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ORIGINAL PAPER

# Summer temperatures during the Medieval Warm Period and Little Ice Age inferred from varved proglacial lake sediments in southern Alaska

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**Abstract** For the heavily glaciated mountains of southern Alaska, few high-resolution, millennial-scale proxy temperature reconstructions are available for comparison with modern temperatures or with the history of glacier fluctuations. Recent catastrophic drainage of glacier-dammed Iceberg Lake, on the northern margin of the Bagley Icefield, exposed subaerial outcrops of varved lacustrine sediments that span the period 442–1998 AD. Here, an updated chronology of varve thickness measurements is used to quantitatively reconstruct melt-season temperature anomalies. From 1958 to 1998, varve thickness has a positive and marginally significant correlation with May–June temperatures at the nearest coastal measurement stations. Varve sensitivity to temperature has changed over time, however, in response to lake level changes in 1957 and earlier. I compensate for this by log-transforming the varve thickness chronology, and also by using a 400-year-long tree-ring-based temperature proxy to reconstruct melt-season temperatures at Iceberg Lake. Regression against this longer proxy record is statistically weak, but spans the full range of occupied lake levels and varve sensitivities. Reconstructed temperature anomalies have broad confidence intervals, but nominally span 1.1°C over the last 1500+ years. Maximum temperatures occurred in the late twentieth century, with a minimum in the late sixth century. The Little Ice Age is present as three cool periods between 1350 and 1850 AD with maximum cooling around 1650 AD. A Medieval Warm Period is evident from 1000 to 1100 AD, but the temperature reconstruction suggests it was less warm than recent decades—an observation supported by independent geological evidence of recent glacier retreat that is unprecedented over the period of record.

**Keywords** Alaska · Holocene paleoclimate · Glacial lake · Little Ice Age · Medieval Warm Period · Varves

This is one of fourteen papers published in a special issue dedicated to reconstructing late Holocene climate change from Arctic lake sediments. The special issue is a contribution to the International Polar Year and was edited by Darrell Kaufman.

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## Introduction

Quantitative reconstructions of temperature history are important for placing contemporary climatic changes into the context of natural variability. The Little Ice Age (LIA, ~1580–1850 AD, Osborn and Briffa 2006) and Medieval Warm Period (MWP,

~890–1170 AD, Osborn and Briffa 2006) constitute a complete pre-industrial climatic oscillation that presents a compelling target for comparison with contemporary warming. Proxy reconstructions indicate considerable global variability in the timing and magnitude of these anomalies, however, so a globally coherent understanding of climate in recent millennia requires multiple reconstructions that represent a wide variety of geographic locations (Bradley et al. 2003; Crowley and Lowery 2000; Jansen et al. 2007; Jones and Mann 2004; Osborn and Briffa 2006). Certain locations are underrepresented by proxy-based reconstructions. In some cases this is a consequence of inadequate sampling efforts, but in others it reflects the relative rarity of high-resolution, millennial-scale climatic records. Southern Alaska, where the world's most extensive non-polar glaciers are still active, is one such place. Because the region is remote, and because many potential archives were destroyed or obscured by recent (LIA) glacial advances (Calkin et al. 2001; Wiles et al. 2002), there currently are only a few millennial-scale quantitative temperature reconstructions from southern Alaska (e.g., D'Arrigo et al. 2006; Hu et al. 2001; McKay et al. 2008; Wilson et al. 2007).

Recently, Loso et al. (2004, 2006) described a varve record (annually laminated deposits of lacustrine sediment) of over 1500 years from Iceberg Lake, a proglacial lake on the northern margin of the Bagley Icefield. The record is unusual in both its length—the longest yet described from Alaska—and its location, in the heart of southern Alaska's coastal mountains. Varve thickness is commonly interpreted as a proxy for melt-season temperatures (e.g., De Geer 1926; Hardy et al. 1996; Hughen et al. 2000; Leemann and Niessen 1994; Leonard 1985), although varves at some sites have been shown to be more directly influenced by other factors, including rain and snowfall (e.g., Cockburn and Lamoureux 2007; Østrem and Olsen 1987). Iceberg Lake—only a few kilometers downstream of its primary glacial sources, in a heavily glacierized basin, and with rare subannual laminae—is not likely subject to the latter "hydrometeorological" controls (Cockburn and Lamoureux 2007), and the lake's varve record was previously interpreted as a robust, qualitative indicator of regional warm season temperatures (Loso et al. 2006).

Here, I present an updated varve thickness chronology from Iceberg Lake and use it to quantitatively reconstruct melt-season temperatures. A quantitative reconstruction is challenged by several phenomena: (1) the only continuous instrumental temperature records available for calibration are hundreds of kilometers distant and less than 60 years long; (2) episodic lake-level changes have altered the sensitivity of varve thickness to temperatures over the calibration and reconstruction period; and (3) the varve record provides annual resolution but with dating errors estimated at ±4% (Loso et al. 2006). Despite these challenges, I find a weak but consistently positive relationship between varve thickness and temperature records (both instrumental and proxy-based) at a variety of time scales and argue that the Iceberg Lake record provides a coherent record of melt season temperatures since the fifth century AD.

## Study area and previous results[1]

Iceberg Lake (60°47′ N, 142°57′ W; 933 m asl) is a proglacial lake impounded by an unnamed tributary of Tana Glacier in the eastern Chugach Mountains of Alaska (Fig. 1). Large glaciers, including the Bagley Icefield complex, characterize the region, and the Iceberg Lake drainage basin itself is small but heavily glaciated; alpine glaciers currently cover 52% of the 74 $km^2$ watershed and constitute the dominant source of sediments for the lake (Loso et al. 2004). Historical observations record no jökulhlaups (floods caused by sudden drainage of an ice dammed lake) from Iceberg Lake until August 1999, when the 60-m-deep, 4.4-$km^2$ lake suddenly and unexpectedly emptied completely through a subglacial breach of the glacier dam. Inlet streams and ephemeral snowmelt channels began rapidly eroding the dry lakebed, and during most summers since then the lake has partially refilled before again catastrophically draining. Based upon stratigraphic evidence, Loso et al. (2006) concluded that, over the period recorded by this exposed stratigraphy (mid-sixth century to 1999), catastrophic drainage events have not occurred, corroborating the lake's historic stability.

