# 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, palaeo-climate

# 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
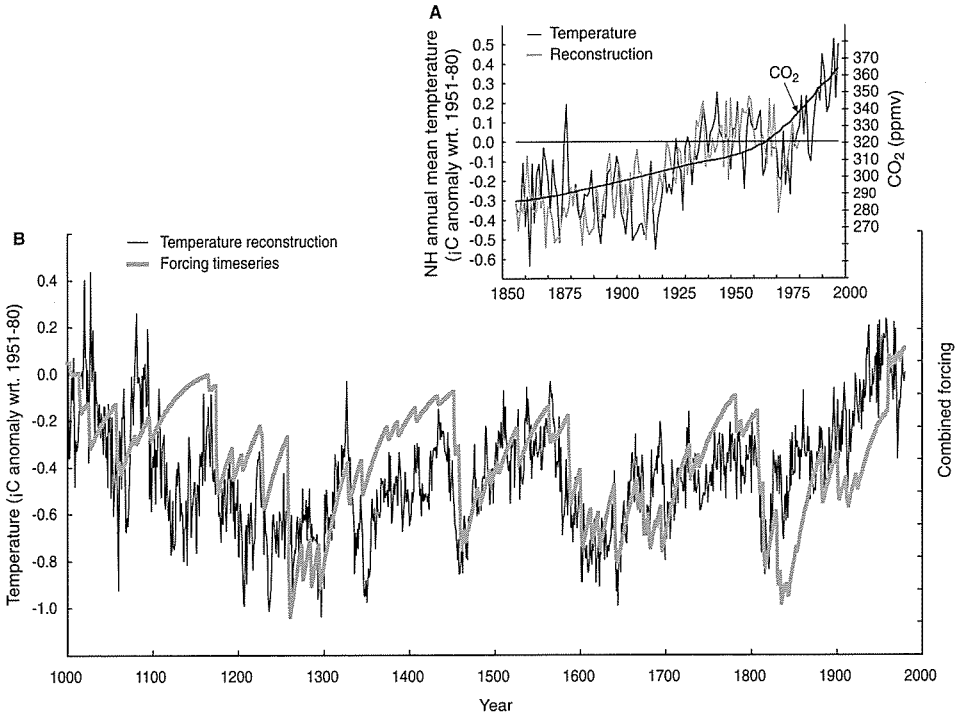


Fig. 1. Recent temperature and $CO_2$ timeseries, together with a millennial-long temperature reconstruction and a simple forcing timeseries. (A) Annual mean temperatures obtained from averaging Northern Hemisphere meteorological station data indicate a warming trend of about 0,6 °C over the past 140 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 signifi-cant 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 projec-tions 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 negli-gible. 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 geo-graphic 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 $CO_2$ con-centration 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 $\delta^{13}C$ 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 $\delta^{13}C$ 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 $\delta^{13}C$ 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
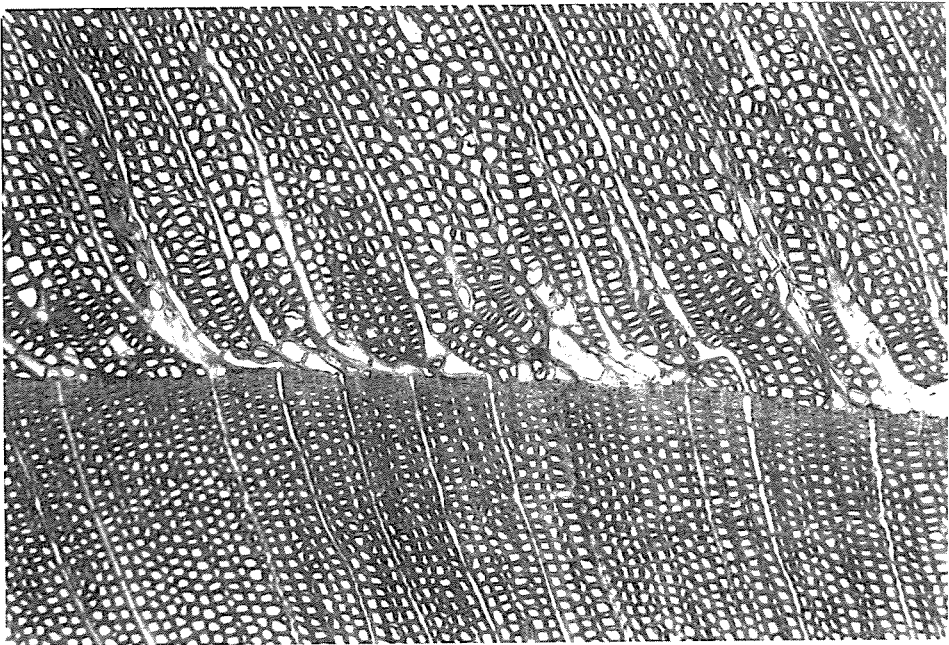


