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Tree Rings as Temperature Proxies

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Tree-ring series provide the most widely distributed and easily accessible archive of annually resolved proxy climate data. In regions with well-defined seasonal growth the annual growth rings of trees provide both chronological control and a continuous time series of proxy environmental variables. The year to year variability of the physical (e.g. width, density) and chemical properties of these annual rings provides potential proxies for the environmental factors that influence tree growth. Over the last 30 years dendroclimatology has become a major tool in the reconstruction of climates of the last millennium in many areas of the world (see Hughes, 2002 for a comprehensive review).

The process of matching patterns of tree-ring width between series (crossdating) is fundamental to dendrochronology. It is used to verify the dating of tree-ring series and, in some cases, to demonstrate that the series are annual. For crossdating to be successful**,** the ring parameters must vary synchronously between series—reflecting a common response to an external control. Although tree-growth is influenced by many factors, often only one is strongly and consistently limiting. Successful dendroclimate studies target sampling sites where a single climate parameter is, or is expected to be, the limiting factor to growth and therefore the primary control of interannual variability in ringwidth. The presence and strength of the common signal between tree-ring series within a site is a measure of the degree of climate control of growth: correlation between tree-ring series from different sites across a broad area almost inevitably reflects a common climate control as no other controlling factors vary systematically across these spatial scales. Trees growing at their range limits are often the most sensitive to climate variability whereas trees in mid-range or interior forest sites may show little interannual variability or be dominated by local signals related to forest dynamics. Classically, open-grown latitudinal and altitudinal treeline sites are most sensitive to temperature variations whereas lower treeline and/or forest border sites are moisture sensitive. However, growth at many treeline sites in arid mountains is sensitive to both precipitation and temperatures (e.g. Bristlecone pines). The key to dendroclimate research is careful site selection as the limiting factor to growth can also vary based on microsite considerations. Dendroclimate studies further assume that the growth-limiting factor at a site does not change over time and therefore contemporary tree-ring climate relationships can be used to reconstruct past climate conditions.

Traditionally ring width (RW) is the primary variable utilized for dendroclimate work but more recently tree-ring densitometry has also been used. In densitometry, precise thin sections are cut from cores, x-rayed and negatives scanned to produce a continuous, high resolution density trace orthogonal to the rings. Several ringwidth and density variables can be obtained from these scans. Maximum latewood density (MXD) reflects the thickening of cell walls at the end of the growing season and represents a narrower climatic window than more traditional ringwidth parameters. (Schweingruber, 1988). MXD in northern conifers is very strongly related to summer temperatures and has been used in several important recent temperature reconstructions. In recent years isotopic data have also been used to infer temperature but, at present, such data are not available in sufficient quantity for large scale temperature reconstructions.

The fundamental data in dendroclimatology are tree-ring chronologies- average series of RW or MXD data from paired radii of 10-20 erect trees of the same species at a site without growth anomalies. The age assigned to each ring is verified by crossdating to ensure secure dating. Prior to averaging, each tree-ring series is converted to indices by removing low frequency age-related growth trends. This “standardization” process is accomplished by dividing the measured ring parameter for each year by values derived from a theoretical curve converting the data to a stationary series with a mean of one and similar variance. This ensures that each sample contributes equally to the average series by removing differences in mean ringwidths between e.g. wider rings in relatively young trees and narrower rings in older trees. Many approaches to standardization are available (see e.g. Fritts 1976; Cook and Briffa, 1989) and are the subject of continuing discussion as standardization can modify the common (climate) signal retained within these chronologies. This is a significant concern in the construction of long chronologies built from overlapping cross-dated segments of living and subfossil material where standardization may remove climatically-related low-frequency trends from tree-ring series. Recent studies indicate that the frequencies retained may be as little as one third of the mean segment length in the chronology (Cook et al 1995). Special techniques have been developed to try and retain this low frequency signal (see D’Arrigo et al., 2006). In any chronology sample depth decreases back in time. An objective measure of signal strength, based on intercore correlation and sample size, is used to identify those parts of a chronology (usually the oldest sectors) where signal strength falls below acceptable levels (see Briffa and Jones 1989).

Isolation of the climate signal in tree-ring series relies on standardization, site selection and replication to isolate the common signal that is assumed to be climate driven (Cook 1989). Exploratory analyses identify the strongest temperature relationships between tree growth and a wide range of monthly, seasonal or annual temperature variables. Subsequent analyses develop a transfer function model between the most significantly related climate variable(s) and the desired tree-ring variable (RW, MXD, etc). The tree-ring data are then entered into the model to reconstruct or hindcast the climate variable. Calibration trials for temperature data normally indicate that tree-rings rarely capture more than 40-50% of the variance in instrumental climate series and are least effective in estimating extreme years. However much we might wish, trees are not simple thermometers. Any single chronology contains elements related to site, regional or large scale controls; the strength of reconstructions ultimately depends on cross verification with chronologies from adjacent areas or comparison with other proxies that confirm the nature of the signal and can be used to distinguish local vs. larger scale controls.