[1] The individual chronologies, as presented in Loso et al. (2006), are tabulated in the Electronic Supplementary Materials, and are available on-line through the World Data Center for Paleoclimatology (ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/northamerica/usa/alaska/iceberg2008.txt).

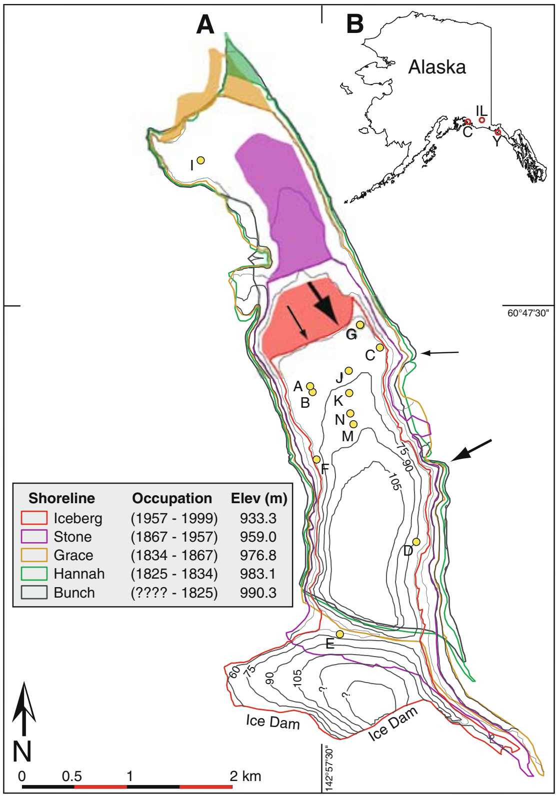


**Fig. 1** Paleoshorelines, paleobathymetry, and sample locations at Iceberg Lake (**a**). Shorelines (open polygons) and deltas (shaded areas) are color coded with informal names, intervals of occupation (year AD), and shoreline elevations (meters) in legend. Yellow dots indicate sites where detailed varve chronologies were collected. Most recent inlet locations for primary (largest arrow) and secondary (smaller arrows) streams are shown with black arrows. For each stable lake level, a bedrock spillway formed the outlet at the southeast corner of the lake. Bathymetric contours (labeled with 15 m contour interval) indicate depth below highest ("Bunch") shoreline; question mark indicates uncertainty of bottom topography in southern, distal basin. Alaska state map (**b**) shows general location of Iceberg Lake (IL), Cordova (C), and Yakutat (Y)

Four discrete strandlines ring Iceberg Lake above the most recent (pre-1999) stable shoreline. These strandlines, each with an associated delta and bedrock spillway (Fig. 1), reflect a bimodal behavior in which periods of stability—with the lake outlet held steady by a spillway over a bedrock sill—are punctuated by episodic changes from one stable lake level to another, apparently in response to gradual changes in thickness of the glacier dam (Loso et al. 2004). The highest, least-distinct shoreline was last occupied during the LIA maximum advance of the impounding glacier. Subsequent occupations of each of the lower lake levels have been confidently dated using stratigraphic evidence (Fig. 1), but the timing of earlier (pre-LIA) lake levels is not well constrained (Loso et al. 2004). After the drainage of Iceberg Lake in 1999, rapid fluvial incision of the lakebed created steep-walled gullies and exposed lacustrine stratigraphy that records over 1500 years of continuous suspended sediment deposition. Eleven outcrops (Fig. 1) were examined, photographed, and sampled (for grain size, bulk density, organic-matter content, and for $^{14}C$ and $^{137}Cs$ dating) during the summers of 2001–2003, mostly without the need for traditional coring equipment. All laminae thicknesses were measured in situ using digital calipers. In addition, 5-cm-diameter cylindrical "cores" were hand-carved from eight of these outcrops (sites A, B, C, D, E, F, G, J) for archival storage. Details of that fieldwork, sampling strategy, and resulting data were reported in Loso et al. (2006).

Overlapping, cross-dated varve-thickness chronologies from multiple outcrops provide a record, confirmed by independent radiogenic dating, of continuous sediment deposition at Iceberg Lake from 442 to 1998 AD (Loso et al. 2006). Laminae affected by turbidites, resuspended sediment, or ice-rafted debris were identified by visual inspection and excluded from a master chronology that was based on simple averaging of thickness measurements from all well-dated varves for each calendar year. Individual chronologies were not normalized prior to creation of the master chronology because that would preclude detection of climatic trends at the lowest frequencies (centennial and longer) of interest here. A computational error (mistaken inclusion of some anomalous measurements) led to minor errors in the previously published master chronology; these have been corrected, and the updated master varve thickness chronology, in raw form and smoothed by a 40-year low-pass Butterworth Filter (Selesnick and Burrus 1998) to emphasize decadal and centennial variability, is presented in both tabular and graphic form in the Electronic Supplementary Materials.

