On Selected Issues and Challenges in Dendroclimatology

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Abstract
We discuss selected issues in palaeoclimatic research, with a focus on tree ring based temperature reconstructions. Topics include the difficulty to retain long-term temperature variations in tree ring based reconstructions, the effects of this and other limitations on the estimation of the absolute temperature amplitude over the past millennium, and the potentials and limitations of including precipitation sensitive tree ring data in large-scale temperature reconstructions. To address these issues, we begin with a brief introduction into some principles of proxy data and specific characteristics of tree ring time-series.

Keywords: dendrochronology, tree rings, temperature reconstruchtion, age-trend, proxy, palaeoclimate

F. Kienast, O. Wildi & S. Ghosh (eds.), A Changing World. Challenges for Landscape Research, 113 –132.

Introduction

From the range of potential research questions that can be addressed using dendroclimatic methods, the documentation of natural climate variability from periods prior to evident human impact stands out prominently (Watson *et al.* 2001). An essential component of this more recent impact is the emission of greenhouse gases such as CO_2 into the atmosphere since the beginning of widespread industrialization in the middle of the 19th century (Keeling

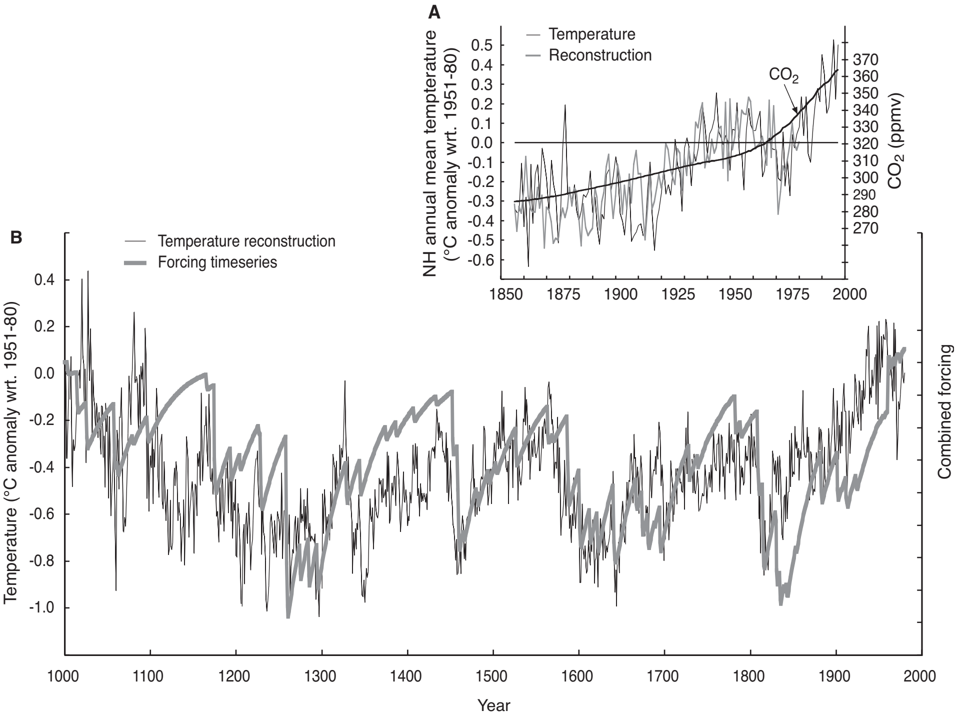

Fig. 1. Recent temperature and CO_2 timeseries, together with a millennial-long temperature reconstruction and a simple forcing timeseries. (A) Annual mean temperatures obtained from averaging Northern Hemisphere meteorological station data indicate a warming trend of about 0,6 °C over the past 140 years (Jones *et al.* 1999). These data represent 90% of the Northern Hemisphere surface area in the 1950s, 50% in the 1900s, and 20% in the 1860s. Numbers are derived utilizing a 1200 km radius for each single met station (Hansen *et al.* 1999). In comparison, the CO_2 content (Robertson *et al.* 2001) increases more steadily from about 285 to 370 ppm, but does not show the significant inter-decadal fluctuations as seen in the temperature data. To understand the forcing of CO_2 (and other greenhouse gases) on temperature, it is necessary to reconstruct natural, pre-industrial, climate variations from periods before the 19th century, and to relate these findings with reconstructions of natural forcing factors, such as the variability of solar irradiance and volcanic eruptions. (B) The large-scale temperature reconstruction over the past millennium averages information from 14 tree ring sites north of 30 °N (Esper *et al.* 2002a). This record is calibrated against annual temperatures, averaged over Northern Hemisphere land and sea surface areas, using the 1856–1980 period as shown in A (Jones *et al.* 1999). Accordingly, the temperature amplitude over the past millennium is in the order of 1 °C. The reconstruction indicates warmth at the beginning of the past millennium, similar to the temperatures recorded during about the middle of the 20th century. Some of the inter-decadal to centennial scale variations in this reconstruction are in line with an average series combining volcanic (Crowley 2000, Robock und Free 1996), solar (Bard *et al.* 2000, Crowley 2000, Lean *et al.* 1995), CO_2 (Etheridge *et al.* 1996), and an estimate of tropospheric aerosol forcing (Crowley 2000, Etheridge *et al.* 1996).

et al. 1996; Robertson *et al.* 2001). During this time, the concentration of CO_2 has risen from about 280 parts per million to about 370 in recent years (Fig. 1A). With this, and projected future emissions, comes the concern that the anthropogenic forcing of temperature (Hansen *et al.* 1999) and change of weather and climate extremes (Katz and Brown 1992; Kharin and Zwiers 2005; Klaus 1993; Stainforth *et al.* 2005; Stott *et al.* 2004) will also become more significant in the future. Such changes would significantly impact natural ecosystems (Nemani *et al.* 2003) and the utilization of these resources by humans (Ahmad *et al.* 2001).

