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Key Points:
- The Last Glacial Cycle altered the thermal regime of the subsurface in a complex fashion
- A glacial system model is used to simulate the Laurentide Ice Sheet basal temperature histories
- The effect of the Last Glacial Cycle is removed. Updated reconstructions are derived showing increased warming over the last centuries

Supporting Information:
- Supporting Information S1

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Impacts of the Last Glacial Cycle on ground surface temperature reconstructions over the last millennium

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Abstract Borehole temperature profiles provide robust estimates of past ground surface temperature changes, in agreement with meteorological data. Nevertheless, past climatic changes such as the Last Glacial Cycle (LGC) generated thermal effects in the subsurface that affect estimates of recent climatic change from geothermal data. We use an ensemble of ice sheet simulations spanning the last 120 ka to assess the impact of the Laurentide Ice Sheet on recent ground surface temperature histories reconstructed from borehole temperature profiles over North America. When the thermal remnants of the LGC are removed, we find larger amounts of subsurface heat storage (2.8 times) and an increased warming of the ground surface over North America by 0.75 K, both relative to uncorrected borehole estimates.

1. Introduction

Among the many indicators of temperature changes over the last several millennia, geothermal data measured as borehole temperature profiles provide estimates of past changes in the Earth's surface energy balance that are independent of meteorological records, because they are direct measures of temperature and therefore do not need to be calibrated. Ground surface temperature (GST) reconstructions from borehole temperature profiles assume that long-term surface air temperature (SAT) changes are coupled to long-term GST changes and that the long-term variability of the surface energy balance propagates by thermal conduction into the subsurface. Changes in surface energy balance are in turn recorded as temperature perturbations to the quasi steady state geothermal conditions in the terrestrial subsurface. These assumptions have been investigated, validated, and discussed extensively in the literature [*Stieglitz et al.*, 2003; *Bartlett et al.*, 2005; *González-Rouco et al.*, 2003; *Bodri and Cermak*, 2007; *Smerdon et al.*, 2009; *Demetrescu et al.*, 2007], and GST reconstructions are important estimates of large-scale temperature changes over the last millennium [*Huang et al.*, 2000; *Beltrami and Bourlon*, 2004; *Harris and Chapman*, 2001; *Pollack and Smerdon*, 2004]. Borehole temperature profiles have also yielded an estimate of the magnitude of continental heat storage over the later half of the twentieth century [*Beltrami*, 2002; *Beltrami et al.*, 2006], which has been an important contribution to assessments of how the energy budget of the climate system is changing [*Hansen et al.*, 2011; *Levitus et al.*, 2012; *Rhein et al.*, 2013].

As with all other climate reconstruction methods, climatic inferences from borehole geothermal data have limitations [*Hu and Feng*, 2005; *Smerdon et al.*, 2009; *Koven et al.*, 2013; *Paquin and Sushama*, 2015]. One uncertainty that has recently received attention is the degree to which GST reconstructions are affected by the remnants of the Last Glacial Cycle (LGC) [e.g., *Rath et al.*, 2012; *Beltrami et al.*, 2014]. Quantification of this subsurface effect is important for estimating uncertainties in quasi steady state geothermal profiles and therefore the reference state against which subsurface signals associated with recent climate change are benchmarked. Furthermore, the effect of the LGC introduces spatially variable influences in the subsurface that further complicates the interpretation of spatially resolved climate reconstructions from underground temperatures [*Beltrami et al.*, 2011, 2015a]. In classical heat flow studies, to correct for the heat flow density from the interior of the Earth, it has been customary to model the termination of the last ice age as a single step change [e.g., *Birch*, 1948; *Jessop*, 1971] of an arbitrary magnitude (e.g., 5 K and 10 K) at an arbitrary time (e.g., 10 ka) for any particular location and forward model its effect into the subsurface. Such a step model, by definition, yields a positive temperature anomaly in the subsurface at all times. This ignores the temporally and spatially complex structure of the LGC that is indicated by data [*Rolandone et al.*, 2003; *Chouinard and Mareschal*, 2009; *Pickler et al.*, 2016] and detailed modeling [*Tarasov and Peltier*, 2007] of the Laurentide Ice Sheet (e.g., see examples in Figure 2 of *Beltrami et al.* [2015a]).

In the present study, we perform, for the first time, a systematic analysis of the effects of the LGC on International Heat Flow Commission (IHFC) terrestrial borehole data in North America, using an ensemble of model simulations from a Glacial System Model (GSM). We quantify the LGC's impact on previous temperature and energy reconstructions from borehole data for the last millennium and derive new estimates of these reconstructions that account for the LGC effects. These new reconstructions are also compared to the reconstructions from the North American PAGES 2k network [*PAGES2k Consortium*, 2013] and with temperature reconstructions from a pollen network in North America.

