A 1500-year reconstruction of annual mean temperature for temperate North America on decadal-to-multidecadal time scales

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14 December 2012
Accepted for publication 26 March 2013
Published 11 April 2013
Online at stacks.iop.org/ERL/8/024008

Abstract

We present two reconstructions of annual average temperature over temperate North America: a tree-ring based reconstruction at decadal resolution (1200–1980 CE) and a pollen-based reconstruction at 30 year resolution that extends back to 480 CE. We maximized reconstruction length by using long but low-resolution pollen records and applied a three-tier calibration scheme for this purpose. The tree-ring-based reconstruction was calibrated against instrumental annual average temperatures on annual and decadal scale, it was then reduced to a lower resolution, and was used as a calibration target for the pollen-based reconstruction. Before the late-19th to the early-21st century, there are three prominent low-frequency periods in our extended reconstruction starting at 480 CE, notably the Dark Ages cool period (about 500–700 CE) and Little Ice Age (about 1200–1900 CE), and the warmer medieval climate anomaly (MCA; about 750–1100 CE). The 9th and the 11th century are the warmest centuries and they constitute the core of the MCA in our reconstruction, a period characterized by centennial-scale aridity in the North American West. These two warm peaks are slightly warmer than the baseline period (1904–1980), but nevertheless much cooler than temperate North American temperatures during the early-21st century.

Keywords: temperature, tree ring, pollen, North America, medieval climate anomaly, Little Ice Age

1. Introduction

Growing concern about ongoing and projected climatic change raises questions about anthropogenic forcing of the climate system and the amplitude of its response. Improving our understanding of the climate system’s sensitivity and its natural variability requires a longer time frame than instrumental data alone can offer. Moreover, knowledge of pre-industrial climate conditions is important to distinguish between anthropogenic and natural drivers of climatic variability. Proxy climate records, derived from geological, biological, and documentary archives, have therefore been...
developed to reconstruct past climate at a wide range of spatial and temporal scales. Due to the high density of available high-resolution climate proxy records and boundary conditions that are comparable to the present, the Late Holocene (here defined as the most recent ∼2000 years) has been the focus of an ever-growing body of paleoclimate research (e.g., Wanner et al 2008, Jones et al 2009).

Hemispheric or global average temperature variability has been a dominant recent focus of Late Holocene climate reconstructions using high-resolution proxy records (e.g., Mann et al 2009, Frank et al 2010). In general, the last 2000 years depict four contrasting periods before late-19th to early-21st century times: the Roman Warm Period (RWP; about 0–400 CE), the Dark Ages Cool period (DAC; about 400–700 CE), the medieval climate anomaly (MCA; about 800–1200 CE), and the Little Ice Age (LIA; about 1300–1850 CE). Our study explores climate over the last 2000 years, but the reader is referred to the chapter on paleoclimate in the 2007 Intergovernmental Panel on Climate Change assessment report (IPCC AR4; Jansen et al 2007) and references therein) for a more complete overview of the Holocene and earlier paleoclimate history.

The LIA has been studied extensively and recent studies have hypothesized that this relatively cool period was more or less homogenous in space and time across the globe (Mann et al 2008, Kaufman et al 2009, Mann et al 2009, Christiansen and Ljungqvist 2012, Ljungqvist et al 2012), although its start appears to have been temporally offset in different sub-continental regions (cf Wahl et al 2012, PAGES2K_consortium 2013). The spatio-temporal coherency of the two earlier warm periods (RWP and MCA) and cool DAC remains a topic of extensive scientific debate (e.g., Bradley et al 2003, Berglund 2003, Diaz et al 2011). Moreover, amongst these earlier periods, the well-documented MCA has been proposed as a benchmark period for distinguishing between natural and anthropogenic forcings. This has recently encouraged several independent large-scale regional climate proxy syntheses and modeling studies aimed at unraveling the dynamics behind the regional climate patterns reconstructed during the MCA (Graham et al 2007, Mann et al 2009, Trouet et al 2009, Graham et al 2011).

The development of more regional-scale temperature reconstructions covering the last 2000 years is needed to address the spatio-temporal patterns of the RWP, DAC, MCA, and LIA (IPCC 2007). Following the IPCC AR4 recommendations, this has been one of the main objectives set by the science and implementation strategy of the Past Global Changes (PAGES) Programme of the International Geosphere Biosphere Programme (IGBP), summarized in IGBP Report 57 under Focus 2, ‘Regional Climate Dynamics Theme 2’.

