Environmental changes of the last 1000 years on Prince of Wales Island, Nunavut, Canada

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ABSTRACT

A pollen record from a lake sediment core from southeastern Prince of Wales Island, Nunavut, Canada (SW08; 72.3177, −97.2678, 104 m a.s.l) provides the first high-resolution July temperature reconstruction for the last 1,000 years for the central Canadian Arctic Archipelago. The vegetation underwent marked transitions during the Little Ice Age (LIA; 1500–1800 CE) and Medieval Climate Anomaly (MCA; 1090–1250 CE), which was primarily observed in the proportion of Cyperaceae, Poaceae, and Salix pollen. Cyperaceae pollen was highest in the samples corresponding to the MCA, whereas Poaceae increased during the LIA. In the last 30 years, Salix and Betula pollen increased. The mean July temperature reconstruction showed a long-term cooling from 1080–1915 CE with a sustained cold period from 1800–1915 CE prior to twentieth-century warming. A synthesis of paleoclimate records from across the Arctic demonstrates that pollen-based reconstructions record both high and low frequency climate variability, when sampling resolution is sufficient, and can improve regional climate reconstructions.

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Introduction

Although considerable progress has been made into understanding the climate of the past 2,000 years, large-scale reconstructions continue to be hindered by poor spatial coverage, dating uncertainties, and low-temporal resolution data (Christiansen and Ljungqvist 2017). These problems are especially noticeable in the Arctic because annually-resolved records (ice cores, tree rings, and varves) are spatially limited, and non-annually resolved records often lack the temporal resolution to address decadal- or centennial-scale climate variability. Consequently, there are gaps in our understanding of regional climate variability across the Arctic, particularly in the Canadian Arctic Archipelago and Siberia. Previous studies have demonstrated the value of pollen-based temperature reconstructions to understand past climate variability in the Canadian Arctic (Peros and Gajewski 2009; Gajewski 2015), but have not produced high-resolution reconstructions (<50 years between samples) for the last 2,000 years. In this study, we demonstrate that pollen-based reconstructions can capture low and high frequency variability as long as the sampling resolution is sufficiently high. Since lake sediments are the only archives available in certain regions of the Arctic, using pollen-based reconstructions can provide important information about multi-decadal to centennial climate variability from these data-poor regions.

There have been several paleoclimate reconstructions of the Common Era for the Arctic region (Overpeck et al. 1997; Kaufman et al. 2009; Shi et al. 2012; Hanhijärvi, Tingley, and Korhola 2013; Tingley and Huybers 2013; McKay and Kaufman 2014; Nicolle et al. 2018; Werner et al. 2018), but these have been primarily based on ice core, tree ring, and varve records since these can be annually-resolved. Although there are broad-scale similarities between these reconstructions, there are important differences in the timing and magnitude of the reconstructed conditions. This is due to the kinds of records used (whether they preserve all frequencies accurately), the reconstruction method applied, and the selection of sites retained for analysis. Reconstructions based solely on annually-resolved records may underestimate low frequency variability (Christiansen and Ljungqvist 2017; Cook et al. 1995; Xing et al. 2016) and are limited to specific regions of the Arctic. Pollen and chironomid...
records from lake sediments have been successfully used to reconstruct Holocene climates in northern North America (MacDonald et al. 2009; Peros and Gajewski 2009; Porinchi, MacDonald, and Rolland 2009; Rolland et al. 2009; Clegg et al. 2010, 2011; Luoto and Helama 2010; Gajewski 2015), and lakes are widely distributed; however, dating the sediments can produce large uncertainties, resulting in less precise chronologies. Varved sediments may alleviate this problem, but microfossils are frequently rare in these kinds of sediments (e.g., Courtney Mustaphi and Gajewski 2013). All of these problems have led to a sparse geographical distribution of the proxy records, particularly in Siberia and the Canadian Arctic, causing spatial underrepresentation and regional biases when attempting large-scale temperature reconstructions (Christiansen and Ljungqvist 2017).

This study presents a quantitative temperature reconstruction for the last 1,000 years from Prince of Wales Island, Nunavut, based on fossil pollen assemblages. Pollen records preserve low frequency variability with the temporal resolution of the sampling governing the high frequency variability. There are no quantitative paleoclimate records from this region, so these new data provide information about this understudied region. We also combine these results with others from the literature and describe millennial and centennial climate variability across the Arctic.

Site description

Prince of Wales Island is located in the central High Arctic, Nunavut, Canada. Lake SW08 (unofficial name; 72.3177, −97.2678, 104 m a.s.l; Figure 1) is located in a drumlin field ~20 km inland from the eastern coast of Prince of Wales Island. The lake has an area of ~128,850 m². Although the site is located primarily on sandstone bedrock, glacial activity likely deposited carbonate-rich till throughout the area (Dyke and Morris 1988). The vegetation is defined as a dry prostrate-shrub tundra (Walker et al. 2002). The nearest weather station is 275 km to the northeast in Resolute Bay, Nunavut, where the mean July temperature (1948–1980) is 4.2 ± 1.2°C (Environment and Climate Change Canada 2018).