2. Theory

Assuming that a temperature profile from the terrestrial surface to depth within the Earth can be approximated by a semiinfinite half-space subject to constant upper boundary conditions, the temperature at depth z, $T(z)$, is given by [*Carslaw and Jaeger*, 1959]

$$T(z) = T_0 + q_0 R(z) + T_t(z) \tag{1}$$

where T_0 is the long-term ground surface temperature, q_0 is the surface heat flow density, and $R(z)$ is the thermal depth. That is, $T_0 + q_0 R(z)$ comprises the quasi steady state geothermal profile from which subsurface temperature anomalies, $T_t(z)$, are estimated. If we assume a homogeneous subsurface with constant thermal properties, and if other nonclimatic effects such as land use change and groundwater flow are excluded, then the subsurface temperature anomalies are assumed to represent the response of the ground to the changes in the upper boundary condition due to climatic variations [*Lewis*, 1992; *Pollack and Huang*, 2000; *Bodri and Cermak*, 2007].

For a given borehole temperature versus depth profile and the assumption of a GST history consisting of a series of k time steps, the data can be inverted to obtain an estimate of past temperatures at the surface of the measurement site. We use singular value decomposition for the inversion procedure [*Mareschal and Beltrami*, 1992; *Clauser and Mareschal*, 1995]. The spatial analysis is performed using the same procedure as in *Beltrami and Bourlon* [2004].

The subsurface heat content also can be estimated from the borehole temperature profiles using minimal assumptions. Because changes in the energy balance at the Earth's surface are recorded as temperature anomalies, $T_t(z)$, as described by equation (1), they can similarly be interpreted as the superposition of changes in energy accumulation in the subsurface. Thus, the subsurface heat content can be written:

$$Q_s = \rho c \int_{z_{\min}}^{z_{\max}} T_t(z)\mathrm{d}z, \tag{2}$$

where, ρc is the volumetric heat capacity, $z_{\min}$ and $z_{\max}$ represent the integration depth range, and $T_t(z)$ is the temperature anomaly as a function of depth. Estimates of Q_s are thus dependent on the depth range of the subsurface temperature anomaly and the choice of the region for determining the quasi steady state geothermal regime. The thermal properties are assumed constant, as these measurements are generally not available for the depth ranges where temperature data exist.

3. Data and Model Description

3.1. IHFC Database

The North American data used in this study are part of the International Heat Flow Commission (IHFC) borehole temperature database, which is publicly available at NOAA's National Centers for Environmental Information. We have chosen the North American region, because it experienced the largest changes in ice sheet area over the glacial cycle and also because this region has the highest density of borehole temperature data, thus allowing for spatial inferences.

3.2. The Glacial System Model

The GSM [*Tarasov and Peltier*, 2004] is a 3-D thermomechanically coupled ice sheet model that includes a permafrost-resolving thermal model at its base and is asynchronously coupled to a viscoelastic model of the