Fig. 2. Callous tissue (frost ring) in the earlywood of a juniper tree *(Juniperus turkestanica)* from the upper timberline in the Tien Shan Mountains, Kirghizia. In the center of the picture a tree ring boundary separating two rings (below and above) is seen. The lower part shows the latewood portion 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.
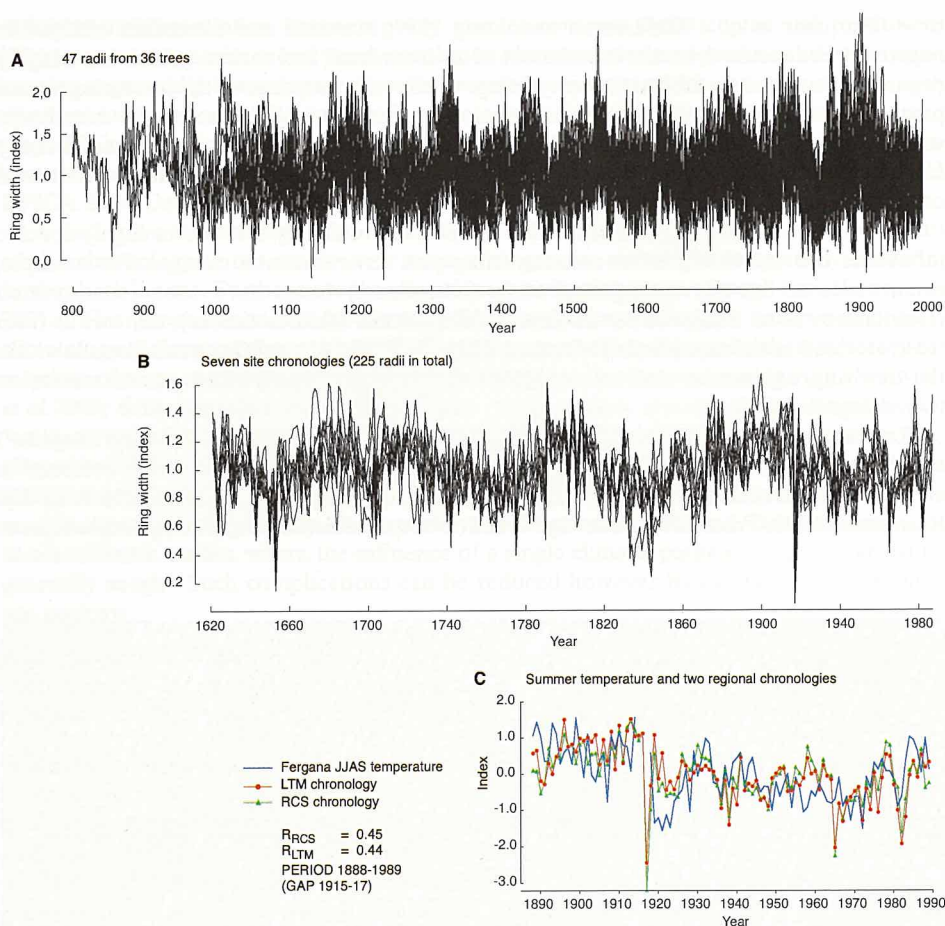
Fig. 3. Synchronous ring width variations in high elevation Juniper trees *(Juniperus turkestanica)* from the Tien Shan Mountains, and correlation with instrumental temperature data. (A) 47 ring width series from 36 trees near the upper treeline in 3,200 m a.s.l. show distinct inter-decadal scale variations. 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 °C) 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.
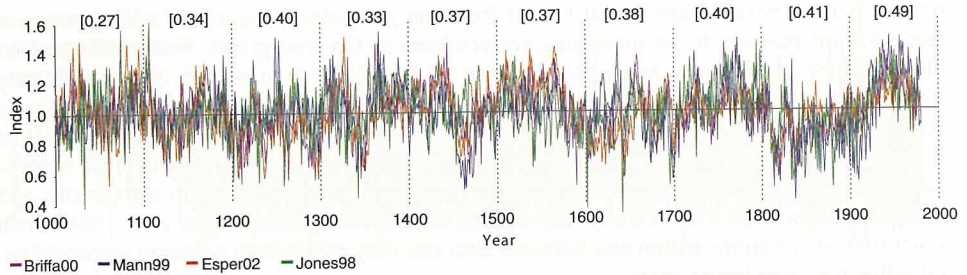
Fig. 4. Annually resolved, large-scale temperature reconstructions (Briffa 2000, Esper *et al.* 2002, Jones *et al.* 1998, Mann *et al.* 1999) showing synchronous multi-decadal variations. The records were detrended using a spline filter to remove low frequency, multi-centennial trends. The significant 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).
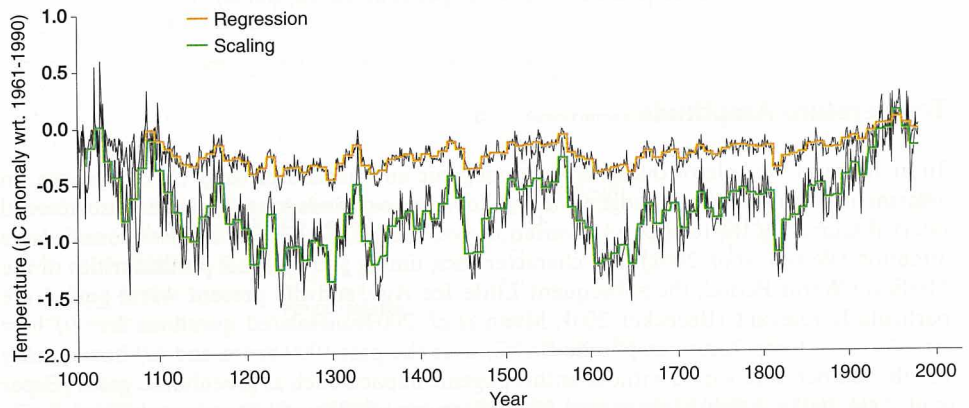