Methods

A sediment core was extracted from Lake SW08 in July 2017 using a plastic tube fitted with a piston. The sediment-water interface was preserved in the tube by adding sodium polyacrylate, and the core was shipped back to the University of Ottawa and refrigerated at 4°C.

In the laboratory, the core was extruded and changes in stratigraphy, texture, and color were noted. Loss-on-ignition was measured at 0.5 cm intervals using a LECO Thermogravimetric Analyzer to estimate organic and carbonate weight percent. Samples throughout the core were analyzed for biogenic silica using a wet chemical digestion technique (DeMaster 1981; Parsons, Maita, and Lalli 1984; Conley and Schelske 2001). Sediment samples were digested in 1% sodium carbonate (Na₂CO₃) for 5 hours in an 85°C water bath. Subsamples were taken at 2, 3, 4, and 5 hours and analyzed using spectrophotometry. Reference samples of known BSi content were processed alongside each batch to ensure experimental control (Tamo 2019). Fossil pollen were analyzed at 0.5 cm resolution, where possible, from the top 25 cm of the core. Pollen was extracted using a heavy-liquid separation technique (Zabenskie, Peros, and Gajewski 2006). Two cubic centimeters of sediment were subsampled and two Lycopodium tablets (batch #938934; 10,678 grains/tablet) were added to enable the estimation of the absolute concentration of pollen and spores. Samples were washed in 10 percent HCl and 10 percent KOH prior to heavy-liquid separation using sodium polytungstic acid (SPT; density: 1.9 g/cm³). The samples were treated with hydrofluoric acid and acetylsalicylic acid before being transferred to vials with silicone oil (2,000 cs) for permanent storage. At least 300 grains were counted for each level, except at 0.5, 1.5, 6.0, 8.0, and 12.5 cm where pollen concentrations were too low to reach this total. In two cases, at 10.0 and 16.5 cm, there was no material left to count after processing.

Chronology

The core was dated using ²¹⁰Pb for the uppermost sediments and ¹⁴C for the remainder of the core. Eight bulk sediment samples were processed by MyCore Scientific Inc. (Ottawa, Ontario) to analyze the ²¹⁰Pb activity and ages were determined using a constant rate of supply model (CRS) (Appleby and Oldfield 1978). There was no terrestrial organic matter visible in the cores, so six 0.5 cm samples of aquatic moss fragments were sent to the André E. Lalonde Accelerator Mass Spectrometry Laboratory at the University of Ottawa for ¹⁴C analysis. The results were calibrated using OxCal v4.2.4 (Bronk Ramsey 2009) and the IntCal13 calibration curve (Reimer et al. 2013).

Numerical analyses and climate reconstruction

Arctic lake sediments contain pollen that have been transported from the boreal or other forest regions. These long-distance taxa were removed from the pollen sums prior to calculating percentages since they tend to produce a warm bias in paleoclimate reconstructions (Gajewski 2015). Three sums were calculated for the pollen stratigraphic
diagrams: (1) pollen sums based on only local and regional pollen for use in numerical analyses, (2) based on the entire assemblage (excluding *Pediastrum* and aquatic pollen) to compute the sum for all taxa, and (3) based on the entire assemblage, including aquatics and *Pediastrum*, to compare *Pediastrum* to the pollen assemblages. The pollen assemblages were analyzed using Principal Components Analysis and the scores were plotted with respect to major periods of climate variability in the Arctic (i.e., MCA (1090–1250 CE), LIA (1500–1800 CE)) to examine how the vegetation was altered during each period.

Mean July temperatures were reconstructed from the pollen data using the modern analog technique (MAT) (Overpeck, Webb, and Prentice 1985; Sawada 2006). The training set used for calibration included Arctic samples (*n* = 665, Gajewski 2015), which were obtained from the North American Modern Pollen Database (Whitmore et al. 2005). The calibration set contained local and regional taxa but excluded pollen transported from south of the Arctic (Table 1). The average of the closest three analogs was used to estimate past July temperatures, and the squared chord distance between the fossil and all modern samples was analyzed to determine if the fossil level had a good analog.

The reconstruction for Lake SW08 was compared to existing records from the Arctic 2k Database (version 1.1.1; McKay and Kaufman 2014) and from primary sources (Peros and Gajewski 2009; Courtney Mustaphi and Gajewski 2013; Lecavalier et al. 2017). For this analysis, only records that contained data between 1090 and 1960 CE and had an average sample resolution of less than 100 years were retained (*n* = 40). The new dataset prepared for this study contains 11 ice core, 18 lake sediment (eight varve, five chironomid, four pollen, and one U^{3}^{17}alkene), four marine sediment, one speleothem, and six tree ring records (Appendix Table A1). To enable comparison between records, those with non-annual resolution were interpolated to 10-year intervals and 10-year block means were calculated for records with annual resolution. Although interpolation will inflate the explained variance of statistical analyses, the dominant trends and