Dendroclimate reconstructions are unique in that they are routinely verified against data withheld from the initial calibration and error terms can be applied to these reconstructions (Cook and Kairiukstis, 1989). Reconstructions are generally modeled linearly using regression based procedures. In addition to simple reconstructions for individual sites, extensive single- or multi-species chronology networks allow the reconstruction of temperature, precipitation or atmospheric fields over large areas.

In the last 25 years the research field has rapidly expanded and diversified, engendered in part by the climate change debate and the need for long, annually resolved temperature records (see Hughes, 2002). Dendroclimatology is now applied to broad range of species and environments that range from forest tundra at 72° N in Siberia to scrubby rainforest at 56° S at Cape Horn or from sealevel in Alaska to over 4900m on the Bolivian Altiplano. Reconstructions of temperature from MXD or RW data are usually for the summer season. Few tree-ring series reflect winter conditions for obvious reasons. Routinely-recoverable tree-ring records in many parts of the world are less than 2-300 years as heart rot, fire or other disturbances limit the age of trees. Long, climate-sensitive chronologies have therefore received special attention at sites with long-lived species, well-preserved sub-fossil wood or both. Many of these sites are at the range limits of species, particularly at Northern Hemisphere treelines with old slow-growing trees and/or good preservation of wood at dry or cold sites (see Briffa, 2000). Millennial chronologies are now developed in Northern Europe, Canada, the Alps and Asia. These long chronologies, combined with other high resolution proxy climate series are primary inputs for several Northern Hemisphere annual or summer temperature reconstructions (e.g. Mann et al, 1999; Esper et al 2002, Briffa et al, 2004) for the last millennium.

Dendroclimatological techniques have been used to reconstruct a wide range of paleoclimate variables that have progressively expanded from local to regional and continental scales. In providing three examples we proceed from a relatively simple, single reconstruction to the results from large scale networks. The Icefields chronology (Figure 1) is based on MXD and RW data from three sites in the Canadian Rockies. It appears to have a strong regional signal as it shows a similar pattern to shorter reconstructions from treeline sites to the west but also shows a good relationship with the glacier record from the Rockies (moraines are formed following the coldest intervals as conditions ameliorate) for the last 300 years and also with the main periods of sunspot minima. However, the absence of other long regional reconstructions makes it difficult to verify the earlier record except by comparisons at continental or larger scales (see below). Unfortunately surface evidence of glacier advances prior to ca 1700 has been obliterated by later more extensive events.

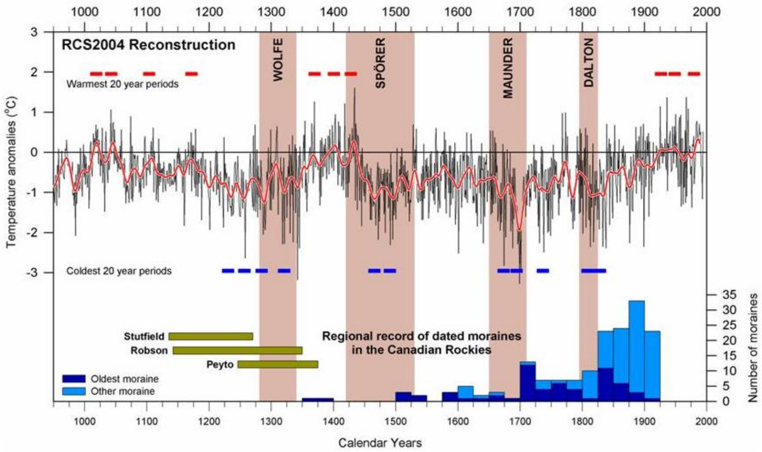

Figure 1: The Icefields reconstruction of summer maximum temperatures based on RW and MXD data from living and sub-fossil material near Athabasca, Peyto and Robson Glaciers, Canada. Also shown are the main sunspot minima and periods of moraine building by glaciers. (Luckman and Wilson, 2005).

Similar long chronologies, combined with other high resolution proxy climate series are primary inputs for several Northern Hemisphere annual or summer temperature reconstructions (e.g. Mann et al, 1999; Esper et al 2002, Briffa et al, 2004, NRC 2006) for the last millennium. Figure 2 shows three Northern Hemisphere summer temperatures reconstructions based entirely on tree ring data. Briffa's reconstruction is based on MXD. Esper and D'Arrigo use RW and MXD records but with different standardization techniques. Although these show a fairly similar pattern for the last 3-400 years there are differences in the earlier records related to the relatively sparse and unevenly distributed sample base and the methods of standardization used. This situation should improve as more and more widely distributed long chronologies become available: however, it is clear from reconstructions of the last few hundred years that, although some variations may be globally synchronous e.g. those forced by solar activity, there is considerably spatial variability at all timescales.