To quantify the influence of greenhouse gases and to be able to develop reliable projections of future climate variations, it is important to understand the forcing from both natural and anthropogenic factors (Fig. 1B). In contrast to the recent period since industrialization, late Holocene greenhouse gas variation prior to the middle of the 19th century was negligible. During this pre-industrial time, changes in solar radiation and stratospheric reaching aerosols from volcanic eruptions were likely the primary forcing factors for climate variations. The quantification of these different forcing factors represents a key objective for model calibration and testing (Gerber *et al.* 2003) and future predictions (Boer *et al.* 2000).

To provide information on longer term regional and large-scale climate history, so-called proxy data are analyzed. Following the discussion of some principles of such data, we address the climatic signals retained in certain tree ring parameters, and stress the challenging issue of preserving low frequency temperature variations in dendroclimatology. This topic is followed by a discussion of the estimation of absolute temperature variations over the past millennium, and the problems and potential to include precipitation sensitive tree ring data in large-scale temperature reconstructions. The review closes by highlighting some challenges of future dendroclimatic research.

Proxy Sources

Proxy data, such as timeseries of the thickness and composition of lake sediments, glacial ice layers, growth increments in corals, speleothems and trees, borehole temperature profiles, and documentary evidence are key to the understanding and quantification of past climatic variations (overview in Bradley and Jones 1992; Jones *et al.* 1996; Jones and Mann 2004; Moberg *et al.* 2005), and, thus, the current global climatic change debate (Watson *et al.* 2001). Data from these archives are generally compared and correlated with instrumental measurements to quantify their climatic sensitivities and signals, and are subsequently used to document climate prior to the period of instrumental data.

The different proxy sources have varying strengths and weaknesses, and comparison of several independent sources, or even their combination, is desirable to develop robust reconstructions of past climate variability (Casty *et al.* 2005a, 2005b; Luterbacher *et al.* 2004, 2005; Mann 2002; Xoplaki *et al.* 2005). Proxy sources are usually confined to certain geographic regions, with ice cores limited to high mountain and polar regions (Watanabe *et al.* 2003), corals to low latitude sea shores (Felis *et al.* 2000), tree rings primarily to extratropical forested ecosystems (Schweingruber 1996; Stahle 1999; Worbes 1999), and documentary evidence to regions from which historic reports are available, such as Europe (Brázdil *et al.* 2005; Bürgi *et al.* 2007; Pfister 1999; Pfister *et al.* 1998), eastern Asia (Ge *et al.* 2005; Qian *et al.* 2003; Wang *et al.* 2001; Yang *et al.* 2002; Zhang and Crowley 1989), and South America (Prieto *et al.* 2004). Also the number and type of measured parameters varies considerably between the proxy sources. In the family of available proxies, ice cores tend to provide the largest variety of commonly measured parameters, including direct measures of CO_2 concentration from trapped air bubbles (Smith *et al.* 1997), the isotopic fractionation of oxygen, and levels of sulfate from volcanic eruptions (Petit *et al.* 1999; EPICA 2004).

Additional differentiation between proxy sources concerns their lengths and resolutions. Whereas tree ring series are of yearly resolution, the resolution and precision of other proxy sources is generally lower (except for documentary evidence which can even resolve daily weather), or decreases with depth, such as for ice core data. In exchange for these resolution tradeoffs, ice core data can extend many hundreds of thousands of years back, whereas continuous tree ring data rarely extend back ten thousand years (Briffa and Matthews 2002; EPICA 2004; Grudd *et al.* 2002; Schaub *et al.* 2003).

A distinctive characteristic of tree ring data, and various other proxies, is that the quality of the chronology is not stable over time, with greater uncertainties typically occurring further back in time. Furthermore the climatic sensitivity also varies through time (Esper *et al.* 2001a). This phenomenon can be illustrated in so-called extreme year analysis in dendroclimatology (Schweingruber *et al.* 1990). Certain years stand out from all others, whereby the majority of trees synchronously produces an exceptionally narrow or wide ring (Neuwirth *et al.* 2003; Schweingruber *et al.* 1991). These years possess greater signal strength than "average" years, in which say seven trees produce wide rings, while 10 produce narrow rings (Esper and Gärtner 2001). Analyses of extreme years (Esper *et al.* 2001b; Neuwirth *et al.* 2003; Schweingruber *et al.* 1991) show that extremes (both positive or negative) of a similar magnitude can be triggered by a wide variety of climatic circumstances. This can complicate dendroclimatic studies, where the influence of a single climatic parameter on tree growth is generally sought. Such complications can be reduced however by careful consideration of site ecology.

