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Reconstruction of climate and glacial history based on a comparison of varve and tree-ring records from Mirror Lake, Northwest Territories, Canada

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ABSTRACT

This study compared the hydroclimatic signals recorded in annually laminated (varved) sediments and tree rings within a small study area in the Selwyn Mountains of the southwestern Northwest Territories/southeastern Yukon Territory border region of Canada. The records were located immediately adjacent to each other and within 6 km of instrumental meteorological and hydrometric records, which permitted a detailed analysis of climate in the area from AD 1704 to 1996. This study explored the challenges of annually-resolved multi-proxy hydroclimate analyses and examined how best to interpret the climate record given the differences in proxy formation and the respective signals. The high-frequency (annual) variability from both proxies showed a good match for some parts of the record (e.g., mid-1700s and much of the 1900s) but revealed different sensitivities at other times (e.g., 1800s). However, both records contained a common low-frequency (decadal) summer climate signal. Glacier dynamics influenced varve formation through altered sediment availability during the inferred Little Ice Age (LIA) maximum ice stand in the catchment from AD 1778 to 1892 and subsequent recession after this maximum. As a result of reduced LIA sedimentation, July mean temperatures reconstructed from varve thickness during the 1800s were underestimated compared to the tree-ring estimates. Other instances of low-frequency divergence were apparent, particularly during parts of the twentieth century, despite the overall similarities. The extended varve record also provided a glacial history for the southern Selwyn Mountains, indicating probable glacier advances during AD 1300–1450 and AD 1600–1670, maximum ice stand during the 1800s, followed by twentieth-century recession.

1. Introduction

Proxy climate indicators are useful tools to develop a long-term perspective of past environmental conditions and natural climate forcing mechanisms. High-resolution records, such as annually-laminated (varved) lake sediments and tree rings, provide detailed climate information and an inherent annual chronology. While some studies have focused on multiple proxy climate indicators from the same record (e.g., biotic and abiotic records within a single lacustrine sediment core), few studies have attempted to compare different annually-resolved proxy sources from a particular location or region (e.g., Luckman, 2000; Koch et al., 2004; Solomina et al., 2005). Some of these studies (e.g., Overpeck et al., 1997; Jones et al., 1998; Mann et al., 1998, 1999) have synthesized multiple records to gain an overall view of regional or hemispheric climate variability but have not compared individual records in detail. Comparison of different proxies is a potentially effective means for studying past climate variability because it permits the verification of past changes from multiple sources. This approach also allows for recognition of dissimilar sensitivities between proxy classes, analysis of the different controls over record formation and examination of a proxy's validity (Lotter, 2003).

This study reports the comparison of varve and tree-ring proxy records obtained simultaneously from near Tungsten, Northwest Territories, Canada. The goal of this study was to carry out a detailed assessment of past climate variability from two different proxy records and compare them to identify mechanisms that generated differences between the records. The close proximity of the records to instrumental meteorological and hydrometric data provided insight into the climate signals recorded by these two proxies and the potential to obtain detailed paleoclimate information from multiple sources in the same study area.

2. Regional setting

The study area (62°02′N, 128°15′W) lies in the southern Selwyn Mountains of the Northwest Territories and Yukon Territory

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border region. This mountainous environment (up to 2100 m above sea level (asl)) is within the zone of discontinuous permafrost (Sloan and Dyke, 1998). Vegetation consists of black spruce (*Picea mariana*) and white spruce (*Picea glauca)* to treeline (ca. 1500 m asl), dwarf birch (*Betula glandulosa*) and reindeer moss (*Claddonia* spp.) at high elevations, and sedges (*Carex* spp.) and moss (*Sphagnum* spp.) in valley bottom bogs (Jackson, 1987).

Mirror Lake (5.4 ha) is located 6 km north of Tungsten, Northwest Territories, within a 50 km^2 catchment (Fig. 1). The lake morphometry consists of a single, flat-bottomed basin with a maximum depth of 13 m. In summer, the lake is nearly isothermal (based on data from August 2002) and the outlet is the primary headwater source for the Flat River. The catchment contains 5 km^2 of cirque glaciers that direct meltwater down Kuskula Creek to Mirror Lake. This creek appears to provide most of the lake's sediment input each year, based on field and aerial photograph observations. The northern portion of the catchment is not glacierized and contains the only other major inflow to the lake. Continuous records of temperature and precipitation were collected at Tungsten from AD 1967 to 1990 (Meteorological Service of Canada, 1999) and hydrometric records were available for the Flat River (downstream of Mirror Lake at Tungsten) from AD 1974 to 1987 (Environment Canada, 2000) (Fig. 1). The meteorological data from Tungsten had relatively few data gaps. For the climate parameters examined, when over half of the daily measurements in a month were absent, the monthly value was left as a data gap. This occurred in only 9% of monthly measurements within the mean and maximum temperature records from AD 1967 to 1990. Additionally, if any month within a season was missing for a given climate parameter, the seasonal value was not calculated.

3. Materials and methods

3.1. Lake sediment cores

In August 2002, five surface sediment cores (<20 cm) and two long sediment cores (138 and 175 cm) were obtained with gravity (Boyle, 1995) and percussion (Reasoner, 1993) coring systems, respectively (Fig. 1). The surface cores were dewatered and transported in vertical orientation. In the laboratory, the cores were split lengthwise, photographed, and subsampled. The uppermost 42 cm of sediment in the proximal long core was sampled for ^{137}Cs determinations. The samples were oven dried at 50 °C for 24 h and crushed before the gamma spectra were measured for 80,000 s in an ORTEC gamma counting system to measure ^{137}Cs activity. Overlapping sediment samples were removed from the cores, freeze dried and embedded with Spurrs epoxy resin (Lamoureux, 2001). Thin sections were prepared from the hardened sediments, scanned at 600 dpi, and compiled in stratigraphic position in CorelDraw 9 for lamina identification, counts, and measurements. Varve thickness was measured to a precision of 0.001 mm. The image composites and standard microscopy were both used to analyse the sedimentary record. Varves were measured on at least three separate occasions in the surface cores, the distal long core and upper section of the proximal long core. The surface core records were compared with the upper portion of the distal long core to determine points of overlap and join the two records. The final thickness measurement for each varve was included in the final varve chronology. The upper sedimentary record was verified with comparisons between the available sediment cores, while the lower sedimentary record could not be cross-correlated due to disturbance in the proximal long sediment core.

3.2. Tree cores

Coincident with the lake sampling, tree rings were collected from three sites in close proximity to Mirror Lake (Fig. 1 and Table 1). The sampling sites, "Grizzly Ridge" (GR, 1500 m asl), "Lower Kuskula Creek" (LKC, 1200 m asl) and "Upper Kuskula Creek" (UKC, 1400 m asl) are located 0.7 km south, 2 km east and 3.5 km east of Mirror Lake, respectively. Generally the oldest and most temperature-sensitive trees are found near the latitudinal and altitudinal limits

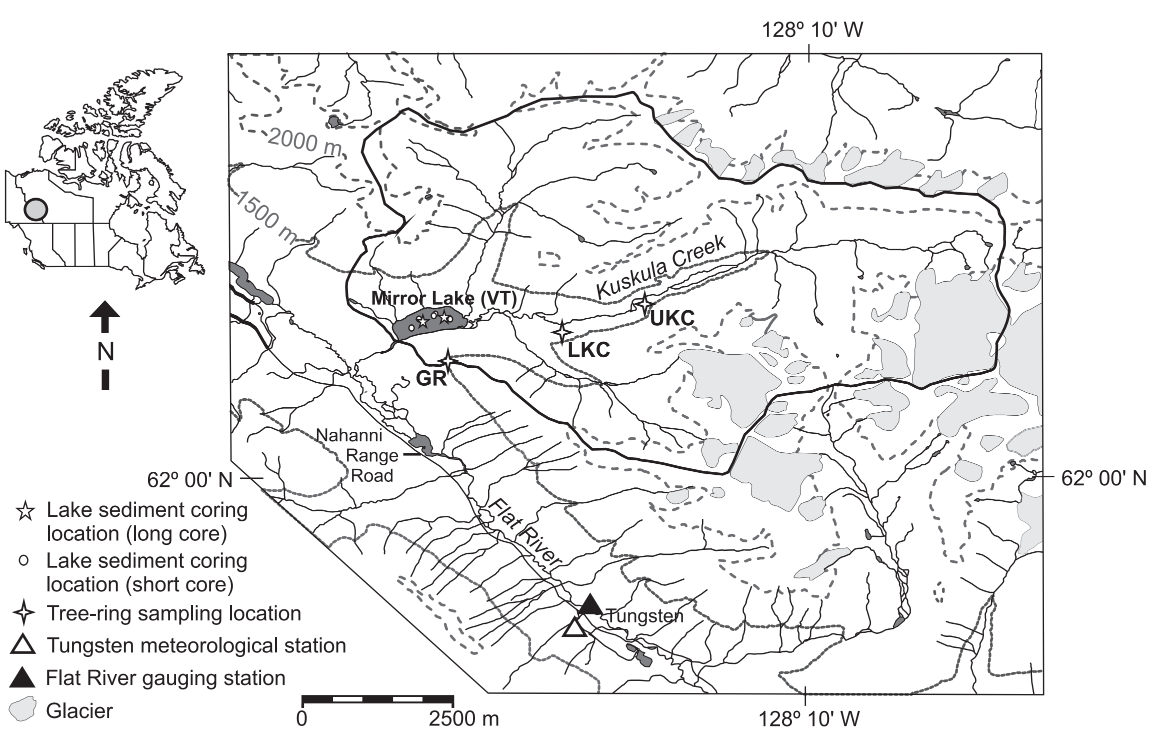

Fig. 1. Mirror Lake study site map showing the catchment outline (thick black line), sampling locations and the meteorological and hydrometric stations at Tungsten (modified from Natural Resources Canada, 2002a, b).

