Biogenic silica concentration as a high-resolution, quantitative temperature proxy at Hallet Lake, south-central Alaska

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[1] High-resolution, quantitative temperature records are valuable for placing recent warming in the context of long-term, natural climate variability. Here we use biogenic silica (BSi) concentrations preserved in lacustrine sediment from an oligotrophic lake to quantitatively reconstruct air temperature at Hallet Lake in south-central Alaska. Mean June through August temperature measured over the past 80 yr at Valdez (Alaska) correlate with BSi from Hallet Lake ($r = 0.87$, $p = 0.01$). We chose a nested function to model the non-linear relation between summer temperature and BSi in the calibration data set, and to reconstruct temperature for the past 2 ka. Our BSi-inferred temperature reconstruction shows synchronous changes with independent paleoclimatic proxies for southern Alaska, and provides evidence for a greater rate and magnitude of 20th century temperature warming at Hallet Lake than recorded by other quantitative temperature proxies in the region. **Citation:** McKay, N. P., D. S. Kaufman, and N. Michelutti (2008), Biogenic silica concentration as a high-resolution, quantitative temperature proxy at Hallet Lake, south-central Alaska, *Geophys. Res. Lett.*, *35*, L05709, doi:10.1029/2007GL032876.

1. Introduction

[2] High-latitude ecosystems are predicted to experience the greatest impacts from climate warming and thus represent critical reference areas for the detection of global climate change. Seasonally ice-covered lakes at high latitudes and altitudes respond sensitively to climate fluctuations because even slight changes to their short growing seasons can have major biological impacts [*Smol*, 1988]. Numerous paleolimnological studies have documented unprecedented ecological reorganizations consistent with recent warming trends [e.g., *Smol et al.*, 2005, and references therein]. Relatively few studies, however, have provided quantitative paleo-temperature reconstructions, which are necessary to place 20th century warming in the context of natural, long-term climate variability.

[3] BSi is a direct measure of diatom and chrysophyte abundance, typically the dominant photoautotrophs in high-latitude lakes [*Douglas and Smol*, 1999], and is often a reliable proxy for whole-lake production in such lakes [*Conley and Schelske*, 2001]. BSi has been used previously to track climate-related changes in aquatic production over millennial [*Hu et al.*, 2003] and orbital [*Colman et al.*, 1995] time scales. Recently, lacustrine BSi flux was used to reconstruct air temperature with decadal resolution back to 1580 AD in the Swiss Alps [*Blass et al.*, 2007]. Here, we use BSi concentrations to quantitatively infer summer temperature for the past 2 ka at Hallet Lake in south-central Alaska.

2. Hallet Lake Setting

[4] Hallet Lake (61.5°N, 146.2°W) is a relatively small (~0.6 km^2), deep (Z_{max} = 41 m) lake situated at 1128 m asl near the crest of the Chugach Range (Figure 1). The lake has a catchment of 9.4 km^2, including seven cirque glaciers. Two glacial meltwater streams enter from the south and west, and are the primary sediment sources. Mean annual air temperature at Hallet Lake from 1976–2005 is estimated at −4°C using temperature data from Valdez, AK [*National Climatic Data Center*, 2007] and an environmental lapse rate determined from Valdez and Greyling Lake (61.4°N, 145.7°W; 1016 m asl) meteorological records [*McKay*, 2007]. In August 2007, Hallet Lake water had a pH of 7.4 and a specific conductivity of 87 μS cm^{-1}. The approximate length of the open-water period each year is 80–100 days, based on 2004–2006 water temperature data from Greyling Lake [*McKay*, 2007].

3. Materials and Methods

[5] Our sedimentary profile is a composite of a 4.5-m-long percussion core (HT01) and a 0.3-m-long companion surface core (HT01-B), both taken from near the center of the lake at a water depth of 40.5 m. The chronology of the percussion core is based on nine AMS ^{14}C analyses on macrophytes [*McKay*, 2007], and calibrated to calendar years prior to 1950 AD (cal BP) using CALIB v 5.02 [*Stuiver and Reimer*, 1993]. A smoothed cubic spline function was used to model the age-depth relation and 95% confidence intervals [*Heegaard et al.*, 2005]. The surface core was dated using a combination of $^{239+240}$Pu activities (the peak activity marks 1963, the time of its maximum discharge to the atmosphere [*Ketterer et al.*, 2004]), and a constant-rate-of-supply (CRS) model using excess ^{210}Pb activities. The $^{239+240}$Pu activities, obtained at 0.5 cm resolution to 10 cm depth, were measured using inductively coupled plasma mass spectrometry. ^{210}Pb measurements were obtained at 0.5 cm resolution to 7 cm depth and measured by gamma spectrometry [*Appleby*, 2001].

