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Ranking of tree-ring based temperature reconstructions of the past millennium

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ABSTRACT

Tree-ring chronologies are widely used to reconstruct high-to low-frequency variations in growing season temperatures over centuries to millennia. The relevance of these timeseries in large-scale climate reconstructions is often determined by the strength of their correlation against instrumental temperature data. However, this single criterion ignores several important quantitative and qualitative characteristics of tree-ring chronologies. Those characteristics are *(i) data homogeneity*, *(ii) sample replication*, *(iii) growth coherence*, *(iv) chronology development*, and *(v) climate signal* including the correlation with instrumental data. Based on these 5 characteristics, a reconstruction-scoring scheme is proposed and applied to 39 published, millennial-length temperature reconstructions from Asia, Europe, North America, and the Southern Hemisphere. Results reveal no reconstruction scores highest in every category and each has their own strengths and weaknesses. Reconstructions that perform better overall include N-Scan and Finland from Europe, E-Canada from North America, Yamal and Dzhelo from Asia. Reconstructions performing less well include W-Himalaya and Karakorum from Asia, Tatra and S-Finland from Europe, and Great Basin from North America. By providing a comprehensive set of criteria to evaluate tree-ring chronologies we hope to improve the development of large-scale temperature reconstructions spanning the past millennium. All reconstructions and their corresponding scores are provided at www.blogs.uni-mainz.de/fb09climatology.

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1. Introduction

Tree-ring chronologies (TRCs) are an important source of information in large-scale temperature reconstructions (IPCC, 2013; St. George, 2014). The latter are used to estimate temperature variability at continental (Luterbacher et al., 2016, Pages 2k Consortium, 2013, Trouet et al., 2013), hemispheric (Christiansen and Ljungqvist, 2012; D'Arrigo et al., 2006; Esper et al., 2002a; Ljungqvist, 2010; Ljungqvist et al., 2012, 2016; Mann et al., 2008; Schneider et al., 2015; Shi et al., 2013; Stoffel et al., 2015; Wilson et al., 2016; Xing et al., 2016) and global scales (Mann and Jones, 2003; Neukom et al., 2014) over the past 1000 years, enabling comparisons between climate variations during pre-industrial and industrial periods. The importance of TRCs in these reconstructions arises from the precise annual dating inherent to this proxy (Douglass, 1941) and a well-defined mechanistic understanding of the influence of temperature on tree growth (Fritts, 1976). The relative significance of tree-ring chronologies, compared to other proxies in large-scale reconstructions, increases back in time, as the number of annually resolved proxies rapidly declines towards the early centuries of the past millennium (Esper et al., 2004).

1.1. *Basic tree-ring chronology characteristics*

TRCs are typically composed of tree-ring width (TRW) or maximum latewood density (MXD) measurement series from many trees (Fritts, 1976). A TRC might extend over the entire past millennium if one or more individual trees are 1000 years or more in age. Such longevity, however, is restricted to only a few known locations (OldList at: www.rmtrr.org/oldlist.htm). Most millennial-length TRCs are therefore produced by combining samples from living trees with older material from archeological and historical structures (hereafter: historical samples), dead wood on the ground (remnant samples), or wood preserved under ground and in lakes (sub-fossil samples). The successful combination of living trees with historical/remnant/sub-fossil material improves when the provenance of all samples is ecologically consistent. If not, older sections of a millennial-length chronology can have different growth rates and climate signals than those sections dominated by samples from living trees (Boswijk et al., 2014; Linderholm et al., 2014; Tegel et al., 2010). For example, remnant samples from a sub-alpine site in the Alps are ideally combined with samples from living trees growing on the same slope, at the same elevation and aspect (Neuwirth et al., 2004); sub-fossil trees from a shallow lake in Fennoscandia are ideally combined with trees growing around the lake, as opposed to drier inland locations (Düthorn et al., 2013, 2015).