## Analysis and discussion

### Varve thickness and climate

To quantify the relationship between varve thickness and temperatures at Iceberg Lake, in the section that follows I: (1) demonstrate that varve thickness is a stable proxy for sediment accumulation rate; (2) show that changes in lake level have altered the sensitivity of varve thickness to summer temperatures over the course of the record and transform the data to address that concern; (3) compare the most recent portion (1958–1998) of the transformed varve record with instrumental temperature records at two stations and show that varve thickness is positively correlated with average May–June temperatures; and (4) argue that at decadal and centennial timescales, the varve record is more appropriately calibrated against a longer-term record and use linear regression to predict melt-season temperatures from a local, ~400 year tree-ring-based proxy record of temperature.

The argument for a positive correlation between temperature and varve thickness depends upon the assumption that varve thickness accurately represents sediment accumulation rate. After the 1999 jökulhlaup at Iceberg Lake, rapid dewatering and subaerial settling of shallow sediments diminished any confounding trend of bulk density with depth in section. This observation is corroborated by the dry bulk density of 11 sediment samples collected at approximately equal intervals between the top and bottom of the deepest continuous outcrop—sample site M. Although bulk density exhibits some variability (mean density = 1170.9 kg $m^{-3}$, SD = 80.1 kg $m^{-3}$, $n = 11$), there is no discernible trend with depth, and in fact the densest sample, at 1248.9 kg $m^{-3}$, came from only 5 cm below the lakebed surface (Fig. 2). It is reasonable to treat varve thickness as a consistent, reasonable proxy for sediment accumulation rate.

Because of Iceberg Lake's history of episodic changes in lake level (Loso et al. 2004), sediment accumulation rate at any given sampling site will vary not only as a function of bulk sediment input (controlled in part by climatic factors of interest), but also as an inverse function of lake size. This is because, when the lake shrinks, sediment inputs are deposited over a smaller surface area, and shoreline regression brings stream inlets closer to sampling sites in the lake bottom. To demonstrate this relationship, I analyzed the relation between distance to nearest stream inlet and average varve thickness during the period of well-dated shoreline occupations (1825–1998 AD, Fig. 3). To do this, all well-dated varve measurements (in this case including those

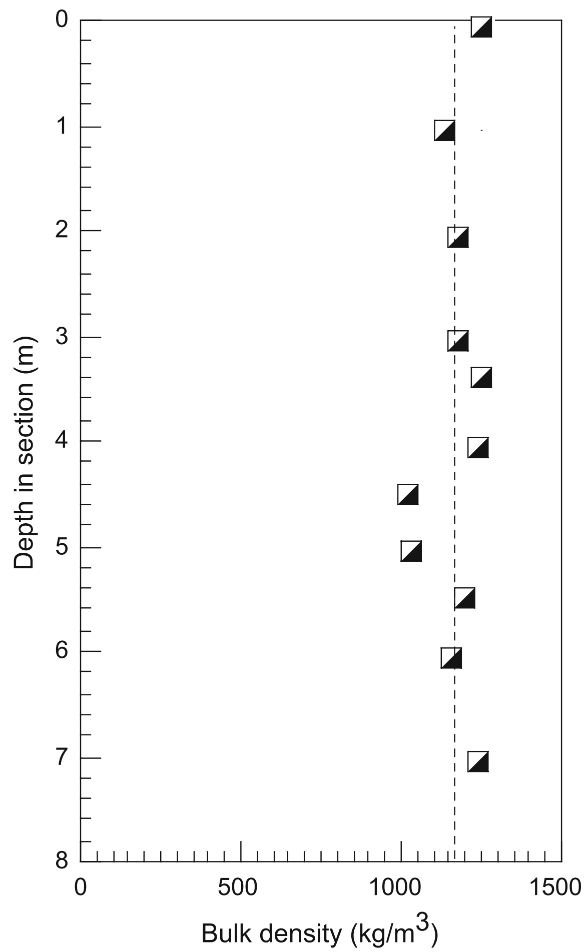


**Fig. 2** Bulk density of varved sediments at various depths (meters below former lakebed surface) from sample site M. Mean density of 11 samples (dashed line) is 1170.9 kg $m^{-3}$ (SD = 80.1 kg $m^{-3}$). Density shows no trend with depth, probably due to subaerial compaction of previously dilated shallow sediments after multiple drainage events

excluded, on the basis of textural anomalies or other criteria, from the master chronology) were separated into contiguous groups so that each group represents deposition at a single sampling site during a single shoreline occupation. The average thickness of all measurements in a group are plotted against the distance from that sampling site to the nearest glacial stream inlet at the time of that particular shoreline occupation. The results (Fig. 3) show clearly that varve thickness, and hence sediment accumulation rate, increases in a nonlinear fashion as proximity to inlets shrinks.

During the period of well-dated shoreline occupations, it is clear that the episodic drops in lake level

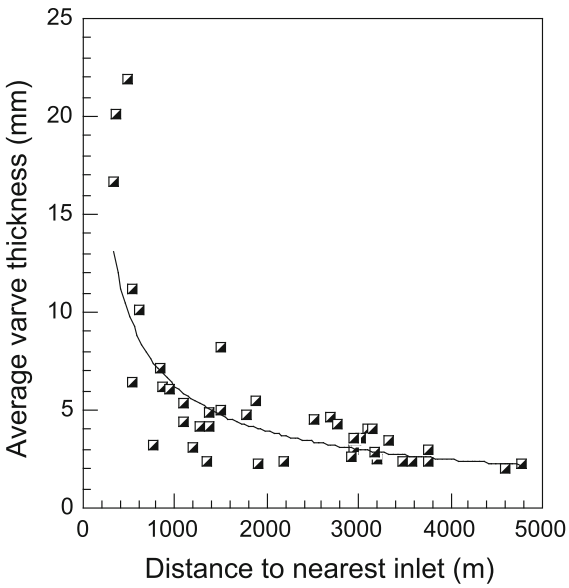


**Fig. 3** Relation between the distance separating the inlet stream and sampling site and average varve thickness. Each point ($n = 42$) represents the average varve thickness (mm) for a contiguous group of varves at one sampling site. For each point, distance from sampling site to nearest inlet (m) is based upon the position of the shoreline at the time the varves were deposited, taking into account the known history of shoreline variability. Contiguous period represented by each point ranges from 9 to 174 years (mean = 78.7 year; SD = 66.1 year). Solid line is a power-law curve fitted to show trend ($y = 622.09 * x^{-0.66662}$), $r^2 = 0.84$