[6] BSi was measured at 1 cm resolution for percussion core HT01 (192 samples), and at 0.25 cm resolution for the top 10 cm of surface core HT01-B (37 samples). Wet-alkaline extraction (10% Na_2CO_3), molybdate-blue reduction, and spectrophotometry were used to determine silica

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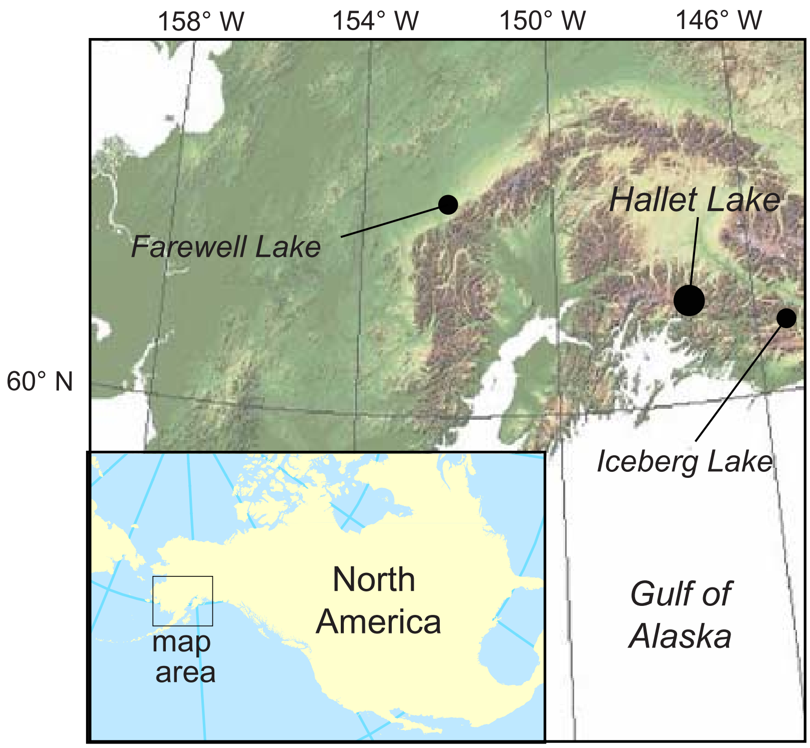

Figure 1. Hallet Lake, Chugach Range, south-central Alaska. Locations of other high-resolution lacustrine paleoclimate records for southern Alaska (Farewell Lake [*Hu et al.*, 2001]; Iceberg Lake [*Loso et al.*, 2006]) are also shown.

concentrations, following *Mortlock and Froelich* [1989]. A large, homogenized reference sample taken from core HT01 was analyzed twice with each batch and used to account for batch effects and to calculate within-batch precision. Preparation of diatom samples for analysis followed standard protocols for siliceous microfossils [*Battarbee et al.*, 2001].

4. Results and Discussion

4.1. Geochronology

[7] All nine ^{14}C ages were used in the age-depth model (see auxiliary material[1] data listed by *McKay* [2007]). They show that the 4.5 m core spans most of the Holocene, with a steady sedimentation rate (0.9 mm yr^{-1}) from 4 ka to present. The $^{239+240}Pu$ profile exhibits a well-defined peak at 3.25 cm, indicating an average sedimentation rate of 0.76 mm yr^{-1} and minimal bioturbation. The ages derived from the ^{210}Pb CRS model corroborate the $^{239+240}Pu$ peak (denoting the 1963 depth), and the mean sedimentation rate (0.82 mm yr^{-1}) is very similar to that inferred from the $^{239+240}Pu$ profile.

4.2. Biogenic Silica

[8] Hallet Lake is a turbid, glacier-fed lake and the productivity is expectedly low, with sedimentary BSi concentrations about an order of magnitude lower than in non-glacial lakes [e.g., *Kaplan et al.*, 2002]. BSi concentration ranges from 4–16 mg SiO_2 g^{-1} dry sediment. The concentrations are low, but significantly greater than the within-batch precision for our internal standard with low BSi (±0.7 mg g^{-1}). The pronounced variations during the last 2 ka exhibit clear, century-scale variability in BSi concentration (Figure 3). Three outliers (>3σ above the mean of the 10 nearest values) were removed from the dataset. Organic matter content (OM) in Hallet Lake sediment varies from 2–4% over the study interval. BSi and OM are significantly correlated over the past 2 ka ($r = 0.57$, $p = 0.04$), although the signals are decoupled from 800–1100 and 1300–1500 AD.