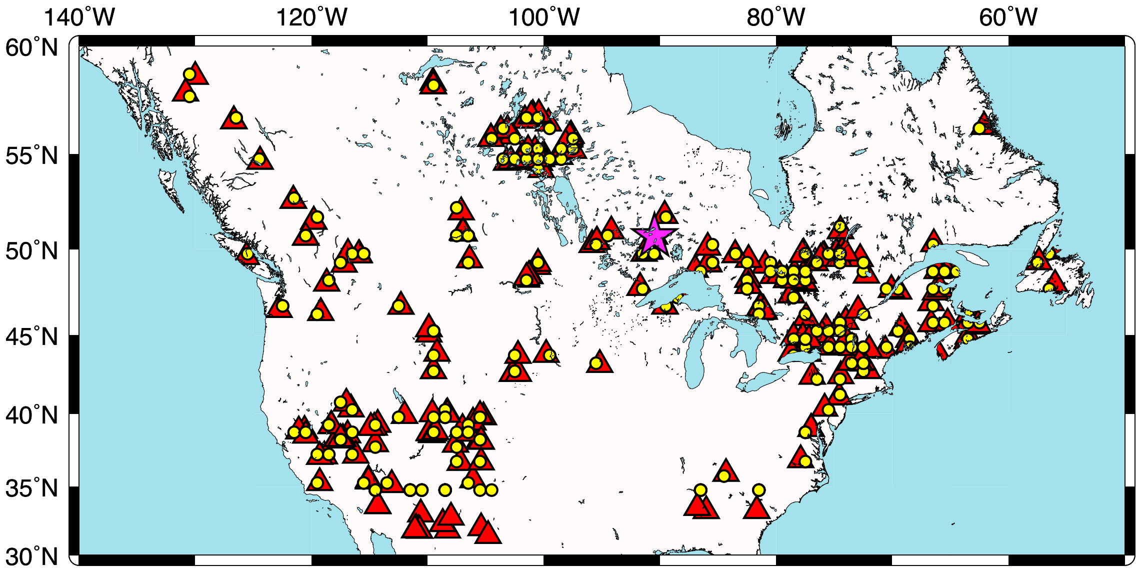

Figure 1. Simulation domain (140°W, 30°N); (52.5°W, 60°N) and grid cell locations within the GSM. Yellow circles mark the locations of the nearest grid cells from which simulated temperatures are used for borehole corrections. Red triangles mark the location of borehole temperature profiles from the IHFC database. The star marks the location of the Minchin Lake borehole temperature profile used as a detailed example in text.

glacial isostatic adjustment process. Ice dynamics were calculated using the Shallow Ice Approximation with fast flow due to sliding or subglacial till deformation when basal temperature approaches the pressure melting point [*Greve and Blatter*, 2009], an appropriate approach for long-term simulations of continental-scale ice sheets away from fast-moving ice streams. More model details can be found in *Tarasov and Peltier* [2004, 2007] and *Tarasov et al.* [2012]. In contrast to other models, the GSM used herein has been calibrated against a comprehensive body of available data [*Tarasov et al.*, 2012] using a Bayesian methodology. The calibration produces a posterior distribution of higher likelihood ensemble parameter sets given model fits to a diverse set of constraint data. This model is driven by a climate based on interpolation between a modern state from the National Center for Atmospheric Research/National Centers for Environmental Prediction reanalysis [*Kalnay et al.*, 1996] and a Last Glacial Maximum state derived from PMIP II and PMIP III archived 21 ka time-slice GCM simulations (http://pmip.lsce.ipsl.fr/).

There are a number of uncertainties that will need to be better addressed in future studies. The GSM calibration probed (though unavoidably incompletely) possible and plausible temperature and precipitation chronologies, and favored those most consistent with getting an ice sheet chronology that reduced the misfit to the proxy constraints. The approach is nevertheless not an inversion and there is no guarantee that the range of chronologies used for this study cover the true deglacial thermal history. Other key uncertainties are those of the thermal properties of the bedrock.

4. Analysis and Results

The spatial distributions of the IHFC data for North America and that of the closest grid point to the IHFC location from GSM simulation are shown in Figure 1. The LGC effect on the subsurface was estimated using the GSM basal temperature simulation as an upper boundary condition. The basal temperature anomaly was estimated as a departure from the overall mean and used as the surface forcing function of a conductive 1-D homogeneous semiinfinite half-space model with initial temperature of zero. The model was run from 120 ka to 1 ka, using the basal temperature from the GSM, thus simulating the thermal effect of 119 kyrs of the LGC basal temperature history on the subsurface. The remaining 1 kyr of the LGC simulation was assumed to have a surface temperature equal to the LGC's long-term mean, thus imposing no climatic changes in the simulated profile after 1 ka. These simulated profiles are then subtracted from the observations in the IHFC data set.

Figure 2a shows the 120 kyr long basal temperature anomaly at Minchin Lake (Canada) — a borehole logging site commonly used as a test standard for its continuous profile and 74 thermal conductivity measurements over its 600 m depth. Subsurface temperature anomalies are generated from the solution of the forward