Climatic Signals in Tree Ring Parameters, and Trend Problems

The ecology of the most suitable sites for dendroclimatic analyses are well known (overview in Schweingruber 1996). A clear climatic signal can be obtained at e.g. treeline sites, whereas intermediate sites often yield somewhat fuzzy signals. Trees from drought stressed locations, such as the lower forest border in the American southwest (LaMarche 1974), Mongolia (Pederson *et al.* 2001) or the Mediterranean area (Akkemik and Aras 2005; Chbouki *et al.* 1995; D'Arrigo and Cullen 2001; Touchan *et al.* 2005) tend to most clearly show a precipitation signal.

Similarly the temperature signal is maximized at the temperature limits of tree growth at, for example, the northern treeline in Siberia (Briffa *et al.* 1998) or upper treeline in the Tien Shan and Karakorum (Esper *et al.* 2002b, 2003b). Even though the vast majority of dendroclimatic reconstructions are based on trees, shrubs and even dwarf shrubs that develop annual rings (Schweingruber 2001) are generally usable. While ring width is the most easily measured parameter used for dendroclimatic reconstructions, other parameters, such as the maximum latewood density (Schweingruber *et al.* 1978) and even specific anatomical features (Schweingruber 2001), can also have great reconstructive power.

Stable isotope ratios measured in tree rings are another data source that is increasingly used for climate reconstruction (Borella *et al.* 1998a, 1998b; Leavitt and Long 1984; Saurer *et al.* 1997; Treydte *et al.* 2001). Here the stable isotope ratio of, for example, ^{13}C and ^{12}C (or isotopes of oxygen), is compared with an internationally recognized standard (Craig 1957) and is expressed as the deviations of δ^{13}C in parts per thousand (‰). For tree cellulose the values are negative. It has been shown that such measurements can be linked, depending upon site ecology, with temperature or precipitation variations (Treydte 2003; Treydte *et al.* 2001). Indeed, highly significant relationships between δ^{13}C series and temperature measurements can be obtained, particularly in the high-frequency domain. These correlations are only valid, however, after removal of an increasingly negative trend in δ^{13}C measurements in time (Farquhar *et al.* 1982; Leavitt and Long 1989; Marshall and Monserud 1996). The negative trend results from the enrichment of air from fossil fuel carbon (which has a highly negative value) and also from plant physiological effects in response to the increasing partial pressure of CO_2. As the plant physiological mechanisms of $\delta^{13}C$ fixation are not totally understood, the low frequency, centennial scale variations can not yet be confidently estimated due to the greater uncertainties that exist during the anthropogenically influenced calibration period.

Specific wood anatomical features that result from relatively few and/or highly specific influences can also be used for reconstructing past environmental changes. For example, occurrences of late (in spring) and early (in autumn) frosts have been reconstructed (Hantemirov *et al.* 2000). To do so deformed cell walls (callous tissues), that result from frost, are used as the characteristic features (Fig. 2). The location of these callous cells within the tree ring, e.g. can be used to reconstruct frost events even at a sub-annual resolution (Schweingruber 2001).

Raw measurements of tree ring width (in mm) and maximum latewood density (in g/cm^3) are the result of a multitude of physiological drivers. Some of them are closely linked to climate, some are linked to non-climatic sources, e.g. the age trend (Bräker 1981; Cook and Kairiukstis 1990; Fritts 1976). The age trend is responsible for decreasing ring width or

