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# Tree-ring derived Little Ice Age temperature trends from the central British Columbia Coast Mountains, Canada

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ABSTRACT

Most glaciers in the British Columbia Coast Mountains reached their maximum Holocene extent during the Little Ice Age. Early- and late-Little Ice Age intervals of expansion and retreat fluctuations describe a mass-balance response to changing climates. Although existing dendroclimatic records provide insights into these climatic fluctuations over the last 400 yr, their short durations prohibit evaluation of early-Little Ice Age climate variability. To extend the duration of these records, submerged coarse woody debris salvaged from a high-elevation lake was cross-dated to living chronologies. The resulting chronology provides the opportunity to reconstruct a regional June–July air-temperature anomaly record extending from AD 1225 to 2010. The reconstruction shows that the intervals AD 1350–1420, 1475–1550, 1625–1700 and 1830–1940 characterized distinct periods of below-average June–July temperature followed by periods of above-average temperature. Our reconstruction provides the first annually resolved insights into high-elevation climates spanning the Little Ice Age in this region and indicates that Little Ice Age moraine stabilization corresponds to persistent intervals of warmer-than-average temperatures. We conclude that coarse woody debris submerged in high-elevation lakes has considerable potential for developing lengthy proxy climate records, and we recommend that researchers focus attention on this largely ignored paleoclimatic archive.



## Introduction

The Little Ice Age (LIA) is recognized as an interval during which most glaciers in Pacific North America reached their maximum Holocene extent (Luckman, 2000; Barclay et al., 2009; Davis et al., 2009). In the British Columbia Coast Mountains, the LIA is characterized by distinct intervals of glacial expansion and retreat (Menounos et al., 2009). Early-LIA glacier expansion began in the 11th century (Clague et al., 2009), with distinct 12th and 13th century advances recorded (Ryder and Thomson, 1986; Allen and Smith, 2007; Koch et al., 2007). Following this interval most glaciers receded and downwasted prior to the late-LIA expansion during the 17th century that led to regional moraine-building episodes in the 18th and 19th centuries (Larocque and Smith, 2003; Allen and Smith, 2007; Koch et al., 2007; Koehler and Smith, 2011; Harvey and Smith, in press). These ice-front fluctuations describe a sensitive mass-balance response to changing LIA climates (Larocque and Smith, 2005a; Wood et al., 2011).

Direct understanding of how climate influences glacier mass balance in this region is limited by the duration of the instrumental record, which only rarely exceeds 100 yr (Zhang et al., 2000; Turner and Gyakum, 2010). While the 20th century was characterized by regime-scale shifts leading to 'cool' (AD 1890–1925 and 1947–1976) and 'warm' (AD 1925–1945 and 1977–mid 1990s) phases (Mantua and Hare, 2002; Labeyrie et al., 2003) that significantly impact glacier mass-balance regimes (Yarnal, 1984; Bitz and Battisti, 1999), appreciably less is known about climatic trends over the duration of the LIA (Walker and Pellatt, 2008).

Proxy insights into the character of late-LIA temperature and precipitation trends in the central Coast Mountains have been derived from the radial growth climate-response of living trees at a network of high-elevation sites in the Coast Mountains (Larocque and Smith, 2005b; Wood et al., 2011; Starheim et al., in press). Collectively, these reconstructions highlight periods of cooling (early 1700s, early 1800s, and late 1900s) and warming (late 1700s, mid 1800s, and early 1900s) that exhibit oscillatory relationships to climate regimes described by the Pacific Decadal Oscillation (PDO) (Gedalof and Smith, 2001a) and the Pacific North America (PNA) pattern (Wood et al., 2011; Starheim et al., in press).

Comparable early-LIA proxy climate records have not previously been developed for high-elevation sites in the central Coast Mountains. As most montane forest stands in this region rarely exceed 400–500 yr in age (Means, 1990; Starheim et al., in press), attention has been directed to understanding the character of regional early-LIA climates by comparison to research in the Gulf of Alaska (Wilson et al., 2007) and the Canadian Rocky Mountains (Luckman and Wilson, 2005). Supplemented by insights derived from annually resolved millennial-long temperature reconstructions from the Northern Hemisphere (D'Arrigo et al., 2006), these studies suggest that early-LIA climates were likely characterized by cooler-than-normal temperatures during the 1200s to mid-1300s,

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and mid-1500s to early 1700s. Despite the broader insights offered by these studies, concern remains that they do not adequately capture early-LIA climatic trends specific to the central Coast Mountains.

In order to describe climate variability at high-elevation sites in the Coast Mountains over the full span of the LIA, tree-ring chronologies extending back beyond the age of living trees are required. The goal of the research presented here was to construct a continuous tree-ring chronology incorporating samples from both living trees and coarse woody debris (CWD). In order to extend the duration of the tree-ring record in this setting, our investigations focused on retrieving CWD from the bottom of a high-elevation lake located in the central Coast Mountains and cross-dating these samples to ring-width records constructed from living forest stands.

## Study site

The Coast Mountains extend northwestward from southwestern British Columbia to the St. Elias Mountains of southwestern Yukon and Alaska. The central Coast Mountain region extends from Eustuk Lake (53° 14′ N, 126° 34′ W) to the Silverthone Icefield (51° 29′ N, 125° 56′ W). The region is underlain by granitic rocks of the Coast Plutonic Complex and includes mountain summits within the Pacific and Kitimat ranges (Baer, 1973). Major coastal fjords and valley drainage systems of the Bella Coola, Atnarko and Talchako rivers bisect the region (Holland, 1976). Profoundly influenced by coastal maritime climates, this region is characterized by orographic precipitation resulting from weather systems originating in the northern Pacific Ocean (Wood, 2001). Annual air temperatures near sea level average 8°C in the community of Bella Coola, British Columbia, with precipitation totals exceeding 1650 mm annually (Environment Canada, 2010).

Fieldwork was focused at M Gurr Lake, a small subalpine lake (0.06 km$^2$, max depth 25 m) located within the Clayton Falls Conservancy accessed by the Clayton Falls Forest Service Road from Bella Coola. M Gurr Lake is located on the crest of a mountain ridge at 1300 masl overlooking South Bentinck Arm (Lat 52°17′ N, Long 126°53′ W; Figs. 1 and 2). The lake drains over a bedrock sill through a narrow outlet before flowing into the Clayton Falls Creek valley (Fig. 2). Coastal montane climate conditions characterize the local environment, with precipitation falling principally as snow from late fall to early spring (Kendrew and Kerr, 1956; Moore et al., 2010).