Combining living trees with historical/remnant/sub-fossil samples is not always straightforward. Habitat homogeneity in a TRC derived from living trees and in-situ remnant or sub-fossil wood from the same location may be high, but their combination with historical material can be more complicated. If, for example, the historical samples were obtained from an old building in a mountain valley, it often remains unclear in which position in the surrounding forests the harvested tree grew (Büntgen et al., 2006b). It is not uncommon for historical structures, particularly in alpine environments, to contain recycled material of unknown origin as a consequence of repairs and additions (Bellwald, 2000; Kalbermatten and Kalbermatten, 1997). Without detailed construction histories the researcher's ability to trace the origin of samples is limited (Büntgen et al., 2005; Wilson et al., 2004). The situation is further complicated if the samples in a TRC are from multiple locations spread over a large region, and if this region extends over several hundreds of kilometers. These problems, affecting the *Homogeneity* of a tree-ring dataset, are seemingly reduced in TRCs from only living trees sampled at a single site.

Another important characteristic of millennial-length TRCs includes the number and temporal distribution of TRW (or MXD) measurement series averaged in the mean chronology. Varying sample replication is often reported when describing a new TRC, but is usually disregarded in large-scale temperature reconstructions. Typically, the number of measurement series included in a TRC declines back in time and might change from more than 100 living-tree samples in the 20th century to only a handful of samples (perhaps from a single historical structure) at the beginning of the last millennium. Acknowledging the effects of changing sample size by calculating temporally varying uncertainty estimates is not usually considered outside the tree-ring community (IPCC, 2013). However, this characteristic is important as the relevance of an individual TRC in large-scale proxy networks is commonly based on the strength of instrumental calibration of only the well-replicated 20th century data, thereby overlooking any pre-instrumental replication changes.

Similarly, the coherence among the TRW (MXD) series combined in a TRC, and temporal change thereof, is not considered in the non-dendrochronological literature (Frank et al., 2007). The inter-series correlation among sample measurements is an important characteristic of a mean chronology and is commonly computed to evaluate temporal changes of the chronology's signal strength (Fritts, 1976). The inter-series correlation is rarely stable and can change at *(i)* the transition from living trees to series from historical/remnant/sub-fossil material, or *(ii)* from a cluster of measurement series of a certain building to another building, or *(iii)* by the proportion of juvenile, mature, and adult growth rings (Cook and Kairiukstis, 1990). Gradual trends in the inter-series correlation, as well as step changes, are common in long TRCs and bare important information on the reliability of dendroclimatic reconstructions during pre-instrumental periods. Measures that assess the affect of changing sample size and inter-series correlation include the *Expressed Population Signal* and *Subsample Signal Strength* (Wigley et al., 1984). However, these metrics are not widely recognized beyond the tree-ring community and their combination with other uncertainties, e.g. from the unexplained variance of the calibration model or the choice of the detrending model, remains challenging (Esper et al., 2007).

Another important TRC characteristic is the degree to which a chronology retains the full spectrum of pre-instrumental temperature variance, which is affected by the method used for chronology development and the age-structure of the underlying data (Cook et al., 1995). Recent assessments of large datasets showed that instrumental meteorological measurements and tree-ring timeseries contain different frequency spectra (Ault et al., 2014; Bunde et al., 2013; Büntgen et al., 2015; Franke et al., 2013; Zhang et al., 2015), and that TRCs are limited in capturing millennial scale temperature trends (Esper et al., 2012b). To minimize the loss of long-term information, dendrochronologists apply detrending techniques that are specifically designed to preserve low frequency variance. The preferred approach is the Regional Curve Standardization (RCS) method, introduced to dendroclimatology by Briffa et al. (1992). However, RCS demands a large number of TRW (MXD) measurement series and requires the underlying data to represent a combination of short segments (trees) distributed more or less evenly throughout the entire chronology (Esper et al., 2003a). For example, if a TRC is composed of only very old living trees, the chronology's biological age will steadily increase towards the present. This causes the biologically younger rings to be concentrated at the beginning of the past millennium and the older rings in the modern period. This age structure limits the comparison of tree-rings of the same age over time, which is the backbone of RCS and related tree-ring detrending techniques (Melvin and