![Figure 1. Sites with paleoclimate reconstructions of the past 1,000–2,000 years used in this study. Lake sediment records are denoted by a circle and color-coded by proxy type. The new record from this study is indicated in red (SW08).](image-url)
relationships should be unaffected by interpolation. Each record was truncated to the common time period for which all records contained data (1090–1960 CE) then standardized by subtracting the mean and dividing by the standard deviation. Two Principal Components Analyses were performed in the program R version 3.5.1 to summarize these data (Oksanen et al. 2018; R Core Team 2018). The first (PCA1) included all sites in the database but was truncated to their common time period (1090–1960 CE). The second analysis (PCA2) was performed using only records with data covering all of the last 2,000 years (1090–2018 CE). The first PCA was performed using a Euclidean distance measure and Ward’s method of clustering (Kassambara and Mundt 2017). The second principal component identified the local and regional pollen assemblage (PCA2), while the first principal component (PCA1) was a measure of the local pollen assemblage (Kassambara and Mundt 2017).

Results

Sedimentary stratigraphy and characteristics

The sediment in core SW08 was very dark gray (10YR 3/1) in the top 7 cm (1900–2017 CE) then became mottled with dark yellowish brown (10YR 3/4) sediment until 12 cm (1650–1900 CE). From 12 to 32 cm, the sediment was uniformly dark yellowish brown (10YR 3/4). Below 32 cm, the sediment was dark grayish brown (10YR 4/2). Organic matter was low throughout the core, never exceeding 6 percent, and carbonate percentages were high, ranging between 22 and 27 percent. Nineteen samples were analyzed for biogenic silica along the core, but no values above detection were measured.

Chronology

The unsupported 210Pb activity in the uppermost sediment was 134 Bq/kg and reached the supported level of 64 Bq/kg by 3.25 cm at 1962 CE (Table 2). The six 14C dates included one anomalously old age and two age reversals at 12, 37 and 45 cm, respectively, which were excluded from age-depth modeling (Table 3). The resulting age-depth model was created by linear interpolation of eight 210Pb and three 14C dates; however, this only established a reliable chronology for the top 25 cm of the core (1082 CE). The age-depth curve (Figure 2) shows an unusually large sedimentation rate between 10 and 15 cm. Results such as this are frequently seen in Arctic sediments (MacDonald, Beukens, and Kieser 1991; Gajewski et al. 2000; Peros and Gajewski 2009) and suggest a reservoir effect due to hardwater. Following Peros and Gajewski (2009), a hardwater correction was estimated by calculating the intercept of a linear regression of the accepted radiocarbon dates. The estimated hardwater correction for core SW08 is 856 years, which was subtracted from the remaining calibrated radiocarbon dates to generate an age-depth model whose oldest date at 25 cm is 1082 CE (Figure 2).

Pollen stratigraphy

Cyperaceae, Poaceae, and Salix dominated the local and regional pollen (Figure 3). At the bottom of the core Cyperaceae pollen dominated, comprising up to 70 percent of the assemblage. The general trend of Cyperaceae was a decrease to the present, while Poaceae pollen percentages increased. Both Cyperaceae and Poaceae percentages decreased in the uppermost 5 cm (1930–2017 CE), concurrent with an increase in both Betula and Salix. Other taxa, such as Dryas, Oxyria, Papaver, and Saxifraga

Table 1. Pollen and spore taxa identified in core SW08. The local and regional taxa were used in numerical analyses. Taxa denoted with an asterisk (*) were part of the modern training set but were not found in the core.

| Local and Regional | Saxifraga oppositifolia |
|--------------------|------------------------|
| Betula             | Saxifragaceae undiff   |
| Alnus              | Salix                  |
| Ericeae            | Ranunculaceae undiff   |
| Artemisia          | Thalictrum*            |
| Caryophyllaceae    | Rosaceae undiff        |
| Chenopodiaceae     | Potentilla*            |
| Brassicaceae       | Rubus chamaemorus      |
| Asteraceae         | Lycopodium annotinum*  |
| Cyperaceae         | L. clavatum*           |
| Dryas              | Huperzia selago*       |
| Poaceae            | Lycopodium undiff      |
| Fabaceae*          | Selaginella            |
| Oxyria             | Polyodiaceae*          |
| Papaver            | Equisetum              |
| Pedicularis*       | Sphagnum               |

Table 2. 210Pb results and ages based on constant-rate-of-supply (CRS) (Appleby and Oldfield 1978) model. The supported activity for all samples was 64.0 Bq/kg.

| Depth (cm) | Unsupported Activity (Bq/kg) | CRS Error (years) |
|------------|-----------------------------|-------------------|
| 0.0        | 134.78                      | 2017              |
| 0.5        | 763.80                      | 2015              |
| 1.0        | 786.60                      | 2011              |
| 1.5        | 750.70                      | 2004              |
| 2.0        | 719.10                      | 1993              |
| 2.5        | 386.40                      | 1962              |
| 3.0        | 537.50                      | 1920              |
| 3.5        | 841.90                      | 1880              |

