funkhouser, 1998 — thick line); (b) El Malpais, New Mexico (Grissino-Mayer, 1996); and (c) North Carolina (Stahle et al., 1988). The jagged curves accompanying each reconstruction show 50-year moving standard deviations (plotted on the central value) to illustrate changes in the interannual variability through time.

2.4.2. New Mexico

By combining measurements from living trees and remnant wood, from a mixture of Douglas fir and ponderosa pine, Grissino-Mayer (1996) was able to construct a ring-width chronology published extending over more than 2000 years (from 136 B.C.) for the region of El Malpais National Monument, in New Mexico. This is the oldest continuous chronology published in this region. Ring-width variability in these trees, growing on extensive lava flows, correlates well with total annual (July–June) rainfall. The smoothed regression-based precipitation estimates for the last two millennia are also shown in Fig. 3. This series clearly demonstrates major long-term fluctuations in rainfall and a largely different history from that shown by the long reconstructions in Nevada, some 1000 km to the northwest. The general long-term level of interannual variability, at least over the last millennium, is also much more stable in this area. The worst long-term droughts at El Malpais lasted from A.D. 258–520 and for much of the 15th and 16th centuries. Shorter periods of intense drought occurred in 1133–1161, 1271–1296 and 1566–1608. Rainfall was very high in 521–660, and unprecedentedly so in recent decades. Many of the changes in hydrologic conditions indicated by these data correspond well with other southwestern US tree-ring-based drought inferences and with independent physical evidence of long-term moisture conditions; all of which point to a very significant climate influence on local societal development during much of the last two millennia (Dean, 1996; Grissino-Mayer, 1996; Grissino-Mayer et al., 1997).

The tremendous surge in growth rate after 1976 at El Malpais is also clearly paralleled in at least 5 other new millennial-length tree-ring series from high elevation locations in New Mexico and Arizona (Swetnam and Betancourt, 1998). All of these are primarily responsive to cool season precipitation which has increased markedly in this region, along with the increased frequency of El Niños, following a post-1976 shift into a protracted negative phase of the Southern Oscillation Index. The fact that the recent growth surge is unprecedented for at least 1000 years in all of these tree-ring series also suggests that the recent frequency (and perhaps duration) of El Niño events is certainly very unusual (Swetnam and Betancourt, 1998).

2.4.3. Southeast United States

The final series shown in Fig. 3 represents a 50-year-smoothed, 1614-year history of summer moisture variability (June Palmer Drought Severity Index, PDSI) in North Carolina (Stahle et al., 1988) and its associated smoothed record of changing interannual variability. Though this reconstruction is not new and is based on only a single bald cypress chronology, it is still the longest in the southeast United States and provides a good example of the mould-breaking work of Stahle and Cleaveland at the University of Arkansas in building and interpreting what is now a network of chronologies of this species (see Stahle and Cleaveland, 1992; Cleaveland, 1999).

Even when they grow in swamp conditions, these trees respond to changing moisture supply. Simple regression (against the single prewhitened chronology) explains between 40 and 50% of the measured PDSI, apparently on both interannual and multidecadal timescales. Again, as with the western records, conditions in recent decades and through the 20th century as a whole, are relatively wet in the southeast USA. Here, however, they were wet also around 600; in both the early and late parts of the 8th and 12th centuries; and, particularly, through much of the late 15th and the 16th centuries. Throughout the 17th and 18th centuries, it was noticeably dry. However, long-term changes in interannual variability are small, except during the generally dry period from about 1650 to 1780.

In a more recent reconstruction of July drought (Palmer Hydrological Drought Index, PHDI) for the Tidewater region of southeastern Virginia and North Carolina, based on two local baldcypress chronologies, Stahle et al. (1998a,b), present an evocative picture of how the most extreme growing season droughts in nearly 800 years, in 1587–1589 and 1606–1612, corresponded with the disappearance of early British colonists on Roanoke Island in 1587, and with the varying but appallingly high year-by-year levels of mortality in the Jamestown Colony, between 1608 and 1624, that probably contributed to its near abandonment at that time.

Taken together, the three examples in Fig. 3 illustrate something of the complexity and spatial differences in the history of rainfall variability, on short and long timescales, in the southern United States. They also illustrate the potential for development of a long and more spatially complete picture of the way such data covary during periods considerably longer than the instrumental record. This sort of information can inform us about the large-scale dynamics of climate variability; a subject we will now develop further in the context of more recent centuries.

3. Reconstructing large-scale patterns of climate change

While one chronology, or a group of chronologies may be used to infer climate change at a point, extended networks of tree-ring chronologies offer the prospect of reconstructing large-scale patterns of climate change.

From the 1970s on, Hal Fritts and his coworkers in Arizona pioneered the development of a multivariate statistical approach to reconstructing temperature, precipitation and atmospheric pressure patterns across North America and the Pacific Ocean, using as predictors a set of 65 moisture-sensitive ring-width chronologies in the western United States (Fritts, 1991). This work inspired the development of other dendroclimatic networks, both temperature and precipitation sensitive, in various, and still expanding, areas of the globe. It also gave momentum to continuing experimentation with statistical methods for analysing the climate sensitivities of networks of tree-ring data and for exploiting their potential to provide detailed spatial climate reconstructions.

