Extending the duration and dendroclimatic potential of mountain hemlock (*Tsuga mertensiana*) tree-ring chronologies in the southern British Columbia Coast Mountains

by

Kara Jane Pitman
B.Sc., University of Victoria, 2009

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Supervisory Committee

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Abstract

Tree-ring records collected from living mountain hemlock trees in the southern British Columbia Coast Mountains have been used to provide insights into the character of historical climatic fluctuations and the behaviour of individual climate forcing mechanisms. The relatively short-duration of these records limits, however, their ability to describe climate variability and atmospheric processes that change gradually or undergo long-term regime shifts. The objectives of this research were to extend the duration and quality of proxy climate information extracted from mountain hemlock tree-ring chronologies.

In coastal British Columbia most existing mountain hemlock tree-ring chronologies extend from ca. AD 1600 to present. To extend the duration of these chronologies, coarse woody debris recovered from the bottom of M Gurr Lake, a high-elevation lake in the vicinity of Bella Coola, British Columbia, was cross-dated to nearby living chronologies surrounding M Gurr lake and increment core samples of ancient trees at Mt Cain on northern Vancouver Island. From this, a regional continuous 917-year long record of radial growth was constructed. The resulting regional chronology was used to construct a 785 year-long proxy record of gridded air temperature anomalies displaying periods of cooler and warmer than average regional air temperatures that contained century-long low frequency trends. Cross-dating and tree morphological evidence of snow avalanche activity displayed within living trees surrounding the lake, and within the coarse woody debris, revealed that low-magnitude avalanches occurred in the winter months of AD 1713-1714, 1764-1765, 1792-1793, 1914-1915, 1925-1926, and 1940-1941. High magnitude avalanche events occurred in the winter months of AD 1502-1502 and 1868-1869.

A second objective of the thesis was to investigate the radial growth response of mountain hemlock trees to subseasonal climate variables using standardized ring-width and densitometric analyses. Mountain hemlock chronologies from M Gurr Lake, Cyprus Provincial Park, and Mount Arrowsmith were used to describe the inherent climate-growth trends. Maximum annual tree-ring density values provided a robust data series for constructing site-specific proxy records of late-summer temperature. Annual tree-ring width measurements provided independent proxies of spring snowpack trends. Regionally-derived proxy models indicated that intervals of cooler-than-average and higher-than-average air temperatures correspond to years of higher-than-average average and cooler-than-average snowpacks, respectively. Of note were the significant decreases in air temperature and increases in snowpack depths during the early-1700s and early-

1800s coinciding with documented glacier advances in the Coast Mountains. Identification of these subseasonal climate signals within the tree-rings of mountain hemlock trees demonstrates the value of incorporating investigations of multiple tree-ring parameters.

Table of Contents

List of Tables

List of Figures

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Chapter 1 – Introduction

1.1 Introduction

Dendroclimatology offers the opportunity to use tree-ring indices to describe localized climate fluctuations, broad-scale oceanic-atmospheric conditions and solar irradiance fluctuations beyond the length of instrumental records (Fritts, 1976; Hughes, 2002). In coastal British Columbia, high-elevation mountain hemlock tree-ring records have proven to be useful proxies of past climate due to their radial growth response and relationship to growing season climate variables (Gedalof and Smith, 2001a, 2001b; Larocque and Smith, 2005a). Most chronologies from this region begin around, if not after, the 13th century (Lewis, 2001; Gedalof, 1999; Laroque, 2002; Larocque, 2003; Penrose, 2007; Starheim, 2011). This temporal restriction limits the detection of low-frequency trends or regime shifts to those with frequencies of less than 100 years (Smith and Laroque, 1998; Gedalof and Smith, 2001b; Larocque and Smith, 2005).

The intent of this research was to extend the duration and quality of proxy climate information available from mountain hemlock tree-ring chronologies in the southern British Columbia Coast Mountains. It was recognized that, globally and nationally, extended multi-millennia chronologies have been constructed from the remains of trees found submerged in lakes (Schweingruber, 1988; Zhang and Hebda, 2005).These coarse woody debris (CWD) deposits retain valuable pre-instrumental climate information, with exceptional examples having been used to reconstruct proxy climate and humidity records extending over 1000s of years (Eronen *et al*., 1999; Eronen *et al*., 2002; Helama *et al*., 2005; Linderholm and Gunnarson, 2005). Given the propensity for trees to fall or be transported into lakes in montane regions (Grabner *et al.*, 2001), it was considered opportune to explore whether the CWD found in high-elevation lakes in coastal British Columbia contained tree-ring records useful for extending the duration of mountain hemlock tree-ring chronologies.

The annual radial growth of mountain hemlock trees in coastal British Columbia is governed, at least in part, by an autocorrelated relationship to spring snowpack and summer growing season temperatures (Smith and Laroque, 1998; Gedalof and Smith, 2001b). Given that cell wall division and enhancement (ring-width growth) occurs primarly during the spring and early-summer season, and that cell wall thickening (cell density) is primarily a late-summer activity (Conkey, 1986; Schweingruber, 1988), the present research sought to compare the findings of traditional ring-width analyses with those derived from densitrometric investigations.

1.2 Research Objectives

The specific objectives of the thesis were to:

1) Build an extended mountain hemlock tree-ring chronology by cross-dating coarse woody debris to living tree-ring chronologies. Attention focused on the remains of coarse woody debris recovered from the bottom of a high-elevation lake.

2) Use the extended tree-ring chronologies to construct long-term proxy climate records.

3) Describe the relationship between radial growth in mountain hemlock trees and seasonal climate variables using standardized ring-width and densitometric analyses.

4) Construct long-term climate proxy records of subseasonal climates in south western British Columbia.

1.3 Thesis Format

This thesis consists of four chapters. Chapter One provides a broad introduction to the research, and reviews the goals and objectives of this project. Chapter Two presents the research undertaken to develop an extended mountain hemlock tree-ring record. It discusses the findings of these investigations and presents a multi-century proxy climate reconstruction. Chapter Three presents the analysis of mountain hemlock tree-ring records derived from standardized ring-width analysis and densitometry. The results of these analyses are used to describe the intra-annual response of mountain hemlock tree-rings to subseasonal climates. The fourth and final chapter summaries the research findings, provides conclusive remarks and identifies research limitations and suggestions for future research.

Chapter 2 – An extended mountain hemlock (*Tsuga mertensiana*) tree-ring record from the southern British Columbia Coast Mountains

2.1 Introduction

Significant relationships exist between climate, ocean-atmospheric climate forcing mechanisms and the annual radial growth trends of trees growing at high elevation (Luckman, 1994; Cook *et al.*, 2003; Frank and Esper, 2005; Christie *et al.*, 2009). In the British Columbia Coast Mountains tree-ring records collected from living trees have provided valuable insights into the character of past climatic fluctuations (Larocque and Smith, 2005a) and the behaviour of individual climate forcing mechanisms (Gedalof and Smith, 2001a; Wood *et al.*, 2011). In order describe climate variability and atmospheric processes that change gradually or undergo long-term regime shifts, tree-ring chronologies extending back beyond the age of living trees are required (LaMarche, 1974; Hughes and Diaz, 1994; Linderholm and Gunnarson, 2005).

Previous research indicates that coarse wood debris (CWD) recovered from dead standing trees (Kellner *et al.*, 2000) or from detritus on the forest floor (Daniels *et al.*, 1997: Luckman *et al.*, 1997), buried within bogs (Pilcher *et al.*, 1995), submerged in lakes (Zetterberg *et al.*, 1994; Grabner *et al.*, 2001; Gunnarson, 2001; Zhang and Hebda, 2005), or buried in glacial forefields (Jackson *et al.*, 2008), contain tree-rings that can be used to develop extended chronologies. For instance, Eronen *et al*. (2002) and Grudd *et al*. (2002) working in Finnish and Swedish Lapland constructed a 7500 year long tree-ring record from living trees, dead standing logs, and subfossil wood from lakes. Their supra-long chronologies have been used to reconstruct proxy climate records extending over timescales of centuries to millennia (Eronen *et al.,* 1999; Eronen *et al.,* 2002; Helama *et al.*, 2005: Linderholm and Gunnarson, 2005).

The objective of this research was to construct a mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) chronology extending the living tree-ring record at a high elevation site in the central British Columbia Coast Mountains. Mountain hemlock forests are common on snowy high-elevation mountain-sides and -tops along windward Coast Mountain slopes (Means, 1990). While ancient mountain hemlock trees with ages approaching 1000 years are reported from stands at Mt Cain on northern Vancouver Island (Laroque and Smith, 2003; Parish and Antos, 2004, 2006), most Coast Mountain stands rarely exceed 400-500 years in age (Means, 1990).

During a reconnaissance survey in 1997, increment cores were collected from mature mountain hemlock trees found growing in close proximity to M Gurr Lake. While the maximum age of the living trees sampled was just over 300 years (Gedalof, 2002), numerous submerged detrital boles were observed resting in the muddy littoral zone of the lake. This research sought to extend the duration of the tree-ring records available at this site by retrieving and sampling CWD from the lake bottom.

