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Invited review

Last millennium Northern Hemisphere summer temperatures from tree rings: Part II, spatially resolved reconstructions

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ABSTRACT

Climate field reconstructions from networks of tree-ring proxy data can be used to characterize regional-scale climate changes, reveal spatial anomaly patterns associated with atmospheric circulation changes, radiative forcing, and large-scale modes of ocean-atmosphere variability, and provide spatiotemporal targets for climate model comparison and evaluation. Here we use a multiproxy network of tree-ring chronologies to reconstruct spatially resolved warm season (May–August) mean temperatures across the extratropical Northern Hemisphere (40-90°N) using Point-by-Point Regression (PPR). The resulting annual maps of temperature anomalies (750–1988 CE) reveal a consistent imprint of volcanism, with 96% of reconstructed grid points experiencing colder conditions following eruptions. Solar influences are detected at the bicentennial (de Vries) frequency, although at other time scales the influence of insolation variability is weak. Approximately 90% of reconstructed grid points show warmer temperatures during the Medieval Climate Anomaly when compared to the Little Ice Age, although the magnitude varies spatially across the hemisphere. Estimates of field reconstruction skill through time and over space can guide future temporal extension and spatial expansion of the proxy network.

1. Introduction

Global and hemispheric temperature anomalies reflect the

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influence of both internal variability in the climate system as well as the consequences of changes in radiative forcing, such as insolation, volcanic eruptions, and greenhouse gas concentrations. Surface temperature is determined by the planetary energy balance and serves as a symptom of perturbations to that balance, but also contains variability due to natural climate system dynamics. Rising global mean surface temperature is a key diagnostic for the influence of increasing greenhouse gases on the Earth's climate system. Yet changes in incoming solar radiation, orbital (Milankovich) changes, albedo and land use alterations, and natural and anthropogenic aerosols also influence surface temperatures. Different radiative forcing mechanisms as well as internal modes of coupled ocean-atmosphere variability may have distinct fingerprints on temperature anomalies across different spatial, temporal, and seasonal scales (Hegerl et al., 1997; Rind et al., 1999; Shindell et al., 2001b; Hegerl et al., 2003; Rind et al., 2004; Shindell et al., 2003, 2004; Hegerl et al., 2006, 2007; Shindell and Faluvegi, 2009; Shindell, 2014; Shindell et al., 2015). Surface temperature anomalies are therefore controlled by the superposition of various external radiative and internal dynamical influences on the climate system. Detection and attribution of the causes of temperature fluctuations, as well as the prediction of future regional-scale changes, thus depend on accurate quantification and understanding of spatial and temporal variations in surface temperature (Hegerl et al., 1997; Stott and Tett, 1998; Meehl et al., 2004; Lean and Rind, 2008; Stott and Jones, 2009; Stott et al., 2010; Solomon et al., 2011; Hegerl and Stott, 2014).

Paleoclimate reconstructions of past temperature extend knowledge of climate system variability beyond that available from the limited instrumental observational record. They offer longer timescales over which to observe a more complete range of variability in solar and volcanic forcing, extended opportunities to characterize internal climate system fluctuations at decadal and longer timescales, and the potential to separate forced and unforced responses to better understand their magnitude and spatiotemporal patterns (Hegerl et al., 2003, 2007). Spatially-explicit reconstructions provide additional opportunities to refine our understanding of fundamental climate system characteristics, diagnose the influence of different forcings on various aspects of the climate system, and provide insight into both regional climate changes and the response of large-scale modes of ocean-atmosphere variability (Seager et al., 2007; Cook et al., 2010a, b; Hegerl and Russon, 2011; Phipps et al., 2013; PAGES 2k-PMIP3 group, 2015; Goosse, 2016). Comparisons between paleoclimatic data and models also provide out-of-sample tests of the general circulation models (GCMs) used for future climate projections and can indicate where the modeled forced response or internal variability requires further evaluation and continued refinement. Such comparisons may help constrain the probable range of model parameters or identify the forcing configurations most consistent with past climate variability (Edwards et al., 2007; Anchukaitis et al., 2010; Schmidt, 2010; Hegerl and Russon, 2011; Brohan et al., 2012; Schurer et al., 2013; Schmidt et al., 2014; Harrison et al., 2015; Tingley et al., 2015).