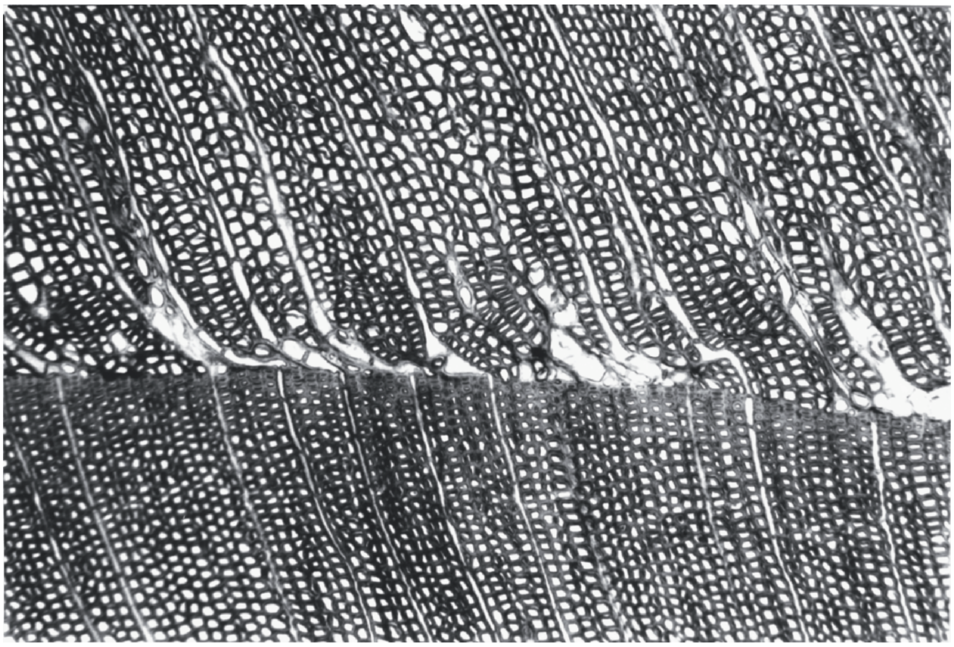

Fig. 2. Callous tissue (frost ring) in the earlywood of a juniper tree *(Juniperus turkestanica)* from the upper timberline in the Tien Shan Mountains, Kirghizia. In the center of the picture a tree ring boundary separating two rings (below and above) is seen. The lower part shows the latewood portion of the (older) ring with smaller cells and thicker cell walls, followed by the earlywood portion of the (younger) ring with larger cells and thinner cell walls. During the beginning of the formation of this younger ring, a frost occurred affecting the cambium. The freezing of the cambium resulted in deformed, callous cells (center of the picture). Typical for such frost rings is also the curvilinear offset of the ray cells cutting through the ring boundary. The frost occurred in spring, immediately after the tree started to build earlywood.

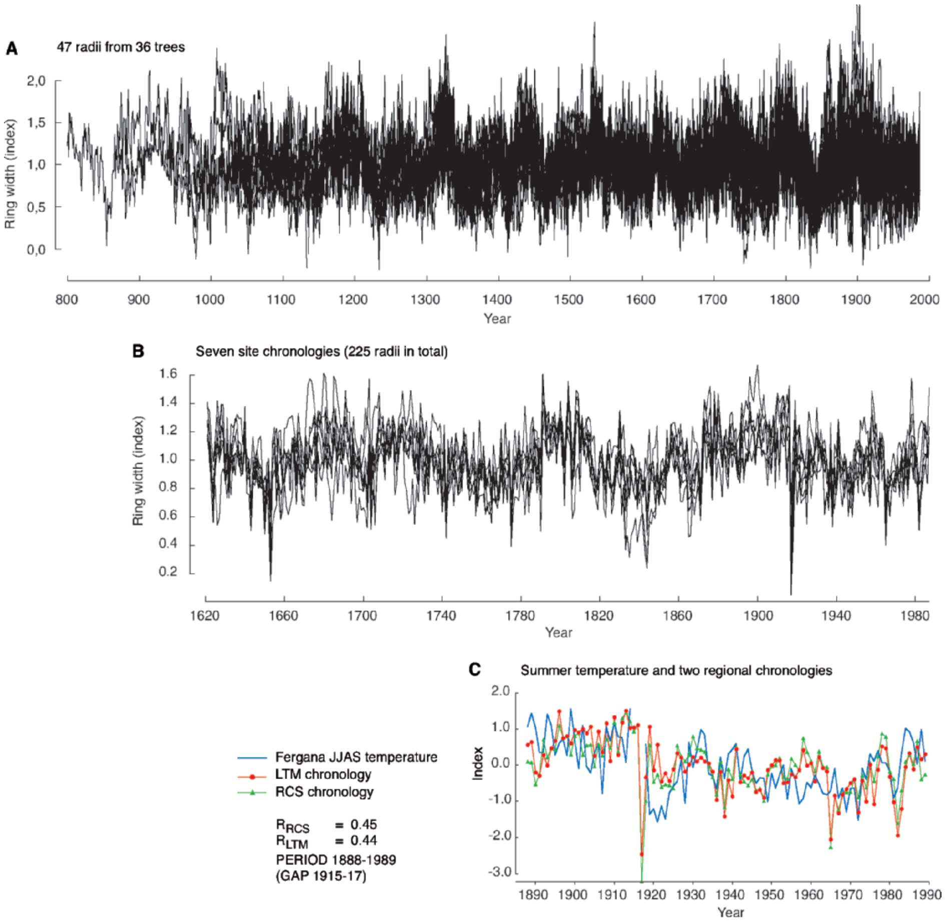

Fig. 3. Synchronous ring width variations in high elevation Juniper trees *(Juniperus turkestanica)* from the Tien Shan Mountains, and correlation with instrumental temperature data. (A) 47 ring width series from 36 trees near the upper treeline in 3,200 m a.s.l. show distinct inter-decadal scale variations. These variations are synchronous throughout most periods of the past millennium, indicative of a strong common signal between the trees. Age trends were removed with a spline standardization technique (Cook 1985) and an adaptive power-transformation (Cook and Peters 1997). Details are given in Esper *et al.* (2003b). (B) Ring width variation between seven high-elevation stands in the Tien Shan Mountains since 1620. The variation here is extremely synchronous suggesting that a spatially common climate signal (likely temperature) is controlling tree growth. (C) This connection can be additionally validated through a comparison between two regional mean chronologies (LTM, RCS) and summer temperature measured at the Fergana instrumental station. Of particular note is the absence of a 20th century warming trend in western central Asia that is, for example, evident in Europe and large-scale temperature timeseries. The portions of the RCS and LTM chronologies shown here were standardized using methods to specifically preserve multi-centennial trends (Esper *et al.* 2003b). These trends are not preserved using the more traditional spline standardization shown in A.

density with increasing tree age. It results from the geometric property of adding more or less constant biomass to an increasing surface area as the tree grows. This trend must be eliminated prior to climatic analyses, otherwise the ring width or maximum latewood density values are biased and reflect tree age rather than a climate signal. This age trend is commonly removed with detrending procedures, while still preserving the common climatic signal of interest. By common variation, we mean the positive and negative deviations (after standardization) of ring width or density, that are synchronous between trees at a given site, and ultimately between different study sites (Fig. 3) (Esper *et al.* 2001a; Wigley *et al.* 1984). Such synchronous variations within and between sites can only result from common environmental influences over larger areas.