have occurred in response to gradual thinning of the impounding glacier. The pace of that thinning appears to be broadly consistent with the pace of post-LIA retreat for other large glaciers in the region (Calkin et al. 2001; Wiles et al. 1999, 2002), and also with lichenometric evidence for terminus retreat of the much smaller glaciers that feed Iceberg Lake (Loso 2004). I therefore suggest that the impounding glacier—and hence, the level of Iceberg Lake—fluctuates in rough correspondence with the regional climate that drives these other glacier fluctuations. There is typically some lag, varying with glacier size, in the response of glacier thickness and terminus position to warming temperatures, but for these modestly sized land-terminating glaciers the lag is probably <15 years (Porter 1986) and thus within estimated error bounds of the varve-based age model (±4%) over century timescales. If that is true, then throughout the lake's history varves should have thickened during warm periods not only because of enhanced sediment delivery to the lake, but also because that sediment would be concentrated in a smaller lake.

The net effect of these shoreline changes is a heightened sensitivity to summer temperatures during warm periods that, when combined with the known non-linear relationships among stream discharge, suspended sediment concentration, and varve thickness (Gilbert 1975; Meade et al. 1990), contributes to the strong positive skew of the raw varve thickness measurements (Fig. 4a). To compensate for this heightened sensitivity, which violates the goal of stationarity—a constant relationship over time between climate variable and proxy response—in proxy reconstruction (National Research Council 2006), I log-transform the raw measurements from the master varve chronology. This transformation brings the time-series close to normality (Fig. 4b), though it still narrowly fails the Lilliefors Test for normality ($p = 0.0075$; Lilliefors 1967). More importantly, this transformation reduces the magnitude of changes in varve thickness when the values are large and the sensitivity of the record was presumably greater. For subsequent analysis, this transformed dataset is used as the proxy.

For the purpose of testing the correlation between the transformed varve chronology and temperature, the instrumental record is patchy and brief. Near Iceberg Lake, four stations have been recording temperatures for over 50 years (Fig. 1): Cordova (140 km from Iceberg Lake) and Yakutat (225 km) on the coastal side, and Gulkana (206 km) and Northway (252 km) on the interior side. The time period is short, but it at least overlaps completely with Iceberg Lake's occupation of a single stable shoreline: the lake dropped to its lowest (and final) stable shoreline in 1957 AD and remained stable at that level, according to local residents, National Park Service staff, and geological evidence, until it drained completely in 1999 (Loso 2004). I therefore assessed the correlation of varve thickness with station temperatures during the period 1958–1998 to avoid the confounding issue of changing lake size. I obtained temperature data from the Western Regional Climate Center and found that transformed varve thickness shows a positive correlation with mean annual temperatures from all four sites, but the relationship is stronger with the coastal sites: Cordova and Yakutat (Table 1). Datasets from these sites also have fewer missing measurements than from the

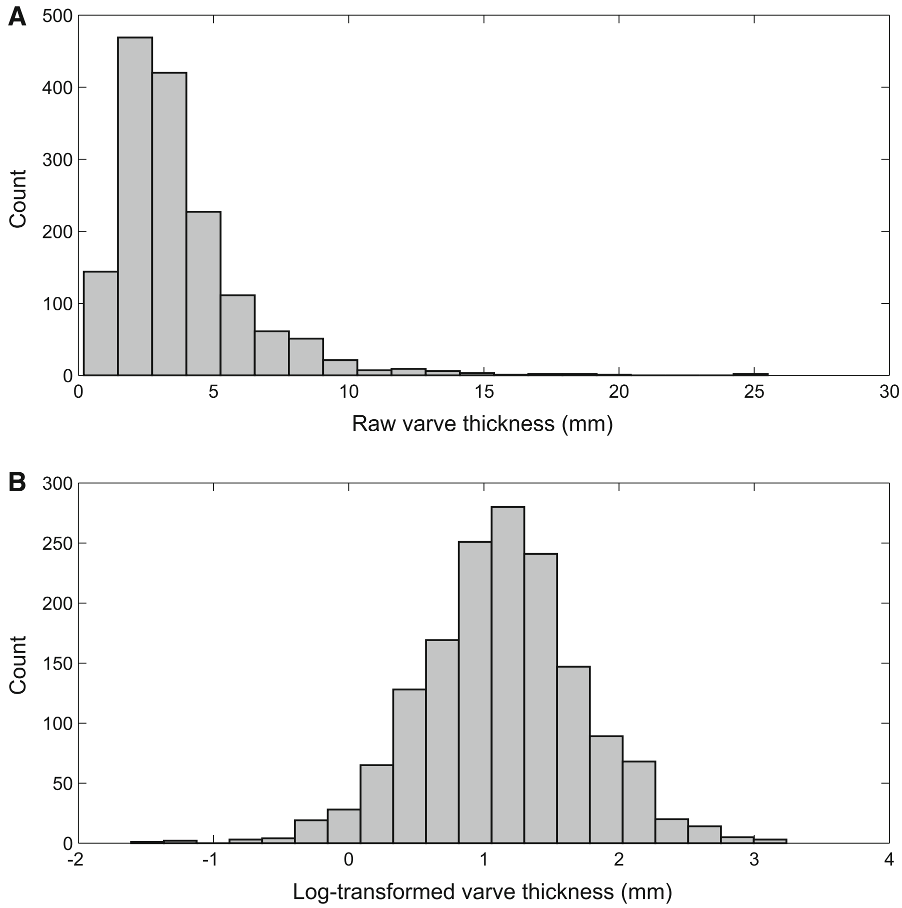


**Fig. 4** Histograms depicting distributions of raw (**a**) and log-transformed (**b**) master varve chronology. Raw data are clearly skewed and rejected by the Lilliefors test for normality ($p < 0.0001$). By visual inspection the log-transformed master varve chronology more closely approaches a normal distribution, but is also rejected by the Lilliefors test ($p = 0.0075$)