High elevation lakes provide ideal sites for preserving submerged logs. Their cold water acts to reduce anaerobic activity and ensures that logs sinking to the bottom retain their structural integrity (Schweingruber, 1988). Lakes surrounded by steep cliffs and slopes provide ideal transportation routes for dead logs or broken trees to slide down slope into the lake (Zetterberg *et al.,* 1994; Grabner *et al.,* 2001). These site conditions were met at M Gurr Lake, and during a return visit in 2010 tree-ring samples were collected from the submerged CWD and from living trees located within nearby stands. Cross-dating of the CWD to the living chronologies enabled construction of an extended tree-ring chronology, providing an opportunity to develop long-term climate and snow avalanche event records.

2.2 Study Site

M Gurr Lake is a small subalpine lake (0.06 km^2, max depth 25 m) located on the crest of a mountain ridge at 1300 m asl overlooking South Bentinck Arm (Lat 52°17’ N, Long 126°53’W; Figures 2.1 and 2.2). The lake is located within the Clayton Falls Conservancy and accessed by the Clayton Falls Forest Service Road exiting the nearby community of Bella Coola, British Columbia. Annual air temperatures at Bella Coola average 8°C and precipitation totals exceed 1650 mm/yr (Environment Canada, 2010).

M Gurr Lake drains over a bedrock sill through a narrow outlet before flowing into Clayton Falls Creek valley (Figure 2.3). The lake is surrounded by steep partially-vegetated to vegetated avalanche slopes and rockslide pathways that enter directly into the lake. Maritime conditions characterize the local environment, with precipitation falling principally as snow from late-fall to early-spring (Kendrew and Kerr, 1955; Moore *et al.*, 2010). The surrounding parkland vegetation consists predominantly of scattered to continuous stands of mountain hemlock, with sparse cohorts of young subalpine fir (*Abies lasiocarpa*) and yellow cedar *(Chamaecyparis nootkatensis)*. Alpine wildflowers and heather (*Calluna vulgaris*) occupy the forest understory and surrounding tundra slopes.

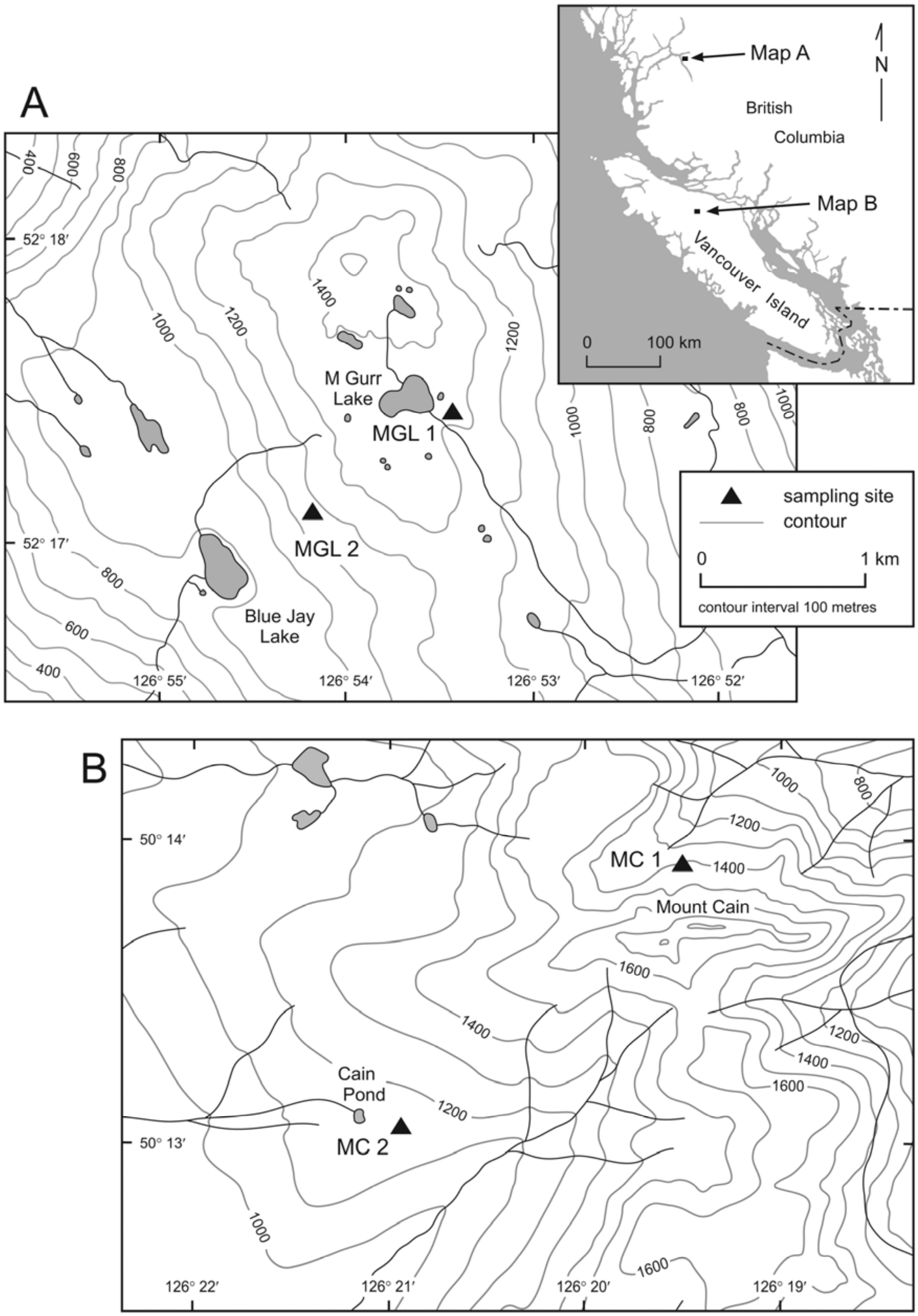

Figure 2.1: Map of M Gurr Lake and Mt Cain showing location of sampling sites.

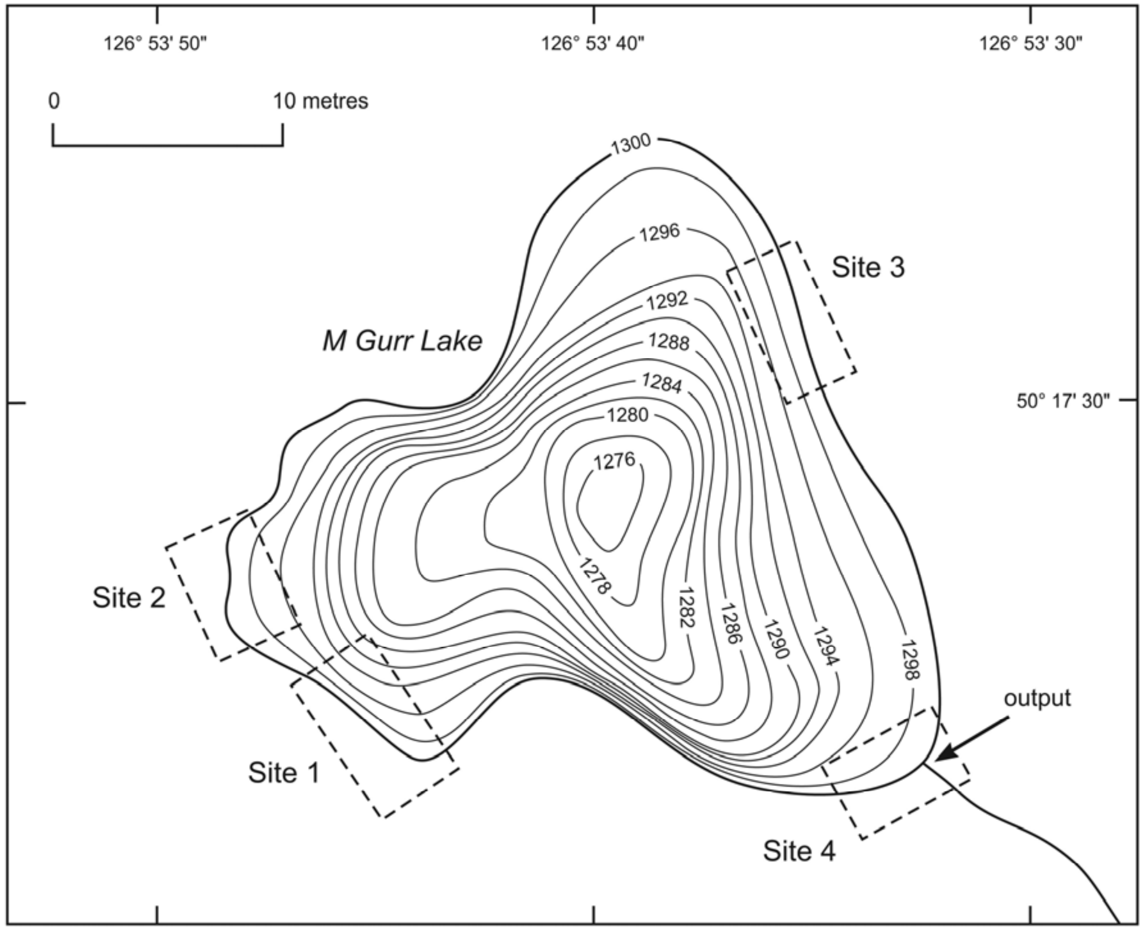

Figure 2.2: M Gurr Lake bathymetric map showing the four sampling sites and 2 m contour lines indicating lake depth.

