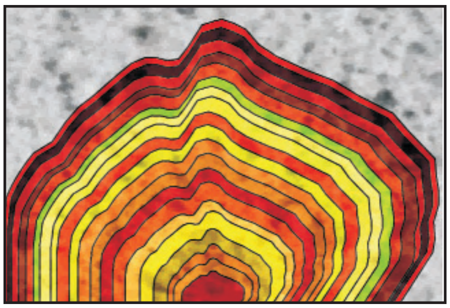
SERIES



Geoscience of Climate and Energy 6. Tree Rings as Temperature Proxies

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SUMMARY

Tree rings have provided annually resolved and precisely dated proxy climate records for large areas of the earth's land surface. These records are considerably longer than instrumental climate data and allow the reconstruction of climate history, trends and patterns over a wide range of temporal and spatial scales. This paper briefly reviews the principles and assumptions that underlie the reconstruction of temperatures from tree-ring data, and provides three examples of their application at differing spatial and temporal scales over the last millennium.

SOMMAIRE

Les anneaux de croissance des arbres ont permis d'expliquer et de dater avec précision, bien qu'indirectement, des événements climatiques portant sur de grandes étendues de la surface terrestre. La portée temporelle de ces archives naturelles dépasse de beaucoup celle de tout registre climatique d'instruments humains et permet de reconstituer l'histoire, les tendances et patrons climatiques pour une gamme étendue d'échelles dans le temps et l'espace. Le présent article présente une revue sommaire des principes et postulats qui fondent la reconstitution des conditions météorologiques à partir des données des anneaux de croissance des arbres, ainsi que trois exemples d'application pour différentes échelles temporelles et spatiales au cours du dernier millénaire.

INTRODUCTION

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. Within the last 30 years, dendroclimatology has become a major tool in the reconstruction of climates over 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 (i.e. crossdating) is fundamental to dendrochronology. In this context, the term series refers to a temporal sequence of measured tree-ring characteristics, usually from a single radius in a tree. Crossdating is used to verify the dating of tree-ring series and, in some cases, to demonstrate that the series are annual. For it 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 factor is strongly and consistently limiting. Successful dendroclimatic 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 (see below). 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; similarly, correlation between tree-ring series from different sites across a broad area almost invariably reflects a common climate control, as no other controlling factors influence tree growth across these spatial scales.

Trees growing at their range limits are often the most sensitive to climate variability, whereas tree-ring series from trees in mid-range or interior forest sites may show little interannual variability or else may 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 more moisture-sensitive. However, growth at many treeline sites in arid mountains is sensitive to both precipitation and temperature (e.g. Bristlecone pines). The key to dendroclimate research is careful site selection, as the limiting factor to growth can also vary at the microsite scale. Dendroclimate studies further assume that the growth-limiting factor at a site does not change over century to millennial time scales, and, therefore, that contemporary tree-ring climate relationships can be used to reconstruct past climate conditions.

DEVELOPING TREE-RING CHRONOLOGIES

Traditionally, ringwidth (RW) is the primary variable utilized for dendroclimatic studies but, more recently, tree-ring densitometry has also been used. In densitometry, precise thin-sections are cut from tree cores, x-rayed, and 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). The MXD in northern conifers is very strongly related to summer temperatures and has recently been used in several important 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 given site with no obvious growth anomalies in the ring series. The age assigned to each ring is verified by crossdating with previously obtained, absolutely dated, reference chronologies 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' is accomplished by dividing the measured ring parameter for each year by values derived from a theoretical curve that converts the data to a stationary series having a mean of one and a similar range of variance throughout the series. This ensures that each sample contributes equally to the average series by removing differences in mean ringwidths that are related to tree age; e.g. relatively young trees typically have wider rings than older trees. Many approaches to standardization are available (e.g. Fritts 1976; Cook and Briffa 1990) and are the subject of ongoing 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 crossdated segments of living and subfossil material, because standardization may remove climate-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 in attempts to retain this low frequency signal (D'Arrigo et al. 2006). In any chronology, sample depth decreases with increasing antiquity, as progressively fewer records are available for sampling. 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 a statistically acceptable level, usually due to low replication (Briffa and Jones 1990).

IDENTIFYING THE CLIMATE SIGNAL

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 1990). Exploratory analyses identify the strongest relationships between tree growth and a wide range of monthly, seasonal or annual temperature variables. Similar analyses are used to identify relationships with other climate variables, e.g. precipitation, but only analyses based on temperature are discussed here. Subsequent analyses develop a transfer function model between the most significantly related climate variable(s) and the desired tree-ring variable (e.g. RW, MXD, etc). The tree-ring data are then entered into the model to reconstruct or hindcast the climate variable. However much we might wish, trees are not simple thermometers: calibration trials for temperature data normally indicate that tree rings rarely capture more than 40−50% of the variance in instrumental temperature series and are least effective in estimating extreme years. Any single chronology contains elements related to site, regional and large-scale controls; the strength of reconstructions ultimately depends on cross-verification with chronologies from adjacent areas, or on comparison with other proxies that confirm the nature of the signal and can be used to distinguish local vs. larger scale controls.