3.1. Patterns of Northern Hemisphere temperature change

Throughout the 1980s and 1990s, Fritz Schweingruber at Birmensdorf, Switzerland, has played the major role in advancing the technique of tree-ring densitometry far beyond early experiments that demonstrated the potential for climate interpretation of interannual wood density variability (Polge, 1970; Parker and Henoch, 1972). Tree-ring density from cool moist sites responds strongly to interannual variations in warm season temperatures, often in both spring and summer (Schweingruber et al., 1991, 1993) while ring-widths at similar sites may show warm and some cool season responses, often integrated over several years (Jacoby and D'Arrigo, 1995). There now exists a significant body of temperature sensitive tree-ring density data, the greater part of which has been processed at the Swiss laboratory: from trees sampled at some 400 cool and moist sites: in the western United States, Canada, Europe, Fennoscandia and northern Siberia (Schweingruber and Briffa, 1996). This network contains a record of circum hemispheric summer temperature variability, reaching back between three and six centuries, and at one or two locations well over one thousand years. Wood densitometric facilities are now operational in a number of laboratories in other countries such as the US, Canada, France and Russia. Below, are described some aspects of the analyses of the Swiss densitometric chronology network.

Due to relatively short sample length and equal age of most trees, it was not possible, when producing these individual site chronologies, to employ statistical techniques that preserve potential long-timescale climate variability for the large majority of locations. However, all of the sample collections were processed in a similar manner so that they represent timescales of growth variability up to centennial, but, for most sites, not longer. Virtually all of the chronologies throughout the network display consistently high correlations with average summer seasonal temperature data and, for the network as a whole, they have an optimal overall response in April–September. Contoured spatial maps of the density chronologies are now available, representing summer temperature patterns over the northern landmasses, year by year, from A.D. 1400 onwards (e.g. Briffa et al., 1998a, 1999b).

Fig. 4 is selected here as one illustration of how the large network of tree-ring density chronologies contains information on the dynamics of Northern Hemisphere temperatures and their associated modes of atmospheric pressure variability (note that the example is chosen here for illustrative purposes only and the association between temperature, pressure and the loading patterns as described below are equally good for the other significant PCs, as can be seen in Briffa et al., 1999c). The upper panel shows the amplitude timeseries of one of the major principal components of the full density network (EOF4, explaining 6% of the variance of the full chronology network over 270 years). The loadings on the individual chronologies, that define the spatial pattern for this component, are shown as coloured circles in the lower right map; red for positive and blue for negative. Their magnitudes are indicated by their relative size. When the amplitude series for this component is correlated (for the period indicated by the horizontal red line, 1920–1975) with gridded instrumental temperatures ($5^\circ \times 5^\circ$ boxes, April–September mean) over the hemisphere, the pattern of contoured correlation coefficients (shown as red for positive and blue for negative) corresponds extremely well with the pattern of loadings. High density matches relative warmth in western N. America and the extreme east of Siberia and in southern Europe and north central Siberia. Large negative loadings are associated with cool summers in northern Europe, Yakutia and eastern North America. The correlations also show that this amplitude series is associated with temperature anomalies in areas devoid of trees: relative warmth over southern Greenland and cold in the north Pacific.

If we examine the equivalent m.s.l. pressure correlations with the EOF amplitude series, it seems that this large-scale mode of tree-ring variability represents a combination of two well-known modes of circulation variability. The first is the summer manifestation of the North Atlantic Oscillation that has large pressure anomalies of one sign over Greenland and the eastern Mediterranean, and anomalies of opposite sign across eastern north America and the Labrador Sea, and over northern Europe (note that the continuous belt of high pressure that extends right across the Atlantic from the southern United States into western Europe, in the mean winter NAO pattern, is weaker, northward shifted, and discontinuous in the central Atlantic in the summer, e.g. Barnston and Livezey, 1987). This is precisely reproduced in the lower left map in Fig. 4. The correlation between the EOF4 amplitude series and the summer (April–September) NAO index is $r = -0.44$ (1950–1976).

The large area of negative correlation extending offshore along the Pacific coast of America and just over eastern Asia (and the weaker positive correlation across North Africa) matches the pattern of opposing pressure anomalies that characterise the summer 'North Pacific' (NP) pressure pattern (Barnston and Livezey, 1987). Hence the timeseries of EOF4 represents a history of the combined influence of the summer NAO and NP circulation modes, here back until 1700. Other important modes of the tree-ring density network similarly represent