The lake is surrounded by parkland vegetation consisting predominantly of scattered to continuous stands of mountain hemlock (*Tsuga mertensiana*) with sparse cohorts of young subalpine fir (*Abies lasiocarpa*) and yellow cedar (*Callitropsis nootkatensis*) (Brooke et al., 1970; Klinka and Chourmouzis, 2001). Alpine wildflowers and mountain heather (*Phyllodoce empetriformis*, *Cassiope mertensiana*) characterize the forest understory and surrounding tundra slopes.

Steep partially vegetated to vegetated avalanche slopes and rockslide pathways enter directly into the lake. The four most prominent avalanche paths have an average surface slope of 20°, with 35 m of relief over the ca. 160 m from their initiation zones to the lakeshore. Largely treeless, the avalanche paths are bordered by mature trees displaying scars characteristic of those associated with snow avalanche activity (Glen, 1974; Burrows and Burrows, 1976; Carrara, 1979; Shroder, 1980). The presence of reaction wood within a sample of eleven living trees indicates that destructive snow avalanches occurred in the winters of AD 1914–1915, 1925–1926, and 1940–1941.

## Research methods

Increment cores collected from mature mountain hemlocks adjacent to M Gurr Lake during a reconnaissance survey in 1997 indicated that most trees had a maximum age of just over 300 yr. To lengthen the duration of the mountain hemlock tree-ring chronology at this site, detrital boles resting on the lake bottom were retrieved and cross-dated to local and regional living tree-ring chronologies. Proxy climate reconstructions were derived from the extended chronology.

### *Living tree-ring chronologies*

Prior research in Pacific North America demonstrates that the radial growth of mountain hemlock trees is positively correlated to summer air temperatures and negatively correlated to seasonally persistent winter snowpacks (Gedalof and Smith, 2001b; Peterson and Peterson, 2001). Response surface analyses illustrate the non-linear impact these parameters have, with warm growing season temperatures promoting early snowmelt, regulating soil temperatures and encouraging rapid leaf-shoot and stem growth (Graumlich and Brubaker, 1986; Smith and Laroque, 1998).

In order to maximize the strength of the living tree-ring record, samples were collected from mature mountain hemlock trees without apical disturbance or obvious rot (Fritts, 1976). A standard 5 mm increment borer was used to retrieve two cores at breast height (minimum 90° apart) from each tree to avoid basal ring distortion (Stokes and Smiley, 1968). The samples were stored in plastic tubes and transported to the University of Victoria Tree-Ring Laboratory (UVTRL) for measurement and analysis.

In order to confirm the existence of a regional mountain hemlock dendroclimatic signal a second chronology was constructed from archived and newly collected tree-ring records from montane forests on Mt Cain, northern Vancouver Island (Lat 50°13′55″ N, Long 126°21′20″ W; Fig. 1). The mountain hemlock zone at this site experiences similar climatic conditions as those expected at M Gurr Lake, with a mean annual temperature of 3°C and precipitation totals averaging 2620 mm per yr (Laroque and Smith, 1999). Increment cores were collected at breast height from mature trees located at ca. 1200 m asl in 1996 and 1997 (Laroque and Smith, 2003). In order to assist with cross-dating of the CWD recovered at M Gurr Lake, supplemental sampling of the 'ancient forest' at Mt Cain (Parish and Antos, 2004) was undertaken by UVTRL researchers in 2009 to strengthen the earliest portion of the existent mountain hemlock chronology.

### *CWD chronology*

While CWD exposed to aerobic conditions decays rapidly in coastal British Columbia (Daniels et al., 1997), CWD submerged in lakes ranges in age from a few hundred to thousands of years in this region (Zhang and Hebda, 2005). Previous research has shown that submerged CWD oftentimes retains sufficient structural integrity for dendrochronological analysis (Zetterberg et al., 1994; Guyette and Cole, 1999; Grabner et al., 2001; Gunnarson, 2001; Guyette and Stambaugh, 2003).

CWD from M Gurr Lake was located and retrieved using two techniques. Littoral zone samples were identified from the shore and collected by assistants wearing chest waders. Deep-water samples (0.5–5 m) were identified by a team of snorkelers and sampled by scientific SCUBA divers. The position, depth, orientation and length of the CWD, as well as the presence of bark or branches were recorded for individual samples (Shroder, 1980). The divers released the CWD deeply entombed in sediment by first excavating a trough around the perimeter of the sample. A chainsaw-driven winch was employed to pull the CWD to shore when human force proved unsuccessful (Fig. 3). Cross-sectional disks (5–10 cm thick) were cut with a chainsaw and the remaining portion returned to its original location on the lake bottom.

### *Laboratory preparation and analysis*

All the samples were allowed to air-dry, after which the cores were glued into slotted mounting boards and any broken disks were