4.3. Diatom Taxonomy

[9] Diatoms were analyzed at 14 select intervals to ascertain the dominant taxa at each interval, and determine if there were major differences in composition between intervals of high and low BSi. Although many sediment intervals (all samples between the ages of 100 and 1350 cal BP) contained too few frustules to enumerate, diatoms and chrysophytes were observed in all samples (see auxiliary material).

[10] On the whole, the same genera appeared in all samples, including *Amphora* (*A. pediculus*, *A. inariensis*, *A. libyca*), *Gomphonema* (mainly *G. angustum*), *Cymbella sensu lato* (mainly *Encyonema silesiacum* and *E. minutum*), and *Nitzschia* (mainly *N. perminuta*, *N. frustulum*, and *N. amphibia*). Planktonic taxa, largely *Cyclotella kuetzingii*, were present in most samples, but rarely exceeded relative abundances of 15%. Although higher taxonomic resolution might reveal distinct differences in species composition, we conclude that diatom assemblage composition has remained generally constant over the past 2 ka.

4.4. Climate as the Main Driver of BSi at Hallet Lake

[11] Sedimentary BSi is primarily controlled by three factors: (1) aquatic production, (2) clastic sedimentation rate, and (3) the post-depositional preservation of siliceous

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl032876. Other auxiliary material files are in the HTML.

Table 1. Correlations Between BSi and Meteorological Data

Correlated Parameter[a]	n	r	p-value[b]	Source[c]
Valdez T_{annual}	22	0.75	0.092	1
Valdez T_{JJA}	26	0.87	0.010	1
Valdez P_{annual}	26	0.31	0.393	1
Valdez P_{JJA}	22	0.03	0.921	1
Gulkana T_{annual}	18	0.52	0.174	1
Gulkana T_{JJA}	18	0.26	0.392	1
Aleutian Low Pressure Index	32	0.55	0.046	2

[a]T = 5-yr average temperature; P = 5-yr average precipitation; JJA = June through August.
[b]p-values calculated with respect to effective sample size [*Dawdy and Matalas*, 1964] to account for lag-1 autocorrelation.
[c](1) *National Climatic Data Center* [2007]; (2) *Beamish et al.* [1997].

organisms. Aquatic production is influenced by water temperature, light and nutrient availability, among other factors [*Wetzel*, 2001]. Consequently, BSi may record lake- and catchment-specific effects that are not directly related to climate. The overriding factor influencing aquatic production at high-latitude lakes is typically the extent and duration of ice cover, which is ultimately governed by climatic conditions [*Douglas and Smol*, 1999]. Numerous studies have documented the association between climate and whole-lake production, diatom abundance, and species assemblages at high-latitudes [e.g., *Smith*, 2002; *Michelutti et al.*, 2005; *Smol et al.*, 2005]. However, BSi is not correlated with air temperature in all high-latitude lakes. At Hallet Lake, the significant relation between BSi and summer temperature is probably attributable to the heightened influence of seasonal ice-cover on aquatic production for this deep, turbid, low-productivity lake. While rapid, 20th century increases in BSi content in glacier-fed lakes can be driven by direct anthropogenic influences [e.g., *Blass et al.*, 2007], such factors are probably insignificant at Hallet Lake, given its remote location.

[12] We do not have decadally resolved age control throughout our sedimentary profile, so we present BSi as concentration, rather than flux. Consequently, BSi is not simply a measure of whole-lake production, but is a balance between BSi flux and clastic flux. While these effects cannot be completely decoupled from the BSi signal, two lines of evidence suggest that changes in clastic flux do not drive the variability in BSi concentration in Hallet Lake sediment. First, one $^{239+240}$Pu age, and seven ^{14}C ages indicate a nearly linear sedimentation rate for the past 4 ka, suggesting that multi-centennial-scale variability in clastic sedimentation rate was minor. This is the timescale of the primary variability in BSi over the past 2 ka (Figure 3). Second, there is no significant correlation between bulk density and BSi concentration over the past 2 ka (r = 0.32, p = 0.22), further suggesting that changes in clastic flux do not control BSi concentration. Post-depositional dissolution does not appear to drive the changes in BSi concentration in Hallet Lake sediment. While evidence of dissolution was observed in some diatom taxa, the degree of dissolution appeared to be largely consistent among all samples. Also, relatively thinly silicified taxa (e.g., *A. minutissima*) were present in most samples, indicating that post-depositional dissolution is minor.