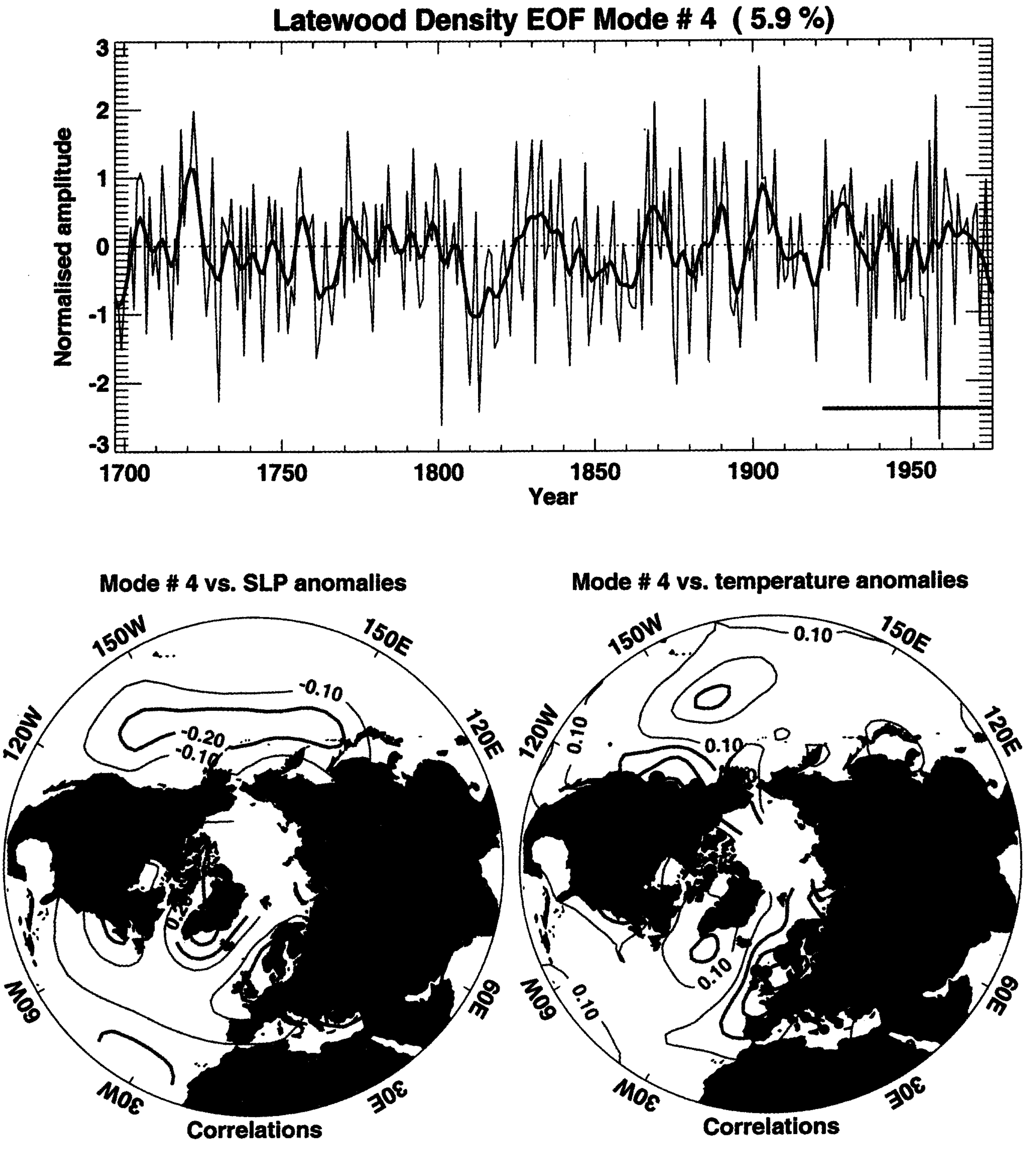

Fig. 4. One example of the correspondence between large-scale patterns of tree-ring density, surface temperature and m.s.l. pressure (Briffa et al., 1999c). The coloured circles represent the loadings on EOF4 of the full tree-ring density network (red positive, blue negative), the amplitude series of which is shown in the upper part of the figure. The contours in the lower maps represent correlations (1920–1975) between the amplitudes and observed summer (April–September) temperatures (right-hand map) and m.s.l. pressure (left-hand map) across the hemisphere. See text for further discussion of these maps.

major large-scale modes of temperature and circulation variability and have been used to reconstruct their past behaviour, certainly with some confidence on interannual and decadal timescales, for some two centuries at least beyond the start of the gridded instrumental record (e.g. see the extended record of the summer 'Euro-Siberian Oscillation' in Briffa et al., 1999a; and others in Briffa et al., 1999c).

3.1.1. A new 'Northern Hemisphere' summer temperature record

An average timeseries of all of the density chronologies, NHD1 (Fig. 5), has proved to be a useful record of yearly summer temperatures that can be considered representative of much of the higher northern landmasses, perhaps back as far as 1400 (Briffa et al., 1998a). The original series indicates the relative magnitude of interannual and decadal fluctuations, rather than longer temperature variations, but provides original insight into the likely cooling effects in Northern latitudes of large historical explosive eruptions: note the dramatic cooling in the same years (for Northern Hemisphere eruptions) or year following (Southern Hemisphere) many famous eruptions: in 1601 (Huaynaputina, 1600), 1816,17 (Tambora, 1815); 1641, 42, 43 (Mt. Parker, 1641); 1453 (Kuwae, 1452); 1912 (Novarupta, 1912), and 1884 (Krakatau, 1883). The NHD1 series also suggests dates for known large, but undocumented, eruptions and indicates the strong likelihood of others (such as in 1695 and 1698/1699) that remain as yet unidentified.

Alone, and in comparison with other high-resolution proxies, tree-ring data will continue to play an important role in helping to identify the dates, and climate influence, of major volcanic eruptions (e.g. see also Jacoby, 1997; Baillie, 1995) and even perhaps other extremely large environmental disruptions (Baillie, 1999!).

For all original tree measurement series, it is possible to employ a technique of averaging the data, first, only within specific tree age bands, and then combining these to produce an average timeseries in which the potential sample age bias discussed earlier is removed, but long timescale information is preserved (Briffa et al., 1998c). The long timescale changes within the density data, shown by processing them in this way, are also indicated in Fig. 5. This provides the best overall indicator to date of long-term temperature changes over the higher northern land areas implied by changes in widespread tree-ring density.