While the synchronous variation between trees and stands represents a clear conceptual strength of dendroclimatology, the age-trend and its necessary removal represent a substantial weakness or limitation of the ring width and density parameters. In general, it is quite difficult to distinguish the biological age-trend from long-term climatic signals, particularly when the long-term climate represents a cooling (e.g. the transition from the Medieval Warm Period into the Little Ice Age), which for temperature sensitive trees, can mimic the shape of the biological age trend. The separation of these trends represents a substantial and critical task in modern dendroclimatology (for further information see Briffa *et al.* 1992, 2001; Cook *et al.* 1995; Cook and Peters 1997; Esper *et al.* 2002a, 2003a).

Temperature Amplitude

To understand the role of different anthropogenic and natural forcings on ecosystems, an assessment of past climatic changes is needed over time periods longer than the instrumental interval. Currently, the temperature variation over the past 1000 years receives considerable attention (Watson *et al.* 2001). The characteristics, timing and regional particularities of the Medieval Warm Period, the subsequent Little Ice Age, and the present warm period are particularly relevant (Broecker 2001, Mann *et al.* 2003b). Related questions are: *(i)* how large was the temperature amplitude (in ºC) over the past 1000 years, and *(ii)* how quickly has the temperature varied without anthropogenic impacts such as greenhouse gases (Esper *et al.* 2004, 2005a, 2005b; Moberg *et al.* 2005; Mann *et al.* 2003b; von Storch *et al.* 2004).

To help answer these questions, millennial-long large-scale reconstructions with annual resolution have been developed (Briffa 2000; Esper *et al.* 2002a; Jones *et al.* 1998; Mann *et al.* 1999). Some of these series (e.g. Briffa 2000; Esper *et al.* 2002a; see also Moberg *et al.* 2005) show that in large parts of the Northern Hemisphere a distinct warm period existed about 1000 years prior to present. According to these reconstructions, temperature patterns similar to those of the middle 20th century existed within the past millennium. The warm periods are separated by distinct cooler episodes associated with the Little Ice Age. In contrast, the reconstruction from Mann *et al.* (1999) shows relatively warm conditions about 1000 years ago, with a very gradual cooling for 900 or so years until a fairly abrupt modern increase.

Much discussion about common features in large-scale reconstructions, and the possibility to retain common multi-centennial climatic variations currently exists (Briffa and Osborn 2002; Cook *et al.* 2004a; Esper *et al.* 2002a; 2004a; Mann *et al.* 2002). It was suggested (e.g. by Esper *et al.* 2004a) that differences in the lower frequency domains of currently used long-term tree-ring series (Fig. 4) may be a result of detrending procedures that were sub-optimal to fully preserve multi-centennial wavelength information. This problem is particularly critical, as mentioned above, for the transition from the Medieval Warm Period into the Little Ice Age, where age-trends and long-term climatic evolution both exhibit decreasing trends.

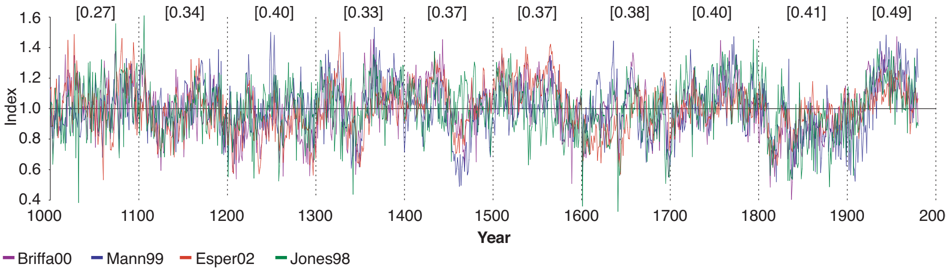

Fig. 4. Annually resolved, large-scale temperature reconstructions (Briffa 2000, Esper *et al.* 2002, Jones *et al.* 1998, Mann *et al.* 1999) showing synchronous multi-decadal variations. The records were detrended using a spline filter to remove low frequency, multi-centennial trends. The significant similarities in the remaining (higher) frequencies suggest that differences in the lower frequencies likely result from differing standardization techniques applied in the original reconstructions (for details see Esper *et al.* 2004a). The average interseries correlation of the records as shown here, is 0.42 over the 1000–1980 period. Average correlations for each century are indicated in the figure. While these reconstructions share some data, tests that minimized this overlap did not reveal substantial differences (Esper *et al.* 2004a).