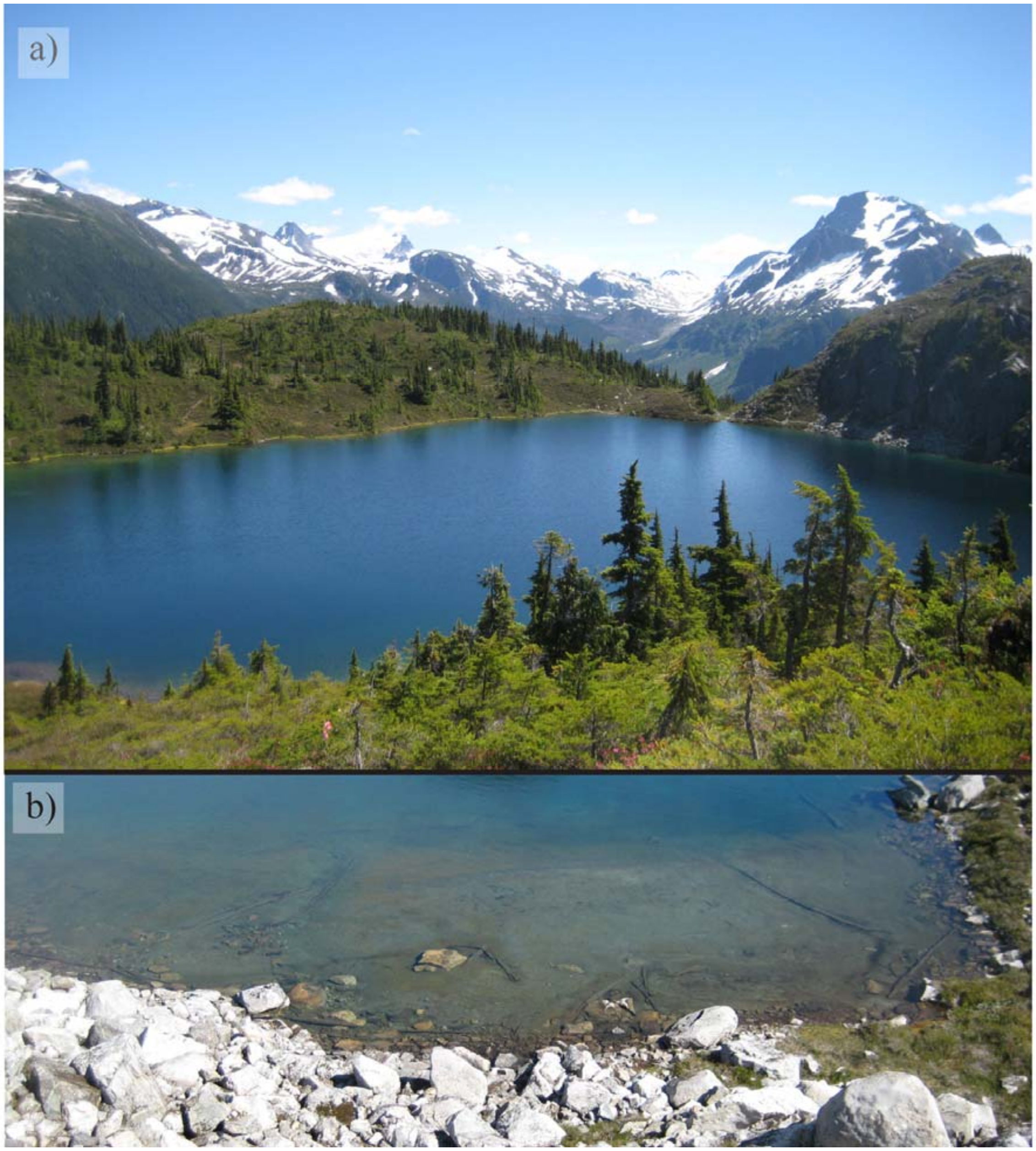

Figure 2.3: M Gurr Lake study site. (a) M Gurr Lake. (b) Coarse woody debris located in the muddy littoral zone of M Gurr Lake at Site 1.

2.3 Research Methods

Tree-ring samples were collected in July 2010 from living mountain hemlock trees and salvaged from submerged CWD in M Gurr Lake. An extended living tree-ring chronology was constructed by cross-dating the local tree-ring chronology to an established multi-century chronology. Absolute dates were assigned to the CWD by anchoring cross-dated floating chronologies to the living chronologies. Proxy climate reconstructions were derived from the developed regional extended chronology. A long-term record of snow avalanche disturbance at M Gurr Lake was established using an event-response index (Butler *et al.*, 1987: Johnson and Smith, 2010).

2.3.1 Living tree-ring chronologies

Living tree-ring chronologies were constructed from increment core samples collected from mountain hemlock trees. Prior research in the Pacific Northwest of North America demonstrates that the radial growth of mountain hemlock trees shows a positive correlation to summer air temperature (Gedalof and Smith, 2001b; Peterson and Peterson, 2001), and a negative correlation to seasonally persistent winter snowpacks (Smith and Laroque, 1998). Response surface analyses illustrate the non-linear impact these parameters can have, with warm growing season temperatures promoting early snowmelt, regulating soil temperatures and encouraging rapid leaf shoot and stem growth (Graumlich and Brubaker, 1989; Smith and Laroque, 1998).

In order to maximize the strength of the tree-ring record, samples were collected from mature trees without obvious apical disturbance or 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.

An additional living mountain hemlock chronology was constructed from archived tree-ring records collected at montane sites at Mt Cain on northern Vancouver Island (Lat 50°13’55” N, Long 126°19’30” W; Figure 2.1). The mountain hemlock zone at this site is similar to that surrounding M Gurr Lake, with a mean annual temperature averaging 3°C and precipitation totals averaging 2620 mm per year (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). Supplemental sampling in 2009 was undertaken by UVTRL researchers.

2.3.2 CWD chronology

Previous research indicates that submerged CWD recovered from streams and lakes frequently 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). While CWD exposed to aerobic conditions decays rapidly in coastal British Columbia (Daniels *et al.*, 1997), tree ring preservation of CWD submerged in water can range from a few hundred to thousands of years in this region (Zhang and Hebda, 2005).

CWD from M Gurr Lake was located using two techniques. Samples found in the littoral zone were identified from shore and collected by assistants wearing chest waders. Deep water samples (between 0.5–5 m) were identified by a team of snorkelers and sampled by scientific SCUBA divers. The position, depth, orientation, length, and presence of bark or branches on the CWD were recorded for individual samples (Shroder, 1980). Terrestrial surveys of the surrounding slopes were completed with a hand-held GPS and laser rangefinder to identify potential CWD source areas.

All the samples were pulled to shore and a cross-sectional disk (5-10 cm thick) was cut with a chainsaw. SCUBA diving techniques were used to locate, secure a rope and dislodge the samples from encasing sediment (Figure 2.4). The divers released CWD entombed in sediment by excavating a trough around the perimeter of the sample. A chainsaw-driven winch was employed to pull deeply embedded CWD to shore when human force proved unsuccessful. After sampling the CWD, the remaining portion was returned to its original location and orientation.

3.3.3 Laboratory preparation and analysis

All the samples were allowed to air-dry, afterwhich the cores were glued into slotted mounting boards and any broken disks secured with glue to preserve their structural integrity. Following this, the samples were sanded and polished to a 600-grit finish with a belt sander to reveal ring boundaries (Stokes and Smiley, 1968).

Digital images of the samples were captured with a high-resolution Epson XL 1000 scanner. The width of each tree ring was measured along a central pathway to the nearest 0.01 mm using a WinDENDRO™ image analysis system (Ver. 2008g, Regent Instruments Inc., 2008). Two or more perimeter-to-pith pathways were measured on each disk. Where reaction wood or ring growth anomalies were observed, an additional pathway was measured.