Table 3. The six 210Pb dates included all sites in the database but were truncated to the common time period for which all records contained data (1090–1960 CE) then standardized by subtracting the mean and dividing by the standard deviation. Two Principal Components Analyses were performed in the program R version 3.5.1 to summarize these data (Oksanen et al. 2018; R Core Team 2018). The first (PCA1) included all sites in the database but was truncated to their common time period (1090–1960 CE). The second analysis (PCA2) was performed using only records with data covering all of the last 2,000 years (1090–2018 CE). The first principal component (PCA1) was a measure of the local pollen assemblage (Kassambara and Mundt 2017). The second principal component (PCA2) identified the local and regional pollen assemblage (Kassambara and Mundt 2017).
Oppositifolia, we were present, but the percentages were low (<5%). The Oxyria curve was similar to that of Poaceae, but with a lower amplitude of change.

Pollen transported from forested areas in the south (long-distance pollen), such as Pinus and Picea, remained relatively constant throughout the core (Figure 4). Betula, which probably originated from the Low Arctic tundra, showed a similar trend as Salix, with a rapid increase in uppermost 2 cm (1970–2017 CE). Concentration was highest in the 1800s CE, corresponding to an increase in Poaceae and decrease in Cyperaceae pollen, and then decreased for the last 100 years. Pollen accumulation rates (grains cm$^{-2}$ yr$^{-1}$) were high in the earliest samples (1080–1250 CE), then low until 1885 CE when they increased until the present (Figure 4).

The green coccol algae Pediastrum was present throughout the core, and comprised mainly of the species P. boryanum var. longicorne. Percentages averaged around 8% and then increased between 6 and 12 cm (1650–1920 CE). The increase, which peaked at 30% at 8 cm (1885 CE), occurred during a decrease in Cyperaceae and increase in Poaceae. Tardigrade eggs were also present throughout the core; however, abundances were not recorded.

### Ordination of pollen assemblages from SW08

The pollen stratigraphy was analyzed with a principal component analysis of all taxa used in the July temperature reconstruction. Component 1 explains 42.5 percent of the variance and component 2 explains 11 percent (Figure 5). Cyperaceae is positively correlated, while Salix and Betula are both negatively correlated with the first axis. Brassicaceae and Poaceae are both positively correlated with the second axis. The scores of the first component were positive until the last 200 years and negative thereafter. The scores show a temporal separation on the biplot. Scores from the MCA and late twentieth/twenty-first century were negative on the second component and positive (MCA) or negative (twentieth century) on the first component. Scores from 1500–1980 CE tended to be positive on the second component.

### Climate reconstruction

Reconstructed July temperatures ranged from 4.5 to 8.0°C and showed a cooling trend of about 1.5°C from 1080–1915 CE and with lowest temperatures (4.5°C) reconstructed between 1800 and 1915 CE. Temperatures rose over the last 100 years to between 5 and 6°C, which is comparable to MCA values (Figure 4).

Gajewski (2015) determined that a good analog has a dissimilarity value of less than 0.2 in the modern dataset used for these analyses; in the present study, all fossil levels were considered good analogs. The sites chosen as the best analogs were generally from Boothia Peninsula ($n = 24$), Banks Island ($n = 12$), and Somerset Island ($n = 5$). One analog was found on Baffin Island and one on Cornwallis Island.
Discussion

Environmental change on Prince of Wales Island, Nunavut

As is typical in the Arctic, the sediment core from SW08 was inorganic and sedimentation rates were low. This led to difficulties establishing a chronology, which was further complicated by the likely presence of a freshwater reservoir effect due to hardwater. Given the consistently high carbonate values throughout the core, applying a reservoir correction was deemed appropriate for this site to enable the derivation of a chronology. The reservoir correction calculated here is comparable to others for Arctic (e.g., MacDonald, Beukens, and Kieser 1991; Snyder et al. 1994; Peros and Gajewski 2009) and temperate lakes (e.g., Ascough et al., 2011; Philippsen 2013; Zhou et al. 2015).

The pollen assemblages were dominated by herbaceous taxa Cyperaceae and Poaceae, but also contained smaller percentages of other typical Arctic plants (Figure 3). Gajewski (2002) described regional differences between High Arctic modern pollen assemblages, which were dominated by Poaceae, Caryophyllaceae, and Papaver, and Middle Arctic sites dominated by Cyperaceae and Artemisia. The decrease in Cyperaceae and increase in Poaceae over time at this site, therefore, suggests a shift from warmer to colder and perhaps drier conditions. This interpretation is further supported by changes in less abundant taxa, such as the increase in Caryophyllaceae and Oxyria observed throughout the core, as well as by the temperature reconstruction.

Transitions in the local and regional pollen assemblages (Figure 5) corresponded to reconstructed changes in climate for the circum-Arctic region (Overpeck et al. 1997; Kaufman et al. 2009; Shi et al. 2012; McKay and Kaufman 2014; Nicolle et al. 2018; Werner et al. 2018). Samples corresponding to the MCA (~1090–1250 CE) and LIA (~1500–1800 CE) form two groups on the biplot and those corresponding to the transition period (~1270–1500 CE) overlap these zones. Samples representing the post-LIA (1800–1980 CE) are grouped together, suggesting a sustained period when the vegetation was characteristic of the High Arctic. In the samples from 1980–2012 CE Salix and Betula were important components of the pollen composition, which is unprecedented in relation to the last 1,000 years.