A significant outcome of this 'hemispheric-scale' comparison between the summer temperatures and NHD1 (Fig. 5, also confirmed in the low-frequency density curve) is an apparent divergence in the post-1950 trends (Briffa et al., 1998b). High-frequency associations (not shown here) remain strong throughout the whole record, but average density levels have continuously fallen while temperatures in recent decades have risen. The disparity is greatest in eastern N. America and eastern Eurasia (Briffa et al., 1998b) (cf. the recent divergence between density-based temperatures and ring growth at Yamal and Torneträsk in Fig. 1 and the discussion in Briffa et al., 1992). As yet, the reason is not known, but analyses of time-dependent regional comparisons suggest that it is associated with a tendency towards loss of 'spring'

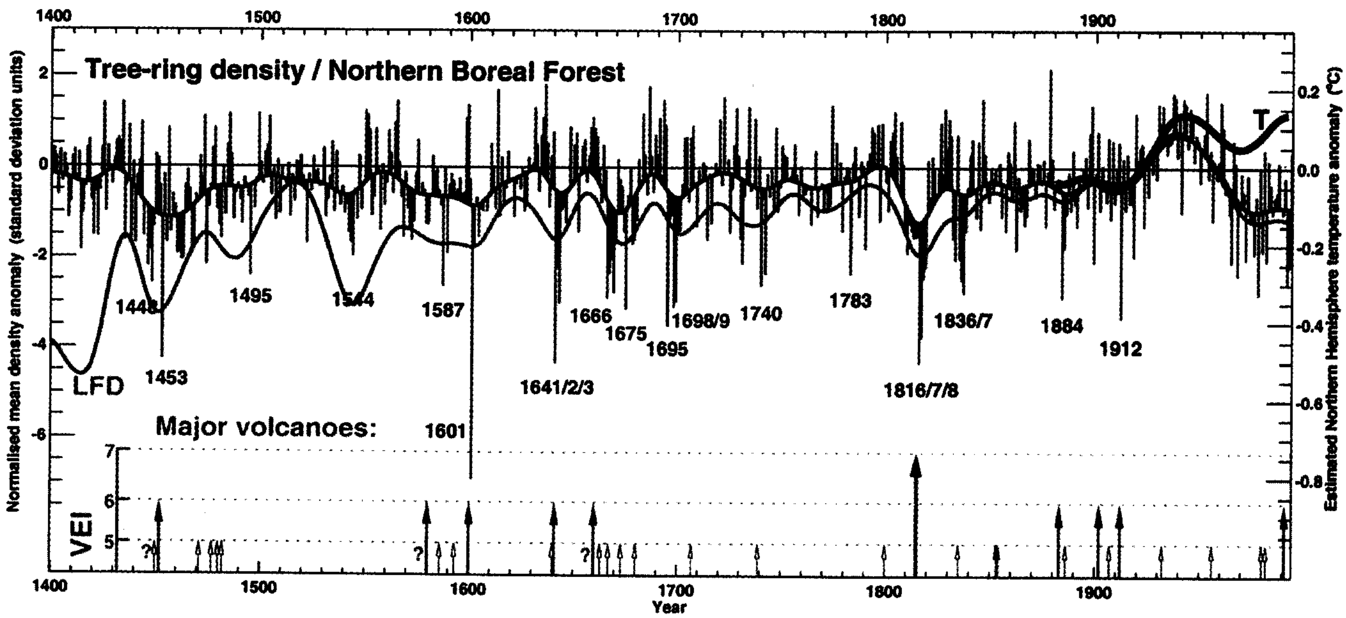

Fig. 5. An indication of growing season temperature changes across the whole of the northern boreal forest. The histogram indicates yearly averages of maximum ring density at nearly 400 sites around the globe, with the upper curve highlighting multidecadal temperature changes. Extreme low density values frequently coincide with the occurrence of large explosive volcanic eruptions, i.e. large values of the Volcanic Explosivity Index (VEI) shown here as arrows (see Briffa et al., 1998a). The LFD curve indicates low-frequency density changes produced by processing the original data in a manner designed to preserve long-timescale temperature signals (Briffa et al., 1998c). Note the recent disparity in density and measured temperatures (T) discussed in Briffa et al., 1998a, 1999b). Note that the right hand axis scale refers only to the high-frequency density data.

growth response (Briffa et al., 1999b) and, at least for subarctic Siberia, it may be connected with changes in the timing of spring snowmelt (Vaganov et al., 1999). There are important implications in this observation not least the possibility of biased regression coefficients in attempts to reconstruct past low-frequency temperature change based on long density series calibrated against recent temperatures. These may overestimate past temperature levels and underestimate the extent of apparent 20th century warming (but see later discussion and that in Briffa et al., 1998c).

3.2. *Patterns of United States moisture variability*

Cook et al. (1999b) have recently completed a project in the United States, that is the culmination of earlier studies, both by these authors and many other dendrochronologists. It provides another powerful illustration of the value of large spatial tree-ring networks. Cook et al. (1999b) have produced a set of summer drought records, comprising timeseries of mean June–August Palmer Drought Severity Indices (PDSI) reconstructed at each of 154 points on a regular (2° lat. × 3° long.) grid, covering all of the United States back to 1700. They gathered together a network of 425 ring-width chronologies and, using principal components regression, developed individual transfer functions with which to estimate PDSI at each point in turn, using selected (significantly correlated at $p < 0.1$) chronology predictors drawn from within a region not more than 450 km away. Though the distribution of tree-ring sites was somewhat patchy, very impressive overall performance, as defined by independent-period (1825–1927) testing of the fidelity between estimated and actual PDSI values, was achieved. Nevertheless, drought in some regions is generally less well modelled, such as in the Upper Midwest and northern New England. In some areas, such as the Great Basin and central Great Plains, comparison with early meteorological data suggest that the reconstructions may not capture the multidecadal timescales of drought variability as well as the shorter timescales, but to some extent this might reflect a diminution in the quality of the early instrumental PDSI records, e.g. in the Great Basin region (Cook et al., 1999b). There is no doubt that these reconstructions will be improved and lengthened, but already they represent a valuable resource for studying different aspects of the nature of changing drought severity in the United States. Indeed, two initial studies, already completed, are worthy of mention in this regard.

