



# A pollen-based reconstruction of summer temperature in central North America and implications for circulation patterns during medieval times

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## ABSTRACT

We present a reconstruction of mean summer temperature for the northern Midwest of the USA based on lacustrine pollen records from three different lakes in Wisconsin. The results suggest a relatively warm period during the earlier part of the record (~1200–1500 CE) followed by a cooler Little Ice Age (~1500–1900) and a subsequent warming to modern conditions. The reconstructed modern summer mean temperature is in good agreement with observations, and the decades of the 1930s to 1950s appear to be the warmest such period in the proxy record (through 1974).

Analyses of circulation features associated with the warmest summers in the recent climate record suggest a prevalence of continental ridging accompanied by generally dry conditions during these warm summers in the Midwest. Drought reconstruction using the Palmer Drought Severity Index (PDSI) and tree-ring records as predictors also yield relatively dry conditions in medieval times for the central US. As reported in a number of recent studies, possible forcing mechanisms include La Niña-like conditions in the equatorial Pacific and warmer than average waters in the tropical Indo-western Pacific Ocean possibly coupled to a positive mode of the AMO/NAO North Atlantic circulation pattern.

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## 1. Introduction

Many aspects of the climate prevailing during the so-called Medieval Climate Anomaly (MCA) in the western United States have been well documented (e.g., La Marche, 1974; Hughes and Brown, 1992; Graumlich, 1993; Dean, 1994; Stine, 1994; Cook et al., 2004; Salzer and Kipfmüller, 2005; Graham and Hughes, 2007), while a number of modeling studies have endeavored to provide possible mechanistic explanations for the occurrence of reconstructed climate patterns during this time (Graham et al., 2007, 2010; Seager et al., 2007). Comparatively fewer paleoclimatic studies focused on the eastern United States have been published for the nominal period of the MCA (~900–1400 CE). Some representative studies covering this period include *inter alia* Booth et al. (2006), Stahle et al. (2007), and Shuman et al. (2009). Studies focused on the western prairies and Great Plains region to the west of our study area have inferred periods of aridity with sand dune mobilization and contraction of lakes for portions of the MCA (Laird et al., 2003; Mason et al., 2004).

Recently, a number of modeling studies that have incorporated the latest information on boundary conditions for parts of the last 500–1000 years (Graham et al., 2007, 2010; Seager et al., 2007) have demonstrated strong connectivity of multi-decadal hydrologic anomalies in North America to both the Indo-Pacific and Atlantic Oceans regions.

Inferred circulation patterns from these studies suggest that the tropical Indo-Pacific was La Niña-like (i.e., with relatively cool waters in the eastern equatorial Pacific and warmer than normal waters in the western tropical Pacific and Indian Ocean) as well as a warm North Atlantic with strengthened subtropical high pressure.

Here we present a new approach to reconstructing summer (June–July–August, JJA) temperature in the northern Midwest of the USA for the last 1000 years using pollen records from three lakes in the state of Wisconsin. We also examine the possibility that circulation patterns associated with some recent extreme summers may be indicative of circulation patterns prevalent during the MCA and discuss their suitability as MCA circulation analogs.

## 2. Data and methods

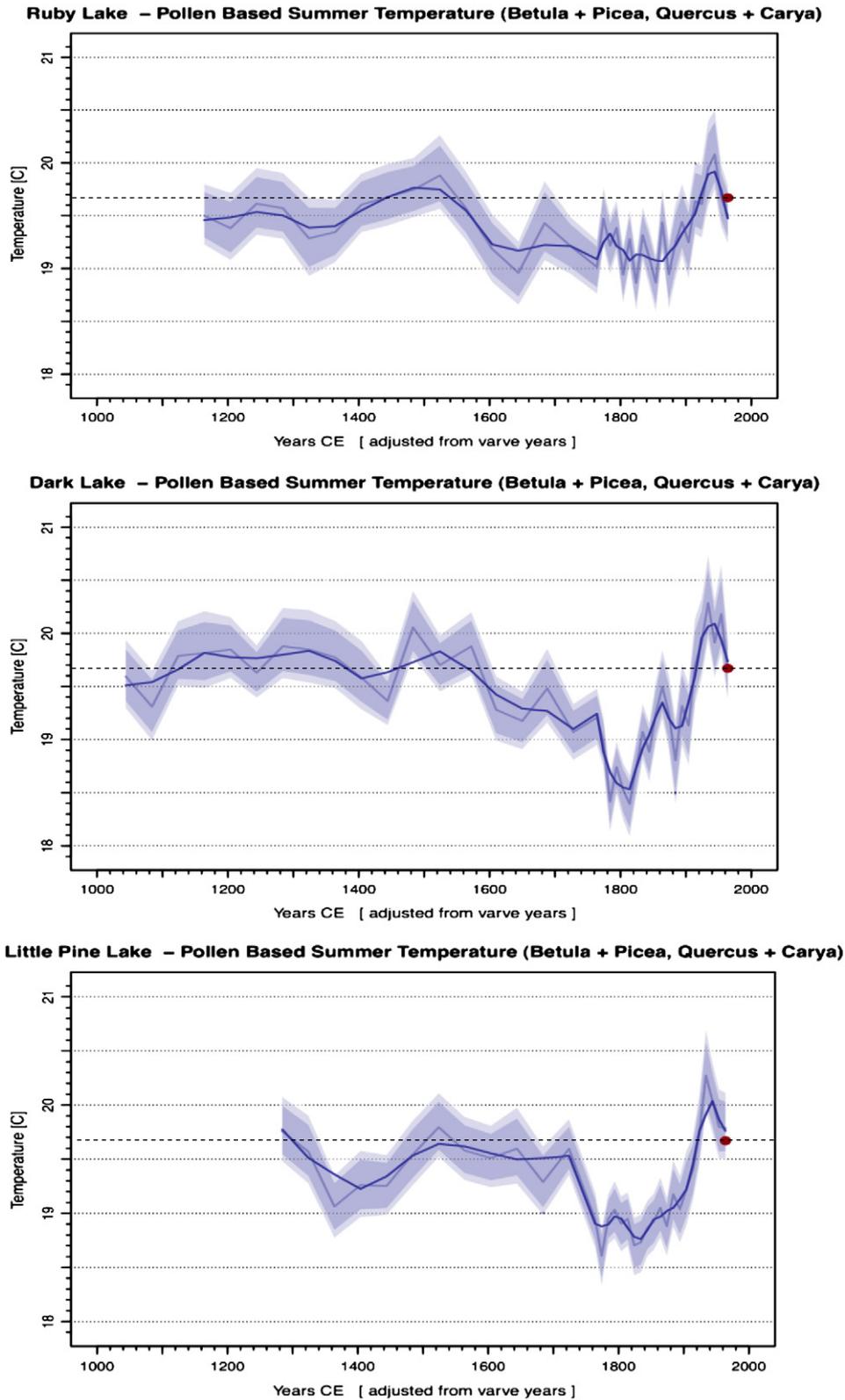
Implementation of a new version of the pollen ratio method of temperature reconstruction (cf. Adam and West, 1983) is introduced. This new approach uses an optimized selection of pollen taxa in the binomial logistic form of the generalized linear model (GLM) to estimate a pollen-climate forward relationship based on modern pollen and associated climate data in temperate northeastern North America. [The methodology used is described in Wahl et al. (2010) and the included supplementary online material (SOM), and in Ohlwein and Wahl (accepted for publication); see also Whitmore et al. (2005) for the modern pollen data and associated bio-climatic information.] The