Reconstructions of last millennium and Common Era surface temperatures have focused predominantly on single time-series to represent continental- to global-scale variations in mean annual or growing season temperatures aggregated over space (Frank et al., 2010; Masson-Delmotte et al., 2013; PAGES2k, 2013; Stoffel et al., 2015; Smerdon and Pollack, 2016) while fewer have used climate field reconstruction (CFR) methods (Fritts, 1991; Cook et al., 1994; Evans et al., 2001; Tingley et al., 2012) to quantify past temperature anomalies simultaneously through time and across space (c.f. Mann et al., 1998; Tingley and Huybers, 2013; Wang et al., 2015). Spatial field reconstructions offer the benefit of characterizing regional-scale climate changes, can reveal spatial anomaly patterns or fingerprints associated with atmospheric circulation, radiative forcing, and large-scale modes of ocean-atmosphere variability, and provide complete spatiotemporal targets for GCM evaluation (Evans et al., 2001; Anchukaitis and McKay, 2014; Kaufman, 2014; Schmidt et al., 2014).

Here, we develop and evaluate a climate field reconstruction of extratropical Northern Hemisphere summer temperatures using an updated network of temperature-sensitive tree-ring proxy chronologies and existing temperature reconstructions back to 750 CE (Wilson et al., 2016). We are motivated by two fundamental challenges to the development of skillful large-scale last millennium temperature reconstructions revealed over the last two decades (c.f. Frank et al., 2010; Smerdon and Pollack, 2016): First, biases arising from characteristics of the proxies themselves; second, uncertainties arising from the choice of reconstruction methodologies.

Tree-ring proxies provide precise annual dating and are broadly distributed across extra-tropical land areas, making them one of the most widely used proxies for climate reconstructions of the Common Era (Hughes, 2002; Jones et al., 2009; Smerdon and Pollack, 2016). Yet despite these advantages, certain challenges or limitations exist: they preferentially reflect growing season temperature conditions, they require some manner of processing to remove non-climatic age or tree geometry related growth trends, and there exist a wide range of climate responses amongst the more than two thousand tree-ring chronologies currently archived in public repositories (Briffa, 1995, 2000; Briffa et al., 2002, 2004; St. George, 2014; St. George and Ault, 2014). A decade ago, D'Arrigo et al. (2006) and Wilson et al. (2007) used small high-latitude networks of tree-ring proxy chronologies to reconstruct mean annual Northern Hemisphere temperatures. These and subsequent efforts have illuminated several extant challenges: a relatively limited number of unambiguously temperature-sensitive chronologies, a predominance of ring-width chronologies in comparison to the more temperature-sensitive wood density measurements (D'Arrigo et al., 1992; Schweingruber et al., 1993; Briffa et al., 2004; Frank et al., 2007; D'Arrigo et al., 2009; Esper et al., 2015; Wilson et al., 2016), and the influence of non-stationarity in climate/tree growth associations (‘divergence’; Briffa et al., 1998b; Wilson et al., 2007; D'Arrigo et al., 2008), a particular problem for North American treeline tree-ring width chronologies (Jacoby and D'Arrigo, 1995; Andreu-Hayles et al., 2011; Anchukaitis et al., 2013) and many previously collected wood density chronologies (Briffa et al., 2002). Since the publication of D'Arrigo et al. (2006) and Wilson et al. (2007), dozens of new tree-ring chronologies and local temperature reconstructions have become available, including many new and updated latewood density (MXD) measurement series that do not appear to exhibit any divergence (c.f. D'Arrigo et al., 2009; Esper et al., 2010; Anchukaitis et al., 2013). We draw on these new, published, and updated data here to develop a spatial reconstruction of past summer temperature stretching back to 750 CE. This work extends the non-spatial hemisphere mean reconstruction published by Wilson et al. (2016).

Methodologies for last millennium climate reconstructions have been extensively investigated and tested over the last two decades (Mann and Rutherford, 2002; Rutherford et al., 2003; Zorita et al., 2003; von Storch et al., 2004; Esper et al., 2005; Mann et al., 2005, 2007; Li et al., 2010; Lee et al., 2008; Smerdon et al., 2008, 2010, 2011; Wang et al., 2015; Smerdon and Pollack, 2016). However, neither reduced space, empirical orthogonal regression methods (c.f. Fritts, 1991; Cook et al., 1994; Mann et al., 1998) nor most variants of regularized expectation maximization (RegEM Schneider, 2001; Rutherford et al., 2003; Mann et al., 2009) explicitly consider the location of the proxies relative to the