In this study, we describe an effort to produce a long (∼480–1980 CE) annual temperature reconstruction for temperate North America at decadal-to-multidecadal resolution by combining tree-ring records with a network of fossil lake pollen sites across most of North America. Tree-ring records have annual resolution, and provide absolute dating, but long-lived (500+ years) temperature-sensitive trees are largely restricted to the western half of the continent. Climate-sensitive pollen records can be used to extend tree-ring-based temperature reconstructions back in time, but they are often limited in temporal resolution (decadal- to centennial-scale) and can be affected by age model uncertainty and therefore do not generally allow direct calibration against high-resolution instrumental records.

In the following, we describe the methodology used to combine these two types of data sets to develop our temperate North America temperature reconstructions, offer a discussion of the main characteristics of our reconstructions, and compare our results with other studies of regional and hemispheric-scale temperature reconstructions.

2. Data and methods

We applied a three-tier calibration scheme to allow for temperature calibration of the pollen records that were sampled at a 30 year resolution: a tree-ring-based reconstruction (1200–1980 CE) was calibrated against instrumental annual average temperatures on (1) an annual and (2) a decadal scale; this was then reduced to a significantly lower resolution using a ∼110 year LOWESS smoothing algorithm and sampled at the same 30 year time step as the pollen-based data; and (3) used as a calibration target for the pollen-based reconstruction. All reconstructions are expressed as anomalies from a 1904–1980 reference period.

2.1. The high-resolution (interannual to decadal scale) series

For the high-resolution component of the reconstruction, we combined two semi-independent tree-ring data sets (with
approximately 30% overlap in contributing series; figure 1). A first set (table 1) includes chronologies from sites in an area of western mid-latitude North America bounded by 30°–55° N, 95°–130° W, with one additional chronology in west-central Mexico (see also Wahl and Smerdon (2012) for details). The proxy records in this data set were calibrated and validated at an interannual scale using the HadCRUT3v 5° × 5° gridded surface annual temperature data for the selected region for the period 1875–1980 CE (Wahl and Smerdon, 2012), cf SOM. The resulting annual temperature reconstruction, hereafter referred to as WS12, covers 1500–1980 CE for the western temperate region of North America, illustrated in figure 1 (portion of solid-outlined region west of dashed line at 95°W). We used a second tree-ring data set to extend the original WS12 reconstruction back in time (1200–1987 CE); this second proxy set included records over a wider area of North America (figure 1; data and metadata available as part of the PAGES 2K Temperature Synthesis data set at www.ncdc.noaa.gov/paleo/ paleo.html, PAGES2K_consortium 2013). It was calibrated and validated in the same manner as WS12 over the period 1850–1987 using the Mann et al. (2009) in-filled version of the same instrumental record (PAGES2K_consortium 2013, cf supplementary online material (SOM)), allowing gridded information in the third quarter of the 19th century to be employed for validation that was not available when the WS12 reconstruction was developed. The resulting reconstruction is hereafter referred to by the term ‘1200-on’.

The WS12 and 1200-on time series are well validated, with \( r^2 \)-values between spatially averaged instrumental and reconstructed values over the validation period of 0.423 and 0.421, respectively, and differences between instrumental and reconstructed validation period spatially averaged temperatures of −0.022°C and 0.013°C, respectively (relative to mean values of −0.352 and −0.258, respectively). The 1200-on time series, however, exhibits lower skill (here evaluated using reduction of error (RE) and coefficient of efficiency (CE) statistics; Cook et al. 1994), particularly at the grid-scale level, than the shorter WS12 reconstruction. WS12 exhibits validation grid-scale RE, spatial-mean RE, and spatial-mean CE of 0.40, 0.62, and 0.42, respectively, while the 1200-on reconstruction exhibits 0.13, 0.53, and 0.31 for the same measures. Decreasing reconstruction skill has previously been noted for other reconstructions that use sequentially nested calibrations as a function of record length back in time (e.g., Cook et al. 2004). We thus used WS12 as the reconstruction for 1500–1980 and joined the 1200-on reconstruction to it to cover the period 1200–1499. To ensure comparability across the splice at 1500, we regressed WS12 onto the 1200-on reconstruction over the 1500–1980 period, and then used this regression and the 1200-on reconstructed values to fit (scale) WS12-consistent values for the western spatial mean of the target region (west of the dotted line in figure 1) during 1200–1499. Annual detail and comparison of the WS12 and 1200-on reconstructions is provided in the appendix.