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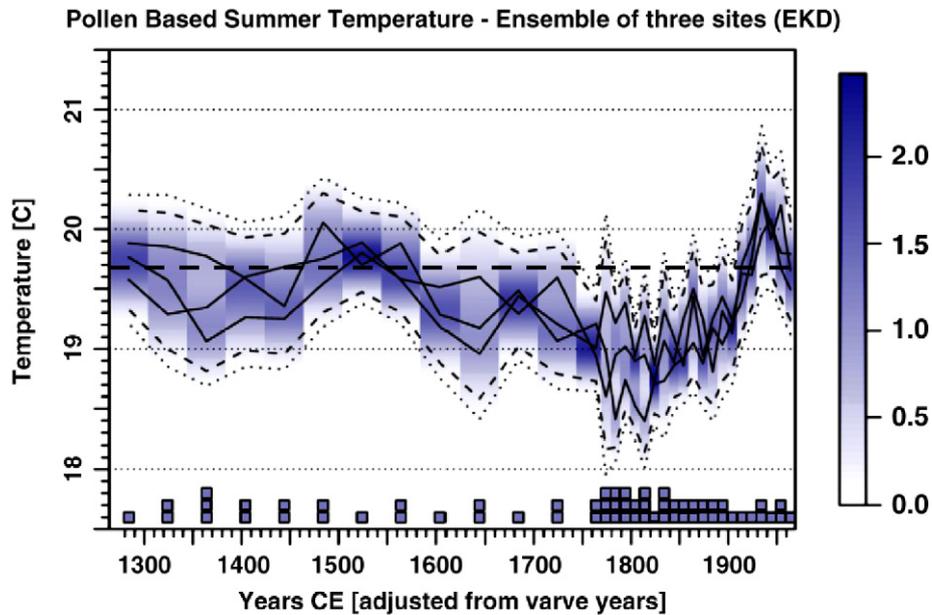
E-mail address: [Eugene.R.Wahl@noaa.gov](mailto:Eugene.R.Wahl@noaa.gov) (E.R. Wahl).

GLM model was estimated using both classical and Bayesian inference methods in the R language (R Foundation for Statistical Computing). This forward relationship was then inverted to yield expected value

(EV) reconstructions of summer temperature, based on fossil pollen assemblages. Explicit modeling of reconstruction uncertainty was done in the inverted form using a 2-way Monte Carlo framework, based on the



**Fig. 1.** Reconstruction of summer surface temperature in central North America over the past millennium (based on pollen preserved in varved sediments) at Ruby Lake, Dark Lake, and Pine Lake, WI, USA. Dark blue/light blue shading represent the 95/99% probability ranges of the reconstructions; the red dot and dashed line represent the modern long-term average (1961–1990) in the vicinity of the lakes; the smoothed line is a LOWESS fit of the ensemble median reconstruction. See appendix for details of reconstruction methods; results from the Bayesian version of the statistical model are shown.



**Fig. 2.** Estimated combined probability distribution (“mixture model”) of the reconstructions for the three sites shown in Fig. 1; the dashed line indicates the modern long-term average (1961–1990) in the vicinity of the lakes. The distribution is derived from an ensemble kernel dressing approach (EKD), described in Schölzel and Hense (2011). Darker blue/lighter blue shading indicates temperatures at which the individual lake’s reconstructions more strongly/less strongly cohere; dashed/dotted lines indicate the 95/99% probability ranges. The number of boxes along the time axis estimates the optimum number of Gaussian mixture model components for each time period reconstructed, using the Bayesian Information Criterion (BIC), which also can be seen in the relative “banding” of the dark blue/light blue shading (Ohlwein and Wahl, accepted for publication). Two or three boxes support the inference that important site-specific representation of pollen in relation to summer temperature occurs across the individual lakes, which implies that reconstruction uncertainty is underestimated at the individual sites and leads to wider estimated probability ranges in the mixture model.

binomial specification of the ratio model and the estimated distributions of the GLM parameters (assuming normality for the classically-estimated model and using the joint posterior distribution in the Bayesian model). Additional information on the GLM ratio model is provided in the Appendix A.