The US gridded PDSI reconstructions provide an excellent database for exploring the time dependence of spatial teleconnection patterns of relative moisture conditions in different regions of the United States associated with the variability of ENSO. Cole and Cook (1998), document the association between the winter SOI and changing drought patterns on decadal timescales over the last 130 years. Generally, extreme warm ENSO (high positive SOI) correlates with cool, wetter conditions across much of southwest USA. During the modern era (post-1920) the La Niña (low SOI) droughts in the southwest were accompanied by significantly wetter conditions in much of the east. During the late 19th and early 20th century, including an early period for which there is no widespread instrumental record of drought variability, the region of significant negative correlation between ENSO and PDSI was very much more extensive than we see, even in the most recent decades. The region of strong negative correlation encompassed most of southwest and northeast states, and almost the entire the southeast, so reversing the sign of the post-1920 correlation in this area. As longer, and, of course, independent reconstructions of SOI are produced, the earlier (pre-1875) tree-ring-derived drought data will provide an invaluable aid to further exploring the changing nature of ENSO/climate teleconnections and their interrelationships with other circulation features such as the Pacific Decadal Oscillation and the NAO (Cole and Cook, 1998).

Another analysis of the extended drought data provides apparent confirmation of what has, for some considerable time, been one of the more convincing pieces of evidence seemingly linking solar variability and/or lunar forcing to surface climate variability. Cook et al. (1997) reexamined earlier analyses of the spectral properties of various indices of the year-by-year spatial extent of drought in the western United States, in which there appeared to be a significant bidecadal rhythm corresponding with the phase of the 22-year Hale solar magnetic cycle. The analyses of the new drought data, considerably improved in spatial coverage and density and updated to cover several recent decades, provides convincing evidence that the 22-year rhythm of expanding and contracting drought influence is a real phenomenon, observable from 1700 onwards. This signal is accompanied by an 18.6-year cycle related to lunar forcing, and both interact additively to modulate the observed drought area rhythm. The authors are guarded about the possibility of bidecadal drought forcing by other internal mechanisms (e.g. atmosphere/ocean interactions). Nevertheless, the possibility that solar and lunar forcings are interacting to influence the extent and timing of US droughts must, on the basis of this evidence, be considered a very real possibility, and certainly worthy of further work to explore longer-term evidence for the modulation of the effect and its potential value in drought forecasting (Cook et al., 1997).

4. Important circulation indices

In critical areas of the world, it has been found convenient to characterise certain typical modes of atmospheric circulation behaviour, and the probability of distinct regional patterns of temperature or precipitation change that accompany them, in terms of simple indices of atmospheric pressure differences. Tree-ring records are now being used to simulate and extend all of the most important of these, and future tree-ring research will further enhance our knowledge of them and other specific regional indices (Woodhouse, 1997). The following is a description of the most recent promising dendroclimatic research in this area.

4.1. The Southern oscillation

The most widely recognised important index of atmospheric circulation variability is the Southern oscillation index (SOI): a simple measure of the tropical Pacific pressure gradient measured between Tahiti and Darwin (e.g. Allan and D'Arrigo, 1999; Fig. 6). Changes in the SOI are associated with spatially coherent ocean temperature changes in the Pacific, and characteristic changes in temperature and precipitation over certain adjacent, and more remote, land areas: the well-known El Niño/Southern Oscillation (ENSO) phenomenon (e.g. see Diaz and Kiladis, 1992). Achieving an accurate extension of the (120-year) observational record of SOI, so as to establish the longer history of its extreme variability and its long-timescale oscillatory behaviour, would surely be the priority ambition for any collaborating group of palaeoclimate, modelling and climate-change impacts researchers. Well-dated, highly resolved, continuous climate proxies do not yet exist in the specific regions of the equatorial Pacific where ENSO variability is optimally characterised. However, it has been long recognised that clear signals of ENSO-related rainfall variations can be recognised, to varying degrees, in the growth patterns of various extratropical trees: in the southwestern United States, Texas, Mexico and Java (see papers in Diaz and Markgraf, 1992). One highly important recent study successfully exploits these various sensitivities and demonstrates the great value of tree-ring data for reconstructing early SOI variability (Stahle et al., 1998a,b; Fig. 6).

The predictors in this work are derived from a network of only 21 chronologies, all but one of which are located in the sub-tropics of the southern United States and Mexico. Winter rainfall and subsequent soil moisture availability in this region is strongly influenced by ENSO variability. Hence these chronologies, and especially the early (spring) wood widths that make up a number of them, are perhaps the best proxies for the winter (October–March) SOI yet identified. The single non-sub-tropical predictor used in this work was a teak chronology from Java, which, although close to the western node of