For reconstruction at the decadal scale, a larger area of temperate North America, extending from 75° to 130° W over the same latitudinal range (figure 1), is considered an appropriate regional target, as indicated by the spatial

### Table 1. Reconstruction and calibration characteristics.

| Reconstruction | Period (CE) | Resolution | Calibration target | Calibration period (CE) | Region          |
|----------------|-------------|------------|--------------------|-------------------------|-----------------|
| WS12           | 1500–1980   | Annual     | HADCRUT3v          | 1875–1980               | 30°–55° N, 95°–130° W |
| 1200-on        | 1200–1987   | Annual     | HADCRUT3v (infilled) | 1850–1987               | 30°–55° N, 95°–130° W |
| D1200          | 1200–1980   | Decadal    | HADCRUT3v (infilled) | 1850–1980               | 30°–55° N, 75°–130° W |
| NAM480         | 480–1950    | Tri-decadal| D1200              | 1200–1950               | 30°–55° N, 75°–130° W |
correlation maps between the decade-averaged spatial-mean time series of WS12 and 1200-on and decadal averages of the instrumental annual temperatures for each grid box (figure 2). These correlations indicate that the western North America reconstruction captures the essential features of spatio-temporal variability in this domain over the instrumental annual-scale 1200–1980 period. Decadal averages of the spliced annual-scale 1200–1980 reconstruction were therefore used as predictors in a calibration against instrumental decadal averages of annual temperatures over the full target region (30°–55°N, 75°–130°W), for a period covering 1850–1980, with very high skill ($r^2 = 0.93$, $p < 0.01$, $n = 13$, using the in-filled instrumental HadCRUT3v data set of Mann et al (2009)). Finally, this calibration fit was used to reconstruct decadal averages of annual temperature for the entire 1200–1980 period ($n = 78$). In both the annual and decadal reconstructions, the fitted values were scaled so that their variance matched that of the target data during the fitting period. The results are shown in figure 3, where the red (blue) curves give the full (western) North American expected value (EV) reconstructions, and the black curve shows the 1850–2000 CE full North American instrumental values.

Uncertainty for the spliced reconstruction was estimated using probabilistic uncertainty ensembles ($n = 1000$) generated using bootstrapped realizations of the regression residuals for both the WS12 and the 1200-on reconstructions (cf Wahl and Smerdon 2012). All realizations were modeled to have the same autoregressive characteristics as the residuals in the original regression. The process described above to derive the EV decadal reconstructions was then repeated in a two-step Monte Carlo design across the possible combinations of five hundred WS12 and five hundred 1200-on ensemble members (500 realizations of the 1200-on reconstruction matched with each of the 500 realizations of the WS12 reconstruction). It is important to note that the probability ranges estimated by this analysis (from the percentiles of the Monte Carlo output, figure 3) are calculated for the decadal means and thus are significantly narrower than the corresponding ranges that would be expected for annual values, from theory of the standard error of the mean. The resulting average of the 95% probability ranges for each decade in the 1200–1499 and 1500–1980 periods of the decadal-scale 1200–1980 reconstruction are 0.58°C and 0.44°C, respectively, and are thus 1.3 times higher for the 1200–1499 period compared to 1500–1980.

2.2. The lower resolution (tri-decadal scale) series

In a next step, we extended the tree-ring-based decadal-scale mean annual temperature reconstruction (hereafter named D1200 for decadal-1200) back to 480 CE at a 30 year resolution using pollen data for the regions of North America indicated in figure 1. For this purpose, we performed a principal component analysis (PCA) on four regional composite temperature reconstructions (360–1950 CE; Vaiu et al 2012) that were based on a network of pollen sequences from deciduous, hardwood, boreal, and mountain eco-regions of North America (figure 1). Regional composite reconstructions using pollen sequences have been shown to increase temporal resolution and reduce dating concerns of individual site reconstructions (Vaiu et al 2006, 2012). Moreover, high-resolution varved-lake sediments confirm that low and high-frequency changes are recorded in pollen sedimentary sequences during the past 2000 years in eastern North America (Wahl et al 2012, Gajewski 1987, 1988) and continental-scale North America (Vaiu et al 2006). The prairie eco-region reconstruction for central North America was not used because its vegetation response to climate change appears mainly controlled by precipitation (Vaiu et al...
In our study, the regional mean annual temperature reconstructions were resampled at 30 year intervals to compare to D1200. For a more direct comparison to D1200, we used mean annual temperature reconstructions rather than summer temperature anomalies as in Viau et al. (2012).