Dendroclimatic reconstructions are unique in that they are routinely verified. Initially, climate–tree-ring relationships are developed using half of the temperature data available (calibration) and these relationships are tested (verification) by reconstructing temperatures for the remainder of the instrumental record withheld from calibration. The analysis is then repeated, reversing the roles of the two datasets. If the two reconstructions pass appropriate statistical tests, calibration is then carried out based on the entire overlap period between the tree-ring and temperature data and these relationships are used to reconstruct values for the entire tree-ring chronology. This allows estimation of the error terms that can be applied to the reconstructions (Cook and Kairiukstis 1990). Reconstructions are generally modelled 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 and atmospheric records over large areas.

EXAMPLES OF DENDROCLIMATE RECONSTRUCTIONS

In the last 25 years, dendroclimatic research has rapidly expanded and diversified, engendered, in part, by the climate change debate and the need for long, annually resolved temperature records (Hughes 2002). Dendroclimatology is now applied to a broad range of species and environments, from forest tundra at 72°N in Siberia, to scrubby rainforest at 56°S at Cape Horn, or from sea level in Alaska to over 4900 m on the Bolivian Altiplano.

Reconstructions of temperature from MXD or RW data usually apply to the summer season; for obvious reasons, few tree-ring series reflect winter conditions. Routinely recoverable tree-ring records, in many parts of the world, represent time-spans of less than 200−300 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 (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 for the last millennium (e.g. Mann et al. 1999; Esper et al. 2002; Briffa et al. 2004).

Dendroclimatological techniques have been used to reconstruct a wide range of paleoclimate variables at scales that have progressively expanded from local to regional to continental. The following three examples proceed from a relatively simple reconstruction in a restricted area (Fig. 1), to regional reconstructions (Fig. 2), to reconstructions based on large-scale networks (Fig. 3). The icefields chronology (Fig. 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 pattern that is similar 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 older part of the 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 the more extensive glacier advances of the eighteenth and nineteenth centuries.

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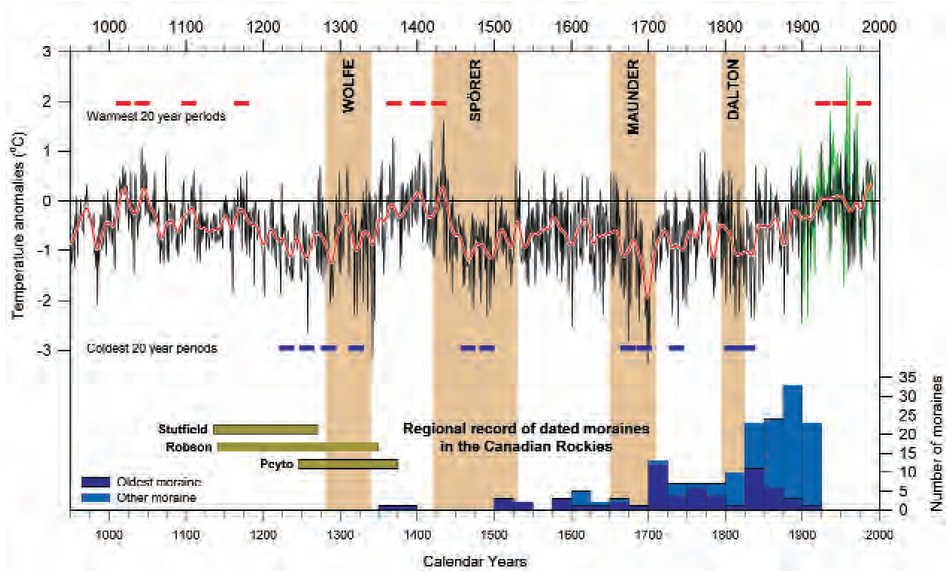

Figure 1: The icefields reconstruction of summer maximum temperatures based on ringwidth and maximum latewood density data from living and sub-fossil material near Athabasca, Peyto and Robson glaciers, Canada. The instrumental record (for the last ca. 100 years) is shown in green. Also shown are the main sunspot minima (light brown vertical bands) and periods of moraine building by glaciers (blue). The olive bars show the duration of tree-ring chronologies developed from sub-fossil trees overridden by glaciers. The last year provides a minimum date for the glacier advance that killed the trees (after Luckman and Wilson 2005).