Table 1
Summary statistics for the standard tree-ring index chronologies

ID[a]	Name	n[b]	Span (yr AD)	r[c]	ms[d]	EPS[e]	AC(1)[f]
GR	Grizzly Ridge	26	1703–2001	0.57	0.20	0.90	0.44
LKC	Lower Kuskula Creek	50	1666–2001	0.54	0.16	0.88	0.69
UKC	Upper Kuskula Creek	31	1709–2001	0.56	0.19	0.81	0.76

[a] Abbreviation used for each site in this paper.
[b] Number of tree-ring series.
[c] Mean correlation among series.
[d] Mean sensitivity (a measure of the high-frequency variation).
[e] Expressed population signal.
[f] First-order autocorrelation coefficient.

of tree growth, where heat is the limiting growth factor and the open canopy tends to inhibit the spread of crown fires (Jacoby and D'Arrigo, 1989). At the three sites, cores were extracted from two opposing radii near the base of 13–25 living trees using a 5.1 mm Haglof increment borer. The tree rings were processed in the University of Regina Tree-Ring Laboratory following standard procedures (Cook and Kairiukstis, 1989). Ring width was measured with a precision of 0.001 mm. Common patterns of annual growth were visually matched among the ring-width series from each site and this crossdating was checked using the program COFECHA (Grissino-Mayer, 2001). The program ARSTAN was used to standardize the tree-ring data and compute dimensionless ring-width indices. The dated chronologies were averaged, using an algorithm that minimizes the effect of outliers, to generate the mean standard (STD) index chronology (Cook et al., 1990). A negative or modified negative exponential curve that is asymptotic with the horizontal axis was chosen to remove the age/size-related trend for most series. A 100-year cubic smoothing spline with 50% variance cutoff was applied to a few series with growth trends other than negative exponential. The negative exponential detrending option is considered to be conservative and is likely to retain most of the low-frequency climatic information (Cook et al., 1990). Autoregressive modeling was applied to the standard chronology to produce a stationary residual (RES) index chronology.

The tree-ring chronologies span the period AD 1666–2001 (Table 1). One measure of chronology strength is the mean correlation among the series from a site. The coefficients in Table 1 are significant ($p < 0.01$) and very similar among the three sites. Mean sensitivity is an index of interannual variability. The GR chronology has the most high-frequency variation implying the strongest external (climate) forcing of ring-width variability. Expressed population signal (EPS) measures the quality of tree-ring data in terms of signal to noise. The EPS for the Upper Kuskula Creek (UKC) chronology (0.81) is slightly below the 0.85 threshold considered desirable for dendroclimatic data (Briffa and Jones, 1990). For the GR and LKC chronologies, an EPS > 0.85 is achieved after 1840 and 1759, respectively. Applying the common but less rigorous subsample strength (SSS) statistic, the 0.85 threshold is exceeded after 1781and 1723, respectively.

Serial autocorrelation is typical of tree-ring series and reflects the persistence of growth rates from 1 year to the next. The first-order autocorrelation coefficients indicate a much lower autocorrelation for the GR standard chronology than for the ring-width data from the two Kuskula Creek sites (Table 1).

4. Results

4.1. Varve hydroclimate record

The Mirror Lake sedimentary record was laminated throughout and primarily composed of silt and clay couplets (Fig. 2). Detailed

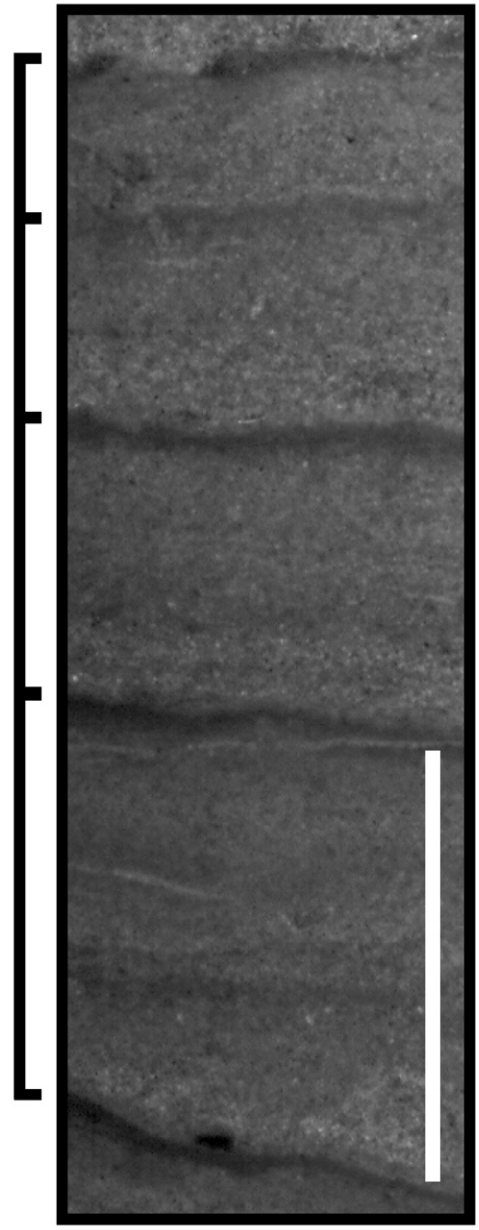

Fig. 2. Image of typical varves within the Mirror Lake sedimentary record scanned at 2400 dpi from a thin section. Varve boundaries are delineated on the left side of the image and the white scale bar represents 3 mm. The image's tone was adjusted using CorelDraw X3.

characterization of the laminae and sedimentological descriptions can be found in Tomkins and Lamoureux (2005). Strongly seasonal sedimentation in the lake and sediment structure suggested that the couplets represented annual accumulations of sediment (varves). Clastic varves are common in proglacial lakes (e.g., Gilbert, 1975; Smith, 1978; Leemann and Niessen, 1994; Cockburn and Lamoureux, 2007) and independent radioisotope (^{137}Cs) dating of the Mirror Lake sedimentary record verified that the lamina couplets were varves. Peak ^{137}Cs fallout from the atmosphere occurred in AD 1963 (Appleby, 2001) and the depth of the highest ^{137}Cs decay determinations within the Mirror Lake sediments corresponded to the depth of the AD 1963 varve year (Tomkins and Lamoureux, 2005). As such, both sediment structure and independent radioisotope measurements indicated that varves were present. Given the high sediment supply available for transport due to glacial activity in the catchment, there is no reason to suspect any interruptions in varve sedimentation and detailed sedimentological analyses of the sedimentary record revealed no evidence for such hiatuses.

Two main varve structures were found within the sedimentary record. One type had a simple couplet structure, composed of a silt unit (deposited during the melt season) and a clay cap (deposited during the winter when ice cover permits clay to settle from suspension). The second varve type contained two prominent silt units, divided by a thin layer of clay or fine silt, and capped by clay. In a similar setting, Smith (1978) noted two clearly defined silt units during years with thick catchment snowpacks and two distinct melt peaks. Tomkins and Lamoureux (2005) also found varves with two primary silt units at Mirror Lake in years following heavy winter snowpacks, and noted multiple discharge peaks in July (nival and glacial melt) and August (glacial melt) immediately downstream in the Flat River. Although climate reconstruction from the Mirror Lake varve record is complicated by the interaction between melt season temperatures and snowpack, melt season temperatures are the dominant influences on varve thickness (Tomkins and Lamoureux, 2005).

A continuous varve thickness (VT) chronology extending from AD 1390 to 1996 was developed (Tomkins and Lamoureux, 2005). During subsequent analysis, a varve (AD 1925) was found to be missed in the original count, and hence we report a chronology that covers AD 1389–1996 (Fig. 3). Correlation analysis of the varve thickness record and meteorological data (temperature and precipitation) from Tungsten indicated significant correlations between varve thickness and several monthly and seasonal (June, July and August or combinations of these 3 months) mean and maximum temperatures (Table 2). The strongest influence on varve thickness observed for the available AD 1967–1990 record was summer maximum temperature (mean value of daily June, July and August maximum temperatures; $r = 0.76$, $n = 22$, $p < 0.01$) (Table 2). When climate influences on varve thickness were examined on a decadal scale, the strongest relationship during AD 1970–1980 was with July mean temperature ($r = 0.94$, $n = 11$, $p < 0.01$). August temperature was not a statistically significant influence on varve thickness during the 1970s. However, during AD 1981–1990, August mean and maximum temperature records had stronger relationships (mean: $r = 0.79$, $n = 10$, $p < 0.01$, maximum: $r = 0.88$, $n = 10$, $p < 0.01$) than corresponding July temperature records (mean: $r = 0.67$, $n = 9$, $p = 0.05$, maximum: $r = 0.71$, $n = 9$, $p = 0.03$). The increased influence of August temperatures on varve sedimentation coincided with substantially higher winter snowfalls at Tungsten in the 1980s that resulted in delayed glacial discharge in the Flat River from Mirror Lake (Tomkins and Lamoureux, 2005).

Table 2
Summary correlation statistics of the relationships between the Mirror Lake varve thickness (VT), unlagged Grizzly Ridge (GR(t)) and Lower Kuskula Creek (LKC(t)) tree-ring residual width series and climate data from Tungsten, NWT, during the period of instrumental records (AD 1967–90) and two selected periods (AD 1970–1980 and 1981–1990) after Tomkins and Lamoureux (2005)

Period (yr AD)	Temperature variable	VT			GR(t)			LKC(t)		
		r^a	n^b	p^c	r^a	n^b	p^c	r^a	n^b	p^c
1967–1990	July mean	0.52	22	0.01	0.64	22	<0.01	0.40	22	0.06
	July maximum	0.52	23	0.01	0.57	23	<0.01			
	August mean	0.59	22	<0.01						
	August maximum	0.59	24	<0.01						
	Summer mean	0.74	20	<0.01	0.47	20	0.04			
	Summer maximum	0.76	22	<0.01	0.51	22	0.02	0.42	22	0.05
1970–1980	July mean	0.94	11	<0.01	0.89	11	<0.01	0.72	11	0.01
	July maximum	0.84	11	<0.01	0.80	11	<0.01			
	Summer mean	0.74	10	0.01	0.69	10	0.03			
	Summer maximum	0.77	10	<0.01	0.70	10	0.02			
1981–1990	July mean	0.67	9	0.05	0.72	9	0.03			
	July maximum	0.71	9	0.03	0.67	9	0.05			
	August mean	0.79	10	<0.01						
	August maximum	0.88	10	<0.01						
	Summer mean	0.85	9	<0.01						
	Summer maximum	0.94	9	<0.01						

Only relationships significant at $p = < 0.06$ are listed.
[a] Correlation coefficient (r).
[b] Sample size (n).
[c] Significance level (p).