We used sea level pressure and 700 mb geopotential height data from the NCEP/NCAR reanalysis (Kistler et al., 2001) to consider possible circulation analogs for the MCA in North America. Instrumental temperatures used for this analysis were based on the HadCRUT3v data set

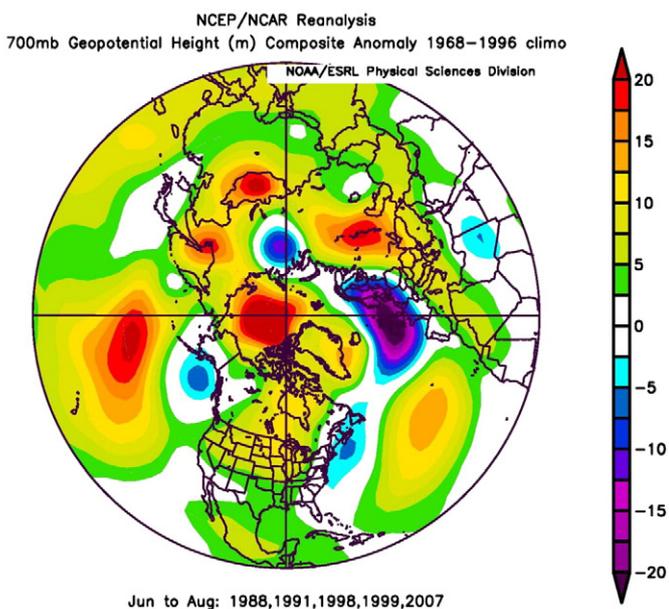
(Brohan et al., 2006) for a square comprising the four 5° grid cells approximately centered on the reconstruction area. For comparison purposes we also used a state-average temperature record for Wisconsin from the USA National Climatic Data Center (NCDC) archive to calculate average summer temperature for the period 1895–2010.

### 3. Results and discussion

#### 3.1. Paleoclimate inferences

Validated summer temperature reconstructions for the northern Midwest of the United States (western central Wisconsin) were developed with the inverted GLM ratio method from three absolutely dated (varved) lake basins (Gajewski et al., 1985; cf. Gajewski, 1988); these are shown in Fig. 1, based on the Bayesian estimation of the GLM model. For these three basins, the modern summer temperature climatology values (1961–1990; from Whitmore et al. (2005)) are well inside the 95% probability ranges of the inversion reconstructions, which constitutes a minimum validation test for the reconstruction methodology (cf. Fig. 1). Where also feasible (i.e., where both the numerator-specific taxa, *Betula* and *Picea*, and the denominator-specific taxa, *Quercus* and *Carya*, were present above trace levels so the model could be reasonably employed), the inverted GLM ratio model was also applied to other lake basins in temperate Northeastern North America with high resolution data coverage over the past millennium. In these other lakes, the modern climatology values are far outside the 99% probability ranges from the inversion reconstructions, and therefore this information was not considered validated and was not reliable for reconstruction use. Thus, the reconstructions examined here are limited to the northern Midwest region, from the western central Wisconsin sites. Similar region-specific reconstruction success/issues using an earlier generation of pollen-based regression models are discussed by Bartlein et al. (2010), cf. sec. 2.3 therein.

The high explained deviance of the GLM model (analogous to explained variation in a standard linear model) (Wahl et al., 2010, SOM) provides reconstructions with 99% probability ranges that are



**Fig. 3.** Seven hundred mb geopotential height composite anomaly for JJA 1988, 1991, 1998, 1999, and 2007. The composite shows a distinct positive-phase NAO-type anomaly pattern over the North Atlantic.