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

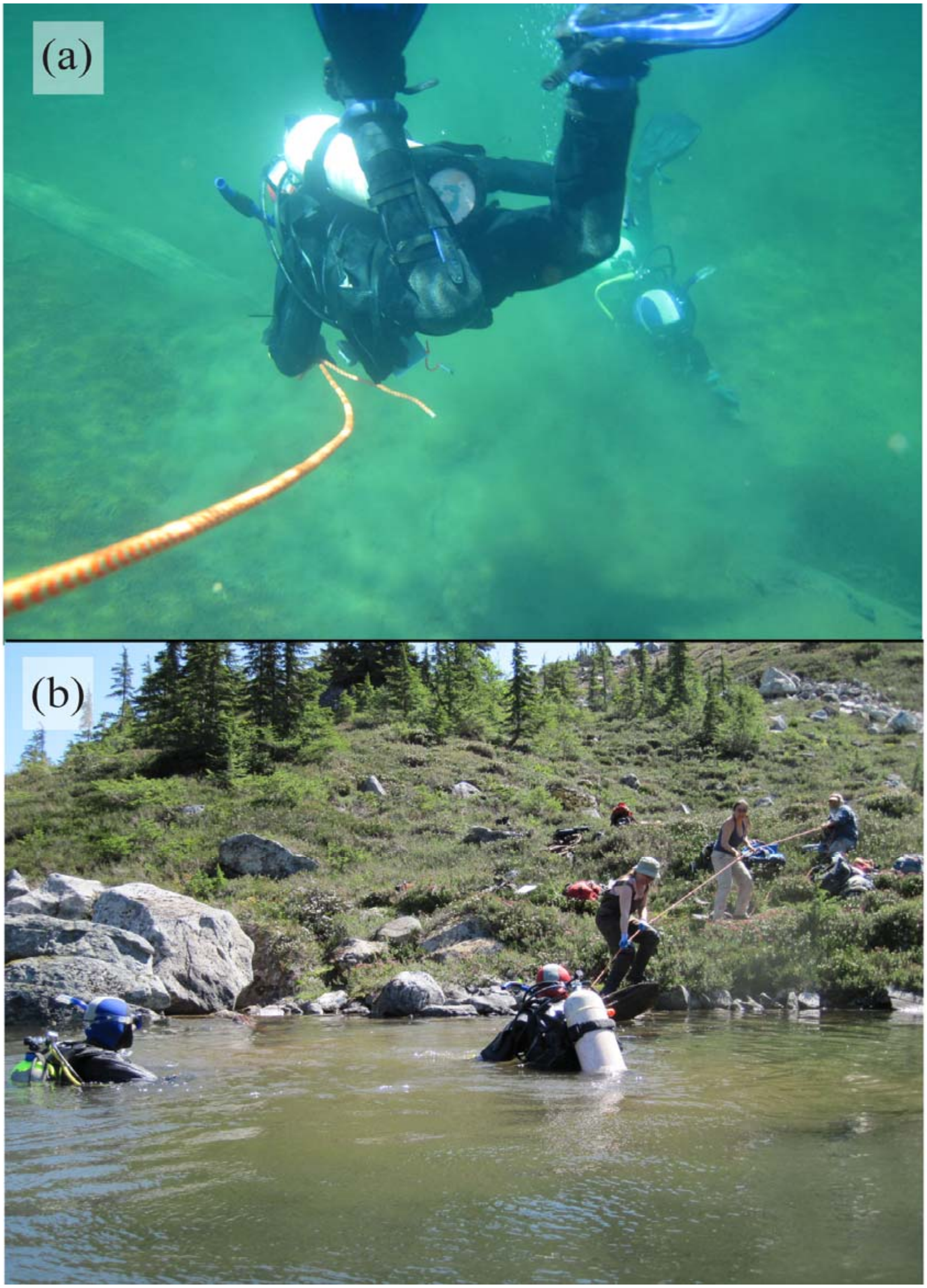

Figure 2.4: Removal of coarse woody debris from M Gurr Lake. (a) SCUBA divers locating and attaching a rope to a submerged coarse woody debris sample. (b) Shore removal of sample once dislodged by SCUBA divers

Database (ITRDB) software program COFECHA 3.0 (Holmes, 1983) was used to verify cross-dating. COFECHA was used to calculate Pearson's (R) correlation coefficients at a 99% confidence interval between 50-year segments with a 25-year 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). The living chronologies were constructed from within-stand core samples verified with COFECHA. Floating chronologies were developed from the submerged CWD samples using CDendro™. 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 to situate them in calendar time and to develop an extended multi-century master chronology. Samples were eliminated from the chronology development process if the tree-ring series was short (<100 years) or showed a Pearson's r correlation coefficient lower than $r = 0.33$ (Grissino-Mayer, 2001).

A standardized master tree-ring chronology including living and CWD samples was constructed by invoking a double-detrending option in the ITRDB software program ARSTAN (Ver41d) to remove non-climatic trends within individual series (Kramer and Kozlowski, 1960; Cook and Krusic, 2005). A negative exponential curve was used to remove age-related growth trends 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 growth variability caused by stand dynamics or disturbance events (Cook, 1985; Cook *et al.*, 1990). The mean sensitivity value measures the amount of variation between the annual rings with intermediate values ranging between 0.20-0.29 and highly sensitive values represented by values above 0.30 (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-year moving periods for each chronology using ARSTAN (Wilson and Luckman, 2006).

3.3.4 Dendroclimatological analysis

Gridded land air temperature anomaly data compiled for a 5° x 5° (Lat 50°-55° N and Long 125°-130° W) grid box by the Climatic Research Unit (1900-2010) was compared to residual tree-ring indices using Pearson's correlation coefficients (CRU, 2010). Pearson's correlation analysis was used to quantify an association between monthly air 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 was employed to develop a model using the strongest correlated monthly climate response variable and tree-ring width explanatory variable using the leave-one-out method. In order to verify the strength of the relationship between tree-ring growth and gridded air temperature, 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 to the instrumental record. The statistically significant correlation value between the gridded air temperature record and the predicted records with sufficient r^2 values proved adequate for reconstructions analysis. Wavelet analysis, using a Gaussian 2 function coupled with a 5% red-noise reduction, was used to reveal any temporal cyclicity in the extended tree-ring record (http://paos.colorado.edu/research/wavelets/; Torrence and Compo, 1998).

2.3.5 Snow avalanche record

Dendrogeomorphological techniques were employed to establish a long-term record of snow avalanche magnitude and frequency at M Gurr Lake (Burrows and Burrows, 1976). Individual avalanche events can be described by dating: scars on trees, the initiation of reaction wood, the timing of abrupt ring-width changes, and tree kill dates (Potter, 1969; Glen, 1974; Burrows and Burrows, 1976; Carrara, 1976; Shroder, 1980).

An event response index (ERI) was computed to highlight the frequency and magnitude of snow avalanche event–responses following Shroder (1978):

$$I_t = (\Sigma R_t)/(\Sigma A_t) * 100$$

where R_t indicates the event-response in the year t and A_t is the sampled trees alive in year t. Butler *et al.* (1987) recommend that the minimum ERI value to determine the geomorphic process should be defined by the user with consideration of sample size and site characteristics. In this instance a 40% cut off was assigned due to sample depth and the likelihood of individual high-and-low magnitude events impacting multiple trees at various locations surrounding the lake (Butler and Malanson, 1985).

2.4 Results

2.4.1 Living tree-ring chronologies

M Gurr Lake chronologies

Tree-ring samples were collected at two sites located in close proximity to M Gurr Lake. Site MGL1 is located 200 m southeast of the lake on a gently- to steeply-sloping southeast-facing slope at 1330 m asl (Lat 52° 17’ 22” N, Long 126° 53’ 37” W; Figure 2.1). The site is a mountain hemlock parkland consisting of clusters of mature trees separated by shrub communities and cohorts of young subalpine fir and yellow cedar. Site MGL2 was located within a closed stand of mature mountain hemlocks trees located 1 km southwest of M Gurr Lake on a moderately-sloped south-facing slope at 1050 m asl (Lat 52° 17’ 02” N, Long 126° 54’ 22” W; Figure 2.1).

Forty-two series from 22 trees were included in the MGL1 chronology (Table 2.1). The chronology spans 329 years from AD 1682-2010 that has a mean series correlation of r = 0.64 and mean sensitivity of 0.31 (Table 2.1). Fifty-three series from 29 trees were used to develop the MGL2 chronology (Table 2.1). The chronology spans 388 years from AD 1623-2010, and has a mean series correlation of r = 0.61 and mean sensitivity of 0.26 (Table 2.1).

A master M Gurr Lake living chronology was constructed by combining and cross-dating the series collected at sites MGL1 and MGL2. Consisting of 95 series from 51 trees (Table 2.1), the chronology spans the interval from AD 1623-2010 with a mean series correlation of r = 0.61 and an EPS cutoff point at AD 1705 (Figure 2.5).

Table 2.1: Chronology statistics for individual and regional mountain hemlock chronologies.

Chronology	No. of cores/ trees	Interval (yrs AD)	Total Length (yrs)	Correlation Coefficient (r)[1]	Mean Sensitivity[2]	EPS[3]
M Gurr Lake 1	42/22	1682-2010	329	0.64	0.31	1740
M Gurr Lake 2	53/29	1623-2010	388	0.61	0.26	1730
M Gurr Lake Master	95/51	1623-2010	388	0.61	0.28	1705
Mt Cain 1	72/45	1337-1997	661	0.54	0.29	1390
Mt Cain 2	19/11	1320-2008	689	0.56	0.25	1555
Mt Cain Master	91/55	1320-2008	689	0.53	0.28	1380
Regional Living	186/107	1320-2010	691	0.53	0.29	1380
M Gurr (Float A)	25/10	1662-1869	208	0.60	0.33	-
M Gurr (Float B)	25/13	1094-1504	411	0.50	0.31	-
Master Regional	183/101	1094-2010	917	0.52	0.29	1225

[1]All correlations are statistically significant to the 0.01 level
[2] Measures the amount of variation between the annual rings with intermediate values ranging between 0.20-0.29 and highly sensitive values represented by values above 0.30.
[3] Date that a decrease in sample depth drops the EPS below 0.80.