Reconstructed temperatures were similar (6.0–6.5°C; Figure 4) during the two warm periods (1090–1250 and 1980–2012 CE); however, the vegetation composition differed. Cyperaceae dominated the earliest samples, which may correspond with the end of the MCA, while samples from the last 100 years saw an increase in Salix.
Figure 4. Long-distance, local, and regional pollen percentages, pollen concentrations, accumulation rates, and mean July temperature (°C) reconstruction for core SW08. Sums were calculated based on entire pollen assemblage (local, regional and long-distance). On the temperature reconstruction, grey lines are the standard deviation of the three best analogs and the red line is a loess curve (span = 0.25) fitted to the reconstruction.

Figure 5. Principal Component Analysis (PCA) for SW08 pollen percentages. Only taxa used in the July temperature reconstruction were included in the PCA (Table 1). Panel (a) shows the loadings and (b) shows the scores coloured by year CE and grouped by climatic periods identified in the literature.
and Betula pollen. Several studies have discussed the impacts of modern warming on Arctic vegetation, particularly in relation to the northward expansion of shrubs such as Alnus, Betula, and Salix (Tape, Sturm, and Racine 2006; Post et al. 2009; Myers-Smith et al. 2011). Both Salix arctica and Salix richardsonii currently grow on Prince of Wales Island (Aiken et al. 2007) and have likely become more abundant with warming temperatures as documented elsewhere in the Arctic (Hill and Henry 2010). Alnus and Betula do not presently grow on Prince of Wales Island, but their increased production in the south could cause more pollen to be transported to the High Arctic, as shown by the increase in pollen percentages as well as pollen accumulation rates after 1980 CE. The increase in shrubs over the last 30 years may also be related to precipitation or hydrological changes, as most regions of the Arctic have experienced increased precipitation over the last 30 years (Hinzman et al. 2005). Unfortunately, precipitation reconstructions are less reliable and there are currently no comprehensive analyses of Holocene precipitation across the Arctic (Miller et al. 2010; Briner et al. 2016; Linderholm et al. 2018). Moreover, precipitation patterns are more spatially variable than temperature because they are primarily controlled by cyclonic activity, topography, and atmospheric circulation (Edlund and Alt 1989).

Lower temperatures in the reconstruction were indicated by changes in the vegetation and supported by concurrent changes in algal production. Although diatom productivity could not be assessed using BSi, probably due to post-depositional diatom dissolution (Ryves et al. 2006; Paull, Finkelstein, and Gajewski 2017), the abundance of Pediastrum was inversely correlated with the July temperature reconstruction. The dominant species, Pediastrum boryanum var. longicorne, is generally associated with cold, dystrophic waters (Jankovská and Komárek 2000; Komárek and Jankovská 2003), so its increase between 1800 and 1915 CE (Figure 3) is consistent with the reconstruction of colder conditions. Pollen concentration decreased during the late 1800s (Figure 4), suggesting reduced terrestrial productivity. Although few studies have been conducted on the use of Pediastrum as a bioindicator, the increase in algal abundance suggests within lake processes were affected during the Little Ice Age.

High temporal-resolution pollen-based reconstructions from the CAA

There are several pollen-based temperature reconstructions in the Canadian Arctic spanning the entire Holocene and these have been recently quantitatively summarized by region (Gajewski 2015). Although previous studies produced longer records (up to 10,000 years), the results from Lake SW08 are the only reconstruction with high-temporal resolution data (<50 years between samples) for the Common Era. Other reconstructions with an average temporal resolution of less than 100 years between data points (SL06 and MB01, Peros and Gajewski 2009) and one slightly lower resolution record (JR01, Zabenskie and Gajewski 2007) showed some between-site congruence with SW08 (Figure 6). Two of the sites (SL06 and MB01) recorded warmer temperatures during most of the first millennium, and the longer records showed a centennial-scale cooling trend in the Common Era. All four sites reconstructed a relative cooling between 1800 and 1930 CE when temperatures decreased by 0.5–1.5°C from the mean of the last 1,000 years for each record. Although each site experienced a cold period of similar amplitude, the duration varied between sites. SW08 and SL06 recorded a longer sustained cold period from 1800–1930 CE and 1775–1950 CE, respectively. At SL06, this period was an intensification of colder conditions that began at ~1100 CE, whereas at SW08 there was more variability prior to 1800 CE.