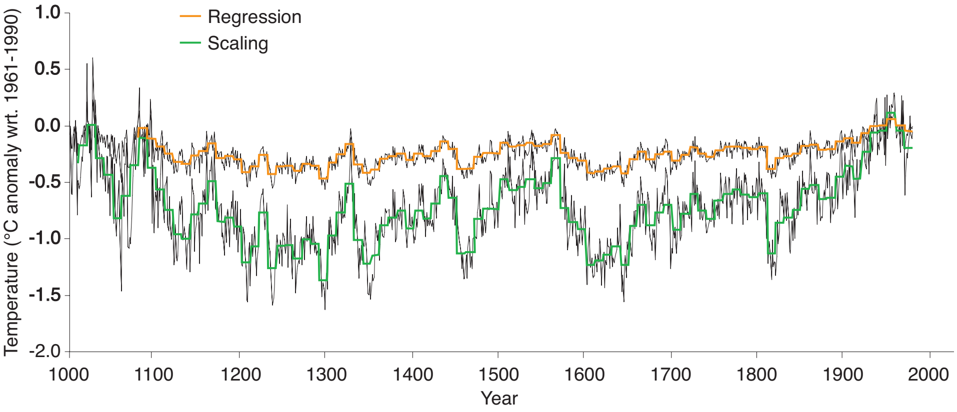

Fig. 5. Varying temperature amplitudes (in °C) obtained after calibrating the same proxy reconstruction (Esper *et al.* 2002a) with different (currently accepted) methods. The record displaying a smaller amplitude was regressed to warm season land and sea surface temperature data over the 1856–1980 period, while that showing greater amplitude, by scaling (mean and variance equalization) to annual land temperature data over the 1900–1977 period. The spatial domain for both instrumental datasets is 20–90 °N latitude (Jones *et al.* 1999). Various estimates of the amplitude of past variability from these calibration choices add additional uncertainty in the magnitude of past temperature variability, and can result in widely diverging views, particularly when instrumental data are spliced to the modern end of such records. See Esper *et al.* 2005b for more details.

In addition to the different "shapes" of these curves, the temperature amplitudes reconstructed from them also tend to differ considerably. The approximate decadal scale amplitude (difference between the warmest to coldest decade) derived from the Mann *et al.* (1999) reconstruction is about 0.5 °C, whereas the amplitude reconstructed by Esper *et al.* (2002a), and then recalibrated by Cook *et al.* (2004a) are both about 1.0 °C (see also Moberg *et al.* 2005). This latter figure is more consistent with large-scale estimates derived from borehole reconstructions over the past 500 years (Beltrami 2002; González-Rouco *et al.* 2003; Huang *et al.* 2000; Pollack and Huang 2000; Pollack and Smerdon 2004), although other analyses using the same data indicate somewhat lower amplitudes (Mann *et al.* 2003a; Rutherford and Mann 2004).

Reconstruction of the temperature amplitude can also be hampered by calibration methods and data used (see e.g. Briffa and Osborn 2002). This issue was recently tested by von Storch *et al.* (2004) using general circulation model (GCM) results as a surrogate for the "true" climate over the past millennia, and "pseudo proxy data" with statistical characteristics similar to real proxy (e.g. long instrumental, tree ring, documentary, coral, etc.) data. Their results suggest that regression based calibration methods – similar to those used by Mann *et al.* (1999) – may consistently underestimate the true temperature amplitude, and in such a way where there tends to be a bias towards greater error, and hence reduced amplitude, in frequencies outside those well captured in the calibration interval (i.e. low frequencies). However, recent work (Mann *et al.* 2005) suggests that the von Storch *et al.* (2004) results depend on the selection of the GCM model, the (varying) radiative forcing applied to these models, and the long-term performance (drift) in climate simulations. It was, for example, shown that the GKSS simulation (as used by von Storch *et al.* 2004) is biased by a 'spin-up' artifact, i.e. the simulation was initialized from a warm 20th century state at AD 1000, prior to the application of pre-anthropogenic radiative forcing, leading to a long-term drift in mean temperature (Goosse *et al.* 2005). The Mann *et al.* (2005) results seem to contradict the suggestion that empirical proxy-based temperature reconstructions suffer from systematic underestimations of low-frequency variability (von Storch *et al.* 2004). Further tests are necessary to solve this issue, and particularly to determine the impact of employing different climate models and forcing series (and their weighting) on reconstructed temperature amplitudes.

Esper *et al.* (2005a) addressed the same issue by systematically surveying the effects on large-scale reconstructions' amplitude that result from the calibration to a variety of instrumental targets with a variety of methods – all of which are used in current literature. The results indicate that both the selection of various "reasonable" instrumental data and calibration periods, as well as various fitting procedures, adds a methodological uncertainty to the reconstructions that easily approaches 0.5 °C (Fig. 5). It is evident that the exact assessment of this variation, and particularly the amplitude, has significant consequences for the quantitative estimations of greenhouse gas forcing in the past 150 years and hence for future predictions (Esper *et al.* 2005b).

Separating Temperature and Precipitation Signals in Tree-ring Measurements

It is important for dendroclimatic reconstructions that in many regions temperature and precipitation variations are significantly negatively correlated. This is, for example, the case in the Alps during summer when precipitation occurs with generally cooler atmospheric conditions or more local convective systems (Böhm *et al.* 2001; Wanner *et al.* 2000). This covariance between temperature and precipitation can have the effect that it is difficult to demonstrate the dominance of a single factor's influence, such as summer temperature, on