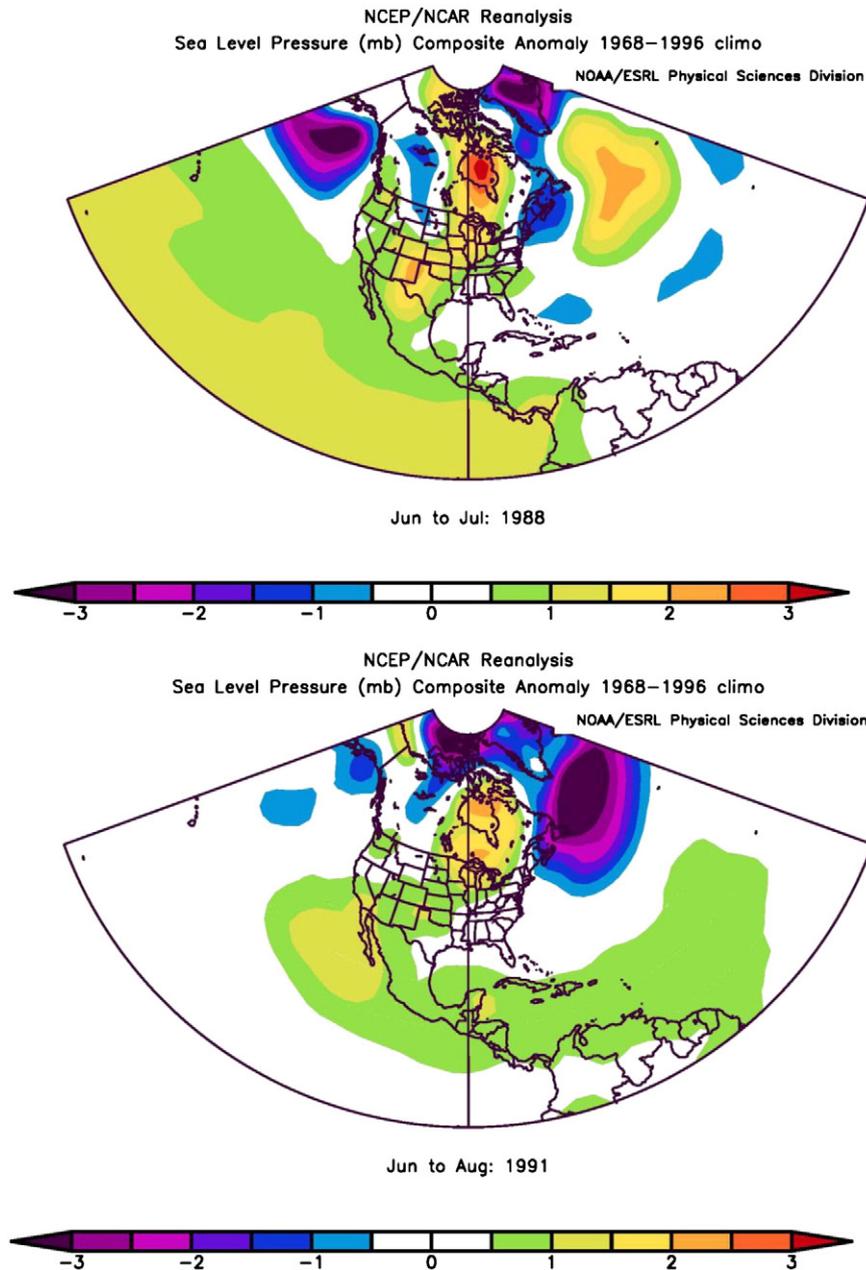


Fig. 4. Sea level pressure anomalies for the summers (JJA) of 1988 and 1991.

narrow enough to allow clear distinction of a cooler LIA in relation to earlier and later times (by  $\sim 1.5^\circ\text{C}$  [somewhat less for Ruby Lake, Fig. 1], compared to a mean 99% reconstruction probability range  $\leq \pm 0.4^\circ\text{C}$ ). The Bayesian median reconstructions are nearly identical to the EV reconstructions from the classical frequentist method, while the corresponding percentile probability ranges from the Bayesian reconstructions are somewhat narrower than those derived from the frequentist methods. The Bayesian median values and probability ranges are reported in Fig. 1.

The reconstructions from all three basins indicate a relatively late onset of the MCA–LIA transition, at approximately 1400–1450 CE, based on the assumption of a median 50–100 year lag in forest vegetation response to climate (cf. Williams et al. (2002); Webb (1986) estimates a similar lag in relation to LIA changes). However, known climatic features, such as the 1930s to 1940s warming and cooling associated with the Tambora and Krakatau volcanic explosions in the 19th century, are indicated in the pollen-based reconstruction from Dark Lake with timing nearly synchronous to the actual events

(Fig. 1); the former feature also clearly occurs in the Ruby and Little Pine Lakes reconstructions. These features suggest that the vegetation could have been responding essentially in real time in terms of pollen production to temperature variations (cf. Viau and Gajewski, 2009). If this is the case, then the inverted reconstructions would indicate a late 15th–early 16th century onset of the LIA in this region. Webb (1986) examines the effect of vegetation lagging climate on the amplitude of pollen-based climate reconstructions. These findings indicate that a lag 1/20 the length of the relevant climate event has little effect on amplitude, whereas a lag equal to the length of the climate event will profoundly impact amplitude. The evidence from Dark Lake, and for the early 20th century from all three lakes, suggests that any lag effect involved in the reconstructions reported here is likely to be less than 40 years in length (perhaps much less), and thus less than 1/10 the length of the LIA, which would indicate that amplitude loss, if present, is likely to be small. The overall interpretation based on the individual reconstructions remains essentially unchanged when ensemble post-processing methods (Schölzel and