Fig. 5. Varying temperature amplitudes (in °C) obtained after calibrating the same proxy reconstruction (Esper *et al.* 2002a) with different (currently accepted) methods. The record displaying a smaller amplitude was regressed to warm season land and sea surface temperature data over the 1856–1980 period, 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 character-istics 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 ampli-tude, in frequencies outside those well captured in the calibration interval (i.e. low fre-quencies). 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 recon-structed 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 instru-mental 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
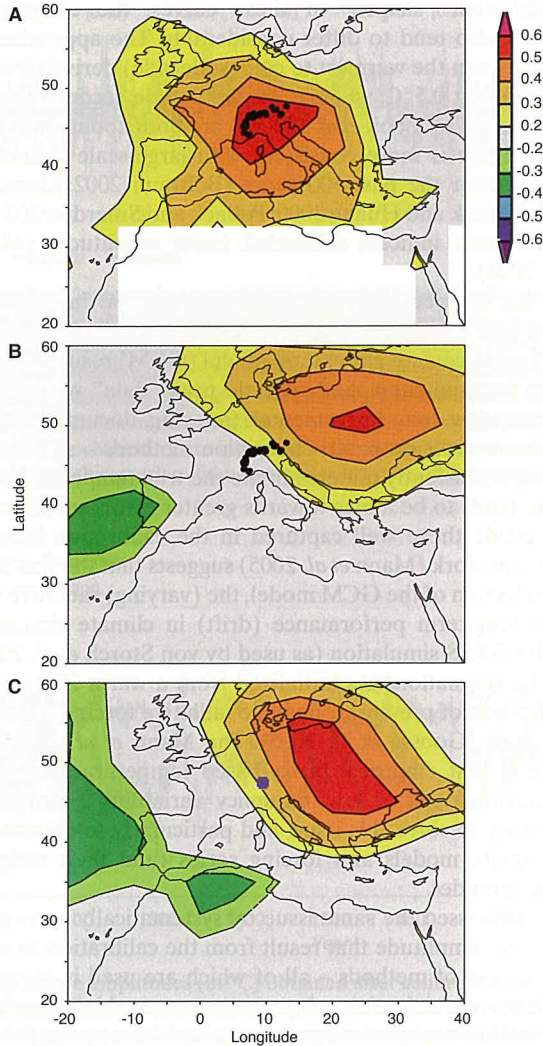
Fig. 6. Correlation fields with the first principal component of 45 high elevation (above 1,500 m a.s.l.) ring width sites (black circles) from the western and central Alps with (A) average June-August temperature, and (B) average June-August sea-level pressure, computed over the 1900–1973 period (white 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.

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## References

Ahmad Q.K., *et al.* (Eds.) 2001. Climate change 2001 – impacts, adaptation, and vulnerability. Summary for policy makers. Cambridge Univ. Press, Cambridge, 17 pp.

Akkemik Ü. and Aras A. 2005. Reconstruction (1689–1994 AD) of April–August precipitation in the southern part of central Turkey, International Journal of Climatology 25: 537–548.

Arnfield A.J. 2003. Two decades of urban climate research – a review of turbulence, exchanges of energy and water, and the urban heat island. International Journal of Climatology 23: 1–26.

Auer I., Böhm R., Jurkovic A., Orlik A., Potzmann R. and 20 co-authors 2005. A new instrumental precipitation dataset for the greater alpine region for the period 1800–2002. International Journal of Climatology 25: 139–166.

Bard E., Raisbeck G., Yiou F. and Jouzel J. 2000. Solar irradiance during the last 1200 years based on cosmogenic nuclides. Tellus 52: 985–992.

Barriendos M., Martin-Vide J., Pena J.C. and Rodriguez R. 2002. Daily meteorological observations in Cadiz – San Fernando. Analysis of the documentary sources and the instrumental data content (1786–1996). Climatic Change 53: 151–170.

Becker M., Bert G.D., Bouchon J., Dupouey J.L., Picard J.F. and Ulrich E. 1995. Long-term changes in forest productivity in Northeastern France – the dendroecological approach. In: Landmann G., Bonneau, M. (eds.). Forest decline and atmospheric deposition effects in the French mountains. Springer, Berlin, 143–156.

Begert M., Schlegel T. and Kirchhofer W. 2005. Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. International Journal of Climatology 25: 65–80.

Beltrami H. 2002. Climate from borehole data – energy fluxes and temperatures since 1500. Geophysical Research Letters 29, doi: 10.1029/2002GL015702.

Bergström H. and Moberg A. 2002. Daily air temperature and pressure series for Uppsala (1722–1998). Climatic Change 53: 213–252.

Bigler C. 2002. VITA – Varves, ice cores, and tree rings – archives with annual resolution. ProClim-Flash 24: 8–9.

Böhm R., Auer I., Brunetti M., Maugeri M., Nanni T. and Schöner W. 2001. Regional temperature variability in the European Alps 1760–1998 from homogenized instrumental time series. International Journal of Climatology 21: 1779–1801.

Boer G.J., Flato G. and Ramsden D. 2000. A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate for the 21st century. Climate Dynamics 16: 427–450.

Borella S., Leuenberger M. and Saurer M. 1998a. Analysis of δ18O analysis in tree rings – wood-cellulose comparison and method dependent sensitivity. Journal of Geophysical Research 106: 19267–19273.

Borella S., Leuenberger M., Saurer M. and Siegwolf R. 1998b. Reducing uncertainties in δ13C analysis of tree rings – pooling, milling and cellulose extraction. Journal of Geophysical Research 103: 19519–19526.

Bradley R.S. and Jones P.D. (eds.) 1992. Climate since A.D.1500. Routledge, London, 679 pp.