4.5. Quantitative Temperature Reconstruction and Error Determination

[13] High-resolution measurements (contiguous 0.25-cm-thick samples) of BSi from the top 10 cm (last 125 yr) of surface core HT01-B were correlated with a suite of instrumental climate records from the two longest-term, nearby weather stations at Valdez (1917–2006) and Gulkana (1942–2006), and with the Aleutian Low Pressure Index (1900–2004) (Table 1). Each BSi sample integrates the BSi content of 3–4 yr of sediment, which was compared

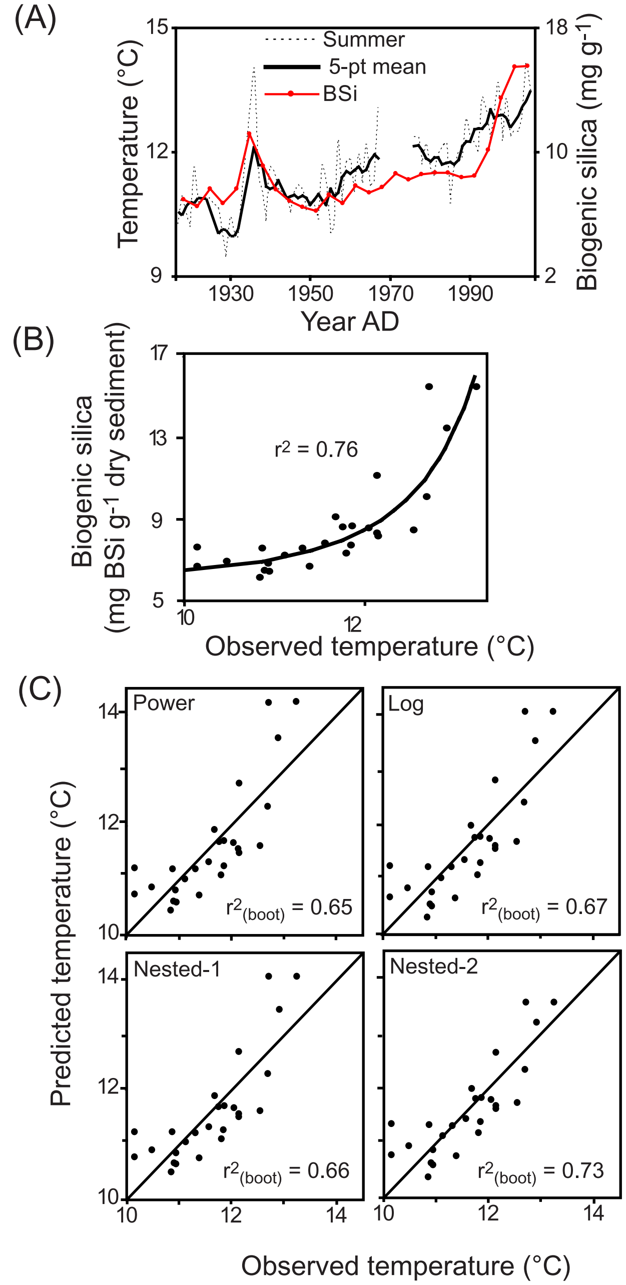

Figure 2. (a) Valdez June through August temperature (1- and 5-year mean) and BSi at Hallet Lake from 1918–2006. (b) Relation between observed summer temperature and BSi at Hallet Lake. Black line shows the best-fit least-squares regression. (c) Relation between observed and predicted summer temperature for each transfer function. Black line shows ideal 1:1 relation.