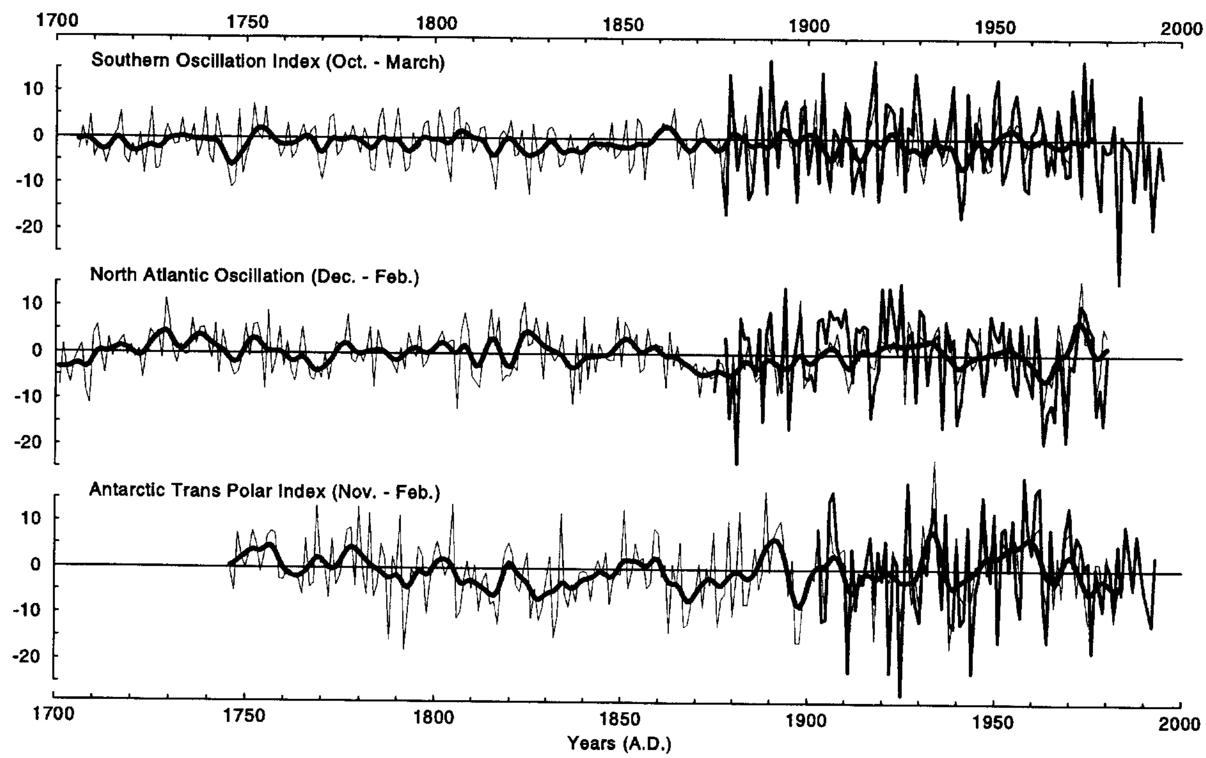

Fig. 6. Yearly values of reconstructed (thin lines) and observational data illustrating important indices of regional atmospheric pressure variability: Winter SOI (Stahle et al., 1998a,b); Winter NAO (Cook et al., 1998); Austral Summer ATPI (Villalba et al., 1997). Note that the thick smoothed curves are 10-year filtered values of the reconstructed data.

the SOI, is much less strongly correlated with it than the other tree-ring data (D'Arrigo et al., 1994).

Stahle et al. (1998a,b) demonstrate an impressive ability to capture some 53% of the variance of post-1879 winter SOI, and provide the best indication yet produced of its earlier behaviour back to 1706. The extended SOI series indicates major and prolonged variability changes beyond those that can be deduced from instrumental records. The interannual variance, low in the 1830s, was generally stable until about 1880, but increased markedly afterwards. The frequency of notable cold events (SOI $\geq$ + 5.0) almost trebled after 1878 (from 1 in 14.4 to 1 in 5.2 years). Warm events also become somewhat more common (1 in 5.6 to 1 in 4 years), so that the probability of experiencing one or other extreme in a year has risen from 0.25 to 0.44. Stahle et al. (1998a,b) also show that much of the post-1880 increase in winter SOI variability can be attributed to a large increase in the amplitude modulation of the 5.8-year oscillatory component (which is identifiable in the instrumental series),. the phase and modulation of which are faithfully reproduced in tree-ring-based SOI estimates. The authors present a well argued case that this increase in reconstructed variability reflects a genuine change in the behaviour of the ENSO system and not just in the nature of the teleconnection with precipitation in the region of the chronology predictors. Their case is supported in part by the evidence of other, non-tree-ring proxies. Invariably, at present, these have weaker predictive capability than the tree-rings but some, particularly coral data, will further enhance the quality of the SOI reconstructions, provided they can attain the equivalent length and dating accuracy of the tree rings. Future improvements and lengthening of the subtropical and perhaps tropical chronologies will certainly yield even better and longer SOI reconstructions.

4.2. The North Atlantic oscillation

The resurgent fascination in recent years with the workings of ENSO has been paralleled on a smaller scale by a growing interest in the natural variability of the North Atlantic Oscillation (NAO) and the extent of its influence on temperature and precipitation variability, over western Europe in particular. Here again tree-ring data may provide at least, the partial means of recapturing past NAO behaviour (Fig. 6). The distinct climate anomaly patterns associated with opposite phases of the NAO (e.g. Hurrell and van Loon, 1997) suggest that chronologies in certain key regions should capture at least part of its variability. Seasons of high positive NAO (when there is strong pressure gradient between Iceland and the Azores and enhanced westerly flow into western Europe) are associated with relative warmth over northwest Europe, Siberia and the southeast United States; cold in northeast Canada; higher rainfall over Scandinavia and northern Egypt and relatively drier conditions in the north and west Mediterranean. These relationships are most pronounced in winter and early spring and are much less apparent in summer. Nevertheless, there are already chronologies in many of these sensitive regions and independent studies have recently explored the feasibility of reconstructing winter NAO variability with some of these tree-ring data.

Cook et al. (1998) used 10 selected tree-ring width chronologies from eastern North America and western Europe, including data from northern Finland that had already been shown to contain a weak, but significant, winter NAO signal (D'Arrigo et al., 1993), to produce a winter NAO index extending from the start of the 18th century. Cook et al., were able to characterise persistent oscillatory behaviour in the NAO, particularly at periods near 2.1, 8 and 24 years during the last 300 years and they suggest that a near 70-year 'oscillation' apparent in the post-1850 instrumental period, may not have existed in the previous 150 years. The words 'may not' should be stressed here, because it is likely that this reconstruction has greatest fidelity at shorter timescales (annual to decadal) as opposed to multidecadal and century (Osborn et al., 1999).