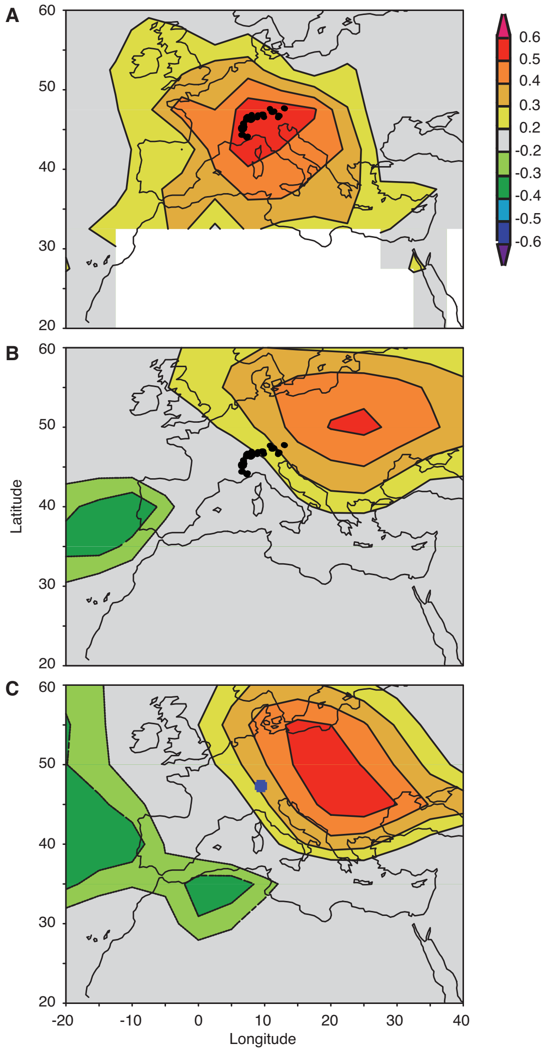

Fig. 6. Correlation fields with the first principal component of 45 high elevation (above 1,500 m a.s.l.) ring width sites (black circles) from the western and central Alps with (A) average June-August temperature, and (B) average June-August sea-level pressure, computed over the 1900–1973 period (white region in A represents missing data). This principle component explains 20% of the network variance over the 1850–1973 period, capturing the dominant mode of ring width variability in this network that is closely related to summer temperature variability. The trees provide temperature information approximately centered over their average geographical locations, but still yield significant correlations over much of Europe. Highest correlations between Alpine ring width and pressure are located further east, likely reflecting continental synoptic influences on temperature. (C) For comparison, average June-August temperatures from the Säntis meteorological station (blue square) in Switzerland correlated with the same pressure field as in B. Similar patterns are evident including the eastward shift in the center of highest positive correlations, and areas of negative correlation west of Spain. The 90% significance level for correlations corresponds approximately to the mapped colored regions. Maps generated using the KNMI Climate Explorer. Säntis temperature data are from GHCNv2 (Peterson and Vose 1997); surface temperature data are from HadCRUT2v (Jones and Moberg 2003; Rayner *et al.* 2003); and SLP data (Trenberth and Paulino 1980).

tree growth. In such cases, with only a positive temperature influence on tree-growth, a negative (secondary) correlation with precipitation is also obtained.

The difficulties in extracting a particular single signal can, however be advantageous for some reconstructions. If, for example, a precipitation sensitive chronology provides a strong correlation with temperature, it might well be incorporated into large-scale temperature reconstructions. For example, 1000-year ring width series from cedar trees growing in Morocco (Stockton 1985; Verstege *et al.* 2004) correlate significantly with precipitation (Chbouki *et al.* 1995) and through this, their growth is also linked with the North Atlantic Oscillation (Glueck and Stockton 2001; Hurrell 1995, Wanner *et al.* 2001). Such Moroccan cedar timeseries were used by Mann *et al.* (1999) for their Northern Hemisphere temperature reconstruction, for example, indicating that it is feasible to use some of the cross correlation and synoptic interaction between temperature and precipitation for temperature reconstructions. Similar considerations would apply to other primarily precipitation sensitive tree ring chronologies from the Mediterranean region (e.g. Akkemik and Aras 2005; Touchan *et al.* 2005).

When including such precipitation sensitive data in large-scale temperature reconstructions, however, an analysis of the frequency spectra of precipitation (and temperature) sensitive proxy timeseries seems useful. This is because measured precipitation data generally possess "whiter" spectra than those for temperature data. If precipitation sensitive tree ring material is included in large-scale temperature records, this limitation could be addressed by allowing only the inter-annual to inter-decadal precipitation information to enter the composite record at decadal and higher frequencies, and let the "true" temperature sensitive proxy data determine the lower frequency trends. Recent work by Cook *et al.* (2004b), however, shows indication of longer term variability in area aridity indices derived using Palmer Drought Severity Index (PDSI; Palmer 1965) reconstructions, thus initiating a discussion on the lower frequency behavior of precipitation related parameters.

Statistical methods, such as Principal Component Analysis (Peters *et al.* 1981; Preisendorfer 1988; von Storch and Zwiers 1999), can be effectively used to isolate a certain fraction of variance from tree ring timeseries, with these fractions subsequently used to explain climatic parameters, such as summer temperature (Frank and Esper 2005; Cook *et al.* 2003). These methods work particularly well if a larger network of tree ring sites is used, and can provide climatic information on regional to continental scales (Fig. 6). Though methods, such as PCA, perhaps perform superiorly for certain applications, it should be noted that highly regarded results based on correlation analysis for huge networks exist and have their own advantages (e.g. Briffa *et al.* 1998). In any case, it is recommendable in dendroclimatic studies to first study and understand connections with simple correlations, prior to using other methods where some of the basic relationships that exist can be more easily obscured. Such correlation approaches strengthen the basic foundations for which climate parameters truly have an influence on growth or isotopic values.