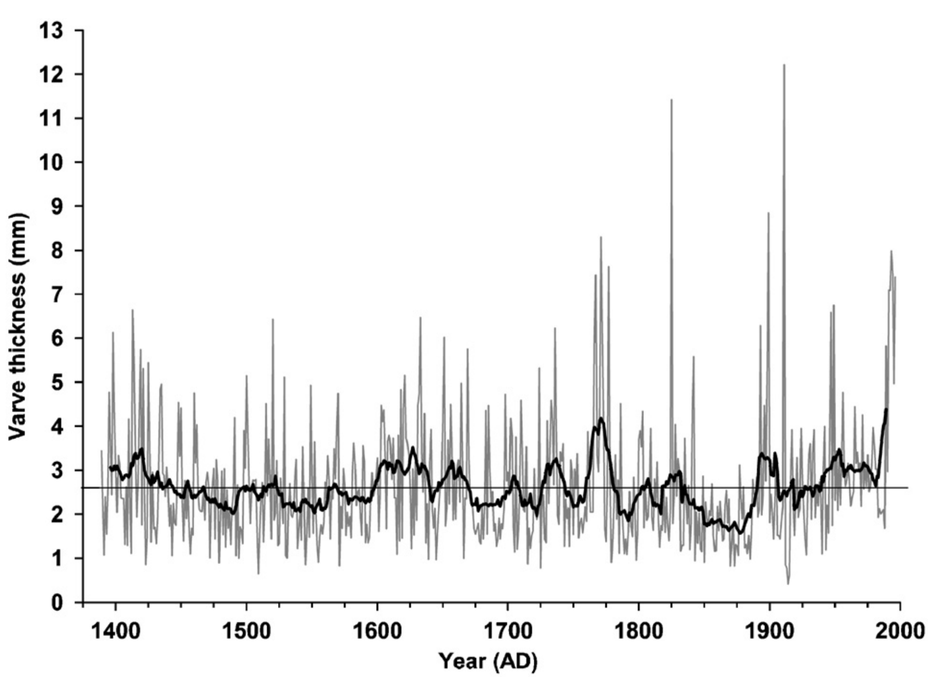

Fig. 3. Mirror Lake varve thickness series and 15-year unweighted moving mean (thick black line). Mean varve thickness for the series is 2.6 mm (horizontal thin black line).

The temperature series developed from the varve thickness chronology for the purposes of this study focussed on July mean temperature (i.e., the mean monthly value of July mean temperature each year). This climatic variable was chosen for comparison with the temperature model created with the tree rings, as these records most closely corresponded to July mean temperature at Tungsten. July is the warmest month of the year at Tungsten and typically has the highest discharge in the Flat River below Mirror Lake (Meteorological Service of Canada, 1999; Environment Canada, 2000), which indicates that it is a time of high nival and glacial melt. Therefore, this month is an important time for both tree growth and varve formation. Although this variable was not most strongly related to the varve thickness record (AD 1967–1990) through linear regression ($r^2 = 0.27$, $r_a^2 = 0.23$, $n = 22$, $p = 0.01$), the varve thickness record was consistently correlated with summer temperature measures and maintained significant relationships with July mean temperature (Tomkins and Lamoureux, 2005) (Table 2).

4.2. Tree-ring climate record

A proxy climate record was independently constructed for the Mirror Lake area by identifying tree-ring predictors that correlated with climate data from Tungsten and using the best predictors in a tree-ring model that was calibrated and validated using the same instrumental climate data. A correlation analysis was based on monthly temperature and precipitation data and the residual index chronologies from the three tree-ring sites. The residual indices were produced from standardized ring-width data by autoregressive modeling to remove the serial autocorrelation that can represent growth persistence as a function of tree physiology. Because growth trends can persist as a function of climate, additional tree-ring predictors were formed by lagging the residual chronologies forward (t+1) and backward ($t-1$) by 1 year. As expected, the highest correlations between tree-ring and climate variables were ring-width and summer temperature in the same year. There were lesser but significant ($p<0.05$) correlations when the tree-ring data were lagged by 1 year. The strongest relationship was between July mean temperature and the unlagged Grizzly Ridge (GR(t)) tree-ring data ($r = 0.64$, $n = 22$, $p<0.01$; Table 2). The correlations with July mean temperature were significant but much lower for the other two tree-ring chronologies, with correlation coefficients of 0.40 ($n = 22$, $p = 0.06$) and 0.37 ($n = 22$, $p = 0.09$) for the unlagged Lower Kuskula Creek (LKC(t)) and Upper Kuskula Creek (UKC(t)) records, respectively.

The correlation analysis results are consistent with the varve chronology statistics (Table 2). Our interpretation of these statistics was that the GR tree-ring data had the highest fidelity and strongest signal. The reduced correlation of summer temperature with tree-ring residual width at the LKC and UKC sites may reflect their location near the limit of tree growth in the bottom of the high elevation valley of Kuskula Creek (1200 m and 1400 m asl, respectively) (Fig. 1). Cold air drainage and katabatic winds from cirque glaciers at the head of the valley could create a microclimate not captured by temperature observations at Tungsten in the main Flat River valley. Conversely, the Grizzly Ridge site is at timberline (1500 m asl) in the main valley opposite Tungsten.

Results of stepwise regression to build a tree-ring model for the reconstruction of July temperature at Mirror Lake confirmed that the GR data were the best predictor of Tungsten temperatures. The best model had 5 predictors: GR(t), GR($t-1$), GR(t+1), LKC(t) and LKC($t-1$), with ($t-1$) and (t+1) representing data lagged back and forward by 1 year, respectively. The tree-ring data from UKC did not contribute to the prediction of July mean temperature as implied earlier by the weaker chronology statistics and correlation with summer temperature. The model derived from the GR and LKC tree-ring data accounted for 61.5% of the variation in the instrumental record, or 53% with an adjustment for degrees of freedom ($r^2 = 0.62$, $r_a^2 = 0.53$, $n = 22$, $p<0.01$). It enables the reconstruction of July temperature from AD 1704 to 2000, the span of shortest record among the predictors based on the lagged GR chronology.

The explained variance (r^2) was relatively high for tree-ring models but this parameter represents a single measure of the strength of the model. Cross-validation was used to assess the predictive skill of the reconstruction equation. Observations were iteratively deleted from the calibration data (full instrumental record) and the resulting model was used to predict the deleted observation. Reduction of error (RE) measures the accuracy of the regression model relative to a prediction based on the calibration period mean of the predictand as the predicted value outside the calibration period. Root mean squared error for the validation period ($RMSE_v$) measures the mean size of the prediction error. The reconstruction RE (0.13) is positive, suggesting predictive skill in the model, and the $RMSE_v$ (1.036) is comparable to the standard error of the estimate (SE_e) for the calibration period (0.795), suggesting a valid model.

4.3. Comparison of the proxy series

To assess the correspondence between the two temperature reconstructions at Mirror Lake, the original proxy series (i.e., the VT chronology and the GR(t) and LKC(t) residual tree-ring-width index series) were examined first. A common, high-frequency climate signal (melt season temperature) was apparent during the period of instrumental meteorological records at Tungsten (AD 1967–1990) (Fig. 4). The VT chronology and GR(t) series corresponded best ($r = 0.57$, $n = 24$, $p<0.01$), but the VT and LKC(t) series had a slightly weaker correlation ($r = 0.54$, $n = 24$, $p<0.01$) (Fig. 4). The VT and GR(t) series were representative of climate signals at or above 1500 m asl, as the GR(t) record was developed from samples at 1500 m asl and the glaciers that contribute much of the meltwater and sediment received by Mirror Lake are located above 1800 m asl. The LKC(t) record was more reflective of valley bottom conditions and, thus, did not correspond as closely with the VT series.

When the records were divided to analyse the decadal periods examined by Tomkins and Lamoureux (2005), the correspondence was strongest between the VT and GR(t) series during the 1970s (AD 1970–1980; $r = 0.90$, $n = 11$, $p<0.01$), when the both records were highly correlated with July mean temperature (Table 2) (Fig. 4). The correlation was weaker between the proxies ($r = 0.47$, $n = 10$, $p = 0.17$) during AD 1981–1990. A comparison of the VT and LKC(t) series showed a similar pattern, with a higher correlation during the 1970s ($r = 0.66$, $n = 11$, $p<0.01$) than during the 1980s ($r = 0.54$, $n = 10$, $p = 0.29$). The 1980s was a time when varve thickness showed reduced correlation with July mean temperature, but was significantly correlated with summer maximum temperature (Table 2).

When the entire period of record overlap (AD 1704–1996) was considered, the tree ring and VT annual series no longer showed statistical correspondence (GR(t) and VT: $r = 0.03$, $n = 290$, $p = 0.57$; LKC(t) and VT: $r = 0.04$, $n = 290$, $p = 0.47$) (Fig. 5). As such, interannual variability in the records did not consistently correspond in the long-term record, resulting in little similarity in the high-frequency climate signals. The tree-ring records showed similar long-term variability with a correlation of $r = 0.57$ ($n = 296$, $p<0.01$) for the period AD 1704–2000 (Fig. 5c). The

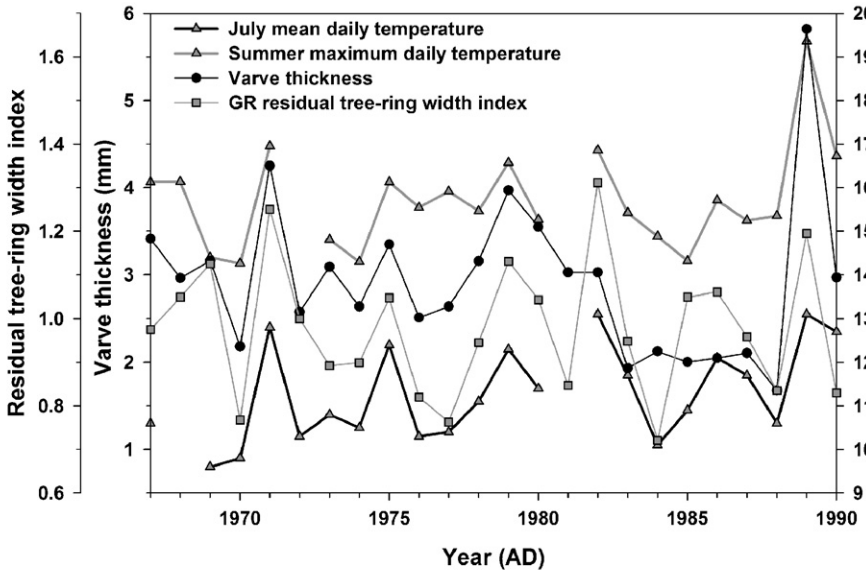

Fig. 4. Comparison of the GR residual tree ring width index and varve thickness record with instrumental records of July mean daily temperature and summer maximum daily temperature from Tungsten (AD 1967 to 1990). Gaps in the instrumental temperature series represent years with missing data.