The resulting PCA scores (360–1950 CE; n = 54) were then included in a stepwise multiple linear regression against D1200. For this purpose, D1200 was smoothed using a ∼110 year lowess filter and sampled every third decade to approximate the time scale and sampling resolution of the pollen-based reconstructions. Three combined PC axes explaining 87% of the common variance in the four pollen reconstructions were retained in the stepwise regression and explained 33.4% of the variance in D1200. This tri-decadal pollen-based reconstruction is designated NAM480 (for North America 480 CE).

For NAM480, uncertainty bands were estimated to reflect error due to the pollen regional reconstruction process and error in the regression model of the pollen-based time series against D1200. Regression error (1) was estimated as 1 and 2 standard error (SE) units of the regression model of the predicted y-value (D1200) for an individual predictor x (pollen-based time series). Additional uncertainty to account for the fact that the predictor (pollen-based time series; x) variables are effectively probabilistic estimates of the true population of x values (2) was estimated based on the ISE and 2SE limits for the four contributing regional pollen-based reconstructions. The SEs for the regional reconstructions were developed using a Monte Carlo resampling technique that generated random pollen-based reconstructions by sampling values at each time step of the individual pollen-based series within their uncertainty limits (Viau et al. 2006). This process was repeated 10,000 times to generate the regional reconstruction uncertainty bands. These uncertainty bands were then entered into the previously developed PCA and multiple linear regression equations to determine the component of the overall 1SE and 2SE uncertainty limits that was inherent to the regional pollen-based reconstruction method.

Further additional uncertainty due to the related fact that the predictand (D1200; y) variables are similarly probabilistic estimates of the true population of y values (3) was estimated by the SE of the smoothed predictand time series. For this purpose, a ∼110 year lowess filter was applied to each of the 250,000 ensemble members of the D1200 reconstruction (see uncertainty calculation description in section 2.1). Estimated standard deviations were then calculated across the ensemble members for each decade, and averaged over the entire reconstruction period (1200–1980). Finally, the squares of the three (assumed independent) errors were added and the square root of this sum was taken as an estimation of total error. Due to the resampling of the regional pollen-based reconstructions at 30 year intervals (for comparison to D1200), reliable SE uncertainty bands were only available from 480 CE onwards, leading us to truncate our reconstruction at this date.

3. Results and discussion

We developed two reconstructions of annual average temperature over temperate North America: a tree-ring-based reconstruction that is presented at decadal resolution and covers the period 1200–1980 CE (D1200; figure 3) and a pollen-based reconstruction sampled at a 30 year resolution that extends back to 480 CE (NAM480; figure 4). We maximized reconstruction length by applying a three-tier calibration scheme to long but low-resolution pollen records. This approach allowed us to provide a temperature calibration for the pollen records, for which the instrumental data record provides too few data points (the period 1850–2010 only includes five 30 year periods). NAM480
Figure 5. Comparison of the tri-decadal annual temperature reconstruction for temperate North America (NAM480; this letter) with three hemispheric-scale temperature reconstructions (Mann et al. 2009, Ljungqvist 2010, Moberg et al. 2005) and one temperature reconstruction for the Arctic region (Kaufman et al. 2009) that cover the same time period. Original annual resolution reconstructions were reduced to 30 year resolution in the same way as our reconstruction (see section 2). All reconstructions are shown as deviations from a 1961 to 1990 average.

represents a reasonable calibration of the PCA time series from four regional pollen-based reconstructions against the low-frequency component of D1200 (figure 4). The smoothed/subsampled D1200 values fall nearly entirely within the NAM480 one standard error (1SE) envelope, with the exception of a peak around 1300 CE; this peak does not approach the upper 2SE uncertainty interval.