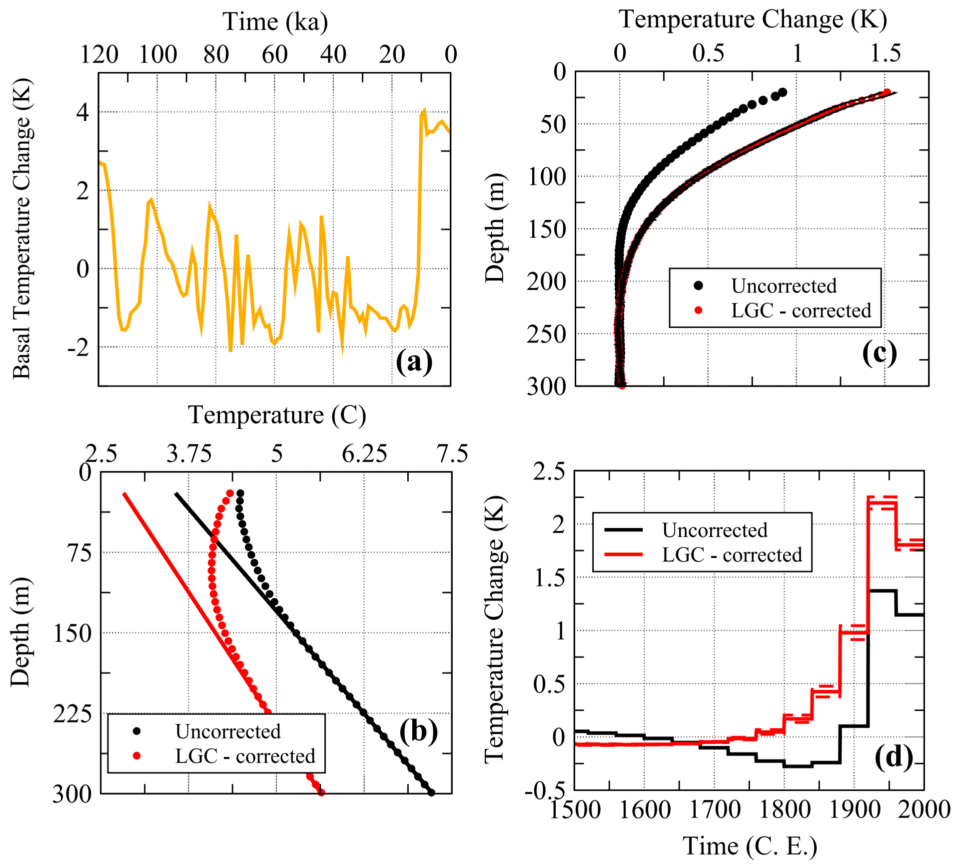

Figure 2. Example of the correction procedure using the borehole temperature profile for Minchin Lake, Canada (−90.480°, 50.710°). (a) Ice sheet basal temperature history for 120 ka from GSM for the model grid point closest to Minchin Lake, (b) Black dots represent the measured borehole temperature profile, while red dots represent the LGC-corrected data. Black and red lines represent the estimated quasi-equilibrium geothermal profiles for this site before and after corrections, respectively. (c) Subsurface temperature anomalies and their 75% confidence levels estimated for the original (black) and LGC-corrected data (red); (d) GST history estimated from the original data (black) and corrected data (red) along with their 75% confidence levels. The uncertainties for the uncorrected data have been examined in detail in *Beltrami et al.* [2015a].

problem described above for the basal temperature history from 120 ka to 1 ka. These anomalies indicate that the LGC introduces a perturbation in the underground thermal regime and thus affects the character of the borehole temperature profiles. All 75% confidence intervals are determined from application of Chebyshev's inequality to the GSM's 2 standard deviation sample range of the ensemble [*Beltrami et al.*, 2014].

Measured borehole temperature profile data contain the subsurface thermal effects induced by the LGC, thus subtraction of the LGC-induced subsurface temperature anomaly from the data corrects for the LGC effect (Figure 2b). The most obvious LGC effect on the subsurface thermal field is the change in geothermal gradient. This implies that the LGC affects the quasi steady state geothermal regime that is used as the reference for estimating recent changes in continental heat storage and GST histories from geothermal data. Such effects are consistent with work that empirically retrieved the unperturbed heat flow density, q_0, $\left(q_0 = -\lambda \frac{\partial T}{\partial z}\right)$ from the Earth's interior, guided by geomorphological data [*Jessop*, 1971].

Removing the quasi steady state from LGC-corrected data yields a subsurface temperature anomaly that indicates larger subsurface temperature changes (Figure 2c). Singular Value Decomposition inversion of the LGC-corrected subsurface temperature anomaly yields GST histories with larger increases in ground surface temperatures at this site over the last 500 years, relative to the uncorrected data (Figure 2d). Some of the features visible in the GST history from the uncorrected data are not present in the LGC-corrected GST history. Namely, the partially retrieved cold period from the uncorrected data is common for several of the deeper