Synthesis of circum-Arctic paleoclimate records of the past 2000 years

Temperature reconstructions of the past 2000 years averaged across the circum-Arctic region (Kaufman et al. 2009; Shi et al. 2012; McKay and Kaufman 2014; Nicolle et al. 2018; Werner et al. 2018) are affected by data selection and availability, as well as by the averaging methodologies applied. The Past Global Changes (PAGES) Arctic 2k working group database consists of 56 proxy records (version 1.1.1; McKay and Kaufman 2014). Since this database emphasizes annually-resolved records such as tree rings, ice cores, and varves, and these sites are regionally-restricted, reconstructions that are based on only these proxies may be biased (Birks and Birks 2006; Christiansen and Ljungqvist 2017). Notably lacking from the Arctic 2k database are quantitative pollen-based reconstructions, which contributes to the underrepresentation of data from the western and central Canadian Arctic Archipelago (CAA). We therefore updated the database with the addition of three pollen-based reconstructions (SW08, this study; SL06 and MB01, Peros and Gajewski 2009), a varve record not previously used (DV09; Courtney Mustaphi and Gajewski 2013), and an updated version of the Agassiz ice core record (Lecavalier et al. 2017), for a total of 40 records. We examined the influence of both increasing the spatial coverage of the proxy network and including lower resolution pollen records. Following
Kaufman et al. (2009), the average of the records standardized relative to their common period (1090–1960 CE) was computed. These results were compared to the average for all the records (SD with respect to 980–1800 CE) from Kaufman et al. (2009) to analyze the influence of adding more proxy records to the reconstruction (Figure 7A). The curves closely paralleled each other during the last 500 years, but diverged slightly prior to 1500 CE. Although the differences are subtle, the average from this study tends to be warmer than the Kaufman et al. (2009) average, except during the LIA.

The averages of the records with and without those from the CAA were similar after ~560 CE, before which they were slightly higher (Figure 7B). McKay and Kaufman (2014) also applied the PaiCo method (Hanhijärvi, Tingley, and Korhola 2013) in another reconstruction. The results are similar to the average for this study, but applying the PaiCo method produced consistently colder

Figure 6. Pollen-based temperature reconstructions in the Central and Western Arctic. The horizontal line is the mean for each record based on a reference period from 1000–2000 CE. Note: the reconstructions for SL06, JR01, and MB01 differ from the original publications because they were redone using the new modern database from Gajewski (2015).
temperatures and higher variance (Figure 7C). However, the PaiCo method does not retain the magnitude of proxy values, so the variance produced may be artificial.

These results demonstrate that the additional records modify the reconstruction but also preserve the temporal trends despite the potential chronological errors and lower resolution. The magnitude of differences are slight since only four new records were included; however, they do demonstrate that inclusion of lake sediment records, which retain lower frequency variability, can be used to increase the spatial extent of the database especially in data poor regions like northern Canada and Asia (Figure 1).

The available records (Table A1; Figure 1) were analyzed using a Principal Component Analysis to determine the spatial and temporal coherence of the data. A first analysis (PCA1) was performed on 40 records that contained data for the past 1,000 years (1090–1960 CE). The first component of PCA1 explains 16% of the variance, the second 13 percent, and the third explains 8 percent (Figure 8). The scores were grouped based on a cluster analysis of the matrix of reconstructions using a Euclidean distance dissimilarity measure and Ward's method, which identified four temporal groups: 1090–1260 CE, 1270–1570 CE, 1580–1910 CE, and 1920–1960 CE.

To assess whether the relationships were the same over a longer timescale, a second study (PCA2) compared records with data for the last 2,000 years (10–1960 CE). There were fewer records (n = 26) spanning this longer time period: four tree ring, seven ice core, four marine sediment, one speleothem, and 10 lake sediment records (see Table A1 for proxy type). The first component explains 16 percent of the variance, the second 9.5 percent, and the third 8 percent. Four temporal groups were again identified by a cluster analysis: 10–1260 CE, 1270–1570 CE, 1580–1910 CE, and 1920–1960 CE.

The first component in both analyses shows a long-term trend that reverses at 1920 CE. In both cases, all but a few records are similarly loaded suggesting that the first component reflects variability that affected the entire Arctic at the same time. On both timescales, the records that have the highest correlation with the first component are in the North Atlantic (Figure 9); however, the spatial coherence is greater in PCA2 and includes more ice cores and records from the CAA. Ice core records are generally weakly correlated with the first component in PCA1 except for those that are in units of temperature (Agassiz and Lomonosovfonna). The higher correlation of uncalibrated ice core records with the first component in PCA2 suggests the raw δ18O values may have a more common signal of longer-term climate variability. In addition to temperature, the isotopic signals in ice cores are influenced by the seasonality of precipitation and changes in circulation patterns and thus moisture transport (Kriinner and Werner, 2003; Masson-Delmotte et al. 2005; Werner et al. 2001). Although there is a linear relationship between modern surface temperature and isotopic composition, changes in the hydrological regime over time could alter this relationship, thereby biasing reconstructions based on raw δ18O values.

Subsequent components in both PCAs show modifications to the dominant trends that occurred in various records. Records that are highly loaded on the second component of PCA1 have either a strong manifestation of the MCA or modern warming. For example, MD99-2275, Lower Murray Lake, SW08, and Moose Lake are all positively correlated with this component and show warming of 1–2°C between 1100 and 1300 CE. On the other hand, records from Big Round Lake and MSM5/5–712 both show a stronger signal of 20th-century warming but a relative weak medieval warming in the last 1,000 years.