Bräker O.U. 1981. Der Alterstrend bei Jahrringdichten und Jahrringbreiten von Nadelhölzern und sein Ausgleich. Mitteilungen der Forstlichen Bundesversuchsanstalt Wien 142: 75–102.

Brázdil R., Pfister C., Wanner H., von Storch H. and Luterbacher J. 2005. Historical climatology in Europe – The state of the art. Climatic Change 70: 363–430.

Briffa K.R. 2000. Annual climate variability in the Holocene – interpreting the message from ancient trees. Quaternary Science Reviews 19: 87–105.

Briffa K.R., Jones P.D., Bartholin T.S., Eckstein D., Schweingruber F.H., Karlén W., Zetterberg P. and Eronen M. 1992. Fennoscandian summers from AD 500: temperature changes on short and long timescales. Climate Dynamics 7: 111–119.

Briffa K.R., Jones P.D., Schweingruber F.H., Karlén W. and Shiyatov S.G. 1996. Tree-ring variables as proxy-indicators – problems with low-frequency signals. In: Jones P.D. et al. (eds.) Climatic variations and forcing mechanisms of the last 2000 years. Springer, Berlin, 9–41.

Briffa K.R., Schweingruber F.H., Jones P.D., Osborn T.J., Shiyatov S.G. and Vaganov E.A. 1998. Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. Nature 391: 678–682.

Briffa K.R., Osborn T.J., Schweingruber F.H., Harris I.C., Jones P.D., Shiyatov S.G. and Vaganov E.A. 2001. Low-frequency temperature variations from a northern tree ring density network. Journal of Geophysical Research 106: 2929–2941.

Briffa K.R. and Matthews J.A. 2002. ADVANCE-10K – a European contribution towards a hemispheric dendroclimatology for the Holocene. The Holocene 12: 639–642.

Briffa K.R. and Osborn R.J. 2002. Blowing hot and cold. Science 295: 2227–2228.

Briffa K.R., Osborn T.J., Schweingruber F.H., Jones P.D., Shiyatov S.G. and Vaganov E.A. 2002. Tree-ring width and density data around the Northern Hemisphere – part 2, spatio-temporal variability and associated climate patterns. The Holocene 12: 759–789.

Broecker W.C. 2001. Was the Medieval Warm Period Global? Science 291: 1497–1499.

Brunetti M., Maugeri M., Monti F. and Nanni T. 2004. Changes in daily precipitation frequency and distribution in Italy over the last 120 years. Journal of Geophysical Research 109, doi: 10.1029/2003JD004296.

Bürgi M., Hersperger A.M., Hall M., (Russell) Southgate E.W.B. and Schneeberger N., 2007. Using the past to understand the present land use and land cover. In: Kienast F., Wildi O. and Ghosh S. (eds.). A Changing World. Challenges for Landscape Research, Vol. 8: 133–144. Springer Landscape Series, Dordrecht.

Camuffo D. 2002a. Calibration and instrumental errors in early measurements of air temperature. Climatic Change 53: 297–330.

Camuffo D. 2002b. Errors in early temperature series arising from changes in style of measuring time, sampling schedule and number of observations. Climatic Change 53: 331–354.

Casty C., Handorf D. and Sempf M. 2005a. Combined winter climate regimes over the North Atlantic/European sector 1766–2000. Geophysical Research Letters 32, doi: 10.1029/2005GL022431.

Casty C., Luterbacher J., Wanner H., Esper J. and Böhm R. 2005b. Temperature and precipitation variability in the European Alps since 1500. International Journal of Climatology 25: 1855–1880.

Chbouki N., Stockton C.W. and Myers D.E. 1995. Spatio-temporal patterns of drought in Morocco. International Journal of Climatology 15: 187–205.

Cocheo C. and Camuffo D. 2002. Corrections of systematic errors and data homogenisation in the Padova series (1725 - today). Climatic Change 53: 77–100.

Cook E.R. 1985. A time series analysis approach to tree-ring standardization. Lamont-Doherty Geological Observatory, New York, 171 pp.

Cook E.R. and Kairiukstis L.A. 1990. Methods of dendrochronology – applications in the environmental science. Kluwer, Dordrecht, 394 pp.

Cook E.R., Briffa K.R., Meko D.M., Graybill D.A. and Funkhouser G. 1995. The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies. The Holocene 5: 229–237.

Cook E.R. and Peters K. 1997. Calculating unbiased tree-ring indices for the study of climatic and environmental change. The Holocene 7: 361–370.

Cook E.R., Buckley B.M., D'Arrigo R.D. and Peterson M.J. 2000. Warm-season temperatures since 1600 BC reconstructed from Tasmanian tree rings and their relationship to large-scale sea surface temperature anomalies. Climate Dynamics 16: 79–91.

Cook E.R., Krusic P.J. and Jones P.D. 2003. Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal. International Journal of Climatology 23: 707–732.

Cook E.R., Esper J. and D'Arrigo R. 2004a. Extra-tropical Northern Hemisphere temperature variability over the past 1000 years. Quaternary Science Reviews 23: 2063–2074.

Cook E.R., Woodhouse C., Eakin C.M., Meko D.M. and Stahle D.W. 2004b. Long-term aridity changes in the Western United States. Science 306: 1015–1018.

Craig H. 1957. Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. Geochimica et Cosmochimica Acta 12: 133–149.

Crowley T.J. 2000. Causes of climate change over the past 1000 years. Science 289: 270–277.

Dai A., Fung I.Y. and Del Genio A.D. 1997. Surface observed global land precipitation variations during 1900–1988. Journal of Climate 10: 2943–2962.