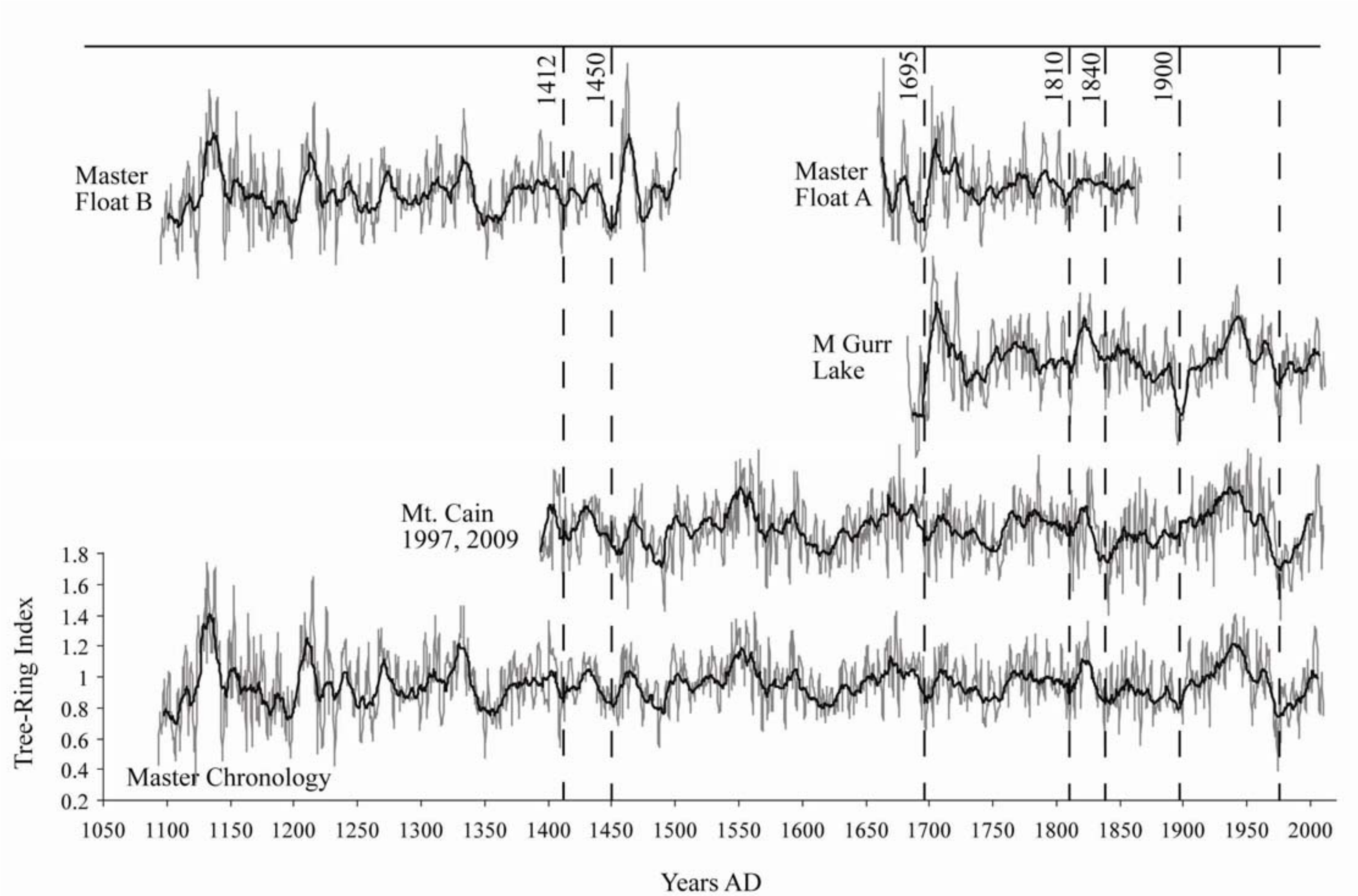

Figure 2.5: Standardized master living and floating tree-ring indices. Grey lines illustrate the annual data. Black lines represent a 10-year running mean of the data. Vertical black dashed lines illustrate years with narrow ring-widths.

Mt Cain Chronologies

Tree ring samples were collected from two sites at Mt Cain. The MC1 site sampled in 1996 and 1997 is located at ca. 1100 m asl (Lat 50° 13’55” N, Long 126° 19’ 30” W; Figure 2.1). The stand is characterized by mature mountain hemlock, amabilis fir (*Abies amabilis*), yellow cedar and western hemlock (*Tsuga heterophylla*) trees (Parish and Antos, 2004). The MC2 site sampled in 2009 is located at 1200 m asl (Lat 50° 13’04” N, Long 126° 21’ 11” W; Figure 2.1) in an open, boggy, mountain hemlock stand on a gentle south-facing slope.

Seventy-two series from 45 trees were included in the MC1 chronology (Laroque, 2002) spanning 661 years from AD 1337-1997 with a mean series correlation of r = 0.54, and mean sensitivity of 0.29 (Table 2.1). Nineteen series from 11 trees were included in the MC2 chronology. Spanning 689 years from AD 1320-2008 (Table 2.1), the chronology has a mean series correlation of r = 0.56 and mean sensitivity of 0.25 (Table 2.1).

A master Mt Cain living chronology was constructed by combining and cross-dating the series collected at sites MC1 and MC2. Consisting of 91 series from 55 trees (Table 2.1), the chronology spans the interval from AD 1320-2009 and has an EPS cutoff point at AD 1380 (Figure 2.5).

Regional Living Chronology

A master regional chronology was constructed by cross-dating the master M Gurr Lake and Mt Cain chronologies. The chronology contains 186 series and spans 691 years from AD 1320-2010, with an EPS cutoff point at AD 1380 (Table 2.1). With a mean series correlation of 0.53 and a mean sensitivity of 0.28 (Table 2.1), the chronology appears to robustly capture a radial growth signal common to both sites. Similar long-distance radial growth relationships involving mountain hemlock trees in this region were previously reported by Gedalof and Smith (2001a, 2001b).

2.4.2 CWD chronologies

Forty-nine CWD samples were collected from M Gurr Lake (Table 2.1). Of these samples, 23 cross-date to form two floating master chronologies. Calendar dates were assigned to each by cross-dating to the living M Gurr Lake chronology and/or the master regional chronology.

Twenty-five series from 10 CWD samples cross-date (r = 0.60) to form a floating chronology spanning 208 years (Float A, Table 2.1). The samples contributing to the chronology were collected at four sites (Figure 2.2) and cross-date to the M Gurr Lake living chronology spanning AD 1662-1869 (Table 2.1). Five of 10 samples had outermost ring dates of AD 1869, with the remaining samples having perimeter dates ranging from AD 1856 to 1868 (Table 2.2). Close examination of the cross-sections showed that most contained reaction wood (Figure 2.6).

Twenty-five series from 13 CWD samples cross-date (r = 0.50) to form a second floating chronology spanning 411 years from AD 1094-1504 (Float B, Table 2.1; Figure 2.5). The majority of the CWD was found in deep water distant to the shoreline and was partially-buried by muddy lake bottom sediments (Figure 2.6). These samples displayed substantially greater peripheral decay than those incorporated into Float A. Three of 13 samples had outermost ring dates of AD 1503, with the remaining samples having perimeter dates ranging from AD 1242-1499 (Table 2.2).

Table 2.2: Coarse woody debris sample locations and ages. Light grey bars highlight the samples cross-dated into Float A with periphery dates of AD 1869. Dark grey bars highlight the samples cross-dated into Float B with periphery dates of AD 1503. The dotted black box illustrates the samples retrieved from the subaerial peat horizon shown in Figure 2.6a.

Floating Chronology	Site Location	Sample Identification	Sample Depth (m)	Distance from Shore (m)	Interval (yrs AD)	Total Length (yrs)
Float A	Site 1	MG01	0.5	1.0	1711-1865	154
	Site 1	MG02	1.0	7.0	1720-1869	149
	Site 1	MG12	0.5	5.0	1736-1869	133
	Site 1	MG21	2.0	2.5	1662-1869	207
	Site 3	MG34	1.0	2.0	1686-1868	181
	Site 3	MG35	1.0	2.0	1687-1856	169
	Site 3	MG41	2.0	9.0	1751-1862	111
	Site 3	MG43	2.5	8.0	1727-1869	142
	Site 4	MG48	4.0	4.0	1687-1862	175
	Site 4	MG49	4.0	4.0	1708-1869	161
Float B	Site 1	MG09	4.5	3.0	1318-1462	144
	Site 1	MG11	3.0	5.0	1174-1313	139
	Site 1	MG18	2.5	4.0	1094-1338	244
	Site 1	MG19	1.5	3.0	1193-1313	120
	Site 1	MG22	2.0	2.5	1284-1503	219
	Site 1	MG24	4.5	22.0	1383-1503	120
	Site 2	MG28	2.5	7.0	1143-1242	99
	Site 2	MG30	4.0	15.0	1313-1503	190
	Site 2	MG33	4.5	15.0	1232-1499	267
	Site 3	MG38	2.0	9.0	1212-1442	230
	Site 4	MG44	0.5	0.25	1191-1409	218
	Site 4	MG45	0.5	0.25	1297-1453	156
	Site 4	MG47	5.0	5.0	1370-1469	99