LKC(t) record, in many instances, had reduced tree-ring widths compared to the higher elevation GR(t) record (Fig. 5c). However, the LKC(t) record had an extended period of thicker tree-ring residual widths than the GR(t) record during the early to mid-1800s.

Despite the lack of interannual correspondence, standardized and filtered series (15-year unweighted moving mean) showed similar patterns of low-frequency variability (Fig. 6a). Anomalously thick varves (> six standard deviations above the mean, AD 1825, 1899 and 1911) were removed for this analysis, as they were likely the result of geomorphic processes (e.g., subaqueous slumps or debris flows) rather than fluvial sediment delivery. The VT and GR(t) series showed the strongest consistent temporal correspondence during AD 1740–1785, 1800–1830, 1860–1890, 1915–1960 and after 1970 (Fig. 6). Less-consistent correspondence between the two records was most evident during the late 1700s and most of 1800s, with notable periods of negative correlations ca AD 1704–1740, 1830–1860 and 1960–1970. The temporal correspondence between the VT and LKC(t) series was similar, with the best correspondence ca AD 1750–1800, 1920–1940 and after 1960. The LKC(t) record showed less correspondence with the VT record than the GR(t) record, with periods of negative correlations and less-consistent correspondence ca AD 1704–1750, 1800–1920 and 1940–1950. Varve thickness diverged from both tree-ring series and showed considerable divergence after AD 1983, when the VT record increased sharply.

The main exceptions to the general low-frequency correspondence between the varve and both tree-ring residual width index series were the first half of the 1700s and portions of the 1800s. An extended period of below long-term mean varve thicknesses from AD 1778 to 1892 was particularly evident through a consistently negative trend in cumulative standardized departures (Fig. 6c). Although data filtering typically increases the correlation between the proxy variables, the degree of correlation was examined to provide a quantitative view of this period of divergence and the differences noted in the first half of the 1700s (Table 3). The filtered GR(t) and VT records had a strong negative correlation from AD 1704 to 1750 ($r = -0.59$, $n = 40$, $p < 0.01$) and a poor correlation from AD 1778 to 1892 ($r = 0.20$, $n = 115$, $p = 0.03$). Strong positive correlations were evident from AD 1751–1777 ($r = 0.93$, $n = 27$, $p < 0.01$) to AD 1893–1996 ($r = 0.60$, $n = 97$, $p < 0.01$). A comparison of the LKC(t) and VT series during the same periods yielded similar results prior to the 1900s. The annual data also showed a similar pattern, particularly for the GR(t) series, although the correlations were lower due to high-frequency noise. These results indicated that divergent thickness trends during the first half of the 1700s and weak correspondence during the main period of divergence (1800s) observed in the annual series remained in the filtered series as well.

To evaluate the correspondence of the records further, the reconstructed July mean temperature records were compared (Fig. 7). The mean values of the varve and tree-ring temperature reconstructions were not statistically different. The varve-based reconstructed July mean temperature (T_{JulVT}) record had a mean value of 11.09 °C, which was only 0.06 °C higher than the equivalent mean value of the tree-ring reconstructed temperature (T_{JulTR}) record (11.03 °C). However, the T_{JulTR} series had more variability than the T_{JulVT} record (standard deviations: $T_{JulTR} = 1.26$ °C, $T_{JulVT} = 0.85$ °C). The mean annual difference ($T_{JulTR} - T_{JulVT}$) between the two records was only 0.05 °C but individual years frequently varied by ca ± 2 °C and, in some instances, as much as ± 6 °C (Fig. 8). The distribution of reconstructed temperatures indicates that the T_{JulVT} series was skewed more towards lower temperature values than the T_{JulTR} reconstruction but the T_{JulTR} record had a broader distribution of temperatures (Fig. 9a). This difference was especially apparent during the period of greatest divergence between the records (AD 1778–1892), when the varve temperature reconstruction values were particularly reduced (Figs. 8 and 9d).

The T_{JulVT} record showed two prominent periods of above-mean temperatures centred on ca AD 1735–1740 and 1764–1770, while the corresponding T_{JulTR} temperatures did not reach the same magnitude as those in the varve record (Fig. 5). The latter period of above-mean temperatures in the T_{JulVT} record represented the warmest period in the record prior to AD 1983. The T_{JulTR} series was consistently warmer from AD 1818–1883 and 1897–1917, after which it showed colder temperatures than those reconstructed in the T_{JulVT} series. Both temperature records showed a warm period during the 1890s, followed by a drop to cool conditions during the early 1900s, although the magnitude of this temperature shift was larger in the T_{JulVT} record. The T_{JulTR} record showed melt season temperatures remaining at or below-

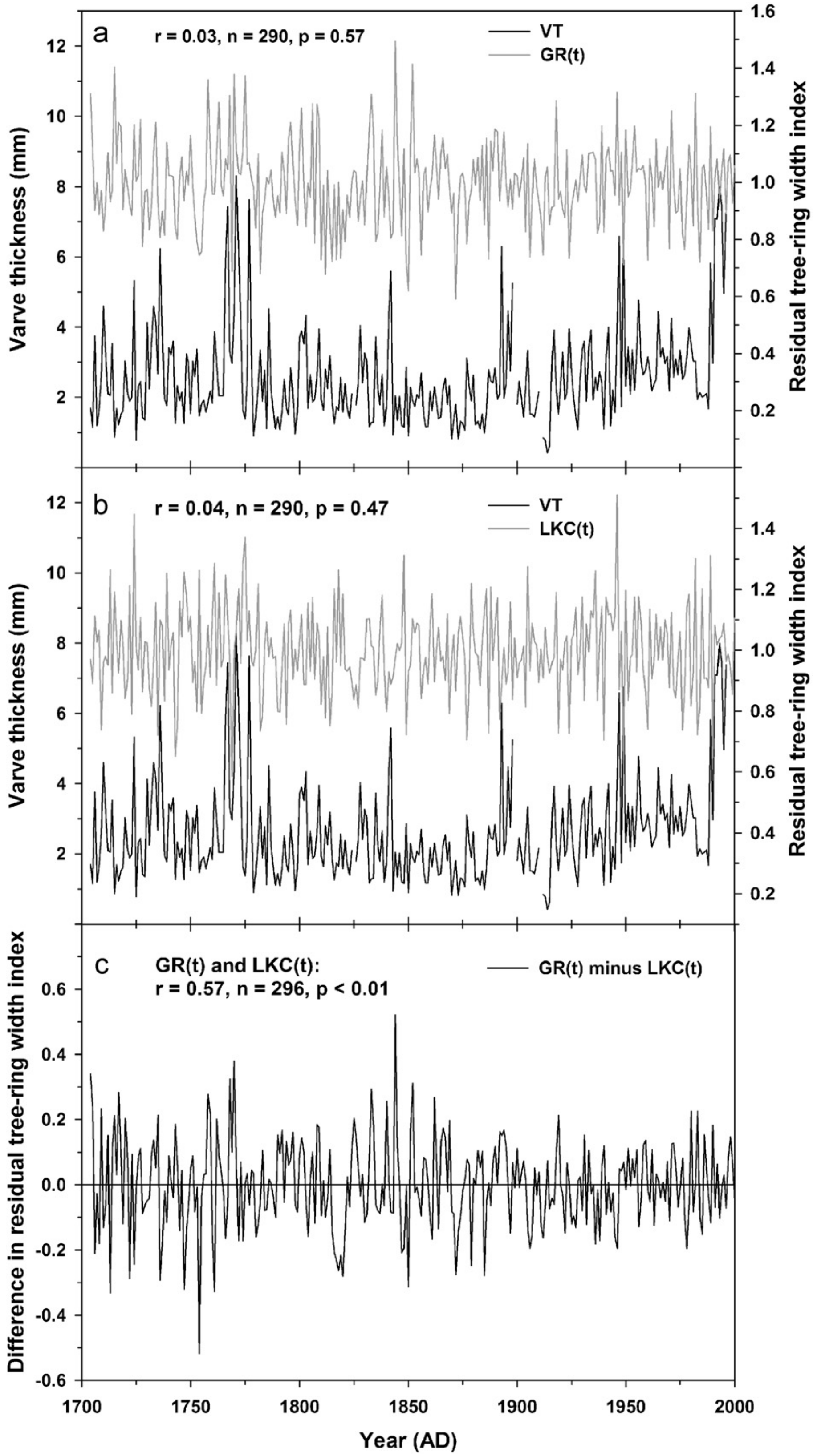

Fig. 5. Interannual comparisons of the varve thickness record (VT) and Grizzly Ridge (GR(*t*)) and Lower Kuskula Creek (LKC(*t*)) unlagged tree-ring residual width indices, including comparisons of (a) VT and GR(*t*) and (b) VT and LKC(*t*). (c) Due to the similarities between GR(*t*) and LKC(*t*), their correspondence is presented as the LKC(*t*) record subtracted from the GR(*t*) record. Three years in the varve thickness record with anomalous deposits (>6 standard deviations above the mean), interpreted as turbidites produced by lake processes and not fluvial sediment delivery, were omitted (AD 1825, 1899 and 1911).