D'Arrigo R.D. and Cullen H.M. 2001. A 350-year (AD 1628–1980) reconstruction of Turkish precipitation. Dendrochronologia 19: 167–177.

Demarée G.R., Lachaert P.J., Verhoeve T. and Thoen E. 2002. The long-term daily central Belgium temperature (CBT) series (1767–1998) and early instrumental meteorological observations in Belgium. Climatic Change 53: 269–293.

Ehman J.L., Schmid H.P., Grimmond C.S.B., Randolph J.C., Hanson P.J., Wayson C.A. and Cropley F.D. 2002. An initial intercomparison of micrometeorological and ecological inventory estimates of carbon exchange in a mid-latitude deciduous forest. Global Change Biology 8: 575–589.

EPICA Community Members 2004. Eight glacial cycles from an Antarctic ice core. Nature 429: 623–628.

Esper J. and Gärtner H. 2001. Interpretation of tree-ring chronologies. Erdkunde 55: 277–287.

Esper J., Neuwirth B. and Treydte K. 2001a. A new parameter to evaluate temporal signal strength of ring chronologies. Dendrochronologia 19: 93–102.

Esper J., Treydte K., Gärtner H. and Neuwirth B. 2001b. A tree ring reconstruction of climatic extreme years since AD1427 for Western Central Asia. Palaeobotanist 50: 141–152.

Esper J., Cook E.R. and Schweingruber F.H. 2002a. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. Science 295: 2250–2253.

Esper J., Schweingruber F.H. and Winiger M. 2002b. 1,300 years of climate history for Western Central Asia inferred from tree-rings. The Holocene 12: 267–277.

Esper J., Cook E.R., Peters K. and Schweingruber F.H. 2003a. Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. Tree-Ring Research 59: 81–98.

Esper J., Shiyatov S.G., Mazepa V.S., Wilson R.J.S., Graybill D.A. and Funkhouser G. 2003b. Temperature-sensitive Tien Shan tree ring chronologies show multi-centennial growth trends. Climate Dynamics 8: 699–706.

Esper J., Frank D.C. and Wilson R.J.S. 2004. Temperature reconstructions – low frequency ambition and high frequency ratification. EOS 85: 113, 120.

Esper J., Frank, D.C., Wilson, R.J.S., Briffa and K.R. 2005b. Effect of scaling and regression on reconstructed temperature amplitude for the past millennium. Geophysical Research Letters 32, doi:10.1029/2004GL021236.

Esper J., Wilson R.J.S., Frank D.C., Moberg A., Wanner H. and Luterbacher J. 2005b. Climate – past ranges and future changes. Quaternary Science Reviews 24: 2164–2166.

Etheridge D.M., Steele L.P., Langenfelds R.L., Francey R.J., Barnola J.M. and Morgan V.I. 1996. Natural and anthropogenic changes in atmospheric $CO_2$ over the last 1000 years from air in Antarctic ice and firn. Journal of Geophysical Research 101: 4115–4128.

Farquhar G.D., O'Leary M.H. and Berry J.A. 1982. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. Australian Journal of Plant Physiology 9: 2599–2609.

Felis T., Pätzold J., Loya Y., Fine M., Nawar A.H. and Wefer G. 2000. A coral oxygen isotope record from the northern Red Sea documenting NAO, ENSO, and North Pacific teleconnections on Middle East climate variability since the year 1750. Paleoceanography 15: 679–694.

Frank D. and Esper J. 2005. Temperature reconstructions and comparisons with instrumental data from a tree-ring network for the European Alps. International Journal of Climatology 25: 1437–1454.

Fritts H.C. 1976. Tree rings and climate. Academic Press, New York, 567 pp.

Ge Q.S., Zheng J.Y., Hao Z.X., Zhang P.Y. and Wang W.C. 2005. Reconstruction of historical climate in China, high-resolution precipitation data from Qing Dynasty archives. Bulletin of the American Meteorological Society 86: 671–674.

Gerber S., Joos F., Brügger P.P., Stocker T.F., Mann M.E., Sitch S. and Scholze M. 2003. Constraining temperature variations over the last millennium by comparing simulated and observed atmospheric $CO_2$. Climate Dynamics 20: 281–299.

Glueck M.F. and Stockton C.W. 2001. Reconstruction of the North Atlantic Oscillation, 1429–1983. International Journal of Climatology 21: 1453–1465.

González-Rouco J.F., von Storch H. and Zorita E. 2003. Deep soil temperature as a proxy for surface air-temperature in a coupled model simulation of the last thousand years. Geophysical Research Letters 30, doi: 10.1029/2003GL018264.

Goodale C.L., Apps M.J., Birdsey R.A., Field C.B., Heath L.S. and 8 co-authors 2002. Forest carbon sinks in the northern hemisphere. Ecological Applications 12: 891–899.

Goosse H., Crowley T.J., Zorita E., Ammann C.M., Renssen H. and Driessschaert E. 2005. Modeling the climate of the last millennium: what causes the differences between simulations? Geophysical Research Letters 32, doi: 10.1029/2005GL022368.

Graumlich L.J., Brubaker L.B. and Grier C.C. 1989. Long-term trends in forest net primary productivity – Cascade Mountains, Washington. Ecology 70: 405–410.

Grudd H., Briffa K.R., Karlen W., Bartholin T.S., Jones P.D. and Kromer B. 2002. A 7400-year tree-ring chronology in northern Swedish Lapland – natural climatic variability expressed on annual to millennial timescales. The Holocene 12: 657–665.

Gurney K.R. et al. 2002. Towards robust regional estimates of $CO_2$ sources and sinks using atmospheric transport models. Nature 415: 626–630.