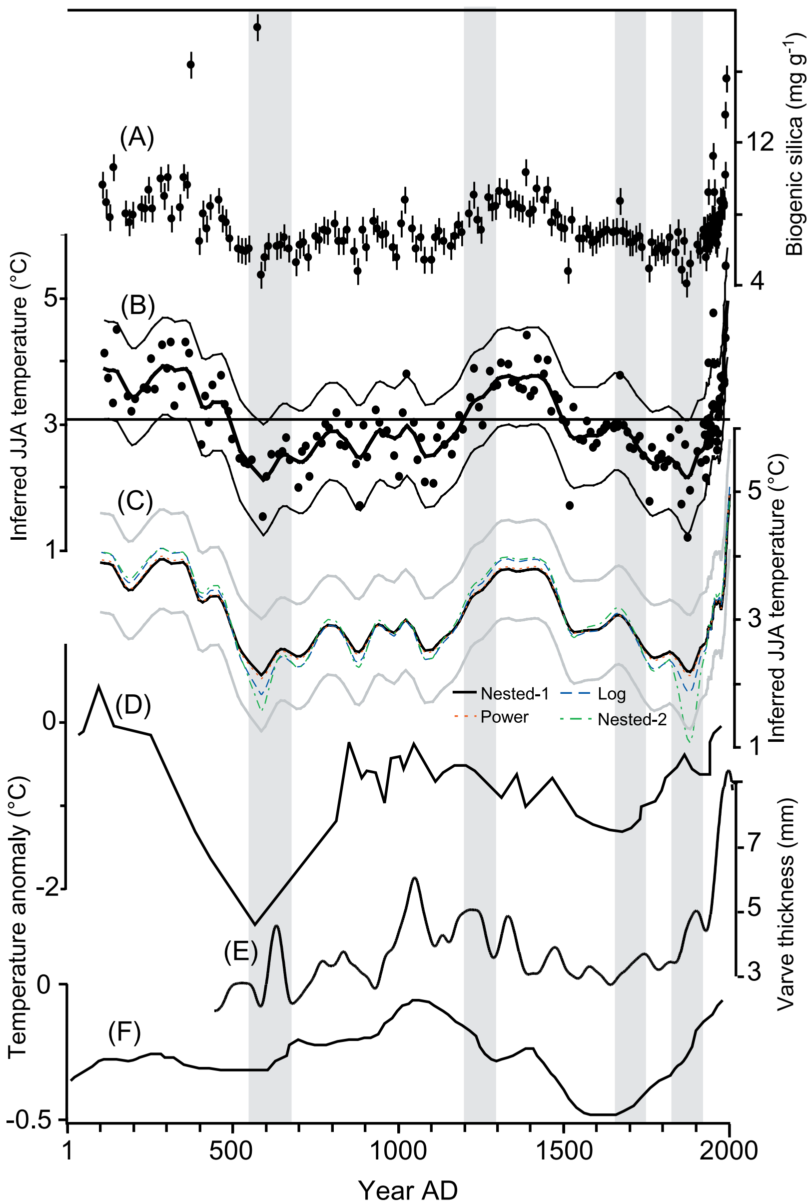

Figure 3. (a) BSi concentration at Hallet Lake over the past 2 ka. Error bars show within-batch precision. (b) BSi-inferred June through August temperature. Black line indicates the 2 ka average. Thick curve is the 50-year Gaussian-weighted low-pass filtered curve. Thin curves are confidence intervals determined as the dynamic $RMSEP_{(boot)}$. (c) 2 ka temperature reconstruction calculated using all four transfer functions. (d) Isotope-inferred temperature from Farewell Lake, northwestern Alaska Range [*Hu et al.*, 2001]. (e) Varve thickness from Iceberg Lake, eastern Chugach Range [*Loso et al.*, 2006]. (f) Multi-proxy Northern Hemisphere temperature reconstruction [*Moberg et al.*, 2005]. Shaded intervals are periods of glacial advance in southern Alaska [*Wiles et al.*, 2008]. Study locations shown on Figure 1.

with mean climate parameters for the corresponding years. The strongest correlation was between BSi and Valdez June through August temperature ($r = 0.87$; $p = 0.01$) (Figure 2). While there are no air temperature data from Hallet Lake, daily air temperature measurements (2005 to 2006) from nearby Greyling Lake are well correlated with temperature measured at Valdez ($r = 0.96$, $p = 1.3 \times 10^{-7}$) [*McKay*, 2007].

[14] On the basis of this empirical relationship, a function was developed to quantitatively reconstruct summer temperature for the past 2 ka from BSi in core HT01. BSi increases exponentially with temperature over the calibration period. Because this relation is non-linear, several regression procedures (e.g., logarithmic, power) may be appropriate (Figure 2). To determine the sensitivity of the choice of function, we developed logarithmic, power, and nested functions. The functions were cross-validated using the bootstrap technique, a statistical resampling approach for assessing the stability of limited datasets. The technique allows the root mean square error of prediction ($RMSEP_{(boot)}$) to be calculated for each point in the reconstruction [*Birks*, 1995].