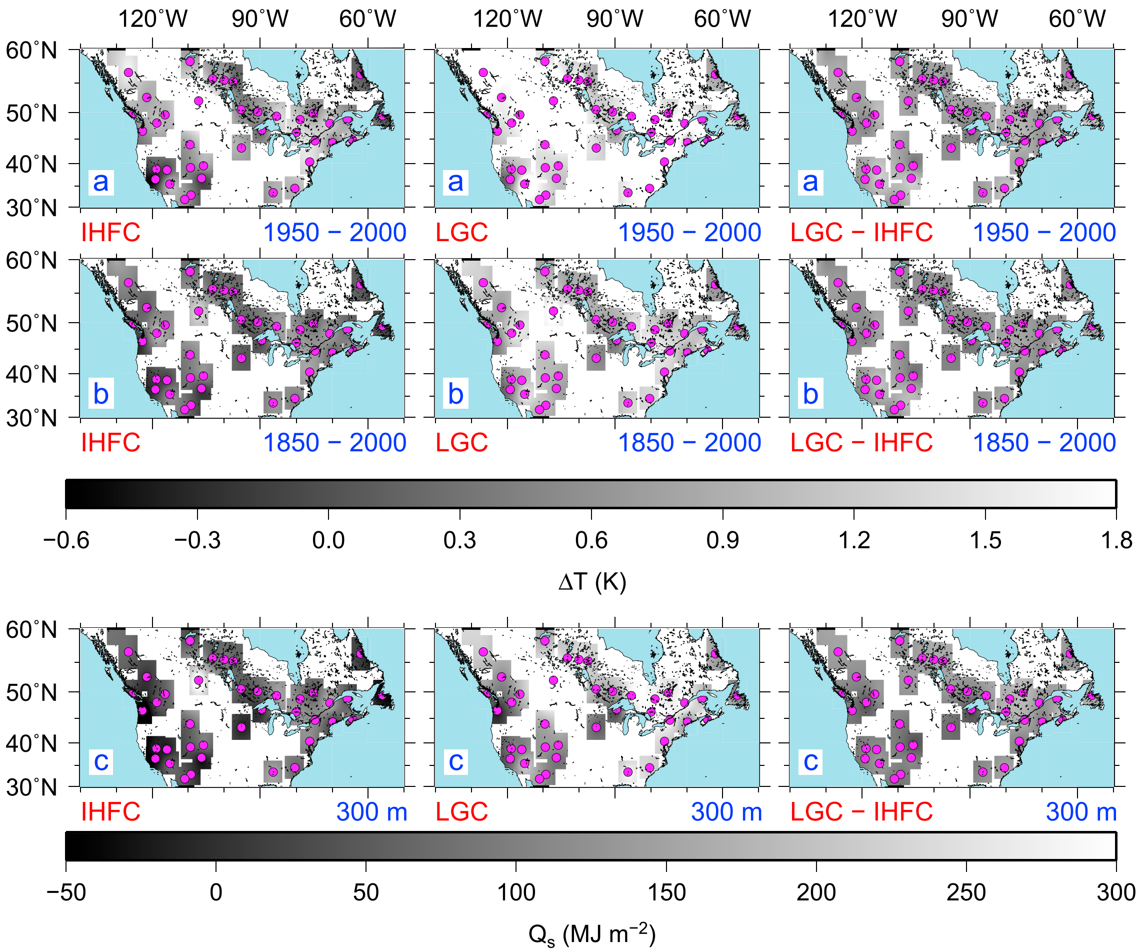

Figure 3. GST history for the IHFC data truncated to 300 m for (a) GST changes from 1950 to 2000, (b) GST changes from 1850 to 2000, and (c) subsurface heat storage for the same data. The left column corresponds to the original data, middle column to the LGC-corrected data, and the right column shows the results for the respective differences (LGC-corrected—IHFC data). See Figure S2 in the supporting information for a different (color) version of this figure.

borehole temperature profiles in Canada, and it is thought to be the signature of the Little Ice Age (LIA) in the region [*Shen and Beck*, 1992; *Beltrami and Mareschal*, 1992].

To maximize the number of temperature depth profiles available in the data set, and because recent work has shown that spatial analysis of geothermal data must be performed for data reaching the same depth [*Beltrami et al.*, 2011, 2015b], we truncated all available data for North America at a depth of 300 m and used the deepest 100 m to determine each quasi steady state reference profile and subsurface temperature anomaly. Because there is not much information available for the spatially variable subsurface thermal properties, we used a constant value of the thermal conductivity (3.0 W/m K) and diffusivity $\left(10^{-6}\ \mathrm{m}^2\ \mathrm{s}^{-1}\right)$ in order to span the same thermal depth. The spatial distribution of the ground surface temperature changes obtained by inversion for North America (Figure 3) shows that in northern regions the inferred warming since 1850 and 1950 from LGC-corrected data are larger than the results reported from analyses of the original data [*Beltrami et al.*, 2015b]. This is consistent with the example illustrating the analytical procedure using the Minchin Lake data (Figure 2). The spatial differences indicate a larger amount of heat that penetrated the subsurface when we account for the LGC effect. The subsurface heat storage for the LGC-corrected data is higher than the previous estimate $\left(0.80 \times 10^8\ \mathrm{J/m}^2\right)$ [*Beltrami*, 2002] by a factor of 2.8 for North America. In LGC-relevant regions, the perturbations introduced by the LGC therefore must be considered an important part of the subsurface energy storage and GST histories estimated from the borehole database, in addition to the confidence intervals from the GSM LGC simulation uncertainties [*Saw et al.*, 1984] (Figure S1 in the supporting information). For North America, the mean GST history from LGC-corrected data reveals warmer surface conditions in the recent