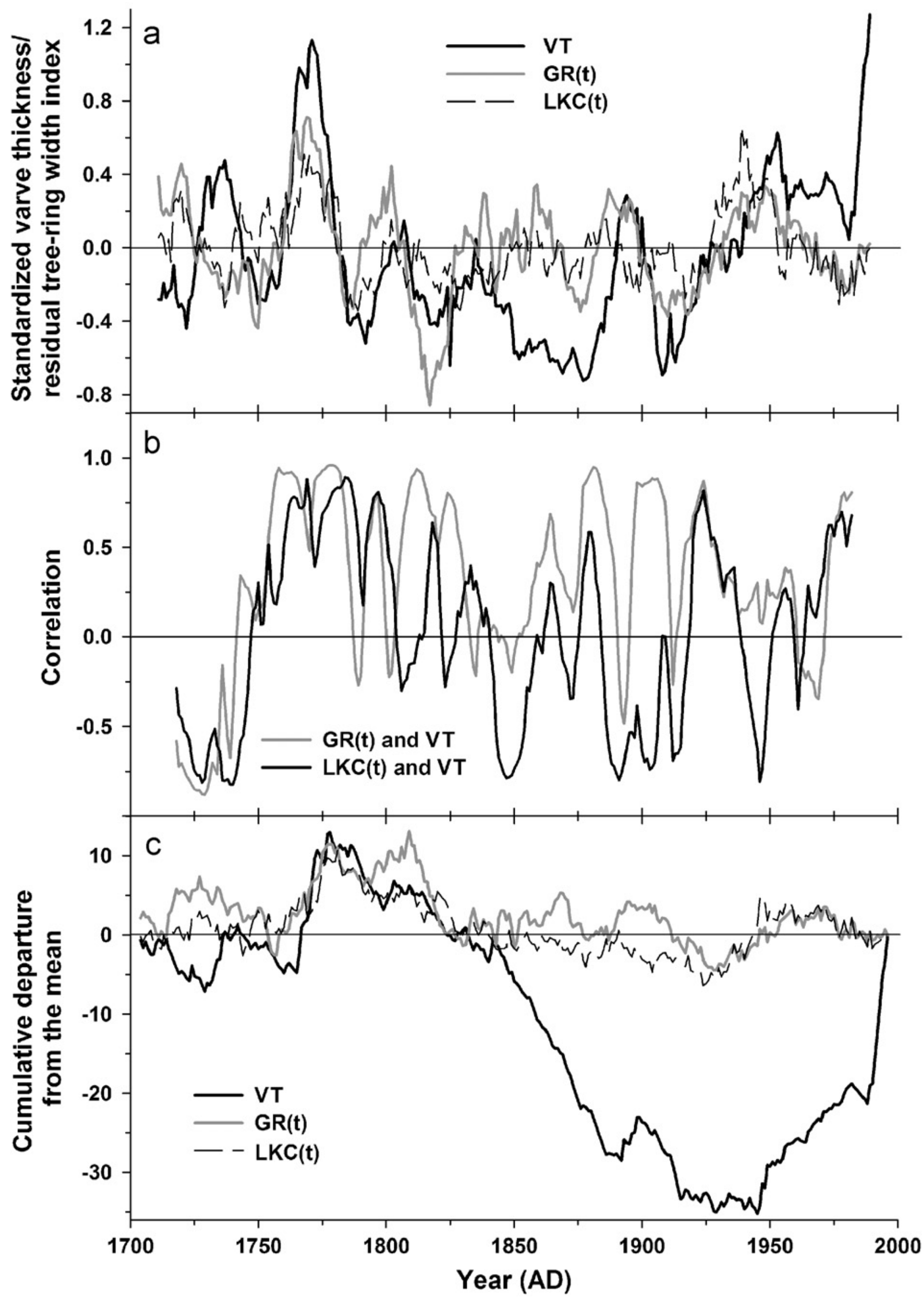

Fig. 6. (a) Filtered (15-year unweighted moving mean) plots of the standardized values of the VT, GR(t) and LKC(t) records, (b) 15-year running correlations between the VT record and tree-ring residual width indices (15-year running mean) and (c) cumulative standardized departures from the mean for the three series. Gaps at AD 1825, 1899 and 1911 in the VT record in (a) represent years omitted due to anomalously thick sediment deposits (>6 standard deviations above the mean).

mean until AD 1945, including an extended cold period during from AD 1919 to 1945. However, the T_{JulVT} record showed a warming trend during AD 1909–1947, with temperatures reaching above-mean values after ca AD 1940.

The warming trend in both records ended in the late 1940s, after which the records remained at above-mean temperatures. This pattern remained until ca AD 1983, after which the varve record showed the strongest warming trend of the entire record and the tree-ring record remained near the long-term mean. These consistently positive temperature departures in the T_{JulVT} record were unprecedented in duration during the 292-year record, although similar temperatures were attained in the mid-1760s to mid-1770s in several years (Fig. 7a). This divergence may indicate changes in the proxies' formative processes, in addition to changes in temperature, during this time.

5. Discussion

5.1. Limitations of the varve thickness and tree-ring series

Each proxy climate record has unique formative processes and environmental sensitivities and, as such, two proxies from the same region should not be expected to record identical climate signals. A proglacial sedimentary record, such as the one found in Mirror Lake, is primarily the result of sediment transport from catchment glaciers, which is a function of meltwater generation controlled by climatic conditions and glacier dynamics that vary on annual, decadal and centennial timescales (Leonard, 1985; Hodder et al., 2007). Moreover, there may be substantial delays between the onset of climate change and glacial response, due to the variable, but relatively slow response time imposed by ice

Table 3
Summary correlation statistics for the filtered (15-year unweighted moving mean) and unfiltered (annual data) Mirror Lake varve thickness series (VT) and the unlagged Grizzly Ridge (GR(t)) and Lower Kuskula Creek (LKC(t)) tree-ring residual width indices for selected periods of interest during AD 1704–1996

Period (yr AD)	Correlated variables (filtered data):					
	VT and GR(t)			VT and LKC(t)		
	r[a]	n[b]	p[c]	r[a]	n[b]	p[c]
1704–1996	0.43	279	<0.01	0.35	279	<0.01
1704–1750	−0.59	40	<0.01	−0.63	40	<0.01
1751–1777	0.93	27	<0.01	0.75	27	<0.01
1778–1892	0.20	115	0.03	0.15	115	0.11
1893–1996	0.60	97	<0.01	0.09	97	0.37
	Correlated variables (annual data):					
1704–1996	0.03	290	0.57	0.04	290	0.47
1704–1750	−0.16	47	0.30	0.14	47	0.35
1751–1777	0.11	27	0.60	0.14	27	0.48
1778–1892	−0.04	114	0.65	−0.20	114	0.03
1893–1996	0.07	102	0.50	0.05	102	0.64

[a] Correlation coefficient (r).
[b] Sample size (n).
[c] Significance level (p).

mass, area, flow and variable adjustment times (Benn and Evans, 1998). In addition to glacier dynamics, non-climatic influences such as sediment supply, fluvial and lake processes also contribute to varve formation and may mask the climate signal at different timescales (Hodder et al., 2007). By contrast, a tree-ring record is largely a function of growth conditions integrated during the year, and in some instances, conditions in previous years (Fritts, 1976). Non-climatic controls, such as tree physiology, stand competition, pests, fire and disease also affect tree-ring growth. Nonetheless, tree response is specific to the immediate and antecedent physiological controls that are essentially independent of the catchment's glacial dynamics. Moreover, tree rings integrate seasonal conditions through their growth (Fritts, 1976), whereas varve thickness often represents a shorter period (e.g., days to weeks) of sediment delivery to a lake (Smith, 1978). Despite these different influences, a common climate signal may be identified between different proxy records if similar climate factors broadly or specifically affect their formative processes.

To date, relatively few comparisons between tree-ring and varve series have been undertaken. Luckman (2000) compared smoothed (25-year Gaussian filter) tree-ring and varve thickness records (25–200 km apart) and glacial records from the southern Canadian Rocky Mountains, and found some low-frequency similarities, but overall, no close correspondence between the records was observed. Conversely, Solomina et al. (2005) found a strong relationship between smoothed (11-year mean) tree-ring and varve records located 150 km apart in Crimea, Ukraine ($r = 0.57$ from AD 1673 to 1873). The Crimean varves were from a non-glacial environment, potentially eliminating some complicating factors described above, including sediment supply controls caused by glacial advance and retreat (Leonard, 1997; Hodder et al., 2007).

At Mirror Lake, the comparison of adjacent proxy climate reconstructions and local meteorological data provided an unprecedented opportunity to examine the sensitivities of two proxy records to essentially the same climatic conditions. Analyses showed that temperature influenced both varve formation (via melt season processes) and tree growth relatively directly, and resulted in a common climate signal of summer temperature. However, the annual data demonstrated the different sensitivities of each record, and revealed that high-frequency (i.e., interannual) variability in the records did not correspond in detail prior to the late twentieth century and might have overshadowed lower frequency, common climate signals. Minor (and apparently non-cumulative) chronological uncertainties may have contributed to the observed results with the annual series, as slight chronological errors in either record could have caused small offsets. However, the low-frequency correspondence suggested that these possible chronological errors had a minimal cumulative effect.

5.2. Reconstructed July mean temperature records (AD 1704–2000)

The common low-frequency variability in the long-term proxy records showed the overarching effect of summer temperature on varve and tree-ring formation in the Tungsten area (Fig. 7). In this alpine environment, temperatures during the short summer growing period and glacier melt season are integral to the formation of both tree-ring and varve proxy climate records. Despite the non-climatic influences of glacier dynamics and sediment availability on the varve thickness record, the two proxies recorded a common, dominant climate record of summer temperature. The reconstructed July mean temperature records (Fig. 7) did not show the same level of low-frequency correspondence that was apparent in the original varve thickness and tree-ring residual width series (Fig. 6) because each proxy was recording a slightly different climate signal. While the varve thickness record captured July mean temperature at the elevation of the catchment's glaciers (>1800 m asl), the tree ring temperature model incorporated the higher elevation GR series and the lower elevation LKC series. Neither climate record represented the unique July mean temperature record in the Mirror Lake area, due to differences in location and formative processes. Each climate record varied but similarities were apparent throughout that represented the broader record of July mean temperature variability in the region.

Both reconstructed temperature records indicated similar decadal variability fluctuating above and below the long-term mean during the 1700s, with much higher magnitude shifts apparent in the varve temperature record (Fig. 7). While the reasons for the differences in magnitude were not clear, the sensitivity of sediment transport and deposition processes to changes in meltwater production may have caused an exaggeration of July temperatures during the two notable warm periods of that century (i.e., the 1730s and 1760–1770s). Alternatively, the tree-ring records may not have been as sensitive to the temperature shifts due to summer moisture stress. However, tree-ring widths from the GR sampling site were somewhat thicker than those at the LKC site during the warm period of the 1760-1770s, suggesting more favourable growing conditions at higher elevations in the catchment due to differences in microclimate parameters (e.g., shading or cold air drainage from glaciers) (Fig. 5). As the tree-ring July mean temperature reconstruction incorporated both tree-ring records, the GR components of warmer conditions that more closely coincided with the VT series interpretation at this time (Fig. 5), were moderated by the lower elevation LKC components, and likely contributed to the reduced magnitude of estimated warmth (Fig. 7).