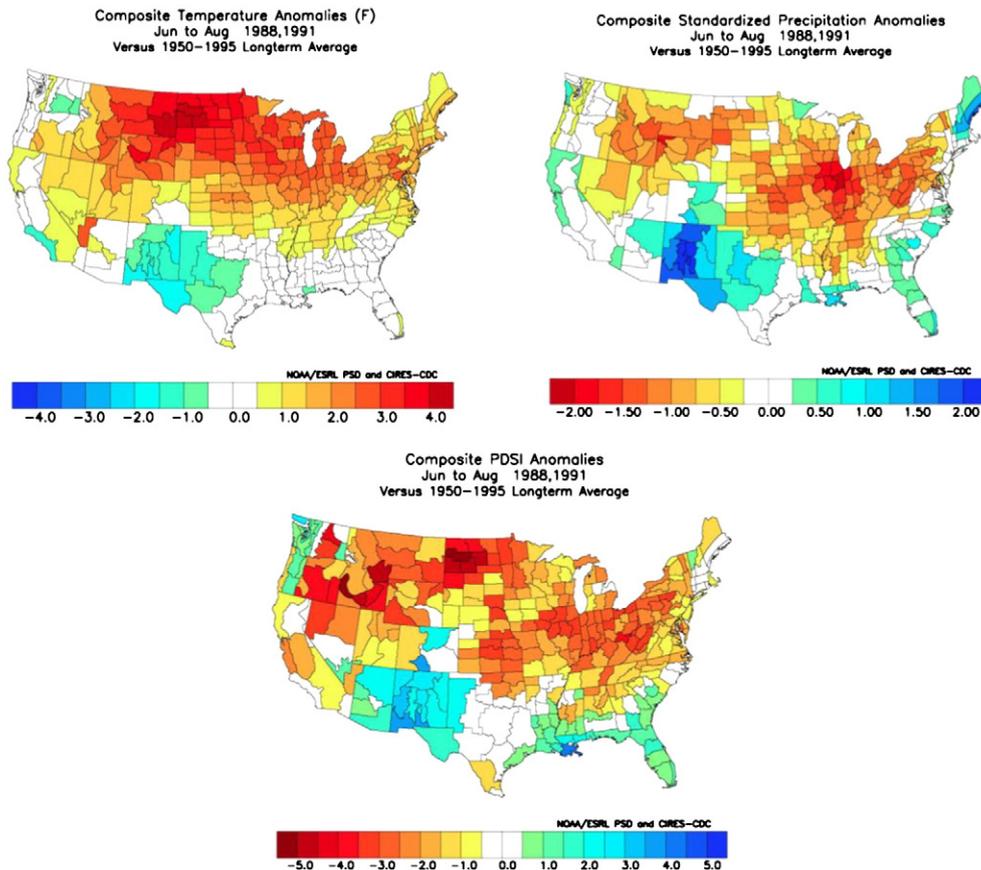


Fig. 5. Maps showing mean summer temperature anomalies (top left panel), standardized summer precipitation anomalies (top right panel), and Palmer Drought Severity Index (bottom panel) in the USA for the years 1988 and 1991.

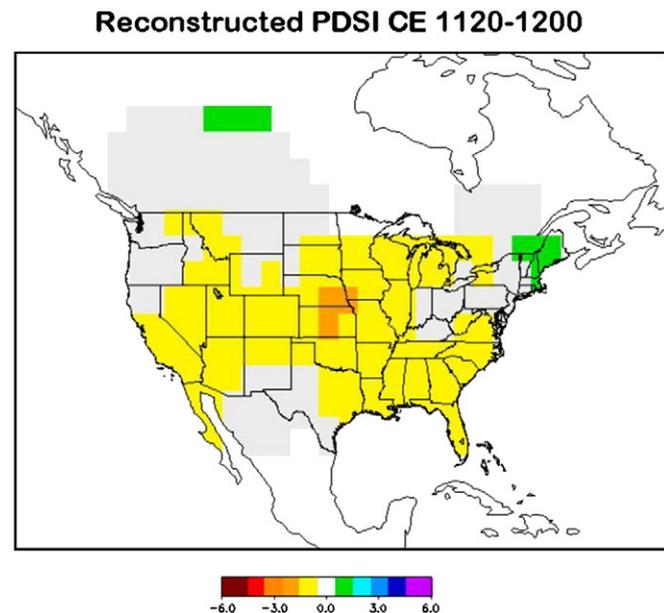


Fig. 6. Reconstructed PDSI for the period CE 1120–1200 during the MCA interval with mid-summer temperature reconstruction at Dark Lake (our longest pollen record) indicating relative warm summers in the northern Midwest of the USA. Data are from Cook et al. (2004), as updated in 2008, at NOAA's National Climatic Data Center, Paleoclimate Branch/World Data Center for Paleoclimatology (<http://www.ncdc.noaa.gov/cgi-bin/paleo/pd08plot.pl>).

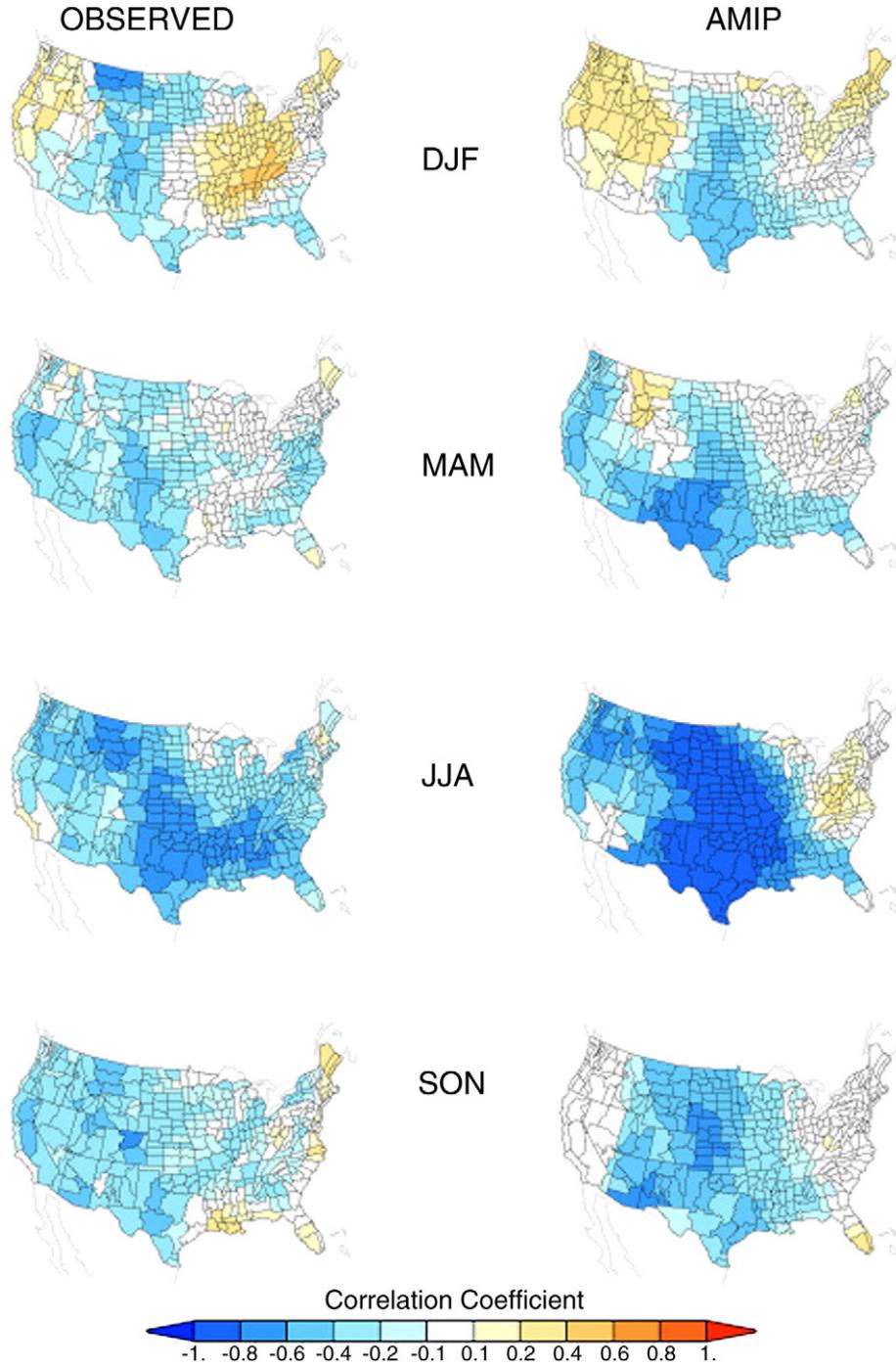
Hense, 2011) are used to combine the estimated probability distributions of the individual lakes (Fig. 2); note that the most likely excursion of LIA cooling reduces to  $\sim 1.0$  °C and the width of the overall 99% probability range expands to  $\leq \pm 1.05$  °C (generally  $\leq \pm 0.8$  °C).