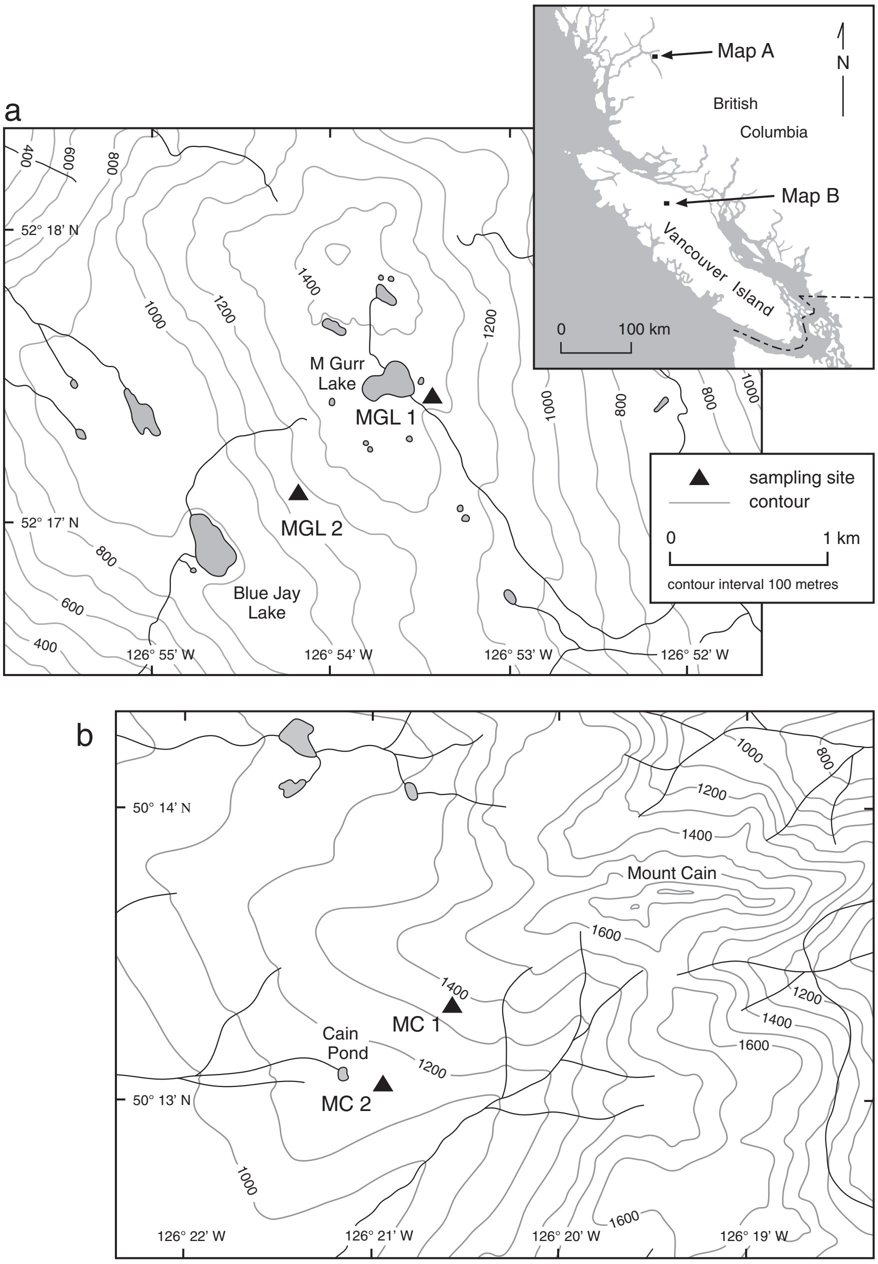


**Figure 1.** Map showing location of sampling sites at M Gurr Lake and Mt Cain, British Columbia Coast Mountains.

secured with glue before being polished to a 600-grit finish to reveal ring boundaries (Stokes and Smiley, 1968). Digital images of the samples were captured with a high-resolution Epson XL 1000 scanner and the width of each ring measured along a central pathway to the nearest 0.01 mm using a WinDENDRO™ image-analysis system (Ver. 2008g, Regent Instruments Inc., 2008). A minimum of two perimeter-to-pith pathways were measured on each disk.

Individual ring-width series (A and B cores, disk pathways) were first visually cross-dated using CDendro™ (Ver. 7.1, Larsson, 2003). The International Tree Ring Database (ITRDB) software program COFECHA 3.0 (Holmes, 1983) was used to verify cross-dating calculating a Pearson's r correlation coefficient at a 99% confidence interval between 50-yr segments with a 25-yr lag (Grissino-Mayer, 2001).

Following internal cross-dating, independent ring-width chronologies were constructed using established cross-dating protocols (Stokes and Smiley, 1968; Fritts, 1976; Grissino-Mayer, 2001). Individual series were visually compared and, through cross-dating, combined to create variable-length floating chronologies. The floating chronologies were subsequently cross-dated to the living chronologies from M Gurr Lake and Mt Cain to situate them in calendar time and to develop an extended and continuous tree-ring chronology. Samples were eliminated if the tree-ring series was short (<100 yr) or showed a Pearson's r correlation coefficient lower than $r=0.33$ (Grissino-Mayer, 2001).

An extended tree-ring chronology that included living and CWD samples was constructed by invoking a double-detrending option in the ITRDB software program ARSTAN (Ver41d) to reduce the impact of biological and endogenous disturbance events (Kramer and Kozlowski, 1960; Cook and Krusic, 2005). A negative exponential curve was used to remove age-related growth trends within each tree-ring series and a smoothing spline, with a 67% frequency response cut off preserving 50% of the variance in the ring width, was applied to remove any remaining growth variability caused by stand dynamics or disturbance events (Cook et al., 1990). Standardized and residual chronologies

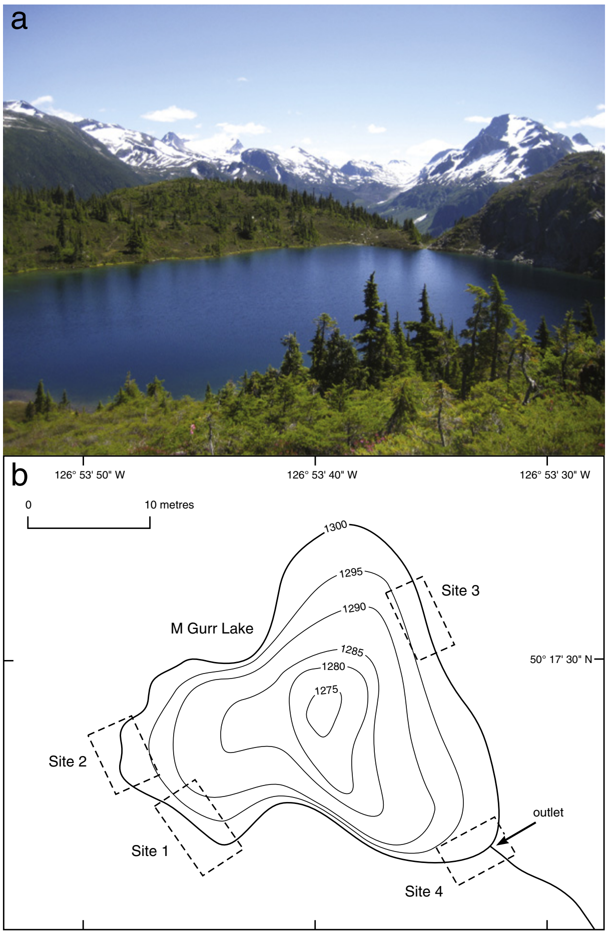


**Figure 2.** M Gurr Lake study site. (a) M Gurr Lake. (b) M Gurr Lake bathymetric map showing the four sampling sites and 5 m contour lines indicating lake depth.