Challenges in Dendroclimatology

From the range of challenges this discipline currently faces, the task to produce robust estimates of low-frequency (multi-centennial) climate variations is particularly notable (Briffa *et al.* 2001; Cook *et al.* 1995, 2000; Esper *et al.* 2002a, 2003b). This assumes, however, that the chosen climate parameter actually varies in the lower frequency domain. This seems to be the case with temperature, and from various examples with precipitation as well, depending upon the time-scale of interest (Cook *et al.* 2004b; Dai *et al.* 1997). In this context, due to the greater challenge, it is particularly important to preserve long-term cooling trends, such as from the Medieval Warm Period into the Little Ice Age with an equal fidelity as warming trends, such as those since the Little Ice Age. Composite detrending methods, such as Regional Curve Standardization (RCS; Briffa *et al.* 1992, 1996; Becker *et al.* 1995; Mitchell 1967) and Age-Banding (Briffa *et al.* 2001) will increasingly be applied to preserve and study multi-centennial trends. These methods depend upon extensive datasets (Esper *et al.* 2003a), whereby it is likely that shifts in sampling strategies will need to occur to meet these requirements. More trees per stand and all age-classes (young through old) should be collected. At the same time, it will be necessary to conduct network analyses to tie together new and existing timeseries for the above-mentioned applications. This will also allow comparison of long-term trends in different, independent datasets, which is necessary to help overcome the limited statistical tests that can be conducted to calibrate centennial scale proxy variations against instrumental data. The aggregation of local tree ring series, where standardization methods were applied that were not designed to preserve long-term variability, should be avoided to study lower frequency climatic changes (Esper *et al.* 2004a).

Multi-proxy comparisons will perhaps play a greater role in the future. It is, however, rather ambitious to merge different archives, developed with discipline specific methods, with different temporal responses, and different climatic and seasonal sensitivities (Moberg *et al.* 2005). However, in principle, the merging should only serve to strengthen the picture of past climate variability by using the strength from the individual archives, rather than transporting unexplained portions of variance from individual records. Projects that seek to study and compare various proxy archives within a defined region, such as the project VITA (Varves, Ice cores and Tree ring Archives with annual resolution) within the Swiss NCCR-Climate program, should prove valuable towards this objective. Within this project, ice core, lake sediment (and organisms deposited therein), and tree ring data are collected and compared from a geographically focused region in the central Alps (Bigler 2002).

Additionally, opportunities exist in dendroclimatology to help approach important questions from related disciplines. For example, quantifying carbon sequestration and fluxes in terrestrial ecosystems (Janssens *et al.* 2003) is a challenging task where tree ring data can be used to provide insight. So far, this topic has received only marginal efforts by dendrochronologists, and instead has been driven by shorter term estimations through eddy flux measurements (Ehman *et al.* 2002), and verified by forest inventories (Goodale *et al.* 2002) and model calculations (Gurney *et al.* 2002). At the same time, current estimations for large-scale terrestrial carbon fluxes are highly variable and inconsistent (Houghton 2003; Körner 2003). In our opinion, dendrochronology can provide a substantial contribution to these efforts by quantifying biomass dynamics in forests over long timescales. Furthermore, dendrochronology can be used to study whether mid- to long-term fluctuations in biomass (as a surrogate for carbon) have been stimulated by climatic or other (CO_2, nitrogen) factors (Graumlich *et al.* 1989).

A rather long-term challenge in dendroclimatology is to potentially question and at the same time iteratively confirm early instrumental measurements. Currently, instrumental measurements are used almost exclusively to calibrate tree ring timeseries and other proxy data. However, even the temperature and precipitation measurements themselves contain uncertainties, and are fundamentally changed during necessary homogenization (Auer *et al.* 2005; Barriendos *et al.* 2002; Begert *et al.* 2005; Bergström and Moberg 2002; Böhm *et al.* 2001; Brunetti *et al.* 2004; Camuffo 2002a, 2002b; Cocheo and Camuffo 2002; Demarée *et al.* 2002; Klein Tank *et al.* 2005; Klingbjer and Moberg 2003; Maugeri *et al.* 2002a, 2002b; Moberg *et al.* 2002; Peterson *et al.* 1998; Slonosky 2002). These homogenization methods are particularly relevant, yet limited, in the early instrumental time period (e.g. around 1800 in Switzerland) during which few station records exist for comparison and verification, and also during more recent times through trying to understand the so-called urbanization effects (warming in cities through construction and changes near climate stations; Arnfield 2003, Kalnay and Cai 2003, Landsberg 1981, Peterson 2003, Parker 2004). In particular, there is high potential for dendroclimatic studies to validate the instrumental homogenization at locations where hundreds of tree ring sites (Briffa *et al.* 2002) and only a few long instrumental timeseries (e.g. Siberia) exist.

Acknowledgements

Supported by the Swiss National Science Foundation, project Millennium (# 2100-066628), and the Swiss National Science Foundation, NCCR-climate program. We thank Ulf Büntgen, Holger Gärtner, and Kerstin Treydte and two anonymous reviewers for helpful comments.

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