The other powerful contribution of tree-rings is to allow the reconstructions of large scale regional or global patterns of temperatures based on large networks of chronologies. Figure 3 shows examples of circum-polar summer temperature patterns reconstructed for 5˚ x 5˚ grid squares based on a network of 303 MXD chronologies from arctic and alpine tree-line sites (Briffa et al., 2002).

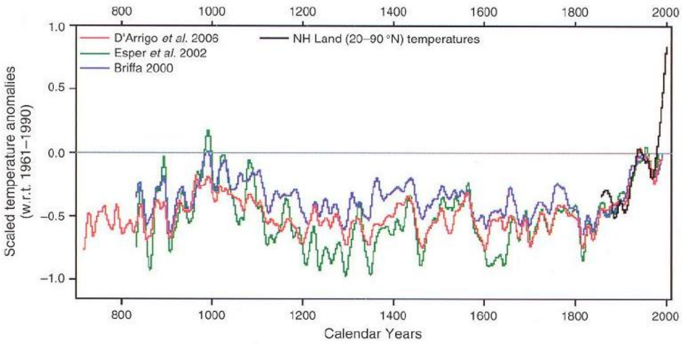

Figure 2: Comparison of three millennial length Northern Hemisphere Temperature reconstructions based on tree-ring data: Briffa is based on MXD, Esper and D'Arrigo are based on RW and MXD data using different standardization methods.(R. Wilson, pers comm. In Luckman 2007).

These two examples clearly demonstrate that temperature varies spatially as well as over time. Even though global temperatures were depressed following the 1816 eruption of Tambora (resulting in the "Year without a summer" in Europe and NE North America) the cooling was not universal and shows a distinct spatial pattern related to atmospheric circulation. Marked differences in relative warmth also occur in 1828. The composite Northern Hemisphere (20-70˚N) temperature series developed from these data also shows the global impact of major volcanic eruptions on summer temperatures over the last 600 years. Similar variability is demonstrated in the instrumental temperature records- as western Canada has been warming in the last 20-30 years, Newfoundland and Labrador have cooled slightly. Therefore one should expect some regional variability between long temperature reconstructions.

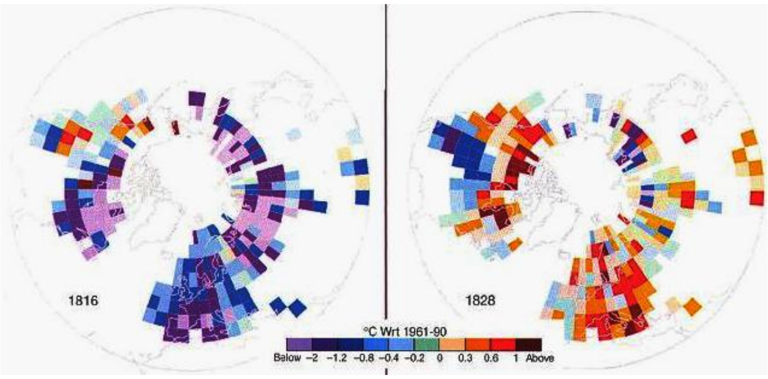

Figure 3. Mean April-September gridded temperature anomalies for the Northern Hemisphere in 1816 and 1828 estimated from MXD data. These are two of the most extreme years in the 19th century (1816 follows the Tambora eruption) See Briffa et al, 2002 from Luckman 2007.

Dendroclimatic reconstructions, like many other paleoclimatic techniques are based on uniformitarian assumptions. However, several authors have noted a decline in the temperature-related signal in both ring width (e.g. Jacoby and D'Arrigo 1995) and MXD series from high latitude Northern Hemisphere sites (Briffa et al., 2004). A variety of causes have been suggested including increased moisture sensitivity once summer temperatures pass a critical threshold (D'Arrigo et al., 2004), possible ozone-related effects (Briffa et al, 2004) or even chronology development techniques (Wilmking et al., 2005). Although not universal these effects need careful scrutiny and further study to resolve this potentially critical issue.

Tree-rings are providing new, annually resolved and precisely dated proxy climate records for large areas of the earth's land surface and parts of the adjacent oceans. These allow the reconstruction of climate history, trends and patterns at an expanding range of temporal and spatial scales. The increasing availability of long chronologies from major continental areas can address climate variability at decadal to millennial timescales whilst retaining annual resolution. The increasing density and distribution of chronologies provide networks that can examine the spatial variability and teleconnection patterns associated with major modes of global climate variability such as ENSO, PDO, NAO, etc. seen in the instrumental record. As these networks of annually resolved data are at least double or triple the length of instrumental records (in many remote areas they may be the only records) they can be used to establish whether these patterns are time stable or how they have responded to past changes in forcing. In conjunction with other proxy climate data, they provide the best records to benchmark and understand the natural modes of climate variability at decade to century scales over much of the earth's surface.

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