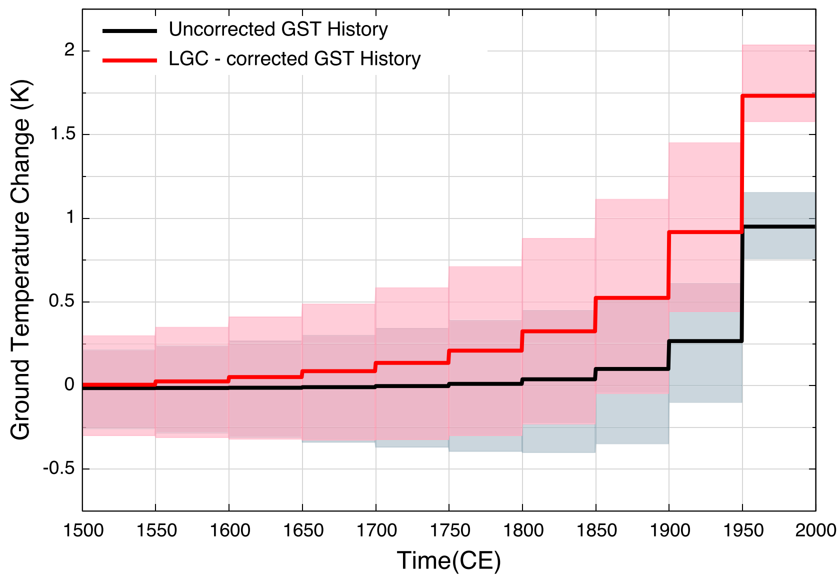

Figure 4. Mean GST history as departures from the long-term temperatures at each site for the IHFC borehole database over North America truncated at 300 m (259 borehole temperature profiles) retrieved from the uncorrected data (black line), and LGC-corrected data (red line). Shaded regions represent the uncertainty envelope estimated from the uncertainty from the determination of the semiequilibrium geothermal gradient and the long-term surface temperature for uncorrected (grey shade) and LGC-corrected (pink shade) data. The LGC-corrected uncertainty envelope also includes the additional uncertainties from the 75% GSM ensemble confidence intervals. Both GST histories are referenced to the quasi-equilibrium geothermal regime and its long-term past surface temperature.

past (Figure 4) with respect to the uncorrected data. The twentieth century warming from LGC-corrected data is 0.75 K higher than previous estimates, revealing that the mean temperature increase for 1850 to 2000 from the LGC-corrected data are above the confidence intervals of the previous estimates.

5. GST Histories and Proxy Records Reconstructions

The proxy-based paleoclimatic reconstructions from the PAGES 2k project [*PAGES2k Consortium*, 2013] provide a benchmark against which ground surface temperature histories from the LGC-corrected and uncorrected data can be compared. However, we must emphasize that the agreement (or disagreement) of the LGC-corrected borehole reconstruction with other reconstructions does not provide a test of methodology. The comparison simply reveals how the borehole-based paleoclimatic reconstructions would look under this “correction” and, further, how the thermal condition in the subsurface under this scenario changes the subsurface heat content. The mean North American GST history from the LGC-corrected data shows a better agreement with the PAGES 2k paleoclimatic reconstructions over the last two centuries (Figure 5a). In particular, the brief cold period observed in both tree ring and pollen reconstructions between 1800 common era (C.E.) and 1900 C.E. is better matched by the mean GST history obtained from the LGC-corrected data. Prior to 1800 C.E., because of the nature of heat diffusion, only long-term trends are recovered from the subsurface data. These trends nonetheless reveal the spatially heterogeneous LGC-induced differences in the subsurface thermal state and reduced agreement between the PAGES2k reconstructions and the corrected borehole estimates.

The PAGES 2k proxy network covers mainly areas in the western USA; thus, we would have expected that a comparison of proxy and borehole temperature data constrained to that region would be more relevant. However, borehole data in the western USA include data acquired at low sampling intervals; some as coarse as 50 m. These low data densities, coupled to the logging time differential (some data were acquired in the 1960s), result in large uncertainties making direct regional comparisons inconclusive (Figure 5b). In Eastern Canada, where the majority of the data originates from recent, deep boreholes and at high sampling intervals [*Beltrami et al.*, 2015a, 2015b], results indicate larger GST changes (Figure 5c) from the LGC-corrected data and reveal a warmer continental subsurface than previously estimated.