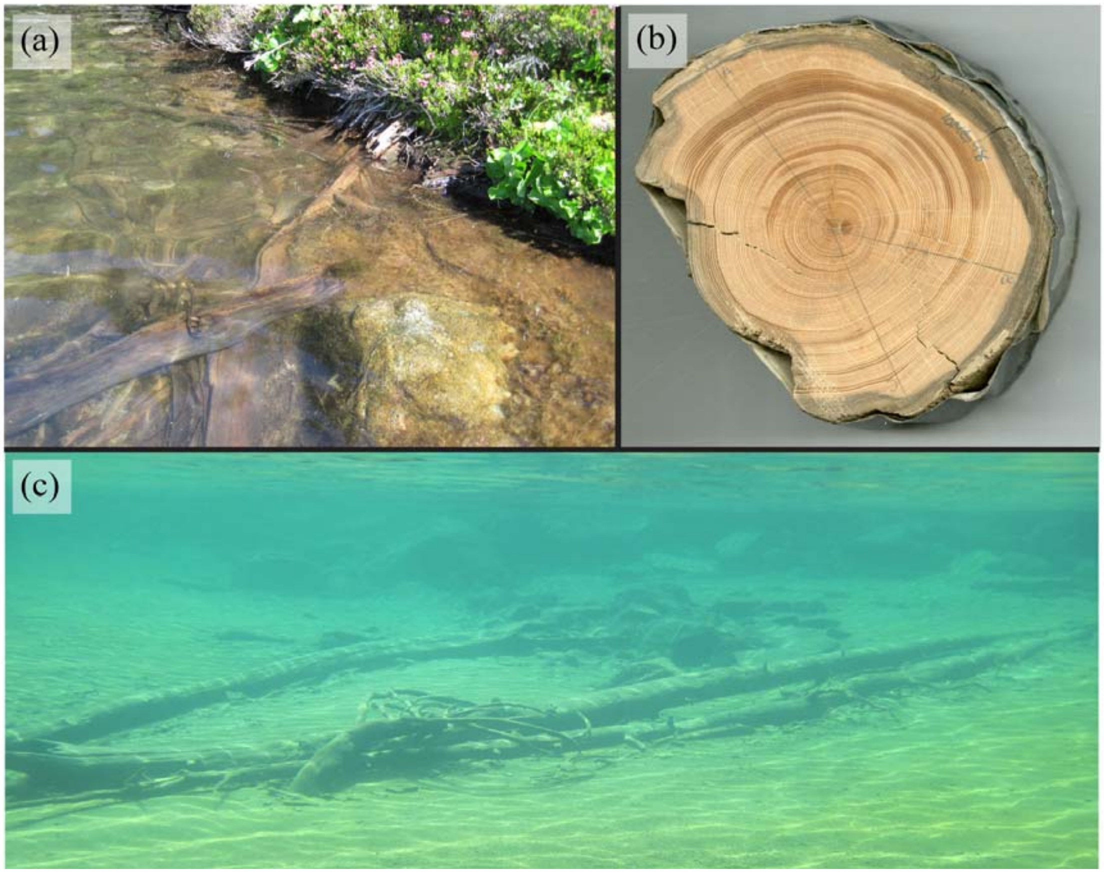

Figure 2.6: Coarse woody debris samples. (a) Samples MG44 and MG45 protruding in the lake from a subaerial peat horizon at Site 4. (b) Sample MG48 displaying reaction wood. (c) Samples located deeper in the lake encased in greater amounts of sediment.

2.4.3 Master regional chronology

The M Gurr and Mt Cain living chronologies, and the Master floating chronologies A and B, cross-date to form a master regional chronology. A total of 183 ring-width series from 78 living trees and 23 CWD samples were included in this chronology (Table 2.1). The chronology spans 917 years (AD 1094-2010) and has a mean series correlation of r = 0.52 and a mean sensitivity of 0.29 (Table 2.1). While the EPS terminated this chronology at AD 1225 (Table 2.1), the entire chronology (AD 1094-2010) was used for snow avalanche observations.

2.5 Discussion

The living and CWD tree-ring samples collected at M Gurr Lake cross-date to those sampled on northern Vancouver Island to form a multi-century regional tree-ring chronology. The chronology was used to construct a proxy climate record from gridded air temperature anomaly data and to reconstruct a record of snow avalanche events at M Gurr Lake.

2.5.1 CWD chronologies

Two floating chronologies (Float A and Float B) were constructed from the CWD recovered from M Gurr Lake. The samples used to build Float A (AD 1662-1869) were structurally intact and were found only slightly buried by littoral sediments (Figures 2.2 and 2.3). With the exception of two samples, all the remaining CWD samples that cross-dated to form Float B (AD 1094-1503) were collected at deep water locations or were sampled from logs (MG44 and MG45, Table 2.2) protruding into the lake from an adjacent subaerial peat horizon (Figure 2.6). The deep water samples typically showed signs of general decomposition, evidence of perimeter wood loss, and were entombed by greater amounts of sediment, characteristics typical of CWD with a long submergence history (Kuder and Kruge, 1999; Eronon *et al.*, 2002).

A 158-year interval from AD 1504 to 1662 separates the two CWD chronologies (Figure 2.5). While 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 areas sampled. An alternative hypothesis arising from 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 distinct germination cohorts. While this hypothesis cannot be rigorously tested, some support arises from the fact that the oldest germination dates of mountain hemlock trees at the study site and in the surrounding region occurred in the mid-17th century (Gedalof and Smith, 2001b; Starheim, 2011). The apparent germination synchrony is possibly climate-related (Rochefort *et al.*, 1994; Woodward *et al*., 1995; Laroque *et al*., 2000), potentially identifying a regional seeding episode in the mid-17th century initiated by deteriorating climates associated with a Little Ice Age glacier advance that terminated in the early-18th century (Larocque and Smith, 2003, 2005b).

2.5.2 Dendroclimatic reconstruction

All of the chronologies exhibit a high statistical similarity that describes a common radial growth relationship to climate variability (Table 2.1). 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 chronology that incorporates the CWD records from M Gurr Lake (Float A and B), the living chronologies from trees found growing in close proximity to M Gurr Lake (MGL1 and MGL2) and to living trees growing at Mt Cain (MC1 and MC2)(Figure 2.5).

Correlation analysis revealed a statistically significant ($p \leq 0.01$) relationship between the June-July gridded air temperature anomaly data (AD 1900-2010) and the master regional tree-ring chronology ($r = 0.47$). Significant predictive capacities verified by strong correlation values between the instrumental and climate model data ($r = 0.41$) allowed for the reconstruction of a 785 year-long proxy record from AD 1225 to 2010. Visualization of the calibration period highlights the tendency of the model to underestimate the magnitude of the air temperatures (Figure 2.7).

Based upon this relationship, a 785 year-long proxy record of June-July air temperature anomalies was reconstructed for the period from AD 1225 to 2010 (Figure 2.8). Explaining 22% of the variance, the reconstruction indicates that cooler-than-average air temperatures characterized the intervals from ca. AD 1245-1295, 1335-1365, 1440-1455, 1475-1495, 1600-1625, 1690-1705, 1740-1760, 1830-1900, and 1965-1990. Warmer-than-average air temperatures are shown from ca. AD 1320-1340, 1500-1560, 1645-1685, 1755-1825, and 1905-1960. These cooler-than-average periods are consistent with negative PDO phases (Gedalof and Smith, 2001a; Mantua and Hare, 2002). Sustained warmer-than-average phases were much more frequent and spanned over longer time periods, which is in accordance with positive PDO phases (Gedalof and Smith, 2001a; Mantua and Hare, 2002).

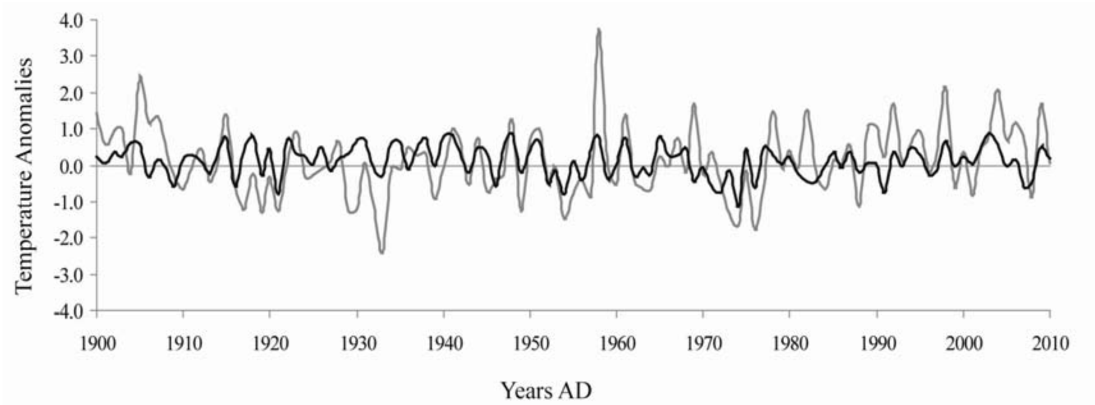

Figure 2.7: Comparison of between the instrumental (grey line) record of June-July gridded air temperature anomalies and the modeled proxy reconstruction (black line).