interior sites. Examining monthly values individually, the best and most consistent correlations are between transformed varve thickness and temperatures from late winter through early summer (Table 1). Correlation with combined May–June temperatures from the two coastal stations is presented in Fig. 5a; this relationship between varve thickness and peak melt-season temperatures is positive and marginally significant ($r = 0.23$, $p = 0.153$; Fig. 5a).

Use of the brief instrumental record to calibrate a reconstruction of earlier temperatures is inappropriate given the pre-1958 history of changing lake levels. Log-transformation minimizes, but does not eliminate, the impact of those changes on varve sensitivity, and significant auto-correlation in the raw varve chronology ($d = 0.647$, $p < 0.001$ for the raw values; Durbin and Watson 1950, 1951) may be due to transient, multi-year effects of lake-level changes on sediment accumulation rates. A full reconstruction should therefore be based upon a temperature history that spans all known lake levels. No instrumental record meets these requirements, but the tree-ring-based temperature reconstruction of Davi et al. (2003) does. Use of a proxy-based temperature reconstruction as the basis of a second reconstruction is unconventional, but the length of Davi et al.'s quantitative reconstruction (1593–1992) offers the distinct advantage of calibrating the Iceberg Lake varve chronology over a period that includes both the lowest and the highest known lake levels.

## Temperature reconstruction

The Davi et al. (2003) reconstruction used here is based upon correlation of maximum latewood density (from trees just inland of Iceberg Lake) with the first principal component of average late summer (July–September) temperatures at Northway, Slana, and Gulkana. This record is shorter, and less strongly correlated with the Iceberg Lake varve chronology,

**Table 1** Correlation ($r$) values comparing monthly mean temperatures from four stations to log-transformed varve thickness over the calibration period AD 1958–1998

| Station | Lat | Long | Elev (m) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cordova | 60°30′ | 145°30′ | 2 | 0.13 | 0.44 | 0.12 | 0.11 | 0.19 | 0.16 | −0.18 | −0.01 | −0.19 | −0.04 | 0.17 | −0.17 | 0.21 |
| Yakutat | 59°31′ | 139°40′ | 10 | 0.11 | 0.38 | 0.15 | 0.15 | 0.17 | 0.25 | 0.05 | 0.09 | −0.12 | −0.01 | 0.11 | −0.08 | 0.20 |
| Gulkana | 62°09′ | 145°27′ | 482 | 0.03 | 0.46 | 0.03 | 0.04 | 0.27 | 0.02 | −0.30 | −0.16 | −0.33 | −0.21 | 0.00 | −0.22 | 0.02 |
| Northway | 65°58′ | 141°56′ | 524 | 0.13 | 0.52 | −0.02 | −0.05 | 0.17 | 0.01 | −0.17 | −0.09 | −0.27 | −0.03 | 0.20 | −0.13 | 0.12 |

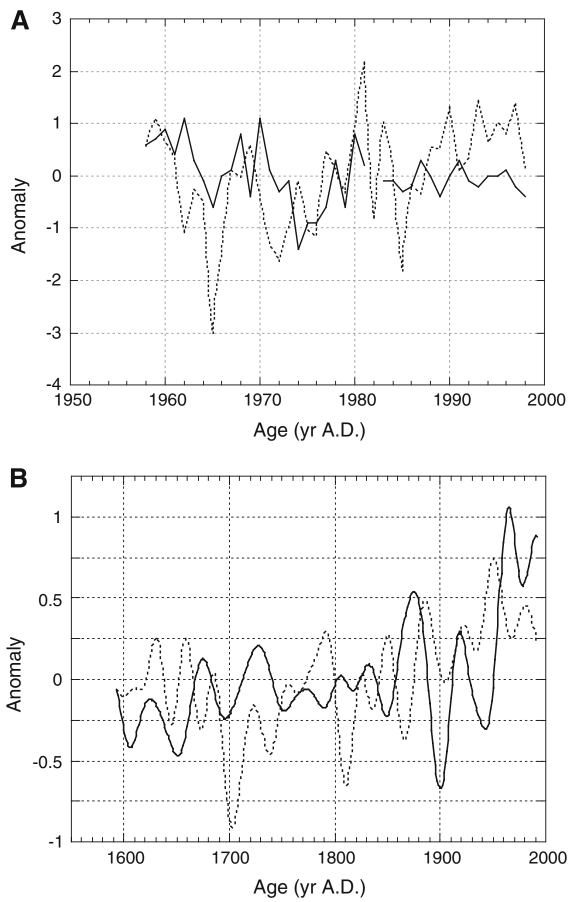


**Fig. 5** Time-series of log-transformed master varve chronology (in mm; represented by solid line in each panel) and selected temperature records/reconstructions (°C; dotted lines). All series are normalized to zero mean. Panel (**a**) compares varve thickness (mm) with average May–June temperatures (°C) recorded at Cordova and Yakutat, Alaska for 1958–1998 AD. The two annual time-series are positively correlated ($n = 40$, $r = 0.23$, $p = 0.153$). Panel (**b**) compares varve thickness with the tree-ring-based temperature reconstruction of Davi et al. (2003) for 1593–1992 AD. The two time-series in panel (**b**) are smoothed with a 24-year low-pass filter, and are positively but not significantly correlated ($n = 400$, $r = 0.24$, $p = 0.47$)

than a ring-width-based reconstruction (from the same paper: Davi et al. 2003) compared to the varve chronology in an earlier manuscript (Loso et al. 2006), but this proxy is used here because latewood density is more strongly correlated with summer temperatures than is ring width ($r = 0.73$), and because the density-based reconstruction has been validated over independent calibration and verification periods. It therefore provides a robust record of warm season temperatures. The varve chronology being regressed against latewood density is also different from the one used by Loso et al. (2006) because, as discussed previously, it has had minor errors corrected and it has also been log-transformed.