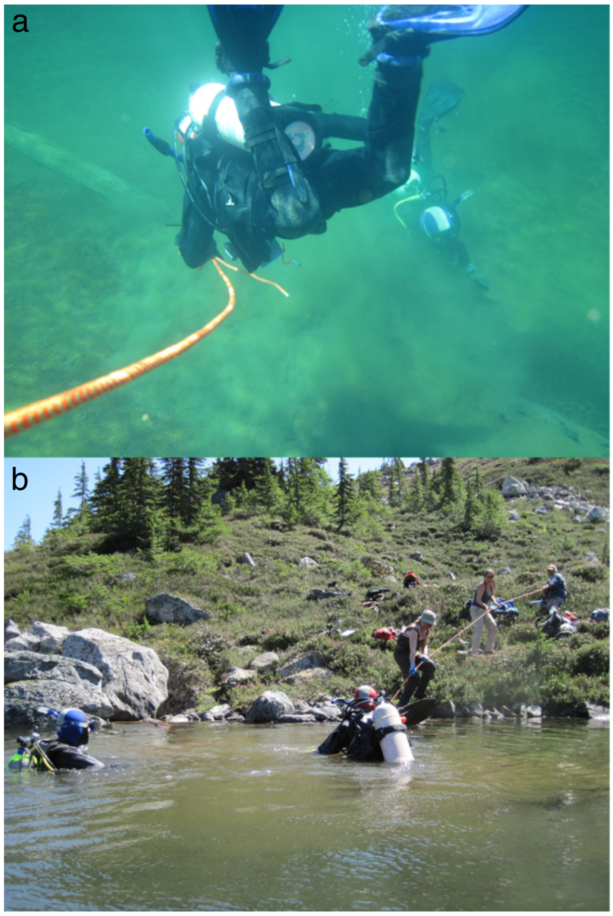


**Figure 3.** Removal of coarse woody debris from M Gurr Lake. (a) SCUBA divers locating and attaching a rope to submerged coarse woody debris sample. (b) Shore removal of sample dislodged by SCUBA divers.

were constructed, with the latter allowing for the removal of low-order autocorrelation relationships associated with the influence of prior growth on current-year growth (Cook et al., 1990). A mean sensitivity value was computed to measure variations between the annual rings (Grissino-Mayer, 2001). An expressed population signal (EPS) was used to quantify signal strength through time (Wigley et al., 1984). EPS values were calculated at 25-yr moving periods for each chronology using ARSTAN.

### *Dendroclimatological analysis*

Land air-temperature anomaly data compiled for a 5° × 5° grid box (Latitude 50°–55° N and Longitude 125°–130° W) by the Climate Research Unit (2010) was compared to the residual extended tree-ring chronology indices using Pearson's correlation coefficients to quantify the association between monthly temperature and radial tree-ring growth. Months demonstrating the strongest Pearson's r significant to the 0.01 level were used for reconstruction. Simple linear regression using the leave-one-out method was employed to develop a predictive model based upon the strongest correlated monthly climate response variable and tree-ring width. To verify the strength of the relationship, one year was left out over the entire instrumental record and individual linear regression models were developed over the calibration period (Gordon, 1982). The values predicted for each left-out year were then combined and correlated with the instrumental record to verify the strength of the reconstruction (Rv). A rigorous reduction of error (RE) statistic was computed as an additional model quality check providing a sensitive measure of reliability, with positive RE values indicating that the regression model has enough skill for reconstructions to be made (Fritts, 1976). Model adequacy for climate proxy reconstruction was proven by statistically significant correlations, strong $r^2$ values, and positive RE values. Wavelet analysis, using a Morlet 2 function coupled with a 5% red-noise reduction, was used to reveal temporal cyclicity in the extended tree-ring record (http://paos.colorado.edu/research/wavelets/; Torrence and Compo, 1998).

## Results and discussion

### *Tree-ring chronology construction*

Tree-ring samples were collected at two sites located in close proximity to M Gurr Lake. Site M Gurr Lake 1 (MGL1) was located at 200 m southeast of the lake on a gently to steeply sloping southeast-facing slope at 1330 masl (Latitude 52° 17′ 22″ N, Longitude 126° 53′ 37″ W; Fig. 1). It was characterized as a mountain hemlock parkland consisting of clusters of mature trees separated by shrub communities and cohorts of young subalpine fir and yellow cedar. Site M Gurr Lake 2 (MGL2) was located within a closed stand of mature mountain hemlock trees located 1 km southwest of M Gurr Lake on a moderately sloped south-facing slope at 1050 masl (Latitude 52° 17′ 02″ N, Longitude 126° 54′ 22″ W; Fig. 1). An M Gurr Lake living chronology was constructed by combining and cross-dating the series collected at MGL1 and MGL2 (Table 1).

Tree ring samples were collected from two sites at Mt Cain. The Mt Cain 1 site (MC1) sampled in 1996 and 1997, located at ca. 1300 masl (Latitude 50° 13′55″ N, Longitude 126° 19′ 30″ W; Fig. 1), was characterized by mature mountain hemlock, amabilis fir (*Abies amabilis*), yellow cedar and western hemlock (*Tsuga heterophylla*) trees (Parish and