The overall amplitude for the EV’s of the two reconstructions is 1.23 °C for decadal changes in D1200 and 0.55 °C for multidecadal changes in NAM480. We compared NAM480 to three high-resolution hemispheric-scale temperature reconstructions (Moberg et al. 2005, Mann et al. 2009, Ljungqvist 2010) and one temperature reconstruction for the Arctic region (Kaufman et al. 2009) that cover the same time span (500–1980 CE for Mann et al. 2009, 480–1980 CE for the other reconstructions). For this purpose, we reduced the resolution of the original annual (decadal for Kaufman et al. (2009) and Ljungqvist (2010)) time series to tri-decadal resolution using the same approach that we applied to D1200: annual values were averaged over 10 year periods, smoothed with a 110 year lowess filter, and then every third decade was selected for comparison (figure 5). We found that the overall EV amplitude for tri-decadal changes in NAM480 is lower than the amplitude in the other reconstructions (ranging between 0.66 °C for Ljungqvist (2010) and 0.74 °C for Kaufman et al. (2009)), but falls within the range of amplitudes reported for annual resolution hemispheric-scale temperature reconstructions over the last millennium (ranging from 0.4 °C in Mann et al. (1999)) to 1 °C in Esper et al. (2002), see also Esper et al. (2012)).

The 19th century is the coldest period in both D1200 and NAM480. The warmest period in D1200 is the early 14th century, but it is worth noting that this is the warm peak that falls outside of the 1SE envelope of NAM480 (figure 4). The 9th century is the warmest century of NAM480, closely followed by the 11th century. EV warm peaks in NAM480 and D1200 are slightly warmer than the baseline period (1904–1980), but nevertheless much cooler than North American temperatures during the most recent 30 years and the early 21st century in particular (figure 4), which are outside the estimated upper 2SE range over the entire reconstruction period. A related analysis of WS12 (Wahl and Smerdon (2012), cf SOM) finds that recent (1986–2005) temperatures in temperate western North America are not exceeded by any member of an ensemble of 462 000 bidecadal means for the period 1500–1980 CE (1000 reconstruction ensemble members times 462 sequential 20 year periods between 1500 and 1980), and thus very likely represent the warmest bidecadal average during the past 500 years, conditional on the method of uncertainty ensemble generation. The EV temperature differences between the coldest periods in NAM480 (1845–1875) and D1200 (1810–1849) and the most recent 30 year period (1970–1999) are 0.86 °C and 0.73 °C, respectively; similar and very close, respectively, to the difference of 0.7 °C found by Frank et al. (2010) in a comparable, ensemble-based analysis of 521 estimates of hemispheric-scale temperature variability over the last millennium (with their coldest period being 1601–30).

Both of our reconstructions show an overall cooling trend over the last millennium until 1900 CE, which is reflected by the negative slopes of linear regressions with rates of −0.32 °C ka⁻¹ (D1200; 1200–1900 CE) and −0.34 °C ka⁻¹ (NAM480; 1000–1900 CE; cf PAGES2K consortium 2013).
This millennium-scale cooling trend is possibly related to orbital forcing (Berger and Loutre 1991), and is visible in regional late Holocene temperature reconstructions for all continents except Antarctica (PAGES2K_consortium 2013) but is particularly evident (>0.3°C ka⁻¹) in temperature reconstructions from high-latitude Northern Hemisphere regions (Kaufman et al 2009, Esper et al 2012, PAGES2K_consortium 2013). The start date of NAM480 is too recent to capture warmth during the RWP (0–400 CE) and this is likely one of the reasons why the cooling trend in this record is not as strong compared to high-latitude temperature reconstructions over the last two millennia (Esper et al 2012).

Before late-19th to early-21st century times, there are three prominent low-frequency periods in our extended reconstruction starting at 480 CE, notably the cooler DAC (about 500–700 CE) and LIA (about 1200–1900 CE), and the warmer MCA (about 750–1100 CE). Cool temperatures during the DAC have been recorded at the hemispheric-scale (figure 5) and were accompanied by falling lake levels in the British Isles (Charman et al 2006), dry conditions in various tropical monsoon regions (Gupta et al 2003, Wang et al 2005, Shanahan et al 2009), and by political turmoil and social upheaval over large parts of Europe (Berglund 2003, Buntgen et al 2011). Our reconstruction suggests that North American temperatures were also cool during this period (figure 4) and thus supports the global extent of this cold period and a possible link to an explosive, near-equatorial volcanic eruption in 536 CE (Larsen et al 2008), though it is unlikely that a single eruption would have been the sole causal factor for the DAC.