Annual measurements of varve thickness are not well correlated with Davi's temperature reconstruction, but smoothing of the two records improves the correlation. Estimated maximum dating errors in the varve chronology (±4%, or a range of 32 years over the period of overlap between these records) likely explain the poor correlation between the unsmoothed records, and justify the use of smoothed records that emphasize decadal variations. Smoothing enhances the autocorrelation already intrinsic to these records, however, so a Butterworth 24-year low-pass filter (Selesnick and Burrus 1998) was chosen as a compromise between autocorrelation ($d = 0.014$, $p < 0.001$ for the smoothed records; Durbin and Watson 1950, 1951) and the need to account for dating errors. Due in part to this autocorrelation, and in part to residual impacts of changing lake levels on the response of the log-adjusted varve chronology, the resulting correlation is positive but not significant ($r = 0.24$, $p = 0.471$; Fig. 5b).

The statistics of this correlation with proxy-based temperatures are weaker than those of the correlation with the shorter record of instrumental temperatures, but regressions of varve thickness against the two temperature records differ only in the slope of the line

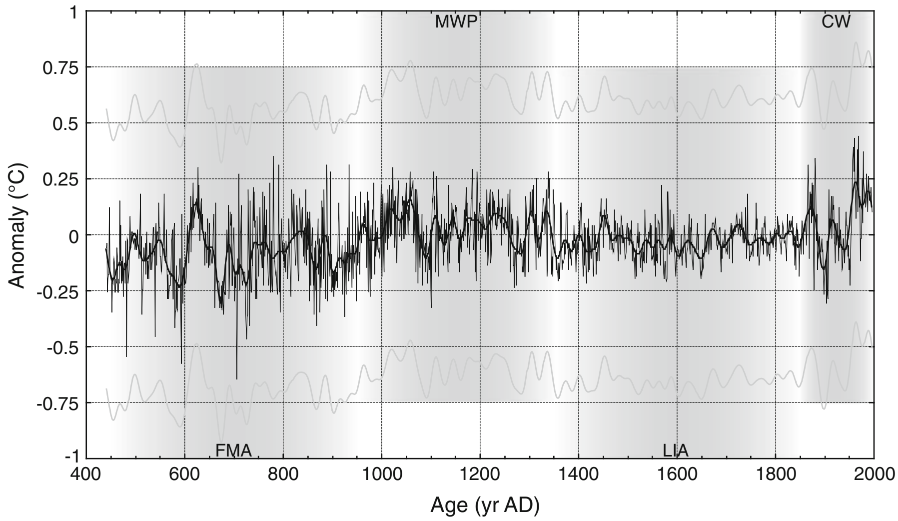


**Fig. 6** Reconstructed melt-season temperatures and 95% confidence intervals from the Bagley Icefield region based on Iceberg Lake varve thickness ($V$). Temperatures are presented as anomalies from reconstructed mean temperatures of the last millennium (1000–1998 AD) and the raw values (thin line) have been smoothed (bold line) with a 24-year low-pass filter. Regression based upon temperature reconstruction (*TD*) of Davi et al. (2003) where $\mathrm{TD} = 9.905 + 0.226 * \ln(V)$ ($r = 0.24$, $p < 0.471$). General climatic intervals referred to in text: FMA = first millennium AD; MWP = Medieval Warm Period; LIA = Little Ice Age; CW = contemporary warmth

($0.445 * \ln(V)$ based on instrumental temperatures and $0.226 * \ln(V)$ for the latewood density-based reconstruction, where $V$ is varve thickness). A temperature reconstruction based upon the longer record therefore differs only on the basis of the reduced sensitivity of varve thickness to temperature, and hence in the amplitude (but not the timing or sign) of modeled temperature variations. Since sensitivity to a range of lake levels is precisely what motivates use of the longer record, I base my temperature reconstruction upon the less significant relationship between varve thickness and the proxy-based temperature record, and rely upon the instrumental temperature record to corroborate that relationship, consistent with the theoretical argument that varve thickness in this heavily glacierized basin should at least partly reflect melt-season temperatures.

Using simple linear regression to predict the relationship between varve thickness and temperature ($\mathrm{TD} = 9.905 + 0.226 * \ln(V)$, $r = 0.24$, $p < 0.471$, where TD and $V$ are smoothed versions of the Davi temperature reconstruction and Iceberg Lake varve thickness, respectively), reconstructed melt-season temperatures for the Bagley Icefield region are presented in Fig. 6 as anomalies from the reconstructed mean temperatures of the last millennium. Temperatures are presented as raw values and after smoothing with a 24-year low-pass filter. The confidence interval shown in Fig. 6 is calculated as $\pm 2$ * standard error. A more robust calculation that incorporates error from the proxy-based dependent variable, and also takes into account the effects of autocorrelation, is possible but unnecessary given that with this weak regression the 95% confidence interval is already quite broad (Fig. 6). Gaps in the reconstruction due to missing varve thickness values ($n = 21$) do not show up at the scale of the plotted reconstruction, but are evident in the tabulated annual temperatures (Electronic Supplementary Materials, S2).