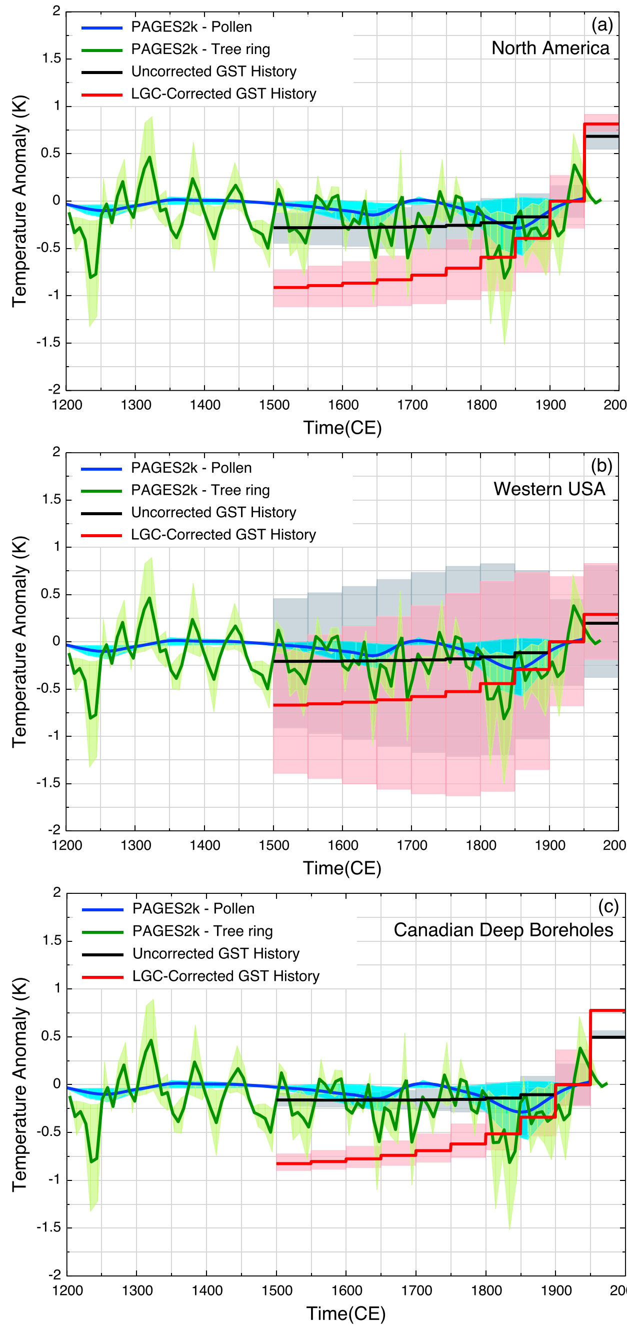

Figure 5. GST history reconstructions and proxy paleoclimatic reconstructions. Time series are expressed as departures from the 1900–1950 mean for (a) North America, (b) Western USA, and (c) Canadian Deep Boreholes. Shading represents 95% confidence range for each reconstruction. For uncorrected and LGC-corrected data, the uncertainty envelope is estimated from the uncertainties from the estimate of the semiequilibrium geothermal gradient and the long-term surface temperature for uncorrected (grey shade) and LGC-corrected (pink shade) data. The LGC-corrected uncertainty envelope also includes the uncertainties from the 75% GSM ensemble confidence intervals.

6. GST Histories and Proxy Records Discrepancies

It is important to recall that some proxy records, such as tree rings, respond to variations in temperature and precipitation differently for short and long time scales [*Franke et al.*, 2013]. On the other hand, because of thermal diffusion, high-frequency variability decays rapidly and the ground continuously integrates small but persistent changes of the ground surface energy balance, thus retaining only the long-term trends and the remnants of the past thermal state of the subsurface. Because of the nature of the response of vegetation to