Temperatures over temperate North America increase after the 7th century and reach warm peaks around 850 and 1050 CE (figure 4). Peak warmth during the 9th through 11th centuries can be found in the hemispheric-scale reconstructions by Mann et al (2009), Ljungqvist (2010) and correspond at a regional scale to intense droughts in the American West, as recorded in tree-ring records from a network of living and dead trees (Cook et al 2004) and from tree stumps rooted in present-day Mono Lake, California (Stine 1994). The 11th century warmth in particular is well represented in other large-scale temperature reconstructions (figure 5) and this was also the warmest period on record in an ensemble-based analysis of northern hemisphere temperature variability that did not extend back in time beyond 1000 CE (Frank et al 2010). These three warm centuries constitute the core of the MCA in our reconstruction, a period characterized in North America by potential anomalous continental summer ridging in the Midwest (Wahl et al 2012) and centennial-scale aridity in the West (Cook et al 2004, Woodhouse 2004). Anomalous MCA climate conditions and their impacts on ecosystems in North America have been recorded in an array of lacustrine and terrestrial proxies (Gajewski 1987, see Graham et al 2007 for an overview). North American Medieval drought and warmer conditions form the regional expression of a global-scale MCA climate configuration (Seager et al 2007, Graham et al 2011, Landrum et al 2013) that is hypothesized to have involved a feedback mechanism between a La Niña-like state of the tropical Pacific (Cobb et al 2003, Mann et al 2005, Graham et al 2007, Emile-Geay et al 2008, Mann et al 2009), a prolonged tendency towards positive-phase North Atlantic Oscillation (NAO) phase (Trouet et al 2009), and an enhanced Atlantic Meridional Overturning Circulation (AMOC; Knight et al 2005, Seager et al 2007, Delworth and Greatbatch 2000, Trouet et al 2012).

Distinctively cooler conditions are already occurring by the early 13th century, and the final relaxation from this particular ocean–atmosphere state into the LIA occurs in NAM480 roughly around 1350 (figure 4). This latter timing corresponds generally with a climatic shift recorded in a wide variety of North American proxies reflecting hydroclimatic conditions (Hughes and Graumlich 1996, Hughes and Funkhouser 1998, Cook et al 2004), wildfire occurrence (Swetnam 1993, Trouet et al 2010), and sea surface temperature (Kennett and Kennett 2000) variability. The timing of the MCA–LIA transition in NAM480 also corresponds to a transition period in hemispheric-scale temperature reconstructions (figure 5). Small differences in the transition timing between records may reflect dating uncertainty and decreasing sampling and temporal resolution of individual records. However, the widespread signature of this climatic shift suggests that changes in tropical sea surface temperatures (SSTs) were involved (Seager et al 2007, Graham et al 2011). Model simulations suggest that this climatic shift between the MCA and LIA could be related to an externally driven change in radiative forcing (Shindell et al 2003; Vaquero and Trigo 2012) or may have occurred in combination with internal variability of the ocean–atmosphere system (Goosse et al 2012, PAGES2K_consortium 2013).

In this study, the MCA–LIA transition (centered on the 14th century) is the period when our two reconstructions D1200 and NAM480 diverge most: cold temperatures prevail in the pollen-based NAM480 record from 1200 CE onwards, whereas the late 13th and early 14th century is the warmest pre-20th century period of the tree-ring-based D1200 record (figure 4). Divergence between the records is however of limited extent (D1200 generally does not exceed the NAM480 1σE uncertainty bands) and may potentially be explained by the difference in the regions of origin of the two proxy archives (figure 1). The majority of tree-ring records in D1200 originate in the North American West, where long-lived trees are relatively abundant and where pollen records are sparse. Previous studies (Douglas 1929, Stine 1994, Ni et al 2002, Woodhouse 2004, Cook et al 2007) have demonstrated that the late 13th century was a period of severe drought (implying warm summer temperatures; Wahl et al 2012) in the American Southwest. This ‘Great Drought’ (Douglas 1929) extended across large portions of the western United States (Woodhouse 2004, Cook et al 2007), but its signal was likely not dominant in the broader region covered by the pollen records of NAM480. This is an interesting area for further research in North American last two millennia paleoclimatology, and in particular in relation to the joining of pollen-derived and tree-ring-derived paleoclimate data.