Both reconstructions showed the early 1800s as colder than the long-term mean. However, while the T_{JulVT} record generally remained below-mean until AD 1892, the T_{JulTR} record suggested cool temperatures from AD 1802 to 1818, followed by warmer conditions until the end of the century (Fig. 7). The early 1800s was a time of reduced tree-ring width at the GR sampling location but average growth at the LKC location (Fig. 5). These differences

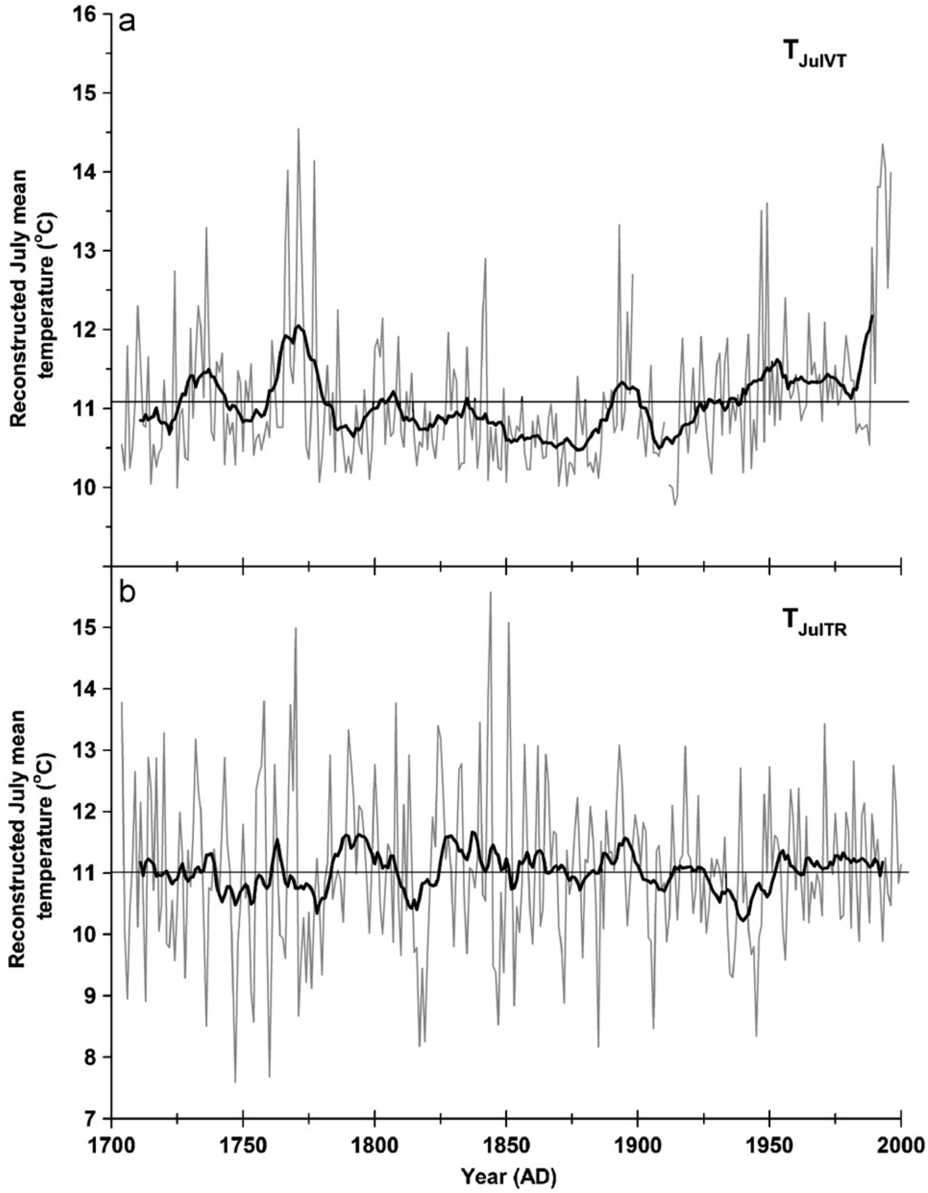

Fig. 7. July mean daily temperature reconstructions from (a) AD 1704–1996 from the varve thickness series (T_{JulVT}), (b) AD 1704–2000 from the GR and LKC residual tree-ring width series (T_{JulTR}). The thick black line in each panel is a 15-year unweighted moving mean and the thin horizontal line identifies the respective mean value for each record. Gaps at AD 1825, 1899 and 1911 in (a) represent years omitted due to anomalously thick sediment deposits (>6 standard deviations above the mean).

were much stronger than those seen during the 1760s to 1770s warm period. The reduced growing conditions shown in the high elevation GR(t) series were also reflected in the VT record, where the colder 1800s may represent a maximum ice stand (i.e., a period of stable ice mass after glacier advance) in the area. Trees at lower elevations (LKC) had more favourable growth conditions during this time and, as such, the tree-ring temperature model showed moderate July mean temperatures. The differences in growing conditions at each tree-ring sampling site were also evident throughout other parts of the 1800s, when the GR(t) and LKC(t) residual ring-width series showed reduced correspondence (Fig. 6). After the early 1800s cold period, the LKC trees had less favourable growing conditions than the GR trees, again indicative of the influence of microclimate parameters on tree-ring formation. These results suggested that the glaciers not only directly affected the varve thickness record, but also likely had an indirect climatic effect on growing conditions at the LKC sampling site by influencing valley bottom climate conditions, particularly during the 1800s.

The different reconstructed climate records during the early 1900s (particularly the 1930s and 1940s) and after AD 1983 suggest potentially dissimilar responses to climate forcings by each record, in part due to localized conditions (e.g., microclimate for tree rings) or the response of the system to changing conditions (e.g., glacial melt, sediment availability for varves) (Fig. 7). Varve structure suggested a changing glacier–sediment system during the earlier period of divergence, with the reappearance of two-silt-unit varves in the varve record at AD 1942. This occurrence indicated the changing seasonality of sediment delivery to the lake as the catchment's glaciers responded to changing climate conditions during ice recession. However, the close correspondence of the varve and tree-ring series during the instrumental period at Tungsten implied that summer temperatures dominated over non-climatic influences and affected both tree-ring growth and varve formation in a similar manner during at least the latter part of the 1900s. This interannual correspondence was highest during the 1970s, when snowpack appeared to have a reduced influence over varve

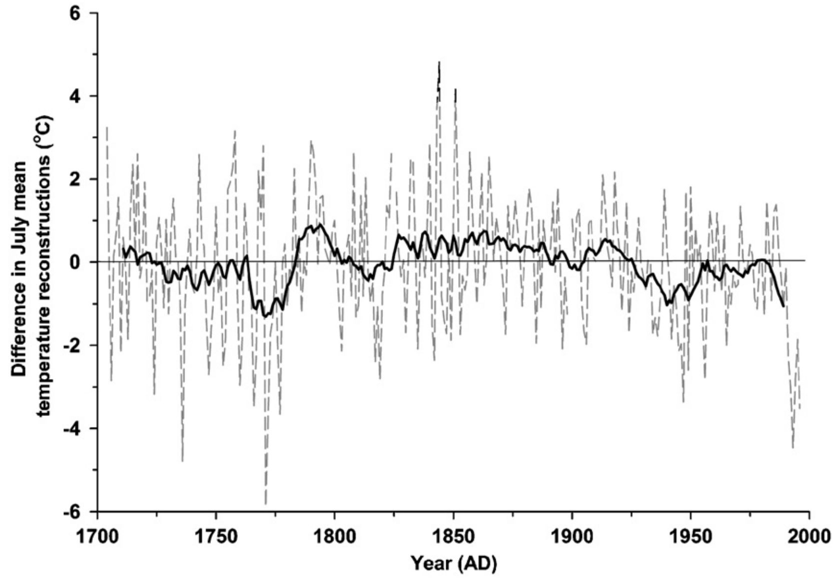

Fig. 8. Differences in July mean temperature reconstructions ($T_{JulTR}-T_{JulVT}$). Gaps at AD 1825, 1899 and 1911 represent years omitted due to anomalously thick sediment deposits (>6 standard deviations above the mean) in the varve thickness record.

formation and the two proxy records matched closely (Tomkins and Lamoureux, 2005) (Fig. 4). The colder temperatures in the T_{JulTR} record during most of the twentieth century may be more reflective of localized conditions at lower elevations and thus, do not capture warmer conditions at higher elevations suggested by the T_{JulVT} record (Fig. 8). Alternatively, the T_{JulVT} record may also be exaggerated due to increased sediment availability and transport associated with ongoing ice recession. However, given the close correspondence of the varve record to melt season temperatures at Tungsten during the latter part of the 1900s, this argument does not appear to be valid throughout the century.

The lack of substantial warming after AD 1983 in the T_{JulTR} record may represent divergence found in some high-latitude tree-ring records because growth becomes more limited by moisture than heat (D'Arrigo et al., 2008). However, the tree-ring series corresponded closely to the instrumental meteorological data from AD 1967 to 1990 (Fig. 4). As such, a more plausible explanation for the divergence is substantially increased sediment delivery to Mirror Lake, possibly due to increased availability of sediment through the exposure of glacial deposits during accelerated ice retreat. Aerial photographs show substantial ice recession after AD 1949. The varves deposited during the 1990s were, on average, three standard deviations above the mean varve thickness of the entire filtered record, suggesting that temperatures during these last few years could have been overestimated due to anomalously high sediment delivery. This non-stationarity in the varve record during the 1990s suggested that varve formation did not likely respond linearly to July mean temperature due to continued rapid glacier retreat.

Overall, the temperature reconstructions suggest mean July temperatures with decadal variability about the mean during the 1700s, below-mean to mean temperatures through much of the 1800s, warming during the 1890s followed by a brief cooling trend until approximately AD 1905, and above-mean temperatures in the southern Selwyn Mountains during the last half of the twentieth century (Fig. 7). Differing localized influences (e.g., the changing glacier–sediment system for the varve record and differing microclimate conditions among the tree-ring records) likely led to the notably warmer varve-inferred temperatures during the 1930s and 1940s and after AD 1983.

5.3. Glacial influences on the varve record

Proglacial varve records can provide important information about not only climate but also glacier dynamics and geomorphic controls over sedimentation (e.g., Karlén, 1976; Leonard, 1997; Ohlendorf et al., 1997; Dahl et al., 2002). However, the latter two influences on varve sedimentation cause complexity in the climate signal recorded within the varve series, leading to potential errors in climate reconstructions. While climate influences proglacial varve sedimentation on an interannual basis through ablation, long-term changes in glacier extent also control sediment availability and transport. As such, low-frequency climatic changes, their influence on glacier extent and the geomorphic responses to these changes all contribute to varve sedimentation on timescales up to centuries or longer (Leonard, 1985; Desloges and Gilbert, 1994a; Hodder et al., 2007). The Mirror Lake varve thickness record contained two-silt-unit varves that were associated with short-term periods of above-mean snowpacks that delayed glacier ablation during melt seasons in the late twentieth century. These conditions resulted in visually distinct nival and glacier melt sediment deposits within a given varve from Mirror Lake (Tomkins and Lamoureux, 2005). This varve type was found only rarely during AD 1669–1941 (3% of the varves), but was more common during the remainder of the sedimentary record (53% of the varves from AD 1389–1668 to 1942–1996) (Fig. 10).