Summer temperature reconstructions for the same three lakes were reported by Gajewski (1988). These reconstructions have generally similar time trajectories over the past millennium to those reported in Figs. 1 and 2 here, with somewhat less cooling during the LIA, and without accompanying estimation of uncertainty ranges. Detailed comparison of the Gajewski (1988) reconstructions with those reported here is provided in the Appendix A.

### 3.2. Connection to the larger-scale circulation

Using the 700 mb geopotential height field as input, simple composite patterns were produced as possible modern analog fields for those periods during the MCA with temperatures that are reconstructed near modern values. This analog analysis is based on the simple assumption that pressure patterns associated with modern anomalously warm summer conditions in the reconstruction region may have been similar to those that occurred during the prior warmest times in these records—the MCA period (Fig. 1, cf. Diaz and Andrews, 1982). We composited the 700 mb Northern Hemisphere geopotential height anomalies for the warmest 10 years of modern (post-1958) JJA temperatures in the reconstruction region. One-half of the modern regional warmest summers are associated with a composite pressure anomaly pattern that is quite similar to a positive phase of the North Atlantic Oscillation (NAO) (Figs. 3 and 4). The other half of the modern warmest summers is associated with a variety of other circulation configurations, including some negative NAO-like patterns. This variation of summer

## Seasonal Temperature / Precipitation Relationship



**Fig. 7.** A comparison of the spatial patterns of correlation between seasonal temperature and precipitation for (left panels) the observed fields, and (right panels) simulated fields (see text). Graph courtesy of Jon Eischeid (NOAA/ESRL-CIRES).

circulation pattern configurations is also indicated by [Fereday et al. \(2008\)](#); see also [McCabe et al. \(2004\)](#).

More generally, using a sophisticated cluster analysis methodology, [Fereday et al. \(2008\)](#) have linked such modern pressure anomaly patterns with La Niña-like conditions in the equatorial Pacific (cf. [Fig. 7](#) therein). Taken together, the modern analog and cluster analyses suggest that the MCA may have exhibited a tendency during summer to exhibit positive NAO and La Niña-like conditions. Such a tendency is similar to recent interpretations by [Trouet et al. \(2009\)](#) and (together with slight

warming of the tropical Indian and western Pacific Oceans) by [Graham et al. \(2010\)](#) for MCA winter conditions.

In addition, the patterns shown in [Figs. 3 and 4](#) are notable for the following. Besides indication of the presence of anomalously strong subtropical high pressure in the North Atlantic, surface pressures are also relatively high in the tropical Pacific during 1988 and 1991, in association with La Niña conditions. Higher than normal pressures, above normal temperatures and drought in interior North America were also associated with these two potential analog years ([Figs. 4 and 5](#)). [Trouet](#)

et al. (2009) and Graham et al. (2010) suggest that prevalence for anomalous ridging in interior North America during the MCA, if correct, would also likely have been associated with Midwestern drought.<sup>1</sup> Fig. 6 shows the spatial distribution of mean PDSI values reconstructed from tree-ring records (Cook et al., 2004, 2007) for the period 1120–1200 CE, reconstructed as the driest period in the last millennium in the northern Midwest, which supports this conclusion. Although these interpretations form a coherent climatological picture, it is important to caution that simple constructs related to idealized pictures of prevailing circulation patterns likely comprise only one among a number of other factors contributing to the inferred mean summer climate in this region (cf. Shinker et al., 2006).

#### 4. Discussion and summary

A reconstruction of summer temperature from pollen records extracted from several lakes in the northern Midwest is presented for much of the last 1000 years. A relatively warm MCA (~1100–1500) and cool Little Ice Age (~1500–1900) are reconstructed using a generalized linear model calibrated against modern summer temperature employing both classical and Bayesian inference methods. We consider plausible circulation “analogs” using surface and upper air composites that may have been more prevalent during the earlier compared to the later period. These “analog” patterns are shown to be consistent with circulation patterns simulated by general circulation models using generalized sea surface temperature patterns consistent with La Niña-like conditions in the tropical Indo-Pacific Ocean region. Independent reconstructions of North Atlantic circulation patterns reminiscent of positive NAO/AMO conditions are also consistent with those presented here.