**Table 1**
Chronology statistics for individual site and regional mountain hemlock chronologies.

| Chronology | No. of cores/trees | Interval (yr AD) | Total length (yr) | Median segment length (yr) | Correlation coefficient (r)[a] | Mean sensitivity [b] | EPS [c] |
|---|---|---|---|---|---|---|---|
| M Gurr Lake 1 | 40/21 | 1682–2010 | 329 | 243 | 0.64 | 0.31 | 1740 |
| M Gurr Lake 2 | 53/29 | 1623–2010 | 388 | 271 | 0.61 | 0.26 | 1730 |
| M Gurr Lake | 93/50 | 1623–2010 | 388 | 267 | 0.61 | 0.28 | 1705 |
| Mt Cain 1 | 72/45 | 1337–1997 | 661 | 453 | 0.54 | 0.29 | 1390 |
| Mt Cain 2 | 19/11 | 1320–2008 | 689 | 466 | 0.56 | 0.25 | 1555 |
| Mt Cain | 91/55 | 1320–2008 | 689 | 459 | 0.53 | 0.28 | 1380 |
| Regional Living | 184/106 | 1320–2010 | 691 | 304 | 0.53 | 0.29 | 1380 |
| M Gurr (CWD1) | 25/10 | 1662–1869 | 208 | 155 | 0.60 | 0.33 | – |
| M Gurr (CWD2) | 25/13 | 1094–1504 | 411 | 144 | 0.50 | 0.31 | – |
| Extended tree-ring chronology | 234/130 | 1094–2010 | 917 | 275 | 0.52 | 0.29 | 1225 |

[a] All correlations are statistically significant to the 0.01 level.
[b] Measures the amount of variation between the annual rings with intermediate values ranging between 0.20 and 0.29 and highly sensitive values represented by values above 0.30.
[c] EPS (Expressed Population Signal). Date that a decrease in sample depth drops the EPS below 0.80.

Antos, 2004). The Mt Cain 2 site (MC2) sampled in 2009 was located at 1200 m asl (Latitude 50° 13′04″ N, Longitude 126° 21′ 11″ W; Fig. 1) in an open, boggy, mountain hemlock stand on a gentle south-facing slope. A Mt Cain living chronology was constructed by combining and cross-dating the series collected at MC1 and MC2 (Table 1).

A regional chronology was constructed by cross-dating the living M Gurr Lake and Mt Cain chronologies. Containing 184 series and spanning 691 yr with a mean series correlation of $r = 0.53$ (Table 1), the chronology robustly captures a radial growth signal common to both sites (Tables 1 and 2). Similar long-distance radial growth relationships involving mountain hemlock trees were previously reported by Gedalof and Smith (2001a, 2001b) for this region.

Forty-nine CWD samples were collected from M Gurr Lake (Table 1). Examination revealed that the majority have broken basal stems consistent with shearing by snow avalanches (Shroder, 1980). Twenty-five series from ten CWD samples cross-date to the M Gurr Lake living chronology ($r = 0.60$) and span a 208 yr interval from 1662 to 1869 (CWD1, Table 1; Fig. 4). Twenty-five series from 13 CWD samples span 411 yr and cross-date to the earliest portion of the regional chronology composed primarily of Mt Cain living samples ($r = 0.50$) from AD 1094–1504 (CWD2, Table 1; Fig. 4). The latter samples that displayed substantial peripheral decay were in deep water distant to the shoreline and were partially buried by muddy lake bottom sediments.

A 158-yr interval from 1504–1662 separates the two CWD chronologies (Fig. 4). Although this interval may reflect a period during which woody detritus was not added to the lake, it is also possible that CWD spanning this period was not located within the area of the lake bottom sampled. An alternative hypothesis, arising from a comparable research on submerged CWD salvaged from lakes in the central Scandinavian Mountains (Gunnarson, 2001; Eronen et al., 2002) and Vancouver Island (Zhang and Hebda, 2005), is that the age distribution of samples from M Gurr Lake describes the transport of snow-avalanche-killed trees associated with distinct germination cohorts on the avalanche pathways. Although this hypothesis cannot be rigorously tested, some support arises from the fact that the oldest germination dates of living mountain hemlock trees at the study site and in the surrounding region largely occur in the mid-17th century (Gedalof and Smith, 2001b; Starheim et al., in press). This apparent germination synchrony is possibly climate-related (Rochefort et al., 1994; Woodward et al., 1995) potentially identifying a regional seeding episode related to warmer-than-normal temperatures in the mid-17th century (Laroque et al., 2000).

All the chronologies exhibit high statistical similarity describing a common radial growth relationship to climate variability (Table 2). This observation follows on the findings of previous research focused on the climate-response of mountain hemlock trees (Gedalof and Smith, 2001b). In this instance it allows for the construction of an extended tree-ring chronology that incorporates the CWD records from M Gurr Lake (CWD1 and CWD2), the living chronologies from M Gurr Lake (MGL1 and MGL2) and the chronologies from Mt Cain (MC1 and MC2) (Fig. 4; Table 1). The extended tree-ring chronology spans 917 yr (AD 1094–2010) and has a mean series correlation of $r = 0.52$ and a mean sensitivity of 0.29, with an EPS cut-off point of 1225 (Table 1).

Wavelet analysis completed on the extended tree-ring chronology reveals the persistence of low-frequency century-scale (ca. 100–150 yr) and intermittent high-frequency (ca. 8–32 yr) trends (Fig. 6b). The low-frequency signal is prominent from AD 1400 to present, but notably depressed from AD 1200–1400. Previous researchers associated similar century-scale growth trends to sunspot cyclicity (Luckman and Wilson, 2005; Wilson et al., 2007; Fig. 6). The higher-frequency trends reflect established radial growth responses to oscillating climates described by the PDO (Gedalof and Smith, 2001a; Hart et al., 2010; Starheim et al., in press).

**Table 2**
Correlation values for the tree-ring chronologies used in this study over their common period. All correlations are significant to the $p = 0.01$ level.

| | MC1 | MC2 | MGL1 | MGL2 |
|---|---|---|---|---|
| MC1 | – | | | |
| MC2 | 0.535 | – | | |
| MGL1 | 0.539 | 0.561 | – | |
| MGL2 | 0.530 | 0.553 | 0.612 | – |
| CWD1 | 0.532 | 0.523 | 0.627 | 0.603 |
| CWD2 | 0.537 | 0.539 | – | – |

### *Dendroclimatic reconstruction*

Correlation analysis revealed a statistically significant ($r = 0.50$; $p \leq 0.01$) relationship between the June–July gridded air temperature anomaly data (AD 1900–2010) and the residual extended tree-ring chronology. This relationship, verified by significant RE (0.22) and Rv (0.47) values, indicates that the model has predictive capacities ($r^2 = 0.25$). Visualization of the calibration period highlights the tendency of the model to underestimate temperature variability (Fig. 5), a common result of dendroclimatic reconstructions in this coastal montane setting where tree growth reacts to, and records, multiple climate signals (Larocque and Smith, 2005b; Wood et al., 2011). Recognizing that the model is most proficient at capturing long-term trends, it allows for the reconstruction of a 785-yr-long temperature anomaly record from AD 1225–2010 (Fig. 6).