[15] The choice of regression did not have a major effect on $RMSEP_{(boot)}$, $r^2_{(boot)}$, or the resulting summer temperature records (Figures 2 and 3). Because the first nested function had the lowest $RMSEP_{(boot)}$ values (min = 0.7°C,

mean = 0.8°C, max = 1.1°C), we select it for the 2 ka temperature reconstruction. The function is:

$$T_{JJA} = Log_{1.002}\left(\frac{(6.017X + 83.494)^{0.5}}{8.636}\right)^{0.5}$$

where T_{JJA} = average June through August temperature and X = BSi content (mg g^{-1}).

[16] While the nested function has the lowest $RMSEP_{(boot)}$, we developed a second nested function with a significantly higher $r^2_{(boot)}$ (0.73 compared to 0.66). Despite the better fit, the second nested function is not useful for reconstructing summer temperature because the maximum $RMSEP_{(boot)}$ is very high (7.7°C). Because the calibration set does not contain the lowest temperatures of the past 2 ka, calculating the coldest temperatures requires extrapolation, consequently, the highest $RMSEP_{(boot)}$ values occur at low temperature in the reconstruction. Because the bootstrapping routine tests the sensitivity of the function to each point in the calibration set, the lower slope at low BSi concentrations in the second nested function makes the function particularly sensitive to the lowest temperatures in the calibration set.

4.6. Temperature Variability at Hallet Lake Over the Past 2 ka

[17] BSi-inferred summer temperatures were warmer than the long-term (2 ka) average (3.1°C) from ~100 to ~500 AD, before decreasing rapidly to ~2°C by 600 AD (Figure 3). This cooling coincides with a period of glacial advance in the Chugach Range, and the Kenai and St. Elias Mountains [*Wiles et al.*, 2008]. After ~600 AD, summer temperature gradually increased from 2 to ~4°C by 1300 AD, and remained above the 2 ka average until ~1500 AD. Summer temperature began to decrease at ~1450 AD, cooling nearly 2°C by ~1875 AD (Figure 3). The maximum cooling at Hallet Lake during the past 2 ka occurred from ~1750 to ~1900 AD. Summer temperature at Hallet Lake increased ~2.5°C in the 130 yr since the coldest part of the Little Ice Age (LIA), and the reconstructed temperatures for the past 20 yr are the highest for the past 2 ka at Hallet Lake. These unprecedented changes over the past 150 yr are consistent with changes recorded in lake sediments throughout the Arctic [*Smol and Douglas*, 2007].

[18] Temperature changes inferred for the last 2 ka from Hallet Lake are largely consistent with hemispheric reconstructions (Figure 3) [*Moberg et al.*, 2005]. The few paleoclimate records of this duration that are available from the region (Figure 1) show similar trends, including the isotope-inferred temperatures from Farewell Lake in the northwest Alaska Range [*Hu et al.*, 2001], varve thickness from Iceberg Lake, and mountain-glacier fluctuations from southern Alaska [*Wiles et al.*, 2008] (Figure 3). A larger number of proxy records are available for the last 500 yr. In southern Alaska, this interval has been divided into three phases of LIA cooling based on glacial evidence and tree-ring chronologies [*Wiles et al.*, 2008]. The BSi record from Hallet Lake indicates cooler temperatures during the middle and late phases, and the coldest during the late phase of the LIA, consistent with the maximum Neoglacial advance of the period, and several tree-ring chronologies recently summarized by *Wilson et al.* [2007]. The rapid 20th century warming inferred from the Hallet Lake BSi record is consistent with other records from southern Alaska; however, the magnitude and rate of change recorded here are greater than in other quantitative temperature proxies (Figure 3) [*Hu et al.*, 2001; *Wilson et al.*, 2007].

5. Conclusions

[19] The 2 ka paleo-temperature reconstruction from Hallet Lake is the longest available quantitative temperature record with decadal resolution for southern Alaska. BSi is controlled by many factors, and this approach is not appropriate for all lakes. However, the excellent agreement of our temperature reconstruction with other regional and hemispheric paleoclimatic records suggests that high-resolution, BSi-inferred, quantitative temperature records may be developed from other deep, low-productivity, seasonally ice-covered lakes.

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