While effective moisture changes are not reconstructed here, the climatic patterns that generally lead to warmer summers in the region where the lake pollen records were derived are more broadly associated with anomalous high-pressure and continental scale drought (Figs. 3–6). Furthermore, a comparison of maps of observed correlations between seasonal temperature and precipitation for the contiguous USA with those produced by AMIP simulations (forced by observed global SSTs) is consistent in showing a tendency for large scale moisture deficits in association with warmer than average temperatures (Fig. 7).

In summary, in contrast to a colder period evident from about CE 1600–1900 the early part of the reconstructed summer temperatures is comparable to the 20th century in the region of the northern Midwest of the USA. The decades of the 1930s to 1950s are the warmest period in the reconstruction record (ending in 1974 when the lake sediments were extracted), consistent with instrumental data from NCDC for the 20th century in Wisconsin (not shown), and somewhat higher than multi-decadal periods within the nominal MCA period.

#### Appendix A

##### A.1. Detail on GLM pollen ratio model

The GLM pollen ratio model used in this paper can be viewed as a refinement of the traditional pollen ratio method (cf. Adam and West, 1983). The ratio method has been known for some time to be a useful tool in pollen-based paleoclimate reconstruction, especially in situations in which one (or a few) dominant pollen type(s) in a region have a strong positive correlation with a climate variable of interest and another (or a few) dominant pollen type(s) have a strong negative correlation with the same climate variable. The binomial-logistic formulation of the generalized linear model (GLM) (Gelman et al., 2004) represents a new way to specify the ratio method, which provides a statistically, mathematically, and biophysically well-expressed structure

<sup>1</sup> The correlation between average summer temperature and total precipitation for Wisconsin in the modern record is  $r = -0.14$  (not significant at the 10% level).

for the following reasons. First, the numerators of ratios formed from Poisson distributed pollen count data (for each taxon  $P$ ) of the form  $\Sigma P_i / (\Sigma P_i + \Sigma P_j)$  are binomially distributed, conditional on the pollen sum (across taxonomic groupings  $i$  and  $j$ ). [In terms of nomenclature, the taxonomic grouping  $i$  can be called the “numerator-specific taxa” and taxonomic grouping  $j$  can be called the “denominator-specific taxa”, which are also binomially distributed conditional on the overall pollen sum.] Second, the logistic formulation of the modeled climate-to-pollen relationship is both mathematically appropriate (the ratio values are constrained by construction to be limited to the range 0,1) and physically appropriate (i.e., it is a forward model, expressing the physically correct direction of causation).

For calibration, the modern data forward model is as follows:

$r_{\text{num}} \sim \text{bin}(n, p)$ , where

$$E(r|C) \equiv p = \exp(\eta) / [1 + \exp(\eta)] \text{ and } \eta = \alpha + \beta(C).$$

Here,  $r$  is the pollen ratio defined in the prior paragraph,  $\Sigma P_i / (\Sigma P_i + \Sigma P_j)$ ;  $r_{\text{num}}$  is the ratio numerator,  $\Sigma P_i$ ;  $n$  is the ratio denominator,  $\Sigma P_i + \Sigma P_j$ ; the denominator-specific count is  $n - r_{\text{num}}$ ,  $\Sigma P_j$ ; and  $C$  is the climate value at each modern data site corresponding to a value of  $r$ . Once  $\alpha$  and  $\beta$  are estimated, which can be done using either Bayesian or classical GLM methods (Hadfield, 2010), climate reconstruction can be done by solving the GLM equations for  $C$  as a function of  $\alpha$ ,  $\beta$ , and  $p$ . This solution is

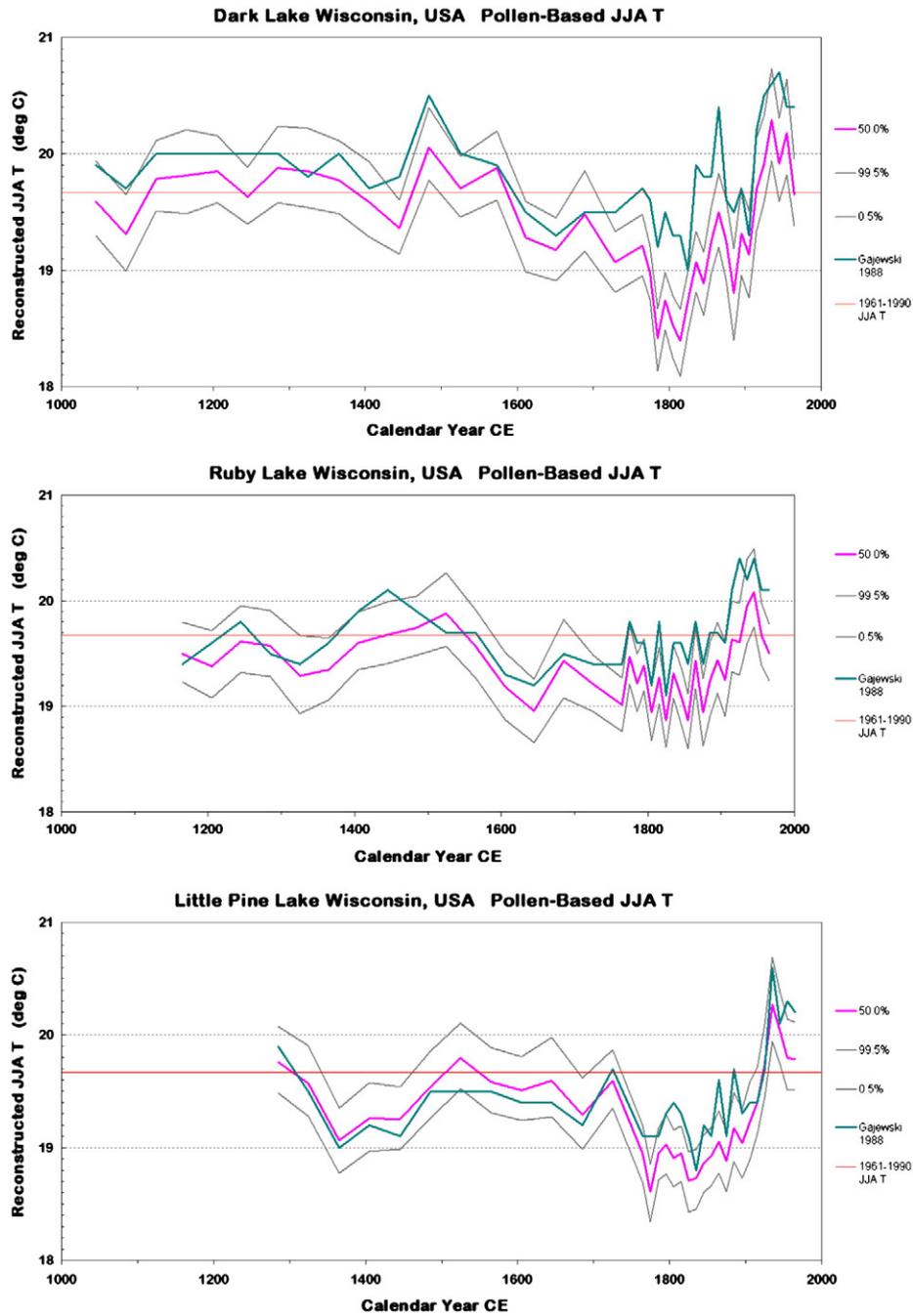
$$C = \{ \ln[p / (1 - p)] - \alpha \} / \beta.$$