The reconstruction indicates that cooler-than-average air temperatures characterize the intervals from ca. AD 1250–1300, 1330–1365, 1440–1455, 1475–1495, 1600–1625, 1690–1705, 1725–1760, 1830–1900, and 1965–1990 (Fig. 6a). Sustained warmer-than-average air temperatures occurred from ca. AD 1300–1340, 1500–1560, 1645–1685, 1755–1825, and 1905–1960 (Fig. 6a). The duration and

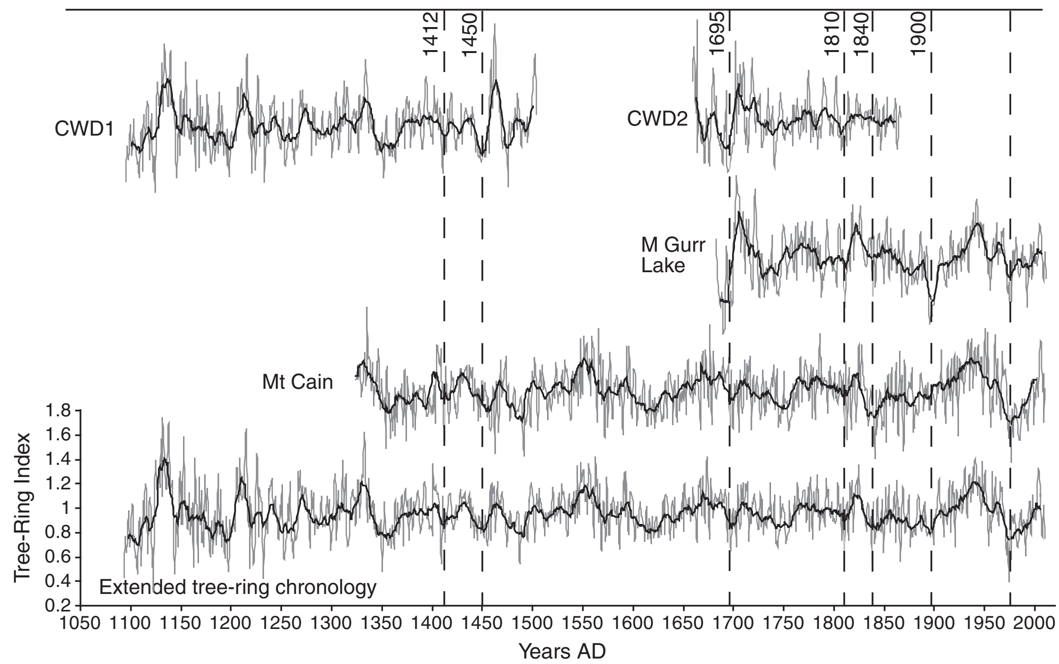


**Figure 4.** Standardized master living and coarse woody debris tree-ring chronologies. Gray lines illustrate the annual data. Black lines illustrate 10-yr running means. Vertical black dashed lines illustrate years with narrow pointer rings.

character of these cooler- and warmer-than-average intervals are consistent with the climatic consequences of negative and positive PDO phases in Pacific North America (Gedalof and Smith, 2001a; Mantua and Hare, 2002).

### *LIA moraine-building activity*

The temperature-anomaly reconstruction shows that the intervals AD 1350–1420, 1475–1550, 1625–1700, and 1830–1940 were characterized by distinctly below-average June–July temperatures that were followed by intervals of above-average temperatures (Fig. 7). These oscillatory periods correspond to the emerging moraine record of LIA glacial activity in the central Coast Mountain region (Fig. 7).

Moraines deposited in AD 1900–1950 followed minor glacier advances in the mid-19th century that corresponded to significant warming after ca. AD 1830 (Fig. 7) and persistent negative mass-balance conditions in the early 20th century (Larocque and Smith, 2005b; Wood et al., 2011). LIA glacier advances in the early 17th century corresponded to an extended interval of cooler temperatures, with moraine stabilization occurring in the early-18th century as June–July temperatures quickly warmed (Smith and Desloges, 2000; Larocque and Smith, 2003; Harvey and Smith, in press) (Fig. 7).

The early-LIA moraine record is sparse in this region (Larocque and Smith, 2003), with most deposits having been overrun by more recent LIA glacier advances (Menounos et al., 2009). As reported by Harvey and Smith (in press) and shown in Figure 7, however, moraines in the study area dating to the early 15th and early 16th centuries correspond to intervals when the anomaly record indicates that regional climate warming followed periods of cooler temperatures in the mid-14th and mid- to late 15th centuries, respectively (Fig. 7).

### *Comparisons with other multi-century reconstructions in PNA*

Figure 8 compares the temperature anomaly proxy record from this study with reconstructions from the Canadian Rocky Mountains (Luckman and Wilson, 2005) and the Northern Hemisphere (D'Arrigo et al., 2006; Wilson et al., 2007). As shown in Table 3, the strongest correlations and continuity among the reconstructions occurred over the intervals AD 1350–1450, 1650–1700, 1750–1800 and 1900–1950.

In general, the three records that show cooler temperatures characterized the mid-1300s, mid- to late-1400s, early-1700s, and

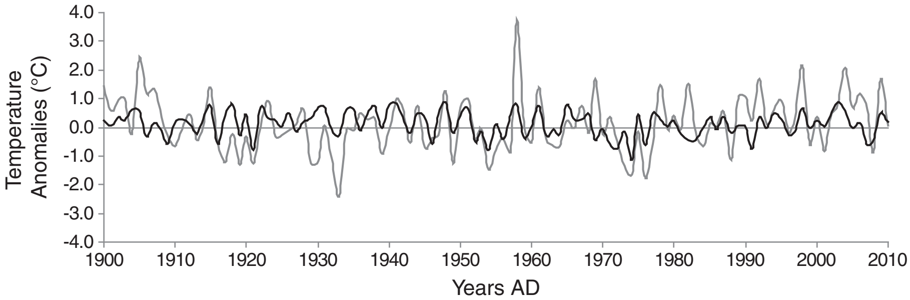


**Figure 5.** Comparison of instrumental (gray line) record of June–July gridded air temperature anomalies and the modeled proxy reconstruction (black line) for the calibration period (AD 1900–2010).