Sites located around Iceland (Hvitarvatn and MD99-2275) show a stronger manifestation of the MCA, which may be due to the influence of an intensified Atlantic Meridional Overturning Circulation (AMOC) due to changes in the North Atlantic Oscillation (NAO) at that time (Trouet et al. 2009). The long-term temporal pattern of the second component of PCA2 is similar to that of the first component, but it includes several multi-decadal deviations from the long-term trend that correspond to periods of increased volcanism. These occur from 520–570 CE, 900–970 CE, 1190–1250 CE, and 1600–1680 CE. The first peak, for example, corresponds to a period of perceived global climate anomalies between 536–550 CE which has been attributed to major volcanic eruptions in both the southern and northern hemispheres (Sigl et al. 2015).

The PCA also indicates that pollen records can capture both low and high frequency variability, although they are highly dependent on the sampling resolution. For example, SW08 and SL06 are in agreement with several other different proxy types (e.g., Lomonosovfonna, MD99-2275, and Lower Murray Lake) over the last 1,000 years, and show a warm MCA, a cool LIA, and the 20th century warming. Although MB01 does not show the same patterns as other records in the last 1,000 years, perhaps due to the lower sampling resolution or to regional differences in climate evolution, it does document the long-term Neoglacial cooling trend over the last 2,000 years.

**Conclusion**

High-resolution pollen data provide new information about climate variability in the Arctic and help put recent vegetation changes in the context of the last 1,000 years. The pollen-based reconstruction from Prince of Wales Island, Nunavut, Canada is sampled at a higher temporal resolution than previous studies and shows more variability than
previous Holocene-scale reconstructions (Zabenskie and Gajewski 2007; Peros and Gajewski 2009). Our reconstruction of temperature provides evidence for sustained colder conditions in the 1800s and unprecedented vegetation change in the last 30 years.

Obtaining quantitative, rather than index-based, reconstructions will enable the production of large-scale reconstructions without standardizing the data so that a more realistic amplitude of change can be produced. Although this has recently been done for the Agassiz ice core
Lecavalier et al. (2017) and several tree ring records (Grud\-d\n2008; Helama et al. 2009), those proxies are regionally limited, so separating proxy-based bias from regional patterns may be difficult. Lake sediments are the only archive with sufficient spatial representation across the Arctic and changes in pollen assemblages have consistently shown direct association with climate (Gajewski 2002, 2015). We demonstrate that pollen-based paleoclimate reconstructions can provide important regional information that preserve the low and high frequency temporal trends when added to existing databases of proxy records. Despite chronological limitations, the addition of pollen and other lake sediment records into a circum-Arctic analysis of spatial and temporal climate variability is necessary to reduce spatial gaps in the proxy network to produce a robust circum-Arctic climate reconstruction.

Figure 8. Principal Component Analysis (PCA) of proxy climate records from the Arctic. (A) Records from 1090–1960 CE (PCA1) showing the loadings colored by proxy type. (B) Scores grouped by clusters established using Ward’s method. (C) Records from 10–1960 CE (PCA2) showing loadings colored by proxy type (same legend as in panel A). (D) Scores grouped by clusters established using Ward’s method. Note the different axis scales.
Figure 9. (A) Maps of the loadings from PCA_1 and associated scores over time for component 1 and (B) component 2. (C) Maps of loadings from PCA_2 and associated scores over time for component 1 and (D) component 2.
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### APPENDIX

**Table A1.** List of reconstructions included in the synthesis study. Sites in bold are included in both PCA$_1$ (1090–1960 CE) and PCA$_2$ (10–1960 CE).