Hansen J., Ruedy R., Glascoe J. and Sato M. 1999. GISS analysis of surface temperature change. Journal of Geophysical Research 104: 30997–31022.

Hantemirov R.M., Gorlanova L.A. and Shiyatov S.G. 2000. Pathological tree-ring structures in Siberian juniper (Juniperus sibirica Burgsd.) and their use for reconstructing extreme climatic events. Russian Journal of Ecology 31: 167–173.

Houghton R.A. 2003. Why are estimates of the terrestrial carbon balance so different? Global Change Biology 9: 500–509.

Huang S., Pollack H.N. and Shen P.Y. 2000. Temperature trends over the past five centuries reconstructed from borehole temperature. Nature 403: 756–758.

Hurrell J.W. 1995. Decadal trends in the North Atlantic Oscillation – regional temperatures and precipitation. Science 269: 676–679.

Janssens I. et al. 2003. Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic $CO_2$ emissions. Science 300: 1538–1542.

Jones P.D., Bradley S.R. and Jouzel J. (eds.) 1996. Climatic variations and forcing mechanisms of the last 2000 years. Springer, Berlin, 649 pp.

Jones P.D., Briffa K.R., Barnett T.P. and Tett S.F.B. 1998. High-resolution palaeoclimatic records for the past millennium – interpretation, integration and comparison with general circulation model control-run temperatures. Holocene 8: 455–471.

Jones P.D. and Mann M.E. 2004. Climate over past millennia. Review of Geophysics 42, doi: 10.1029/2003RG000143.

Jones P.D. and Moberg A. 2003. Hemispheric and large-scale surface air temperature variations – an extensive revision and an update to 2001. Journal of Climate 16: 206–223.

Jones P.D., New M., Parker D.E., Martin S. and Rigor I.G. 1999. Surface air temperature and its changes over the past 150 years. Review of Geophysics 37: 173–199.

Kalnay E. and Cai M. 2003. Impact of urbanization and land-use change on climate. Nature 423: 528–531.

Katz R.W. and Brown B.G. 1992. Extreme events in changing climate: variability is more important than averages, Climatic Change 21: 289–300.

Keeling C.D., Chin J.F.S. and Whorf T.P. 1996. Increased activity of northern vegetation inferred from atmospheric $CO_2$ measurements. Nature 382: 146–149.

Kharin V.V. and Zwiers F.W. 2005. Estimating extremes in transient climate change simulations. Journal of Climate 18: 1156–1173.

Klaus D. 1993. Zirkulations- und Persistenzänderungen des Europäischen Wettergeschehens im Spiegel der Großwetterlagenstatistik. Erdkunde 47: 85–104.

Klein Tank A.M.G., Können G.P. and Selten F.M. 2005. Signals of anthropogenic influence on European warming as seen in the trend patterns of daily temperature variance. International Journal of Climatology 25: 1–16.

Klingbjer P. and Moberg A. 2003. A composite monthly temperature record from Tornedalen in northern Sweden. International Journal of Climatology 23: 1465–1494.

Körner C. 2003. Slow in, rapid out – carbon flux studies and Kyoto targets. Science 300: 1242–1243.

LaMarche Jr. V.C. 1974. Paleoclimatic inferences from long tree-ring records. Science 183: 1043–1048.

Landsberg H.E. 1981. The urban climate. Academic Press, New York, 275 pp.

Lean J., Beer J. and Bradley R. 1995. Reconstruction of solar irradiance since 1610 – implications for climate change. Geophysical Research Letters 22: 3195–3198.

Leavitt S.W. and Long A. 1984. Sampling strategy for stable carbon isotope analysis of tree rings in pine. Nature 311: 145–147.

Leavitt S.W. and Long A. 1989. The atmospheric δ13C record as derived from 56 pinyon trees at 14 sites in the southwestern United States. Radiocarbon 31: 469–474.

Luterbacher J., Dietrich D., Xoplaki E., Grosjean M. and Wanner H. 2004. European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303: 1499–1503.

Luterbacher J., Xoplaki E., Casty C., Wanner H., Pauling A., Küttel M. and 38 co-authors 2005. Mediterranean climate variability over the last centuries; a review. In: Lionello P., Malanotte-Rizzoli P. and Boscolo R. (eds.). The Mediterranean climate variability. Elsevier pp. 27–148.

Mann M.E. 2002. The value of multiple proxies. Science 297: 1481–1482.

Mann M.E., Bradley R.S. and Hughes M.K. 1999. Northern Hemisphere temperatures during the past millennium – inferences, uncertainties, and limitations. Geophysical Research Letters 26: 759–762.

Mann M.E., Hughes M.K., Cook E.R. and Esper J. 2002. Tree-ring chronologies and climate variability. Science 296: 848–849.

Mann M.E., Rutherford S., Bradley R.S., Hughes M.K. and Keimig F.T. 2003a. Optimized surface temperature reconstructions using terrestrial borehole data. Journal of Geophysical Research 108, doi: 10.1029/2002JD002532.

Mann M.E., Ammann C., Bradley R., Briffa K., Jones P., Osborn T. and others 2003. On past temperatures and anomalous late-20th century warmth. EOS 84: 256–258.

Mann M.E., Rutherford S., Wahl E.R. and Ammann C.M. 2005. Testing the fidelity of methodologies used in proxy-based reconstructions of past climate. Journal of Climate 18: 4097–4107.

Marshall J.D. and Monserud R.A. 1996. Homeostatic gas-exchange parameters inferred from 13C/12C in tree rings of conifers. Oecologia 105: 13–21.