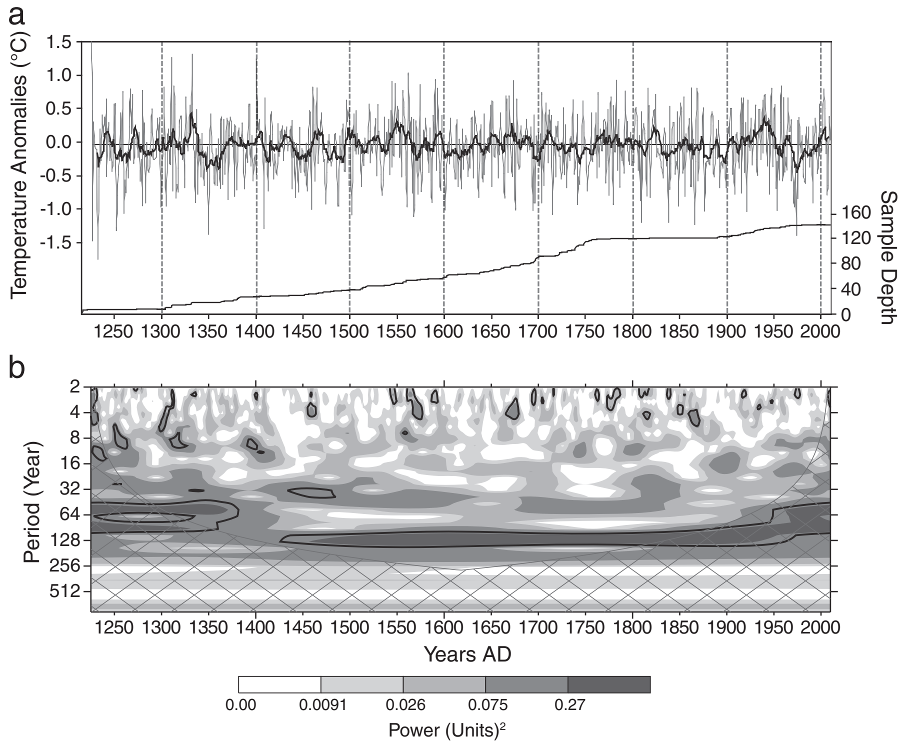


**Figure 6.** Reconstruction of air temperature anomaly ring-width variability AD 1225–2010. (a) June–July air temperature anomaly reconstruction. Gray lines represent annual reconstruction indices and the black line shows a 10-yr weighted running mean. (b) Wavelet power spectrum of extended tree-ring chronology. Cross-hatched regions represent the cone of influence where zero-padding of the data was used to reduce variance using a Marlet-2 function. Black contours indicate significant modes of variance with a 5% significance level using an autoregressive lag-1 red-noise background spectrum (Torrence and Compo, 1998).

the mid-1800s (Fig. 8). These intervals corresponded to periods of decreased sunspot activity and highlight the effects of the Wolf minimum (AD 1280–1350), Spörer minimum (AD 1460–1550), Maunder minimum (AD 1645–1715), Dalton minimum (AD 1790–1820) and Damon minimum (AD 1875–1905) on LIA climates. Globally, this low-frequency oscillating temperature trend is attributed to reduced solar irradiance that led to cooler temperature and persistent intervals of lower-than-average radial growth in temperature-sensitive tree-ring chronologies (Büntgen et al., 2006; Raspopov et al., 2008; Trouet and Taylor, 2010). Cooler temperatures in the mid-to late-1400s, particularly as described by the Northern Hemisphere and Canadian Rocky Mountain reconstructions, resulted in reduced tree growth throughout Pacific North America (Luckman, 1993; Colenutt and Luckman, 1996; Luckman, 1997; Mann et al., 1999; Colenutt, 2000). All the reconstructions record a major decline in air temperature around AD 1700. Briffa et al. (1998) indicate this period as highly ranked in the volcanic aerosol index (VAI), and it may be that the influence of volcanic eruptions and sunspot minima combined to result in cooler-than-normal temperatures at 52° N (Robertson et al., 2001).

Warmer-than-normal conditions generally characterize the mid-1300s to mid-1400s, mid-1550s, mid-to late 1700s, and the early 1900s in all three reconstructions (Fig. 8). Although temperatures are described as warmer between AD 1350 and 1450 in the Canadian Rocky Mountains and Northern Hemispheric reconstructions, temperatures within the central Coast Mountain then were more variable (Table 3). Warmer temperatures from AD 1750–1800 are evident in the Coast Mountain and Northern Hemisphere reconstructions

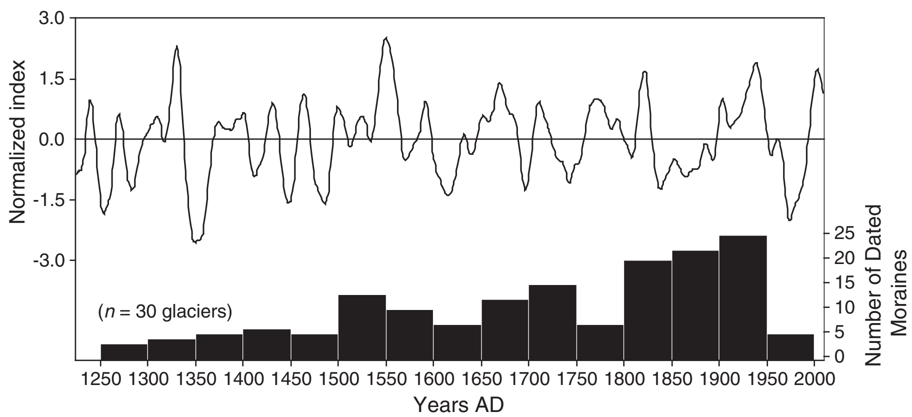


**Figure 7.** Normalized air-temperature tree-ring reconstruction smoothed with a 25-yr spline. Vertical bars represent the number (50-yr increments) of dated central Coast Mountain Little Ice Age moraines reported by Smith and Desloges (2000), Larocque and Smith (2003) and Harvey and Smith (in press) in accordance with air-temperature trends.