The varve-based temperature record shows that, since 442 AD, the warmest inferred melt-season temperatures occurred in the late twentieth century and the coldest temperatures occurred in the late sixth century. The total range of reconstructed temperatures over that time was 1.1°C with a standard deviation of 0.13°C (Fig. 6). For comparison, a temperature reconstruction based upon the more sensitive relationship between varve thickness and 40-year instrumental temperatures would predict a range of 2.2°C and standard deviation of 0.26°C. Temperatures were generally at or below the last millennium average from the beginning of the record until 950 AD, with less marked cooling evident from 1350 to 1850 AD. Temperatures were generally higher than average from 950 to 1350 AD, and after a brief rise around 1850 AD reached their highest levels after 1950 AD. These general trends are interrupted by occasional excursions, including for example a sharp rise in inferred temperature after 600 AD in the midst of what is otherwise the coldest period in the record (Fig. 6).

The trends just noted are based upon a significant but relatively weak regression against a proxy-based temperature record, and the confidence intervals are broad relative to these inferred changes (Fig. 6). Especially given the enhanced autocorrelation introduced by smoothing, there is substantial uncertainty in this temperature reconstruction, and summer temperatures clearly explain only a portion of the variability in the varve chronology. Two lines of evidence suggest that the general patterns and magnitudes of these inferred changes are real, however.

First, varve thickness shows a positive correlation with a variety of temperature records at multiple timescales, including not only the latewood-density record used for the reconstruction and the more significant (though shorter in length) correlation with coastal May–June temperatures measured at Cordova and Yakutat (both mentioned previously), but also with the Northern Hemisphere temperature reconstruction of Mann and Jones (2003), and (qualitatively) with the two-millennium Alaskan temperature reconstructions of Hu et al. (2001) and McKay et al. (2008). Second, geological evidence from the Iceberg Lake basin provides support for the reconstructed temperature record. As discussed in more detail in Loso et al. (2006), in several seasons examining broad outcrops in the dry lakebed no stratigraphic evidence was found for jökulhlaups occurring before 1999. This argues strongly for persistence of the ice dam throughout the Medieval Warm Period, and hence supports the varve-based inference that recent years have seen greater sustained warmth than the MWP. Independent of that argument, lichenometric dating of alpine glaciers at the head of the Iceberg Lake basin shows that post-LIA terminus retreat began in the early 1800s and accelerated in the mid 1900s (Loso 2004; Loso and Doak 2005). Assuming that these glaciers fluctuated, at least partly, in response to summer warming, the independent varve-based temperature record is consistent with the behavior of these small glaciers.

I attribute the noisy relationship between varve thickness and temperature to the pervasive impacts of nearby glaciers. Over the period of record, fluctuations of the impounding glacier have controlled episodic changes in lake size, clearly altering sedimentation patterns in the lake. I have accounted for this factor by log-transforming the varve thickness record and calibrating the reconstruction with a stationary temperature record long enough to span the range of known lake levels. Nonetheless, episodic lake-level changes are likely responsible for some of the weakness in these observed correlations. Meanwhile, fluctuations of the small glaciers upstream of the lake may have affected sediment production and availability for transport (Karlén and Matthews 1992; Loso et al. 2006). I have argued that lags in the responses of both the upstream and impounding glaciers to temperature are small relative to the magnitude of likely errors in the age model, but these glaciers and their effects on sedimentation patterns nonetheless fluctuate slightly out of phase with summer temperatures and with each other, distorting the fidelity of varve thickness to direct impacts of summer temperatures on melt-induced sediment transport. On the basis of all this evidence, I suggest that the smoothed reconstruction presented here (Fig. 6) accurately portrays trends in melt-season temperatures on the margin of the Bagley Icefield, acknowledging that the detailed timing or magnitude of any single excursion in the reconstruction should be interpreted cautiously.

### Climatic interpretation

Four climatically distinct periods recognized broadly by other investigators are evident in the Iceberg Lake record between 442 and 1999 AD: early cold in the first millennium AD (FMA), a Medieval Warm Period (MWP), the Little Ice Age (LIA), and contemporary warmth (Fig. 6). The coldest temperatures of the entire period (0.25°C below the last millennium mean) occur just before 600 AD, in the middle of a broad cold period between 450 and 950 AD. At Iceberg Lake, this period was colder than the subsequent LIA, and other records corroborate this. Both Farewell Lake, on the interior side of the Alaska Range, and Hallet Lake, near Valdez, had

FMA minima around 550 AD that were colder than their respective LIA temperatures (Hu et al. 2001; McKay et al. 2008). Like the Iceberg Lake record, the Hallet Lake chronology also shows a brief (~50 year) warming spell interrupting the FMA cold period around 650 AD, though the anomaly is of smaller magnitude (McKay et al. 2008). Resolution of the Farewell Lake record may be too low to record a 50 year event (Hu et al. 2001). Corroborating the evidence for this cold period, glaciers throughout Pacific North America advanced in an interval centered between 400 and 700 AD (Reyes et al. 2006). In coastal Alaska specifically, FMA ice margin advances comparable in extent to the LIA are concentrated around 500–600 and 700–800 AD, and there is evidence, in the form of multiple outwash deposits, for multiple advances within that interval (Wiles et al. 2008). Collectively, this evidence suggests that the FMA in southern Alaska may have been colder, and marked by more variability, than previously recognized.

