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Temperature variations in the southern Great Lakes during the last deglaciation: Comparison between pollen and GDGT proxies

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ABSTRACT

Our understanding of deglacial climate history in the southern Great Lakes region of the United States is primarily based upon fossil pollen data, with few independent and multi-proxy climate reconstructions. Here we introduce a new, well-dated fossil pollen record from Stotzel-Leis, OH, and a new deglacial temperature record based on branched glycerol dialkyl glycerol tetraethers (brGDGTs) at Silver Lake, OH. We compare these new data to previously published records and to a regional stack of pollen-based temperature reconstructions from Stotzel-Leis, Silver Lake, and three other well-dated sites. The new and previously published pollen records at Stotzel-Leis are similar, but our new age model brings vegetation events into closer alignment with known climatic events such as the Younger Dryas (YD). brGDGT-inferred temperatures correlate strongly with pollen-based regional temperature reconstructions, with the strongest correlation obtained for a global soil-based brGDGT calibration ($r^2 = 0.88$), lending confidence to the deglacial reconstructions and the use of brGDGT and regional pollen stacks as paleotemperature proxies in eastern North America. However, individual pollen records show large differences in timing, rates, and amplitudes of inferred temperature change, indicating caution with paleoclimatic inferences based on single-site pollen records. From 16.0 to 10.0ka, both proxies indicate that regional temperatures rose by ~10 °C, roughly double the ~5 °C estimates for the Northern Hemisphere reported in prior syntheses. Change-point analysis of the pollen stack shows accelerated warming at 14.0 ± 1.2ka, cooling at 12.6 ± 0.4ka, and warming from 11.6 ± 0.5ka into the Holocene. The timing of Bølling-Allerød (B-A) warming and YD onset in our records lag by ~300–500 years those reported in syntheses of temperature records from the northern mid-latitudes. This discrepancy is too large to be attributed to uncertainties in radiocarbon dating, and correlation between pollen and brGDGT temperature reconstructions rules out vegetation lags as a cause. However, the YD termination appears synchronous among the brGDGT record, regional pollen stack, and Northern Hemisphere stack. The cause of the larger and lagged temperature changes in the southern Great Lakes relative to Northern Hemisphere averages remains unclear, but may be due to the effects of continentality and ice sheet extent on regional climate evolution.

1. Introduction and background

The last glacial termination is the most recent time period when large global temperature changes occurred in the context of rising greenhouse gas concentrations (Shakun et al., 2012; Clark et al., 2012). As such, the last glacial termination has become a key target to test the ability of models to simulate climate under boundary conditions that differ from today. This goal requires

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robust, quantitative temperature reconstructions. In eastern North America, fossil pollen records and derived late-Quaternary temperature estimates are plentiful (Webb et al., 1993; Bartlein et al., 2011; Viau et al., 2012; Shuman and Marsicek, 2016; Marlon et al., 2017); but quantitative temperature inferences from palynological records can be complicated by unrecognized shifts in the covariance structure among environmental and ecological variables over time (Jackson and Overpeck, 2000; Jackson et al., 2009; Juggins, 2013), the development and persistence of no-analog vegetation assemblages during the last deglaciation (Overpeck et al., 1992; Gonzales et al., 2009), and site-specific thresholds in environmental response functions (Williams et al., 2011). Moreover, an independent paleoclimatic framework is required to use fossil pollen records to study the responses of terrestrial ecosystems to changing climatic conditions (e.g., Jackson and Overpeck, 2000; Davis and Shaw, 2001; Webb et al., 2004; Ordonez and Williams, 2013; Blois et al., 2013).

Paleotemperature estimates independent of pollen are remarkably scarce in eastern North America, despite its long history of paleoenvironmental research. A recent synthesis of Holocene temperature records from Wyoming to Maine was based on two alkenone sea-surface temperature records and 18 terrestrial fossil pollen records, with no other reconstructions of terrestrial temperatures (Shuman and Marsicek, 2016). Similarly, a synthesis of paleotemperature and hydroclimate records from the northeastern USA for the past 3000 years reported limited availability of non-palynological proxies (Marlon et al., 2017). Geochemical reconstructions have begun to fill this gap, yet many geochemical proxies do not provide quantitative temperature estimates and often respond to multiple climatic drivers (De Jonge et al., 2014). For instance, a record of the hydrogen isotopic composition of aquatic lipids from Crooked Pond, MA, indicated changes qualitatively consistent with a steady rise in temperatures between 15 and 6ka interrupted by colder conditions during the Younger Dryas (YD) (Huang et al., 2002; Shuman et al., 2004). Shuman et al. (2006), however, interpret this isotopic record to reflect seasonal precipitation. To further complicate these issues, some isotopic records of precipitation seasonality and relative humidity from lake sediments and tree rings are partially constrained by pollen-based temperature estimates (Henderson et al., 2010; Voelker et al., 2015). Thus, we lack a well-established independent regional climatic framework for climate model tests and to interpret floral, faunal, and cultural changes in eastern North America during the last deglaciation.