Maugeri M., Buffoni L. and Chlistovsky F. 2002a. Daily Milan temperature and pressure series (1763–1998) – history of the observations and data and metadata recovery. Climatic Change 53: 101–117.

Maugeri M., Buffoni L., Delmonte B. and Fassina A. 2002b. Daily Milan temperature and pressure series (1763–1998) – completing and homogenising the data. Climatic Change 53: 119–149.

Mitchell V.L. 1967. An investigation of certain aspects of tree growth rates in relation to climate in the central Canadian boreal forest. Technical Report 33. University of Wisconsin, Department of Meteorology, Wisconsin.

Moberg A., Bergström H., Ruiz Krigsman J. and Svanered O. 2002. Daily air temperature and pressure series for Stockholm (1756–1998). Climatic Change 53: 171–212.

Moberg A.D., Sonechkin M., Holmgren K., Datsenko N.M. and Karlen W. 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433: 613–617.

Nemani R.R., Keeling C.D., Hashimoto H., Jolly W.M., Piper S.C., Tucker C.J., Myneni R.B. and Running S.W. 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. Science 300: 1560–1563.

Neuwirth B., Esper J., Schweingruber F.H. and Winiger M. 2003. Site ecological differences to the climatic forcing of spruce pointer years from the Lötschental, Switzerland. Dendrochronologia 21: 69–78.

Palmer W.C. 1965. Meteorological drought. Research Paper No. 45, U.S. Department of Commerce (Weather Bureau, Washington, D.C.).

Parker D. 2004. Climate – large-scale warming is not urban. Nature 432: 290.

Pederson N., Jacoby G.C., D'Arrigo R.D., Cook E.R. and Buckley B.M. 2001. Hydro-meteorological reconstructions for northeastern Mongolia derived from tree rings: 1651–1995. Journal of Climate 14: 872–881.

Peters K., Jacoby G.C. and Cook E.R. 1981. Principal component analysis of tree-ring sites, Tree-Ring Bulletin 41: 1–19.

Peterson T.C. and Vose R.S. 1997. An overview of the Global Historical Climatology Network temperature data base. Bulletin of the American Meteorological Society 78: 2837–2849.

Peterson T.C., Easterling D.R., Karl T.R., Groisman P., Nicholls N., Plummer N. and 15 co-authors 1998. Homogeneity adjustments of in situ climate data – a review. International Journal of Climatology 18: 1493–1517.

Peterson T.C. 2003. Assessment of urban versus rural in situ surface temperatures in the contiguous United States: no difference found. Journal of Climate 16: 2941–2959.

Petit J.R., Jouzel J., Raynaud D., Barkov N.I., Barnola J.-M., Basile I., Bender M. and 12 co-authors 1999. Climate and atmospheric history of the past 420 000 years from the Vostok ice core, Antarctica. Nature 399: 429–436.

Pfister C. 1999. Wetternachhersage – 500 Jahre Klimavariationen und Naturkatastrophen (1496–1995). Haupt, Bern, 304 pp.

Pfister C., Luterbacher J., Schwarz-Zanetti G. and Wegmann M. 1998. Winter air temperature variations in western Europe during the Early and High Middle Ages (AD 750–1300). The Holocene 8: 535–552.

Pollack H.N. and Huang S. 2000. Climate reconstruction from subsurface temperatures. Annual Reviews of Earth Planetary Sciences 28: 339–365.

Pollack H.N. and Smerdon J.E. 2004. Borehole climate reconstructions – spatial structure and hemispheric averages, Journal of Geophysical Research 109, doi: 10.1029/2003JD004163.

Preisendorfer R.W. 1988. Principal component analysis in meteorology and oceanography. Developments in Atmospheric Sciences 17: 293–318.

Prieto M.R., García-Herrera R. and Hernandez Martin E. 2004. Early records of icebergs in the south Atlantic ocean from Spanish documentary sources. Climatic Change 66: 29–48.

Qian W., Hu Q., Zhu Y. and Lee D.K. 2003. Centennial-scale dry-wet variations in east Asia. Climate Dynamics 21: 77–89.

Rayner N.A., Parker D.E., Horton E.B., Folland C.K., Alexander L.V., Rowell D.P., Kent E.C. and Kaplan A. 2003. Globally complete analyses of sea surface temperature, sea ice and night marine air temperature, 1871–2000. Journal of Geophysical Research 108, doi: 10.1029/2002JD002670.

Robertson A., Overpeck J., Rind D., Mosley-Thompson E., Zielinski G., Lean J., Koch D., Penner J., Tegen I. and Healy R. 2001. Hypothesized climate forcing time series for the last 500 years. Journal of Geophysical Research 106: 14783–14803.

Robock A. and Free M.P. 1996. The volcanic record in ice cores for the past 2000 years. In: Jones P.D. et al. (Eds.) Climatic variations and forcing mechanisms of the last 2000 years. Springer, Berlin, 533–546.

Rutherford S. and Mann M.E. 2004. Correction to "Optimal surface temperature reconstructions using terrestrial borehole data". Journal of Geophysical Research 109, doi: 10.1029/2003JD004290.

Saurer M., Borella S., Schweingruber F.H. and Siegwolf R. 1997. Stable carbon isotopes in tree rings of beech – climatic versus site-related influences. Trees 11: 291–297.

Schaub M., Kaiser K.F. and Kromer B. 2003. Subfossil pines from loamy slope sediments reflect late glacial climatic variations. In: Schleser *et al.* (eds.) Trace – Tree rings in archaeology, climatology and ecology, Proceedings of the Dendrosymposium 2002, Bonn, 40–46.