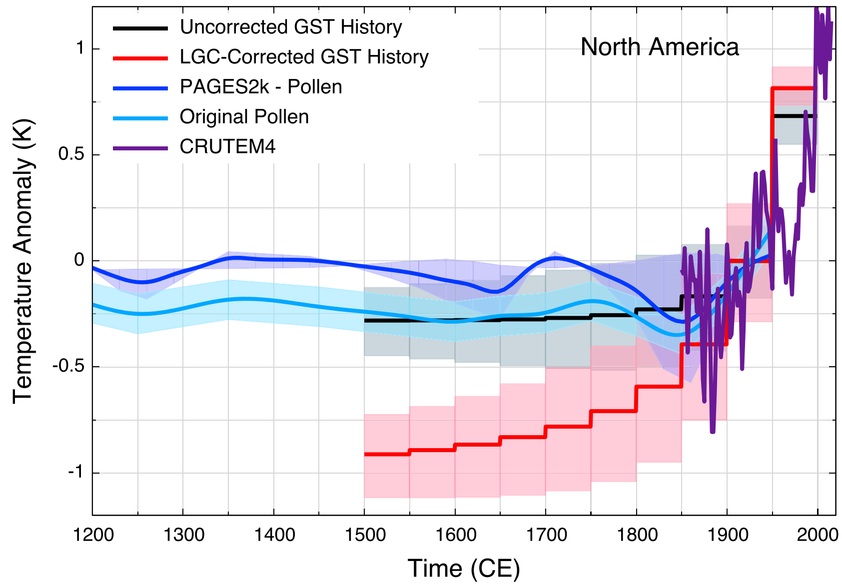

Figure 6. GST history reconstructions compared to pollen mean July temperature reconstructions and the North American SAT annual record from meteorological data. Time series are expressed as departures from the 1900–1950 C.E. interval. The original pollen data has been scaled to match the 1850–1900 to 1901–1950 mean shift in the CRU meteorological data.

climate change, pollen-derived paleoclimatic reconstructions are also expected to retain long-term trends of climate change; thus, we compare our results with pollen-based reconstructions for the mean July temperatures for North America [*Viau et al.*, 2006, 2012]. Figure 6 shows no improved agreement of the LGC-corrected GST reconstruction with the pollen-based reconstructions, relative to the uncorrected GST reconstruction. A similar situation is observed between the PAGES2k pollen-based reconstruction which has been scaled and weighted to match low-frequency component of the tree ring reconstruction in Figure 6 [*PAGES2k Consortium*, 2013]. We note that comparing long-term borehole (i.e., integrated mean annual signal) with seasonally biased (mean July temperature) pollen reconstruction is problematic. It is unlikely for the two records to have the same changes over the last millennium. The North American annual SAT record is also shown [*Osborn and Jones*, 2014]. Understanding the reasons why the tree ring and pollen-based reconstructions are so different becomes very important in order to fully understand the past climate in North America.

7. Discussion and Conclusions

The LGC alters the subsurface steady state thermal regime in a spatially heterogeneous fashion, thus introducing an additional level of uncertainty for climate inferences from the borehole temperature data. The retrieval of climate information, even for borehole temperature profiles spanning the same thermal depth, must therefore account for a previously ignored bias. It is therefore important to characterize the temporal and spatial variability of the subsurface thermal effects of the LGC to improve paleoclimatic reconstructions from geothermal data.

Toward such ends, we have corrected for the impact of ice sheet perturbations during the last 120 ka on measured borehole temperature profiles in North America. These LGC corrections yield larger estimates of temperature change in the recent past and a larger magnitude of continental heat storage compared to previous estimates from geothermal data. Accounting for these effects reveals that the subsurface has absorbed an amount of heat 2.8 times larger than the previous estimate of 1.50×10^{21} J for North America between 1950 and 2000 [*Beltrami*, 2002; *Beltrami et al.*, 2002, 2006; *Huang*, 2006]. This is an important result that may affect the evolution of the stability of permafrost regions and soil carbon stability in model simulations. Both of these processes have potential positive feedbacks on the climate system. Ground surface temperature changes since 1500 C.E. are systematically larger for the LGC-corrected data, with a mean increase of the GST for North America about 0.5 K more than that estimated from the original data. Similarly, the twentieth century warming from LGC-corrected data is 0.75 K higher than previous estimates from geothermal data, consistent with the meteorological records. The mean GST increase estimated from LGC-corrected data is above the uncertainty envelope of that from the uncorrected data since 1850 C.E.

Over the last two centuries, the LGC-corrected GST history shows better agreement with the PAGES2k paleoclimatic reconstructions than the uncorrected GST history since 1800. Differences prior to 1800 between the PAGES 2k and corrected GST histories may be partially tied to differences in the spatial sampling of the underlying data sets and to the different climate response of each data set. It would be worthwhile to expand the PAGES2k proxy database to Eastern Canada where our database contains recent deep boreholes logged at high sampling rates where proxy assessments and comparisons using geothermal data corrected for the LGC effect would be direct and important.

Nevertheless, our results are in striking disagreement with the PAGES2k reconstruction prior to 1800 [*PAGES2k Consortium*, 2013] while suggesting less warming over the last 500 years relative to the pollen-based July temperature reconstructions [*Viau et al.*, 2006, 2012].

On a hemispheric scale, regions of the Northern Hemisphere influenced by the LGC ice sheets include 53% of the data in the global borehole temperature database. The effect of the LGC on the larger data set therefore should be taken into account for estimating global ground surface temperature changes and global continental energy storage changes during the last several millennia. We hypothesize that the effect will be of similar magnitude to that found for North America in the present study.

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