Another preliminary, though not exclusively tree-ring-based, reconstruction of winter NAO has been produced for the period from 1429 onwards (Stockton and Glueck, 1999, not shown here). A combination of (winter) precipitation-sensitive tree-ring chronologies from Morocco, along with other tree-ring data from Finland and oxygen isotope data from Greenland were used as predictors. The authors consider this reconstruction to be a more reliable indication of longer timescale (multidecadal) NAO variability. It indicates generally high values for 1741–1758, and in other earlier periods, lending strong support to the notion that the observed period of high NAO indices in the last two decades may not be unprecedented, even in recent centuries. It should be stressed here, as it is by the authors of both of the papers cited, that neither of these NAO reconstructions should be considered as more than experimental. The Cook et al., prediction equation accounted for some 45% of the observed index variability when tested against various independent periods of data, while the Stockton and Glueck regression explained slightly less. Over 1701–1873 (before the series were optimally 'fitted' to their respective observed data sets) the two reconstructions correlate at about $r = 0.3$, which is statistically significant at the 99% level, but both compare less well with early instrumental estimates of winter NAO that extend back to 1824. Nevertheless, it is likely that both series contain useful information about the past behaviour of the winter NAO.

Given that each reconstruction only uses a small number of predictors, representing different, localised, responses in each case, these experiments imply that future work that incorporates a greater geographical spread of tree-ring, and also other proxy data from a wider range of sensitive areas, is very likely to produce a more reliable winter NAO reconstruction. Similarly, it is also likely that good reconstructions of the (admittedly weaker) spring and summer manifestation of the NAO will be recoverable from other tree-ring data.

4.3. *Antarctic trans polar index*

Villalba et al. (1997), have recently shown that it is possible to extend the observed record of Antarctic MSL pressure variability, by 150 years period to the start of 20th century instrumental observations. Following similar work, reconstructing of New Zealand pressure gradients (Salinger et al., 1994), they used sets of tree-ring chronologies in New Zealand and Tierra del Fuego to reconstruct regional summer (November–February) m.s.l. pressure variations: First, over the region encompassing southern South America and the Antarctic Peninsula, and second, over the New Zealand sector of Antarctica. They then went on to use a subset of these tree-ring networks to reconstruct, directly, the behaviour of the Summer trans-polar index (TPI), a measure of the pressure gradient between Hobart and Port Stanley (Fig. 6). They demonstrate a strengthening of the anti-phase relationship in pressure between these points during the 20th as compared to the previous century, and provide statistical support for a previously postulated link between ENSO and pressure variability in the southern oceans on timescales of 4–5 years, suggested by analysis of shorter instrumental pressure records. Though, at present, the tree-ring TPI reconstructions extend back only to about A.D. 1750, and probably capture only the interannual and some longer-term variability, they represent valuable independent references for comparison with the recent parts of various Antarctic ice records and they highlight the potential for producing very much longer reconstructions using sub-fossil chronologies, such as those currently under construction in southern South America and New Zealand (e.g. Roig et al., 1996; Xiong, 1993; D'Arrigo et al., 1998).

5. Recent developments and challenges

5.1. *The Himalaya*

One of the still largely underexplored and certainly underutilised areas of the world as regards dendroclimatic studies is The Himalaya. It was only by the end of the 1980s, that a number of exploratory studies, mainly in the Karakoram region of Pakistan and the Vale of Kashmir, had established the feasibility of building reliably dated chronologies from several genera of conifers (e.g. Hughes, 1992). The first monsoon precipitation reconstruction, reaching back only to the late 18th century, based on drought-sensitive conifers in southern Kashmir, was published by Borgaonkar et al. (1994). Reconstructions of spring temperatures have been produced for Shimla (Pant and Rupa Kumar (1997) and Uttar Pradesh (Yadav et al., 1999), India.

Since 1994, there has been something of shift in the regional focus of work, away from the western Himalaya. A large collection of conifer chronologies has been assembled from sites on the north slope of the eastern Himalaya in Tibet (Brauning, 1994) and long chronologies of different Juniper species constructed in the Hunza-Karakoram, north Pakistan (Esper et al., 1995; Esper, 1999) demonstrate remarkable synchroneity in growth at high and low frequencies, over the last 500 years, that most likely indicates changing temperatures at these elevations (i.e. 4000 m a.s.l.). Also, Krusic and Cook (1994) describe the development of a large tree-ring network, covering the central-eastern Himalaya, intended as a basis for reconstructing Nepalese and wider-scale synoptic climate variability. All of the recent work cited here is in its early stages. Much more work is justified: in the development of further conifer chronologies, and others from deciduous species in more arid sub-tropical areas (Borgaonkar et al., 1994), and in the study of their climatic interpretation. Clearly, the proven dendroclimatic potential of this region and its climatic significance, will inevitably mean that it must develop into a major area for tree-ring study. It is also disappointing that, in comparison with the obvious enormous potential for dendroclimatic studies in China as a whole (e.g. Wu, 1992; Hughes et al., 1994), relatively little has been achieved in the last decade and this region deserves a greater focus.

5.2. *Developments in other regions*

With the obvious exception of the North (e.g. see Chbouki et al., 1995), most of Africa remains an enormous void as regards tree-ring studies (e.g. Boninsegna and Villalba, 1996; February and Stock, 1998). The lack of regular strong climate seasonality has, for a long time, made it especially problematic to correlate or interpret tree-ring measurement series from any tropical trees (for one very notable exception, see D'Arrigo et al., 1994). For this reason, special mention should be given to the recent work by Stahle et al. (1997, 1999) who have shown that it is possible to construct tree-ring chronologies (using *Pterocarpus angolensis*) in western Zimbabwe. The ring widths of these trees are significantly correlated with wet season rainfall totals (the area has a unimodal seasonal rainfall distribution with a wet season in October–April), and because they are relatively long-lived (> 200 years) and abundant in southern Tropical Africa, this work could provide the impetus for a long awaited, development of dendroclimatology in this region.