Schweingruber F.H. 1996. Tree rings and environment – dendroecology. Haupt, Bern, 609 pp.

Schweingruber F.H. 2001. Dendroökologische Holzanatomie. Haupt, Bern, 472 pp.

Schweingruber F.H., Fritts H.C., Bräker O.U., Drew L.G. and Schär E. 1978. Dendroclimatic studies on conifers from central Europe and Great Britain. Tree-Ring Bulleting 38: 61–91.

Schweingruber F.H., Eckstein D., Serre-Bachet F. and Bräker O.U. 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. Dendrochronologia 8: 9–38.

Schweingruber F.H., Wehrli U., Aellen-Rumo K. and Aellen M. 1991. Weiserjahre als Zeiger extremer Standortseinflüsse. Schweizerische Zeitschrift für Forstwesen 142: 33–52.

Slonosky V. C. 2002. Wet winters, dry summers? Three centuries of precipitation data from Paris. Geophysical Research Letters 29, doi: 10.1029/2001GL014302.

Smith H.J., Wahlen M. and Mastroianni D. 1997. The $CO_2$ concentration of air trapped in GISP2 ice from the last glacial Maximum-Holocene transition. Geophysical Research Letters 24: 1–4.

Stahle D.W. 1999. Effective strategies for the development of tropical tree-ring chronologies. IAWA Journal 20: 249–253.

Stainforth D.A., Aina T., Christensen C., Collins M., Faull N., Frame D.J. and 10 co-authors 2005. Uncertainty in predictions of the climate response to rising levels of greenhouse gases. Nature 433: 403–406.

Stockton C.W. 1985. Current research progress toward understanding drought. In: Proceedings, Drought, Water Management and Food Production. Imprimerie de Fedala, Mohammedia, 21–35.

Stott P.A., Stone D.A. and Allen M.R. 2004. Human contribution to the European heatwave of 2003. Nature 432: 610–614.

Touchan R., Xoplaki E., Funkhouser G., Luterbacher J., Hughes M.K., Erkan N., Akkemik Ü. and Stephan J. 2005. Reconstructions of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation, Climate Dynamics, doi: 10.1007/s00382–005–0016–5.

Trenberth K. and Paolino D. 1980. Northern Hemisphere sea-level pressure data set – trends, errors and discontinuities. Monthly Weather Reviews 108: 855–872.

Treydte K. 2003. Dendro-Isotope und Jahrringbreiten als Klimaproxis der letzten 1200 Jahre im Karakorumgebirge/Pakistan. Schriften des Forschungszentrums Jülich, Reihe Umwelt/Environment 38, 190 pp.

Treydte K., Schleser G.H., Schweingruber F.H. and Winiger M. 2001. The climatic significance of $\delta^{13}C$ in subalpine spruce (Lötschental, Swiss Alps) – a case study with respect to altitude, exposure and soil moisture. Tellus 53: 593–611.

Verstege A., Esper J., Neuwirth B., Alifriqui M. and Frank D. 2004. On the potential of cedar forests in the Middle Atlas (Morocco) for climate reconstructions. In: Jansma E. *et al.* (eds.) Proceedings International Conference TRACE (Utrecht, May 1–3, 2003) 78–84.

von Storch H. and Zwiers F.W. 1999. Statistical analysis in climate research. Cambridge University Press, UK.

von Storch H., Zorita E., Jones J.M., Dimitriev Y., González-Rouco F. and Tett S.F.B. 2004. Reconstructing past climate from noisy data. Science 306: 679–682.

Wang S.W., Gong D. and Zhu J. 2001. Twentieth-century climatic warming in China in the context of the Holocene. The Holocene 11: 313–321.

Wanner H., Luterbacher J., Gyalistras D., Rickli R., Salvisberg E. and Schmutz C. 2000. Klimawandel im Schweizer Alpenraum. ETH Zürich, Zürich, 285 pp.

Wanner H., Brönnimann S., Casty C., Gyalistras D., Luterbacher J., Schmutz C., Stephenson D.B. and Xoplaki E. 2001. North Atlantic Oscillation – concepts and studies. Surveys in Geophysics 22: 321–381.

Watanabe O., Jouzel J., Johnsen S., Parrenin F., Shoji H. and Yoshida N. 2003. Homogeneous climate variability across east Antarctica over the past three glacial cycles. Nature 422: 509–512.

Watson R.T. (eds.) 2001. Climate change 2001 – the physical basis of climate change. Synthesis Report. Cambridge Univ. Press, Cambridge, 34 pp.

Wigley T.M.L., Briffa K.R. and Jones P.D. 1984. On the average of correlated time series, with applications in dendroclimatology and hydrometeorology. Journal of Climate and Applied Meteorology 23: 201–213.

Worbes M. 1999. Annual growth rings, rainfall dependent growth and long-term growth patterns of tropical trees from the Forest Reserve Caparo in Venezuela. Journal of Ecology 87: 391–403.

Xoplaki E., Luterbacher J., Paeth H., Dietrich D., Steiner N., Grosjean M. and Wanner H., 2005. European spring and autumn temperature variability and change of extremes over the last half millennium. Geophysical Research Letters 32, L15713, doi: 10.1029/2005GL023424.

Yang B., Braeuning A., Johnson K.R. and Yafeng S. 2002. General characteristics of temperature variation in China during the last two millennia. Geophysical Research Letters 29, doi: 10.1029/2001GL014485.

Zhang J. and Crowley T.J. 1989. Historical climate records in China and reconstruction of past climates. Journal of Climate 2: 833–849.