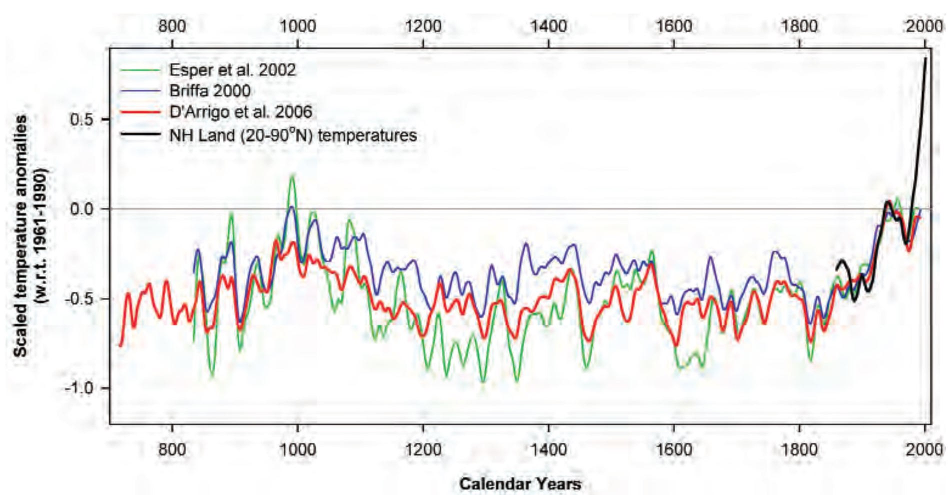

Figure 2: Comparison of three millennia-length northern hemisphere temperature reconstructions based on RW data (Briffa 2000; Esper et al. 2002) or RW plus MXD data (D'Arrigo et al. 2006) using different standardization methods (R. Wilson, personal communication, in Luckman 2007).

Briffa et al. 2004; National Research Council 2006). Figure 2 shows three Northern Hemisphere summer temperature reconstructions based entirely on tree ring data, using different standardization techniques. Although these reconstructions show a fairly similar pattern for the last 300–400 years, the older records display differences related to the relatively sparse and unevenly distributed sample base and the methods of standardization used. This situation should improve as additional 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 considerable spatial variability

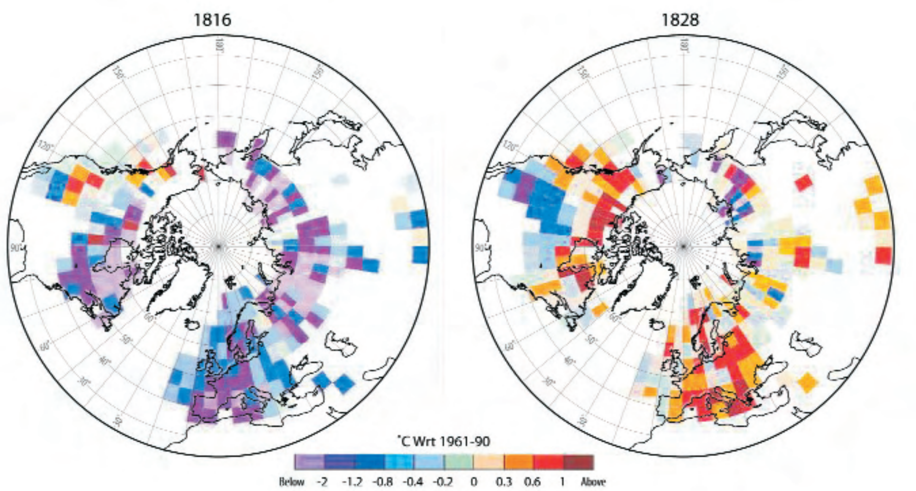

Figure 3. Mean April–September gridded temperature anomalies for the Northern Hemisphere in 1816 and 1828 estimated from MXD data (Briffa et al. 2002; Luckman 2007). These are two of the most extreme years in the 19th century (the 1816 record follows the Tambora eruption).

at all timescales.

Tree-rings also allow the reconstruction of large-scale regional or global temperature patterns defined by large networks of chronologies (e.g. Fritts 1976). Figure 3 shows examples of circum-polar summer temperature patterns reconstructed for a 5° x 5° gridded network of 303 MXD chronologies from arctic and alpine tree-line sites (Briffa et al. 2002). 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 northeastern 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 (not shown) also illustrates the global impact of major volcanic eruptions on summer temperatures over the last 600 years (Briffa et al. 1988). Similar variability is demonstrated in the instrumental temperature records, as western Canada has been warming in the last 20−30 years, but parts of the eastern Arctic have cooled slightly. Therefore one should expect some regional variability between long temperature reconstructions.

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.

CONCLUSION

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 while retaining annual resolution. The increasing density and distribution of tree-ring chronologies provide networks that can examine the spatial variability and teleconnection patterns associated with major modes of global climate variability such as the El Niño Southern Oscillation, Pacific Decadal Oscillation, North Atlantic Oscillation, 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, and 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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