| Site         | Region | Lat   | Long  | Archive | Proxy               | Reference                      |
|--------------|--------|-------|-------|---------|---------------------|--------------------------------|
| Arc_1_Bluelake | Alaska | 68.1  | −150.5| Lake sediment | Varve thickness       | Bird et al. (2009)          |
| Arc_7_GulfAlaska | Alaska | 61.0  | −146.6| Tree sediment | Ring width           | Wiles et al. (2014)        |
| Arc_41_Hudson | Alaska | 61.9  | −145.7| Lake sediment | Chironomids          | Clegg et al. (2011)        |
| Arc_42_Iyrm   | Alaska | 66.1  | −145.4| Lake sediment | Chironomids          | Clegg et al. (2011)        |
| Arc_40_Moose  | Alaska | 61.3  | −143.6| Lake sediment | Chironomids          | Clegg et al. (2010)        |
| Arc_23_Iceberg| Alaska | 60.8  | −143.0| Lake sediment | Varve thickness      | Loso et al. (2006)         |
| MB01         | Victoria Island, NWT | 69.8  | −112.1| Lake sediment | Pollen               | Peros and Gajewski (2009)  |
| SW08         | Prince of Wales Isl, NU | 72.3  | −97.27| Lake sediment | Pollen               | Tamo and Gajewski, this volume |
| SL06         | Boothia Peninsula, NU | 68.6  | −91.9 | Lake sediment | Pollen               | Peros and Gajewski (2009)  |
| DV09         | Devon Island, NU | 75.6  | −89.3 | Lake sediment | Varve thickness      | Courtney Mustaphi and Gajewski (2013) |
| Arc_54_Lake4  | Southampton Isl, NU | 65.1  | −83.8 | Lake sediment | Chironomids          | Rolland et al. (2009)      |
| Arc_44_Devo   | Devon Island, NU | 75.3  | −82.5 | Ice core | δ$^{18}$O           | Fisher et al. (1983)       |
| Arc_20_LakeC2 | Ellesmere Island, NU | 82.1  | −77.2 | Lake sediment | Varve thickness      | Lamoureux and Bradley (1996) |
| Agassiz Ice Cap | Ellesmere Island, NU | 81.0  | −75   | Ice core | δ$^{18}$O           | LeQaivalier et al. (2017)  |
| Arc_4_LowerLake | Ellesmere Island, NU | 81.4  | −69.5 | Lake sediment | Mass accumulation rate | Cook et al. (2009)        |
| Arc_30_BigRoundLake | Baffin island, NU | 69.9  | −68.8 | Lake sediment | Varve thickness      | Thomas and Briner (2009)   |
| Arc_53_Penny  | Baffin Island, NU | 67.3  | −66.8 | Ice core | δ$^{18}$O           | Fisher et al. (1998)       |
| Arc_25_Donard | Baffin Island, NU | 66.7  | −61.4 | Lake sediment | Varve thickness      | Moore et al. (2001)        |
| Arc_43_Braya  | Greenland | 67.0  | −50.7 | Lake sediment | U$^{18}$O           | D’Andrea et al. (2011)     |
| Arc_52_Igaliku | Greenland | 61.0  | −45.4 | Lake sediment | Pollen accumulation | Massa et al. (2012)        |
| Arc_35_DYE3   | Greenland | 65.2  | −43.8 | Ice core | δ$^{18}$O           | Vinther et al. (2010)      |
| Arc_32_NGRIP1 | Greenland | 75.1  | −42.3 | Ice core | δ$^{18}$O           | Vinther et al. (2006)      |
| Arc_11_GISP2  | Greenland | 72.1  | −38.1 | Ice core | δ$^{18}$O           | Groote and Stuiver (1997)  |
| Arc_36_GRIP   | Greenland | 72.6  | −37.6 | Ice core | δ$^{18}$O           | Vinther et al. (2010)      |
| Arc_34_Crete  | Greenland | 71.1  | −37.3 | Ice core | δ$^{18}$O           | Vinther et al. (2010)      |
| Arc_28_B18    | Greenland | 76.6  | −36.4 | Ice core | δ$^{18}$O           | Schwager (2000)            |
| Arc_59_Renland | Greenland | 71.3  | −26.7 | Ice core | δ$^{18}$O           | Vinther et al. (2008)      |
| Arc_22_Hvitvatn | Iceland | 64.6  | −19.8 | Lake sediment | Varve thickness      | Larsen et al. (2011)       |
| Arc_57_MD99-2275 | North Atlantic | 66.6  | −17.4 | Marine sediment | U$^{18}$O           | Sice et al. (2011)         |
| Arc_55_P1003  | North Atlantic | 63.8  | 5.3   | Marine sediment | δ$^{18}$O           | Sejrup, Hafidsson, and Andrews (2011) |
| Arc_58_MS5/S–712 | North Atlantic | 78.9  | 6.8   | Marine sediment | planktic forams      | Spießhagen et al. (2011)   |
| Arc_38_MD95-2011 | North Atlantic | 67.0  | 7.6   | Marine sediment | Diatoms              | Berner et al. (2011)       |
| Arc_49_Okhola Cave | Scandinavia | 67.0  | 13.0  | Speleothem | δ$^{18}$O           | Lingle et al. (2009)       |
| Arc_17_Lomonosovfonna | North Atlantic | 78.9  | 17.4  | Ice core | δ$^{18}$O           | Divine et al. (2011)       |
| Arc_12_Tornetrask | Scandinavia | 68.3  | 19.6  | Tree Ring | Ring Width          | Grud (2008)                |
| Arc_15_Lapland | Scandinavia | 69.0  | 25.0  | Tree Ring | Ring width          | Helama et al. (2009)       |
| Arc_51_Pieni   | Scandinavia | 64.3  | 30.1  | Lake sediment | Chironomids          | Luoto and Helama (2010)    |
| Arc_10_PolarUral | Central Russia | 66.8  | 65.8  | Tree Ring | Max. density        | Esper, Cook, and Schweingruber (2002) |
| Arc_3_Yamal   | Central Russia | 67.5  | 70.0  | Tree Ring | Ring width          | Briffa et al. (2008)       |
| Arc_2_AvamTaimyr | Central Russia | 72.0  | 101.0 | Tree Ring | Ring width          | Briffa et al. (2008)       |