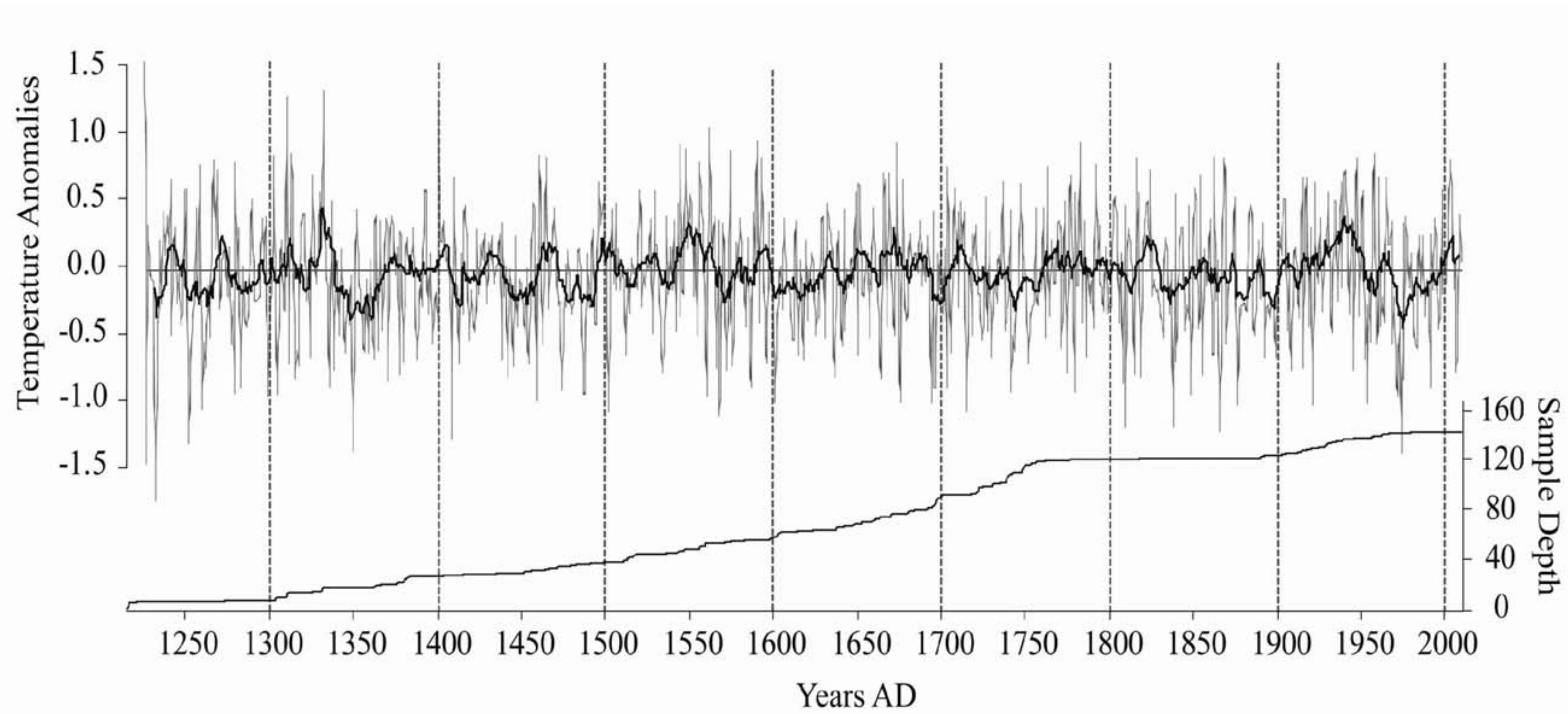

Figure 2.8: Reconstruction of gridded air temperature anomalies from AD 1225-2010. Grey lines represent annual reconstruction indices. The black line shows a 10-year running mean.

Wavelet analysis conducted on the extended tree-ring chronology revealed the persistence a low frequency century-scale ring-width growth trend (Figure 2.9). Previous researchers have associated similar century-scale cyclicity to sunspot minima, reporting that this has led to persistent intervals of lower than average radial growth in temperature-sensitive tree-ring chronologies (Büntgen *et al.*, 2006; Raspapov *et al.*, 2008; Trouet and Taylor, 2010). It may be that the century-long trend occurring in this regional mountain hemlock chronology reflects this influence.

2.5.3 Snow avalanche activity

The slopes surrounding M Gurr Lake contain multiple snow avalanche pathways to the lakeshore (Figure 2.10). The four most prominent avalanche paths display an average surface slope of 20°, with 35 m of relief over the ca. 160 m from their initiation zones to the lakeshore. Although, these avalanche slopes are not typical slopes (Armstrong and Williams, 1986), they appear to be the source of CWD entering the lake. Largely treeless, the paths are bordered by mature trees whose J-shaped trunks display scars characteristic of those associated with snow avalanche activity (Glen, 1974; Burrows and Burrows, 1976; Carrara, 1976; Shroder, 1980). The initiation of reaction wood growth within 11 living trees occurred in the tree-ring years associated with AD 1915, 1926, and 1941 (Figure 2.11).

Examination of the large CWD boles recovered from M Gurr Lake revealed the majority have broken basal stems consistent with having been sheared by snow avalanches (Figure 2.10). Five of 10 boles in Float A were killed by a snow avalanche that occurred prior to the AD 1869 growth year. The presence of reaction wood within

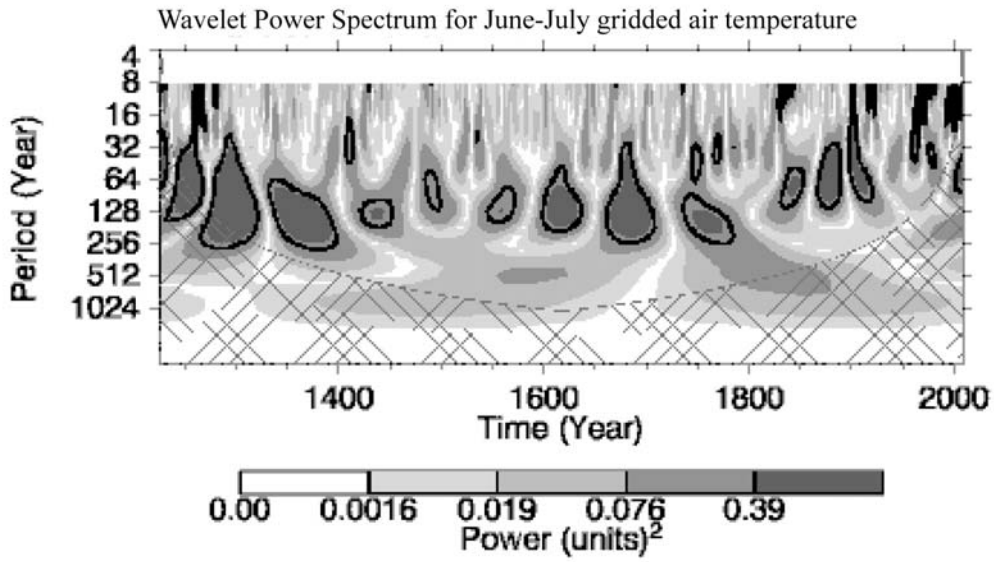

Figure 2.9: Wavelet power spectrum of the modeled regional climate anomaly data. The wavelet power spectrum uses a Gaussian-2 function. Cross-hatched regions of the wavelet diagrams represent the cone of influence where zero-padding of the data was used to reduce variance. Black contours indicate significant modes of variance with a 5% significance level using an autoregressive lag-1 red-noise background spectrum (Torrence and Compo, 1998).

Figure 2.10: M Gurr Lake. (a) Avalanche path surrounding M Gurr Lake. (b) The remains of trees with J-shaped trunks recovered from M Gurr Lake displaying sheared and broken boles typical of those killed by snow avalanche activity.