Most studies in central America and Amazonia deal only with the basics of dendrochronological research (i.e. ring structure, annual growth periodicity) mostly in a context of studying tropical forest dynamics, though this should provide a foundation for future studies more geared toward dendroclimatology (e.g. Devall et al., 1995; Burgt, 1997; Worbes, 1997; Chambers et al., 1998). In 1997, the International American Institute for Global Change Studies (IAI) founded a dendrochronological study programme in tropical South America with a special emphasis on Bolivian forests. Several tropical Bolivian species have been sampled by workers from Mendoza and La Paz and one (*Polylepis tarapacana*) chronology growing at about 4800 m at 18°S on Volcan Sajama has been shown to correlate significantly with local summer (January–March) temperature (Boninsegna, personal communication).

Recent dendroclimatological research in Thailand and Indonesia was described at a workshop in southeast Asia, where links between the monsoon and teak and pine chronologies in Thailand and relationships between Indonesian teak data and the Southern Oscillation were shown (Buckley et al., 1995; D'Arrigo et al., 1997). For a survey of recent advances in tree-ring research in Asia and the Pacific area in general see Ohta et al., 1996.

5.3. Changing Climate Sensitivity and 'New' Growth Influences

In the foregoing discussion, we have alluded to the fact that tree-growth, as represented in various standardised tree-ring chronologies in various parts of the world, often seems anomalous in the 20th century as compared to earlier centuries. Though my no means always true, this is apparent often enough to support speculation that 'unusual things are happening' across large areas. The recent high growth rates of trees in northern and western North America and Siberia in particular, provide major pieces of evidence being used to assemble a case for anomalous global warming, interpreted by many as evidence of anthropogenic activity (e.g. Overpeck et al., 1997; Jones et al., 1998; Mann et al., 1998, 1999a). While this may prove to be a valid interpretation of the data, some caution is still warranted at this time. Large-scale warming is not the only environmental effect of human activities and the expression of this warming differs according to region, season, and in day and night. This adds up to a complicated situation if we wish to isolate a specific climate influence on past, current and future tree-growth measurements. The empirically derived regression equations upon which our reconstructions are based may be compromised if the balance between photosynthesis and respiration is changed by differential heating in the light and dark. Changes in the start, end, or length of growing seasons; changes in the efficiency with which water or limiting nutrients are used, as well as changes in CO_2, UV radiation and a host of other environmental factors may all exert their influence on tree growth. To varying extents, such factors have always affected trees, but their recent influences, and especially the extent of their combined influence, requires serious investigation, beyond that undertaken to date.

It was stated earlier that standardisation of tree-ring data may limit the expression of long-term tree-growth changes, so obscuring real climate trends. This is true also for non-climate trends. Where time-dependent changes of tree growth rates have been explored within discrete age classes of trees (to circumvent the need for normal standardisation) widespread evidence is accumulating of 'enhanced' productivity (ring-width, basal area and wood mass) in the 19th and 20th centuries; similar to positive growth trends observed in early studies of very long-lived trees in the United States (i.e. those with 'strip bark' growth forms: LaMarche et al., 1984; Graybill and Idso, 1993: see Briffa et al., 1992, 1998a,b,c, and references and discussion within). Some of this accelerated growth is no doubt temperature driven but 'fertilisation' by increased nitrogen and/or CO_2 levels may also be involved.

If such fertilisation is occurring over wide areas, it may be masked by some standardisation techniques, but, to some extent, it may still also exaggerate temperature-dependent growth increases in cool locations (hence, acting in the opposite direction to the declining tree-ring density phenomenon described earlier) or increase the growth of drought sensitive trees in dry areas. These effects should be detectable on year-to-year timescales as well as over decades. Systematic, detailed studies of the temporal stability of climate responses in different growth parameters, tree species, and in different regions through the 19th and 20th centuries, are certainly warranted. A few studies, from a variety of locations, show very recent changes in tree growth or in growth responses to climate (Jacoby and D'Arrigo, 1995; Cook et al., 1996; Swetnam and Betancourt, 1998), but none of these authors support the CO_2 (or nitrate) fertilisation theory. The picture therefore remains unclear.

New analyses of combined tree growth data (e.g. stable isotopic composition and inorganic chemistry, along with ring-width and density), may establish the reality, or otherwise, of unusual changes in tree productivity and its causes. Similarly, undertaking comparative or combined analyses that incorporate various types of non-tree-ring palaeodata (e.g. Guiot et al., 1992; Mann et al., 1999b) along with the development of mechanistic models of tree growth (e.g. Vaganov et al., 1990; Fritts et al., 1991) will allow a better exploration of the reliability of statistical inferences on past climates based on modern-day observations of tree-growth/climate linkages. A collaboration between dendroclimatologists, tree physiologists, and vegetation modellers would be of great benefit in this regard.

6. Conclusions

Tree-ring research has come a very long way in recent decades. This review has dealt only with selected examples of its application in the area of global climate change research. Undoubtedly, as with all other climate proxies, a number of factors can potentially complicate the climate interpretation of tree-ring data. Like all other proxies, they have strengths and limitations. Even so, dendroclimatology is undoubtedly a major weapon in the growing armoury that must be employed in the battle to attain a full understanding of the mechanisms of climate change. There are many challenges but much more will be achieved in the coming decades.

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