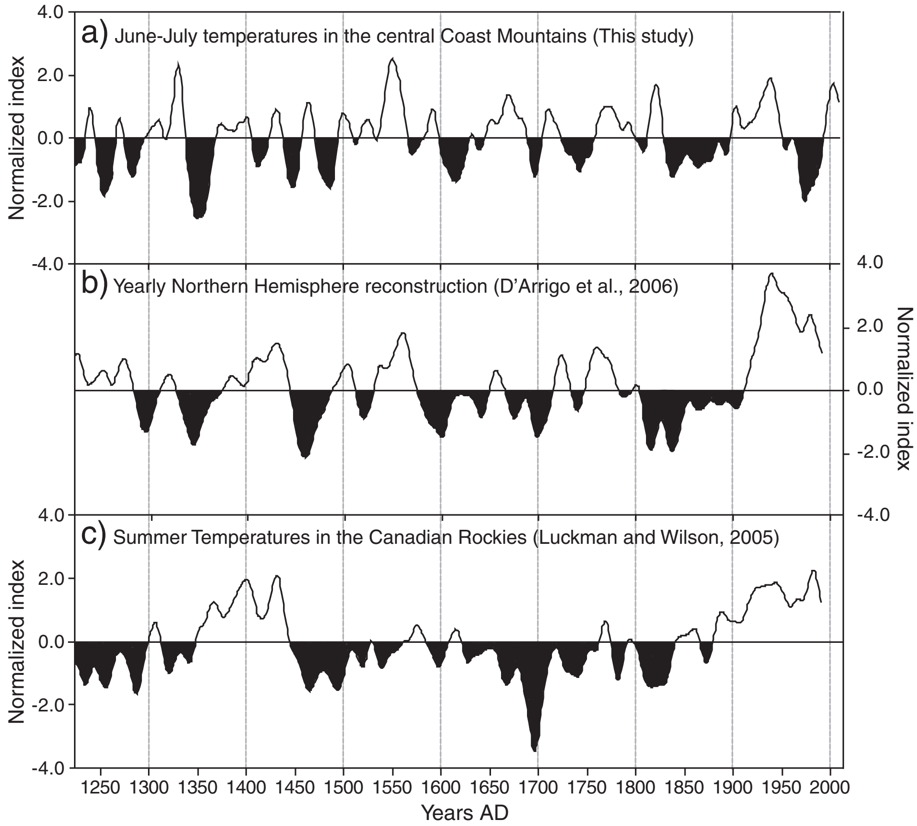


**Figure 8.** Comparison of the temperature reconstruction from this study with a composite yearly Northern Hemisphere reconstruction (D'Arrigo et al., 2006), and a summer-temperature reconstruction from the Canadian Rockies (Luckman and Wilson, 2005). All chronologies are smoothed with a 15-yr smoothing spline and normalized to the common period.

(Fig. 8), and characterize other northern 'high-latitude' reconstructions (Briffa, 2000; Esper et al., 2002). This tendency is weakly expressed in the Canadian Rocky Mountains' reconstruction. While the 20th-century warming is evident within all three reconstructions (Fig. 8), variable temperature states within the Coast Mountain reconstruction appear to highlight trends characteristic of documented PDO phases in coastal British Columbia (Hart et al., 2010; Whitfield et al., 2010; Starheim et al., in press).

**Table 3**
Correlations between the June–July temperature reconstructions from this study with the composite Northern Hemisphere (D'Arrigo et al., 2006) and Canadian Rocky Mountain (Luckman and Wilson, 2005) reconstructions over ca. 50-yr intervals. The bold figures indicate statistically significant correlation values between reconstructions ($p = 0.01$ level).

| AD | D'Arrigo et al. (2006) | Luckman and Wilson (2005) |
|---|---|---|
| 1200–1250 | −0.624 | **0.593** |
| 1251–1300 | −0.251 | **0.798** |
| 1301–1350 | **0.697** | −0.051 |
| 1351–1400 | **0.917** | **0.714** |
| 1401–1450 | **0.645** | **0.937** |
| 1451–1500 | −0.374 | −0.603 |
| 1501–1550 | 0.391 | −0.269 |
| 1551–1600 | 0.308 | −0.452 |
| 1601–1650 | 0.098 | −0.690 |
| 1651–1700 | **0.419** | **0.765** |
| 1701–1750 | −0.207 | 0.126 |
| 1751–1800 | **0.430** | **0.426** |
| 1801–1850 | −0.112 | −0.605 |
| 1851–1900 | 0.320 | **0.445** |
| 1901–1950 | **0.615** | **0.585** |
| 1951–1994 | −0.416 | −0.590 |
| Full | 0.126 | 0.037 |

## Summary

This research provided an opportunity to construct a multi-century tree-ring chronology from living and CWD tree-ring samples. Living tree-ring records were collected from two high-elevation sites in the British Columbia Coast Mountains and cross-dated to floating tree-ring chronologies constructed from submerged CWD samples salvaged from a high-elevation subalpine lake.

The 785-yr-long air-temperature anomaly record constructed in this study provides the first detailed insights into high-elevation climates spanning the LIA in the central British Columbia Coast Mountains. The discovery of repetitive shifts between above- and below-normal temperature regimes offers a long-term perspective on the character of LIA climates at high elevations in this region. The inherent century-long oscillation in climate states is supported by dates assigned to LIA moraines in this region, and serves to highlight the temperature sensitivity of glacier mass-balance regimes in the Coast Mountains. Periods of cooler- and warmer-than-normal temperatures are consistent with reconstructions from the Northern Hemisphere and Canadian Rocky Mountains, highlighting the similarity in climatic trends throughout Pacific North America.

The results of our investigations confirm that CWD submerged in high-elevation lakes has considerable potential for developing extended proxy climate records. Our findings show that CWD can reside in lakes for hundreds of years and that tree-ring dating can be used to establish the CWD age. Given the potential for developing long-term proxy climate records and for elucidating the glacier mass-balance responses that led to the pre-LIA First Millennium Advance (Reyes et al., 2006), we recommend that researchers focus attention on this largely ignored paleoclimatic archive in Pacific North America.

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