It is important to note that the inversion solution is in terms of the modern values of the climate variable used to estimate the GLM, and not strictly in terms of paleo-values. To use this formula to reconstruct paleoclimate, the inversion model is re-expressed as follows: where the subscript “recon” denotes the reconstructed  $C$  value, the subscript “est” denotes an estimate for a component of the reconstruction formula, and the subscript “fossil” denotes fossil pollen information.

$$C_{\text{recon}} = \{ \ln[p_{\text{est}} / (1 - p_{\text{est}})] - \alpha_{\text{est}} \} / \beta_{\text{est}}, \text{ where } p_{\text{est}} = r_{(\text{fossil})\text{est}} \equiv r_{\text{num}(\text{fossil})\text{est}} / n_{\text{fossil}}.$$

Here, the observed  $r$  values from the fossil pollen data are assumed to be good estimators of the true fossil  $r$  value at each time step sampled, and therefore can be substituted for  $p$ . Based on this assumption, the above formula yields the estimated expected values of reconstructed paleoclimate, given the observed fossil  $r$  values and the estimated modal values for the GLM parameters  $\alpha$  and  $\beta$  (for Bayesian estimation) or estimated expected values of these parameters (for classical estimation). A 2-way Monte Carlo method for generating probability distribution envelopes around the modal/EV reconstructions employs random draws from the binomial distributions of the numerator- and denominator-specific pollen counts in the fossil  $r$ -values, in conjunction with random draws from the estimated distributions of  $\alpha$  and  $\beta$ . Further statistical description and mathematical refinement related to this uncertainty ensemble generation process is provided in Ohlwein and Wahl (accepted for publication).

[Note that the mathematical refinement mentioned, which uses the fossil numerator- and denominator-specific counts as parameters in the Beta distribution to derive random draws for  $p_{\text{est}}$ , is asymptotically equivalent to estimating random draws for  $p_{\text{est}}$  as ratios formed from random binomial draws of the numerator- and denominator-specific fossil pollen counts, which is the method utilized here.] The numerator-specific taxa used in here are *Betula* and *Picea*; the denominator-specific taxa are *Quercus* and *Carya*. Full description of determination of the taxa used in the model is provided in Wahl et al. (2010), cf. the supplementary online material, Section S1, first paragraph.



**Fig. A1.** In each plot, the gray lines represent the widths of the 99% probability ranges for reconstructed summer temperature at each lake, estimated using the methods described above for the GLM ratio model. The pink line represents the median reconstructed summer temperature from the GLM ratio model for each lake. These results are identical to those presented in Fig. 1 in the main text, only the formatting has been changed. The green line represents the expected value reconstruction for each lake from Gajewski (1988), and the thin red line represents the 1961–1990 JJA climatology for the three-lake area from Whitmore et al. (2005).

#### A.2. Comparison of reconstructions in this paper with those of Gajewski (1988)

The single-site reconstructions from the GLM ratio model shown in Fig. 1 can be compared to those reported for these sites in Gajewski (1988). Graphs of these comparisons are shown below. The Gajewski reconstruction is shown in green in each panel; the time series data come from NOAA/NCDC-Paleoclimatology/World Data Center for Paleoclimatology, at the following URL <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/pollen/recons/liadata.txt>.

These comparisons indicate that the original reconstructions by Gajewski, based on inverse model multiple regression of JJA temperature on *Betula*, *Picea*, *Quercus* and *Poaceae* (grass) pollen proportions (as reported in the original article, Table 2), are similar to those developed from the ratio model. This is especially true for the Ruby Lake and Little Pine Lake sites. The primary difference is that the 18th and 19th century values tend to be higher for the Gajewski reconstructions at Dark Lake (especially) and Ruby Lake, to the extent that they are often outside the 99% reconstruction probability envelopes of the ratio model outcomes. The 19th century Gajewski

reconstructions for Little Pine Lake show a similar characteristic to a lesser degree, as do the 20th century reconstructions for Dark and Ruby Lakes. Reconstruction of the 1961–1990 summer temperature climatology in the three-lakes area also tends to be high at each of the lakes.

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