In addition to varve structure, the influence of glacier activity on varve sedimentation is also apparent through varve thickness changes on decadal to centennial timescales. Sequences consisting of comparatively thin varves and few anomalously thick deposits suggest lowered meltwater output due to decreased glacier extent or stagnant ice within a catchment (Smith and Ashley, 1985; Desloges and Gilbert, 1994a). Conversely, glacier retreat after a maximum stand is characterized in the sedimentary record as a succession of thicker varves and frequent anomalously thick deposits, due to increased erosion beneath catchment glaciers and on recently exposed land (Church and Ryder, 1972; Desloges and Gilbert, 1994a). Higher sedimentation rates are also notable during glacier advances, as the amount of subglacial erosion is increased, which subsequently increases the sediment potentially

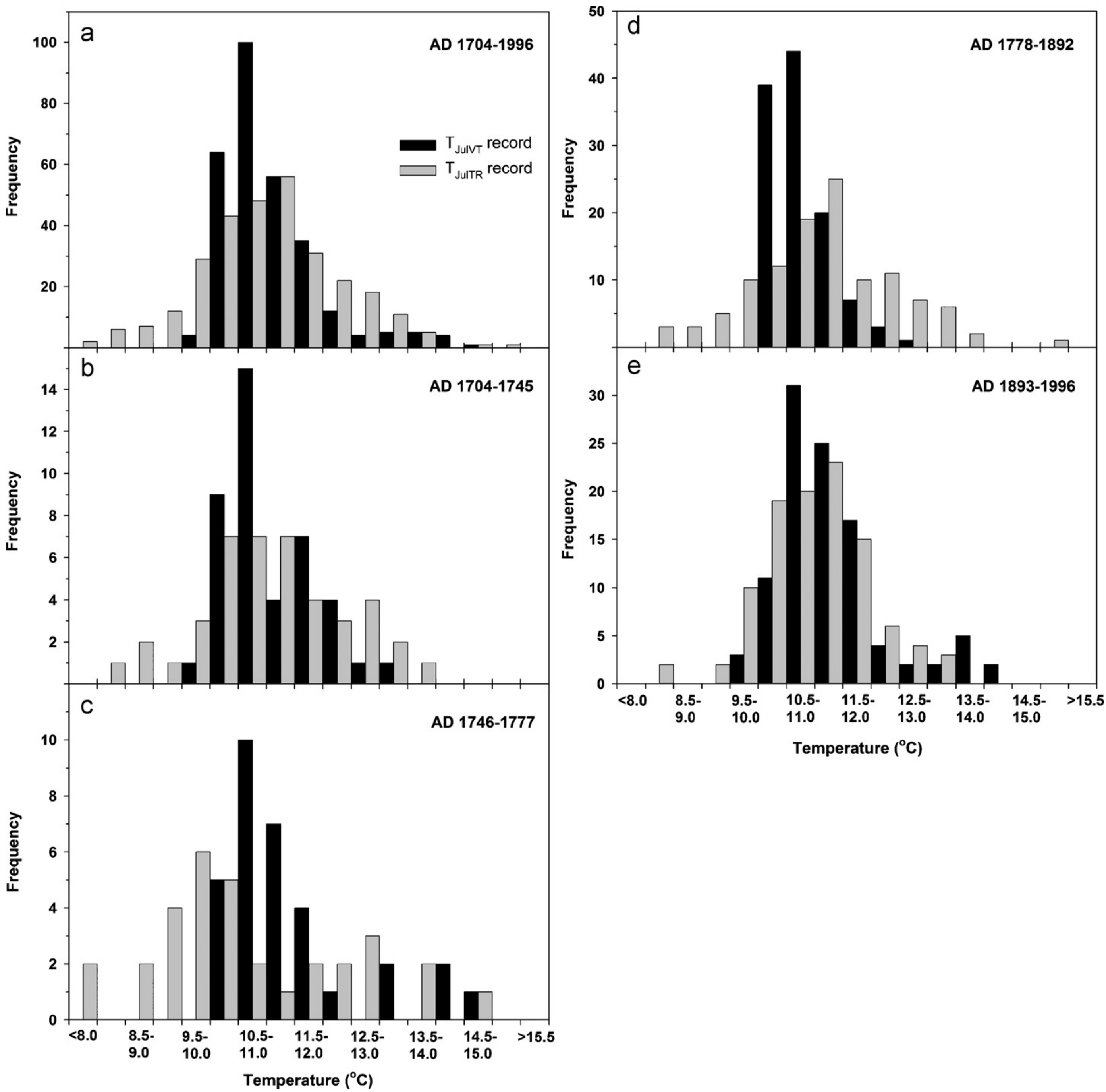

Fig. 9. Histograms of the T_{JulVT} and T_{JulTR} reconstructions including (a) the entire comparison period (AD 1704–1996), (b) AD 1704–1745, (c) AD 1746–1777, (d) AD 1778–1892 and (e) 1893–1996. Anomalously thick deposits (>6 standard deviations above the mean) in the varve thickness record that were omitted in three cases (AD 1825, 1899 and 1911).

available for fluvial transport (Church and Ryder, 1972; Leonard, 1985). The highest sedimentation rates are often found during the paraglacial period after glacial maxima, as meltwater subaerially erodes newly exposed glacial material (Church and Ryder, 1972). After this initial peak, sedimentation rates generally decrease as recession continues, with reduced periods of higher sediment yield during short-lived accelerated glacier recession (Church and Ryder, 1972; Leonard, 1997). As such, the timing of peak sediment yield does not necessarily coincide with periods of maximum ice extent, but rather transitional periods leading and lagging glacial maxima (Leonard, 1997).

To summarize this glacier–sediment system, low-frequency changes in deposition rates on timescales of a century or more in a proglacial lake generally reflect glacier extent in a catchment (Leonard, 1985; Leonard, 1986; Hodder et al., 2007). Periods of low sedimentation (thin varves) can represent ice stagnation (limited glacier activity), reduced ice extent, reduced subglacial erosion and/or reduced sediment availability. Conversely, high sedimentation periods (thick varves) can represent rapid advance or retreat periods, when subglacial erosion is active and sediment availability is increased (Leonard, 1985; Desloges and Gilbert, 1994a, b; Hodder et al., 2007).

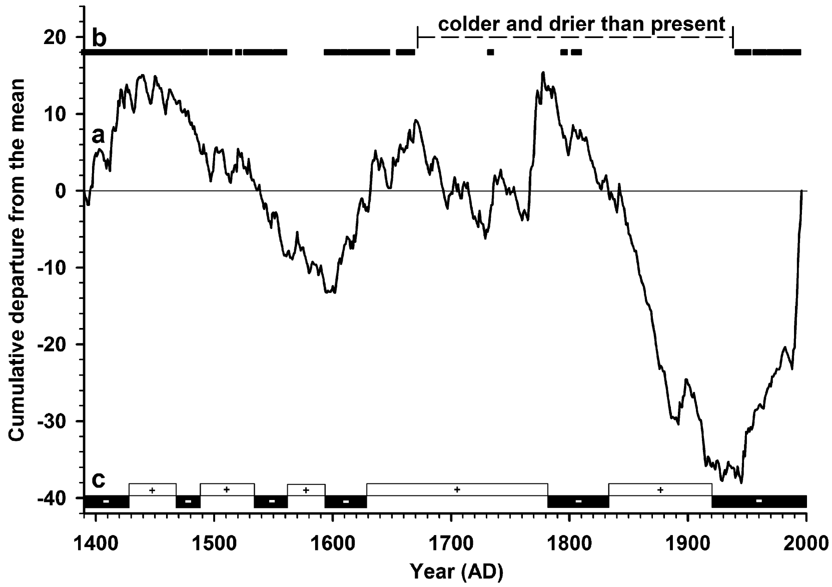

Fig. 10. (a) Cumulative departures of unfiltered varve thickness values from the mean from AD 1389 to 1996, (b) presence of two-silt-unit varves in the sedimentary record and (c) the positive (advance) and negative (retreat) Glacier Expansion Index (GEI) phases (Wiles et al., 2004) for the Brooks Range, Wrangell Mountains and Coastal Ranges of Alaska. The period of inferred below average summer temperature and spring snowfall in the study area (Tomkins and Lamoureux, 2005) using the Mirror Lake sedimentary record, is also shown in (b).

At Mirror Lake, interannual variability in the varve thickness record reflected climatic forcings through direct influences on ablation, but the results of this study suggest that low-frequency variations in sediment availability due to glacier activity likely caused offsets between the tree-ring and varve thickness climate records. The prolonged divergence of cumulative departures from AD 1778 to 1892 was the most notable evidence for the impact of glacial changes, although other periods of cumulative departure divergence were also apparent, particularly after AD 1983 (Fig. 6). The inferred glacial influence over varve formation during the 1800s was suggested through below-mean varve thickness, a thinning trend within the record, and few anomalously thick varves. The divergence of the varve and tree-ring records during this time also supported this assertion, as low-frequency correspondence between these two records was weakened during this period (Table 3).

Tomkins and Lamoureux (2005) suggested that the paucity of the two-silt-unit varve type from AD 1669 to 1941 may suggest colder melt season conditions and drier spring conditions in the Mirror Lake area, using the 1970s as a modern analogue for the relationship between climate and varve structure. Varve record characteristics during AD 1778–1892 suggested a high ice stand or period of stagnation in the Mirror Lake catchment that strongly influenced the climate signal recorded in the varve record (Fig. 6). The comparison between the varve and tree-ring reconstructions corroborated this possibility, as the varve record appeared to underestimate July mean temperature due to reduced sediment input during this time (Fig. 7). This result did not preclude veracity in melt season temperature reconstruction with the varve record, but rather, suggested that some periods may be subject to strong non-climatic influences over varve sedimentation that may affect the record as much as or more than direct climatic influences. The tree-ring reconstruction, which was not directly influenced by glacier activity, may be seen as more reliable during the 1800s, although the comparison of the two reconstructions suggested that the glacial influences did not completely eradicate the climate signal in the varves.