The common cool period LIA in our reconstructions roughly covers 1350–1900 CE and its cold peak occurs in the
19th century in both records (figure 4). The 19th century is a well-documented cool period on both regional (particularly in Europe and North America; Briffa et al. 1992, Lamb 1995, Trigo et al. 2009) and northern hemispheric scales (Jones and Mann 2004; see also figure 5). A combination of anomalously strong volcanic activity (Cole-Dai et al. 2009, Chenoweth 2001, Crowley 2000), continued orbital cooling (Kaufman et al. 2009, Esper et al. 2012), and low solar irradiance (the so-called Dalton minimum; 1790–1830; Lean et al. 1995, Mann et al. 1998) likely contributed to this global-scale cooling event (PAGES2K consortium 2013, cf. figures 3 and 4).

In many hemispheric-scale temperature reconstructions (Moberg et al. 2005, Mann et al. 2009, Frank et al. 2010, Ljungqvist 2010), the 19th century cool anomaly is exceeded in amplitude by coldness in the 16th and/or 17th century. Only a few of these reconstructed 16th–17th century temperatures (e.g., Moberg et al. 2005) fall outside of the 2SE uncertainty range of NAM480 and a comparison between D1200 and other continental-scale temperature reconstructions generates no notable differences for this period (figure 3 in PAGES2K consortium 2013). Nevertheless, both NAM480 and D1200 represent generally higher temperatures during the 16th and 17th centuries than the hemispheric-scale and Arctic region reconstructions (figure 5). A possible explanation for relatively high temperatures during this period, likely associated with warmer than usual summer conditions during this period, is the 16th century mega-drought, a remarkably widespread and persistent period of drought in the late 16th century (Woodhouse and Overpeck 1998). Drought conditions during this period, likely associated with warmer than usual summer temperatures, were widespread and their spatial coverage included northern Mexico, British Columbia, and eastern coastal US regions (Stahle et al. 2000). The atmospheric circulation patterns leading to such widespread yet regional drought and warmth remain to be explored (Woodhouse 2004).

4. Conclusion

A multi-proxy approach, in which tree-ring data were calibrated against instrumental temperature data and in turn used as a calibration target for lower-resolution pollen data, allowed us to develop an annual temperature reconstruction that extends back to 480 CE and spatially covers the majority of temperate North America. Three prominent low-frequency periods (DAC, MCA, LIA) are evident in our reconstruction that are also reflected in other continental (PAGES2K consortium 2013) to hemispheric-scale temperature reconstructions around the globe. Discrepancies between the two reconstructions (e.g., 13th–14th centuries) and between our reconstructions and other temperature reconstructions (e.g., 16th century) can potentially be explained by the presence of regional-scale droughts. The increased spatial and temporal coverage provided by this multi-proxy reconstruction contributes to our improved understanding of natural climate variability in the context of future anthropogenic impacts on North American climate.

Acknowledgments

This study was conducted in the framework of the Past Global Changes (PAGES) Programme of the International Geosphere Biosphere Programme (IGBP). Support for PAGES activities is provided by the US and Swiss National Science Foundations and by the US National Oceanographic and Atmospheric Administration.

Appendix. WS12 and 1200-on reconstructions—detail and comparison

The figures below show the annual reconstruction values for WS12 (figure A.1) and the 1200-on reconstruction (figure A.2), and comparison of the 1200-on reconstruction to the 95% reconstruction uncertainty range of WS12.

![Figure A.1. Temperate North America WS12 reconstruction (30°–55°N by 95°–130°W; 1500–1980).](image-url)
Figure A.2. Temperate North America 1200-on reconstruction (30°–55°N by 95°–130°W; 1200–1980).

Figure A.3. Temperate North America 1200-on reconstruction (30°–55°N by 95°–130°W; 1500–1980).

during their period of overlap (1500–1980) (figure A.3). All reconstructions are for annual mean surface temperature of the defined region, 30–55°N by 95–130°W.

In each case, the 95% probability ranges estimated for each year from the Monte Carlo bootstrapping methodology used (Wahl and Smerdon 2012) is shown by light shading that corresponds to the primary color of the bootstrap median reconstruction. The heavy lines are an approximately 20 year lowess smooth. The corresponding instrumental data in figures A.1 and A.2 is shown in solid gray (calibration) and dotted gray (validation). The zero reference in each case is 1904–1980 CE.

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