In recent years, organic biomarkers have emerged as independent and complementary temperature proxies for lake sediments (Castañeda and Shouten, 2011). Of these, branched glycerol dialkyl glycerol tetraethers (brGDGTs) have shown the most promise for temperature reconstructions using sediments from lakes (Weijers et al., 2007a, 2007b; Zink et al., 2010; Fawcett et al., 2011; Niemann et al., 2012; Loomis et al., 2012, 2015; 2017). brGDGTs consist of a suite of membrane-spanning lipids produced by members of the Acidobacteria phylum (Weijers et al., 2006; Sinninghe Damsté et al., 2011), and are found in many sedimentary environments, including soils, peat, marine sediment, and lakes (Tierney and Russell, 2009; Schouten et al., 2013; Sinninghe Damsté, 2016; Weijers et al., 2006, 2007a). The chemical structure of brGDGTs varies according to fluctuations in environmental conditions, including both pH and temperature (Weijers et al., 2007a; Loomis et al., 2014a, 2014b). In particular, the degree of cyclization of branched tetraethers (CBT) has been shown to vary with soil pH, whereas the degree of methylation (MBT) has been shown to vary with pH and mean annual air temperature (MAT) (Weijers et al., 2007a; Peterse et al., 2009; De Jonge et al., 2014). Weijers et al. (2007a) used these relationships to develop calibrations for both MAT and soil pH, and the proxy has been used to reconstruct regional temperatures during the late-Pleistocene to early-Holocene in New Zealand (Zink et al., 2010), Australia (Woltering et al., 2014), Europe (Niemann et al., 2012), the southwestern United States (Fawcett et al., 2011), and Africa (Loomis et al., 2012, 2015, 2017).

No previous brGDGT-based paleoclimate reconstructions exist for eastern North America, although modern North American lacustrine sediments and soils have been included in several brGDGT-to-temperature calibration indices (Weijers et al., 2007a; Blaga et al., 2010; Peterse et al., 2012). Other calibrations omit North American sites but have been effectively used in other regions and studies (Sun et al., 2011; Pearson et al., 2011; Loomis et al., 2012). These different calibration functions for brGDGTs can produce qualitatively similar temperature reconstructions and trends for late-Quaternary sediments but often differ in magnitude (Loomis et al., 2012). Hence, brGDGTs offer a key opportunity to better constrain the deglacial temperature history of eastern North America, but need evaluation against existing proxies and assessment of which calibration index is most suitable for North American paleotemperature reconstructions.

Poor chronological constraints have also limited the understanding of deglacial climate history in eastern North America and its linkages to hemispheric and global-scale climatic evolution. Shane and Anderson (1993) reported some of the earliest evidence of millennial-scale climate reversals in eastern North America from fossil pollen records in Ohio, but their radiocarbon dates were based upon bulk sediment and could therefore be affected by hard water effects and/or redeposition of ^{14}C-depleted sources such as lignites. This is a common problem; most eastern North American palynological records were collected decades ago and have chronologies based on bulk sediment dates that can deviate by 500–2000 years from true depositional ages (Grimm et al., 2009). Hard-water and other old-carbon effects are pronounced in the Midwest, which is underlain by carbonate-rich Paleozoic sedimentary bedrock and glacial sediments derived from these rocks (Grimm et al., 2009). This has led to efforts to recore and redate classic sites to better constrain the timing of past vegetation and associated environmental events (Grimm et al., 2009; Gill et al., 2012; Liu et al., 2013; Jones et al., 2017) and to develop benchmark records (Blois et al., 2011) that can better constrain the timing of biostratigraphic events in previously published, more poorly dated records.

Even within relatively well-dated records, the timing and rates of past temperature and vegetation changes in eastern North America relative to North Atlantic records remains unclear. For instance, Gonzales and Grimm (2009) report a 300–400 year lag between the vegetation events recorded at Crystal Lake, IL, and North Atlantic climate changes recorded in ice cores from northern Greenland (NGRIP Members, 2004). The Crystal Lake record lacks an independent climate proxy, so the lag could derive from delays in the response of vegetation and/or fossil pollen to changes in climate. Some isotopic records from North American lakes show a close correspondence to North Atlantic events, including the Intra-Allerød cold period, the YD, the Preboreal Oscillation, and the 8.2ka Event (Yu and Eicher, 1998; Yu and Wright, 2001; Yu et al., 2007). However, at White Pond, NJ, isotopic and palynological signals consistently lag the timing of deglacial climatic events at Greenland by 300–400 years (Yu et al., 2007). Low sampling density can also confound estimates of the timing of past climatic and ecological events (Booth et al., 2012; Liu et al., 2012). Although these records have provided valuable information on general patterns of climate and ecological change during the last glacial termination, the scarcity of well-dated, temporally resolved, multi-proxy temperature records limits the understanding of patterns and drivers of