The varve record showed a generally positive sedimentation trend from AD 1892 to 1996, likely due to glacier recession and increased availability of sediment for transport as melting glaciers exposed sediment to erosion (Fig. 6 and 10). The Mirror Lake region experienced a 66% reduction in glacier cover since the mid- to late 1800s (undated, but based on assumed Little Ice Age (LIA) moraine positions and current ice fronts on aerial photographs and topographic maps) that indicates ice cover was more extensive prior to ca AD 1900 (Harrigan, 2003). The diminished glacial meltwater inflows that characterized the 1800s would have been augmented by new paraglacial sediment supplies as recession progressed in the 1900s, allowing the system to respond more directly to melt season temperatures and record this dominant climate signal. The differences between the varve and tree-ring temperature reconstructions during the early 1900s may indicate an adjustment period as the catchment's glaciers responded to increased temperatures, which would have manifested itself within the varve record (e.g., the 1899 and 1911 event deposits and return of the two-silt-unit varve to the varve record in AD 1942). The close correspondence of the varve series and summer temperature at Tungsten during a period of known recession (via aerial photographs) suggests that glacial influences on varve sedimentation did not overshadow the summer temperature signal during recent times of glacier retreat. As such, the varve-based July temperature reconstruction during the twentieth century appears to be valid, specifically representing high elevation climate variability during recession after an inferred high ice stand in the southern Selwyn Mountains.

5.4. *Recent glacial history of the southern Selwyn Mountains*

The sedimentation history and departures between the proxy climate records at Mirror Lake suggest a possible glacial history for the catchment (AD 1389–1996) (Fig. 10). This inferred history is based on the influence of glacial activity on varve sedimentation over prolonged periods of change in ice extent that account for long-term trends (decadal to centennial) in sedimentation in proglacial sedimentary records in conjunction with short- to long-term climate signals (Leonard, 1985).

Using known glacial histories within the western Canadian cordillera and the glacier–sedimentation framework to interpret the Mirror Lake sedimentary record, two phases of ice advance and one major phase of recession were inferred from AD 1389 to 1996. LIA glacier expansion in the Canadian Rocky Mountains was most prominent from the 1600s to 1800s (Luckman, 2000), while the northern part of the cordillera typically had high ice stands during the 1700s and 1800s (e.g., Clague and Rampton, 1982). However, some glaciers did not reach their LIA maximum extents until the late 1800s to early 1900s, depending on location (Ryder, 1987). As such, glaciers must have gradually expanded over time to reach their LIA maximum ice stands. A regional example of this process is from the northern Coast Mountains of British Columbia where glaciers were thicker and more expansive than at present from ca AD 1320 to 1420 and continued to advance slowly until their LIA maximums in the late 1600s to early 1900s (Ryder, 1987). This scenario suggests that more extensive ice than at present also may have existed in the southern Selwyn Mountains over centuries prior to the 1800s, when a strong glacial influence on the varve record was apparent from the divergence of the varve and tree-ring inferred summer temperature records. Twentieth-century recession is evident in many records from the western cordillera (e.g., Luckman, 2000, Harrigan, 2003) and is suggested to be the most rapid recession period of the past 4000 years in some areas (Ryder, 1987).

The inferred primary phase of LIA glacier advance in the Mirror Lake region began by at least the late 1300s and continued through to ca AD 1450. This advance may have begun earlier but the sedimentary record does not extend prior to AD 1389. A second period of ice advance is inferred from AD 1600 to 1670. Both periods resulted in increased subglacial erosion and proglacial sediment yield that resulted in increased varve thickness over multiple decades (Fig. 10). These inferred ice advance periods remain otherwise undocumented outside of this study. The decreasing varve thickness trends from ca AD 1450 to 1600 and 1670 to 1730 suggested periods of stable ice masses with minimal advance or retreat. From AD 1730 to 1778, two brief periods of inferred glacial advance are inferred through increasing trends in varve thickness ca AD 1730–1745 and 1760–1778. The AD 1778–1892 period appears to represent the main period of LIA maximum ice stand in the Mirror Lake area. Reduced snowpack and cool temperatures were inferred from AD 1669 to 1941 through varve structure (i.e., the absence of two-silt-unit varves), suggesting that the glaciers would have been comparatively stable due to reduced snowfall and cool temperatures (Fig. 10). After AD 1892, rapid retreat and a corresponding increase in sedimentation rate and the occurrence of anomalously thick deposits characterized the main phase of recession after the LIA high ice stand.

5.5. Comparison with regional glacial and proxy climate records

The climate reconstruction and glacial history at Mirror Lake is generally supported by other paleoclimate and glacial activity records from northwestern North America. While good correspondence is seen between the Mirror Lake glacial history reconstruction and other regional glacier records, local variations in advance and retreat are evident due to differing glacier dynamics and geographical settings.

Sloan and Dyke (1998) noted that moraines left by glaciers in the Selwyn Mountains represent maximum late-Holocene ice cover during the LIA and Dyke (1990) noted that most rock glaciers in the Selwyn Mountains, including one within 2 km of Mirror Lake, formed during the past 400 years, with enhanced formation conditions at ca AD 1750 and 1800. Tree-ring records from 600 km north of Mirror Lake revealed colder June and July temperatures from AD 1638 to 1880, with the coldest conditions during the late 1700s to mid-1800s (Szeicz and MacDonald, 1995). Similarly, tree rings from the west-central Yukon Territory showed decreased temperatures from AD 1800 to 1850 (Jacoby and Cook, 1981). Both tree-ring records also revealed warming trends after AD 1850, which suggest a slightly earlier end to cooler conditions than in the Selwyn Mountains.

Further west, Clague and Rampton (1982) noted conditions were conducive to glacier advance in the eastern St. Elias Mountains, Yukon Territory, during the 1700s and 1800s, with expansion of the Lowell Glacier between AD 1736–1832 and AD 1848–1891, followed by retreat during the 1900s. Similarly, the LIA in the southern Canadian Rocky Mountains was most apparent during the 1600s to 1800s, with many glaciers reaching maximum extents during the 1800s (Luckman, 2000). Desloges and Gilbert (1994b) inferred LIA glacier advance after AD 1750 by increased sedimentation in Moose Lake, British Columbia. High sedimentation rates from AD 1450 to 1500 in Moose Lake correspond to the earliest inferred high ice stand in the Selwyn Mountains.

In the northern Coast Mountains of British Columbia, Ryder (1987) found that glaciers were more expansive and thicker than at present ca AD 1320–1420 and most reached their Neoglacial maximum extents during the late 1600s and early 1700s, although some further inland did not achieve their maximum ice stands until the late 1800s and early 1900s. Similarly, Lamoureux and Cockburn (2005) used a varve record from White Pass, British Columbia/Alaska, to infer the onset of cirque glacier activity after AD 1677. These periods of increased glacier extent also corroborate the first and second inferred periods of glacier advance and the high ice stand of the 1800s in the Selwyn Mountains.

In southern Alaska, multiple ice advances have been recorded between AD 1200 and 1900 (Calkin et al., 2001; Wiles et al., 2004). Glaciers in different areas of Alaska had their LIA maximum extents at different times, but some periods of widespread advance were evident. In the Chugach Mountains of south-central Alaska, the maximum LIA ice extent occurred before the mid-1800s (Loso et al., 2004), although Calkin et al. (2001) found that the main LIA ice advance in many parts of southern coastal Alaskan mountain ranges occurred between AD 1650 and the early 1700s, followed by less extensive ice in the 1800s. Wiles et al. (2004) compiled a Glacier Expansion Index (GEI) for 130 glaciers spanning much of Alaska. The GEI indicated increased numbers of glaciers advancing (positive index values) at AD 1300, 1450, 1650 and 1850, with the strongest advance in northern areas at AD 1450 and in southern areas from AD 1650 to 1700 (Fig. 10). The inferred Selwyn Mountain glacier advances of late 1300s to AD 1450 and AD 1600–1670 generally coincide with positive GEI periods and ice advance. Additionally, a composite of west coast glacier advance and retreat in Alaska, British Columbia and Washington indicated LIA advances during the 1750s and 1820–1830s that generally coincided with the period of colder conditions and inferred maximum glacier extent in the southern Selwyn Mountains (Larocque and Smith, 2005).

6. Conclusions

This study provided a unique opportunity to conduct a multi-proxy analysis of climate using records from the same location with nearby instrumental climate records. Through this analysis, long-term melt season temperature and glacial history records were developed for the southern Selwyn Mountains in south-western Northwest Territories/southeastern Yukon Territory.

Results of the comparison between tree-ring and varve records demonstrates that sensitivities to baseline conditions (e.g., sediment supply, microclimate) complicate interpretation, but show the potential to use multiple proxy records to identify periods in a proxy record that may be influenced by non-climatic controls. Neither proxy record in this study was shown to have a demonstrably better climate record over the entire period of overlap, but instead, showed variable climate signals from different elevations that reflected differing responses of the proxies to climate variability. Despite these differences, the reconstructed July temperature records still captured common low-frequency trends in the area.

This approach also proved effective in identifying periods when glacial influences on sediment availability and yield changed varve formation and affected the resultant climate signal. The tree-ring record may be more representative of melt season temperature than the varve thickness record during these times. Both records indicated colder than present conditions during the early 1800s and warmer periods during the late 1800s and mid-1900s. These results corresponded well with other regional proxy climate temperature records and were similar to periods of glacier advance and retreat identified elsewhere in northwestern North America. The varve record also captured earlier periods of ice advance (ca late 1300s to AD 1450 and AD 1600–1670), which were also corroborated by other records of glacier advance in northwestern North America.

The results of this study indicated that no single proxy record can be accepted uncritically, but should be compared with another type of proxy record in the study area to identify departures before developing climate reconstructions whenever possible. Discrepancies in the temperature reconstructions during portions of the 1700s, 1930s, 1940s and post-1983 period cannot be simply explained, but glacier changes and localized climate controls likely played major roles in the observed incongruities. Through examination of multiple proxy records, these issues can be identified to determine possible causal factors. Either proxy considered alone would not have revealed the unique proxy sensitivities, possibly leading to a more limited inference of the regional climate. The varve and tree-ring data provide complimentary proxy records of July temperature and summer glacier mass balance.

While this research highlighted some complexity in both proglacial varve and tree-ring records, it does not suggest that these records are not effective climate proxies. Like all proxy climate records, these records are a product of more than one environmental influence. Despite their varying forcing factors, combined records can be used to provide an improved and more reliable climate reconstruction for a given area. As such, the comparison of different proxy records is a useful tool for understanding climatic and environmental variability over time in a study area, when the sensitivities of the records are fully considered.

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