Temperatures at Iceberg Lake were generally warmer than the long-term average between 950 and 1350 AD, although with significant variability that includes brief intervals of cooling around 1100 and 1275 AD (Fig. 6). During MWP at Iceberg Lake, the peak melt-season temperature—just after 1050 AD—was more than 0.45°C warmer than the coldest part of the preceding FMA. Many investigators have concluded that there was too much spatial and temporal variability in the expression of pre-LIA warmth to warrant designation of a single, globally coherent MWP (Bradley et al. 2003; Crowley and Lowery 2000; Jones and Mann 2004), but the strong steady pulse of medieval warming at Iceberg Lake between 1000 and 1100 AD clearly falls within the period of consistent positive temperature anomalies from a multiproxy Northern Hemisphere reconstruction (~890–1170 AD, Osborn and Briffa 2006). It also overlaps with warming seen at other Alaskan sites: the MWP appeared slightly earlier at Farewell Lake (~850–1200 AD, Hu et al. 2001), Wiles et al. (2008) found evidence of forest growth in front of retreated glacier margins between the 900s and 1200s AD, and subfossil trees were growing faster on the Alaska coast between 900 and 1100 AD (D'Arrigo et al. 2006). In contrast, peak temperatures appear a few centuries later in the southern Alaska temperature reconstruction of McKay et al. (2008).

The LIA manifests itself in the varve record as a long interval of moderately cooler-than-average temperatures beginning in 1350 AD and lasting through 1850 AD (Fig. 6), starting earlier and lasting longer than the LIA in hemispheric temperature reconstructions (~1580–1850 AD, Osborn and Briffa 2006). Brief warm intervals separate the LIA, at Iceberg Lake, into three cool periods from 1350–1450, 1500–1675, and 1750–1850 AD. Forests overrun by glaciers provide independent evidence for early initiation of a three-part LIA in southern Alaska, and although the detailed timing of the first part differs from that of the varve record, there is close agreement between the varve-based reconstruction and their observation of LIA maximum glacier advances around 1650 AD (Wiles et al. 2008). The Farewell Lake record also shows maximum LIA cooling around 1650 AD, but without an early onset for the LIA (Hu et al. 2001). Likewise, the Hallet Lake record has no early LIA onset and a cooling event in the 1600s, but the deepest LIA cooling is in the 1800s AD (McKay et al. 2008). It appears, on the basis of these few records, that throughout southern Alaska there is as much regional inconsistency in the reconstructed timing and magnitude of LIA cooling as there is for MWP warming, with the greatest variability during the interval of time between those periods (roughly 1100–1500 AD). In any case, these other reconstructions agree with the varves in showing that the last consistently cool temperatures of the LIA were interrupted by warming in the mid-1800s, similar to the onset of post-LIA warming recorded by nearby tree rings (Davi et al. 2003) and by lichenometric ages on young moraines in the Wrangell Mountains (Wiles et al. 2002), in the nearby Granite Creek watershed (Blair 2005), and in the Iceberg Lake drainage basin (Loso 2004).

Warming since 1850 AD has been episodic, interrupted by a return to cool temperatures around 1900 AD before finally climbing to the highest levels in the period of record after 1950 AD (Fig. 6). The interval of cooling around 1900 AD is in phase with, but more dramatic than, a decline in tree-ring-based temperatures from the Wrangell Mountains (Davi et al. 2003). Late twentieth century warming peaks with a positive 0.3°C anomaly in the mid-1970s, 0.4°C warmer than the coolest part of the LIA and slightly (0.1°C) warmer than the warmest part of the MWP. As previously noted, the confidence intervals on this temperature reconstruction are too broad to claim, on the basis of these data alone, that contemporary warming is more intense than that of the MWP. As with other trends evident in this chronology, however, geological data and other proxy reconstructions argue for a confident interpretation. Specifically, the evidence for a warmer late twentieth century has already been discussed: the 1999 regime shift from stable drainage over a bedrock spillway to quasi-annual catastrophic drainage and partial refilling has no precedent since 442 AD. Despite clear evidence for sustained warmth during the MWP, the impounding glacier never thinned enough to fail. This provides strong evidence that the late twentieth century warming recorded by these varves, though only slightly greater than that of the MWP, truly is unprecedented over the 1500+ years of the record.

## Conclusion

Iceberg Lake sits right on the edge of the largest nonpolar icefields on Earth, yet fortuitously survived late Holocene glacier advances that destroyed the sedimentary records of many similar lakes. As expected in a snow- and ice-melt-dominated lake, varve thickness exhibits a weak and marginally significant positive correlation with a short record of melt-season temperatures measured at two distant coastal stations. Over the longer term the sensitivity of varve thickness to melt-season temperatures probably changes in response to episodically changing lake levels, so summer temperatures at Iceberg Lake were therefore reconstructed by regressing log-transformed varve thickness against a longer, proxy-based temperature record that encompasses the full range of lake levels. The smoothed, quantitative temperature reconstruction is statistically weak and has large confidence intervals relative to the magnitudes of inferred temperature changes ($\sim$0.5°C), but the record's consistency with geological evidence from within the basin, with 40 years of nearby instrumental temperatures, and with other regional proxy reconstructions implies that the varve-based temperature reconstruction depicts real, albeit poorly constrained, trends in melt-season temperatures on the margin of southern Alaska's coastal icefields.

The temperature reconstruction suggests four primary conclusions. First, temperatures during the middle of the first millennium AD, centered on about 600 AD, were colder than the subsequent Little Ice Age and marked by significant variability. Second, the Medieval Warm Period is evident in the record, and based on that and other evidence I suggest that it most clearly and consistently manifests itself in southern Alaska during the eleventh century AD. Third, and consistent with many other studies, I conclude that the deepest cold of the Little Ice Age occurred around 1650 AD, after over a century of sustained below-average temperatures. Finally, temperatures in the late twentieth century exceed those of the MWP. The varve chronology records only a small difference in absolute temperature, but that difference has had at least one important effect, forcing shrinkage and ultimate failure of the ice dam that impounds Iceberg Lake, leading to the lake's recent demise.

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