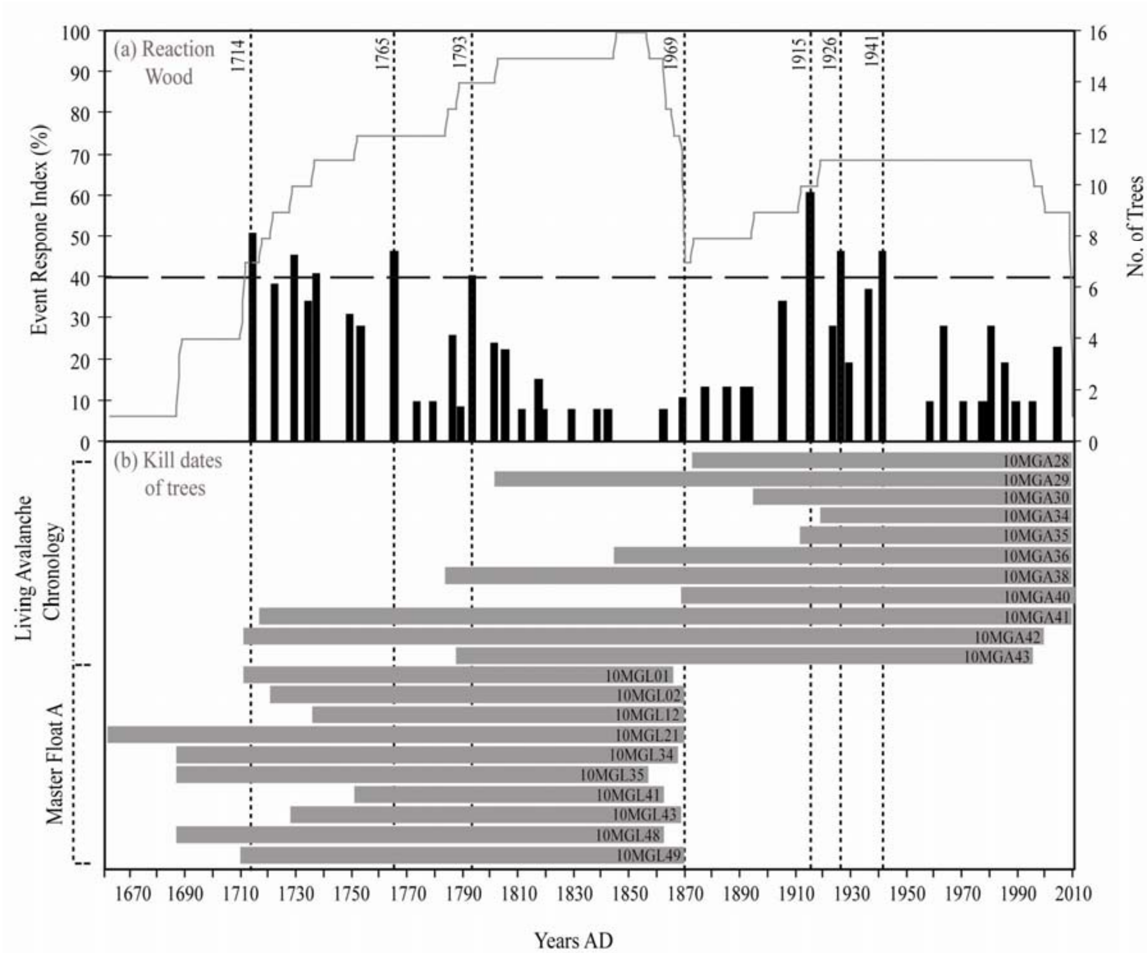

Figure 2.11: M Gurr Lake event response index illustrating reaction wood and kill dates of trees. Vertical black bars in (a) show the 5-year event response index for all samples. The horizontal dashed line is the 40% event response cut off. The grey line represents the sample depth. The grey horizontal bars in (b) highlight the pith and perimeter ages of living trees and coarse woody debris trees used to describe living chronology length and coarse woody debris used to identify individual avalanche events. Vertical dotted lines identify the snow avalanche events recorded at M Gurr Lake.

five samples recorded in the tree-ring years associated with AD 1714, 1765 and 1793 (Figure 2.11). The perimeter date of three samples in Float B suggests a high magnitude snow avalanche event transported the remains of mature trees (99-267 years old) into M Gurr Lake prior to AD 1503. The initiation of reaction wood growth in AD 1414 in four CWD samples describes a previous event in the winter of AD 1413-1414.

Snow avalanches of sufficient magnitude to transport woody detritus to M Gurr Lake appear to be infrequent. Over the last 600 years only two events, in the winters of AD 1502-1503 and 1868-1869, were recorded by the death dates of submerged CWD samples. Smaller, low-magnitude, snow avalanches occurred during the winters of AD 1713-1714, 1764-1765, 1792-1793, 1914-1915, 1925-1926 and 1940-1941. The latter record is likely incomplete as the pace and extent of tree colonization on the avalanche paths surrounding M Gurr Lake appears variable.

No CWD samples were collected with perimeter dates younger than AD 1869. While this finding may be a consequence of incomplete CWD sampling, no ‘fresh’ wood detritus was observed resting on the lake bottom or observed floating on the water surface. Given that trees on avalanche pathways surrounding the lake do contain evidence of historic snow avalanche activity, it seems likely that the last high-magnitude snow avalanche event occurred prior to AD 1869 at M Gurr Lake.

Typically, snow avalanches are initiated by sudden increases in snowfall, structural weaknesses in seasonal snowpacks, or by a sudden loss of cohesion in a snowpack due to melting. In maritime environments snow avalanches are more commonly triggered by sudden increases in snowfall, rain on snow events, or deep snowpacks (Armstrong and Williams, 1986). While there are no direct observations of the conditions leading to historic snow avalanche activity at M Gurr Lake, the 1940-1941 event may be associated with a four-day period (October 8-10, 1940) of heavy rain followed by snow recorded in the nearby Bella Coola valley. During this extreme event abundant precipitation totals led to flooding severe enough to washout several bridges (Septer, 2006). Given the conditions in the Bella Coola valley, the slopes surrounding M Gurr Lake may well have received sufficient snowfall to trigger a full-depth early season snow avalanche.

2.6 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. This 785 year-long regional chronology was correlated to a gridded June-July air temperature anomaly record, allowing for the construction of a mulit-century climate proxy model. Wavelet analysis revealed a low-frequency trend within the proxy record. This observation suggests the radial growth of mountain hemlock trees in this region may be governed, at least in part, by long-term variations in solar irradiance. This climate-induced forcing of tree growth reflects the physiological relationship between tree-ring growth and growing season temperature.

Snow avalanches were identified as the source of the CWD salvaged from M Gurr Lake. While low-magnitude snow avalanches appear to have occurred in the winter months of AD 1713-1714, 1764-1765, 1792-1793, 1914-1915, 1925-1926 and 1940-1941, only two large-magnitude events were described occurring in the winters of AD

1502-1503 and 1868-1869. These two latter events appear responsible for transporting almost all of the CWD recovered from the lake bottom. With only two major events occurring over the tree ring record, these singular events almost certainly record a disturbance event likely to have significantly impacted the structure of the forests surrounding M Gurr Lake. Although, there is strong evidence of avalanche activity at M Gurr lake, it is a possibility that other forces, such as wind, snow creep or fire could have killed and transported some of the CWD into the lake.

Identifying low-frequency trends in tree-ring growth and determining historic geomorphic events over the past millennium is of considerable importance, as few dendrochronologic investigations have been conducted over this portion of the millennium. Extending tree-ring chronologies through cross-dating preserved CWD is an essential tool in displaying historical climatic information beyond the age of living trees.

Chapter 3 – A dendroclimatic analysis of mountain hemlock (*Tsuga mertensiana)* ring-width and maximum density parameters, southern British Columbia Coast Mountains

3.1 Introduction

Dendroclimatological methodologies provide the opportunity to create annually-resolved proxy records of past climate by establishing statistical relationships between radial tree-ring growth and climate variations (Fritts, 1976). While the majority of dendroclimatic reconstructions are derived from tree-ring chronologies demonstrating a robust relationship to a single climate parameter (eg. Wilson and Luckman, 2006; Youngblut and Luckman, 2008; Flower and Smith, 2010), the radial growth of trees in the Pacific Northwest of North America frequently demonstrates a complex relationship to two or more seasonal environmental parameters (Graumlich and Brubaker, 1986; Smith and Laroque, 1998; Laroque and Smith, 1999). The radial growth of mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) trees typically demonstrates a positive relationship to increased summer air temperature (Gedalof and Smith, 2001b; Peterson and Peterson, 2001), and a negative response to seasonally persistent winter snowpacks (Smith and Laroque, 1998, Peterson and Peterson, 2001). This complex growth behavior has prompted the application of species-specific factor analyses (Gedalof and Smith 2001a; Peterson and Peterson, 2001) and/or inter-species principal component analyses (Larocque and Smith, 2005a) to elucidate a climate signal for the construction of robust proxy climate records. In order to improve upon these proxy reconstructions, specific attention needs to be directed to understanding the intra-annual response of mountain hemlock radial growth to subseasonal climates in this setting.

Densitometric x-ray techniques provide records appropriate for constructing intra-annual proxy climate records (Polge, 1963). Wood density measurements are commonly determined from conifers containing one-cell tracheids (Conkey, 1986; Wang *et al.,* 2002), as their cells characteristically vary in behaviour and morphology depending upon the subseasonal climate (Conkey, 1986; Schweingruber, 1988; Wang *et al.*, 2002). In previous studies of subalpine trees, maximum annual tree-ring density has consistently demonstrated a strong correlation to late-summer maximum air temperatures (Parker and Henoch, 1971; Schweingruber *et al.,* 1991; Briffa *et al.,* 1992; D'Arrigo *et al.,* 1992; Davi *et al.,* 2002; Wood *et al.,* 2011).

The purpose of this research was to investigate the potential of using x-ray densitometry to construct proxy climatic records from mountain hemlock tree-rings collected at high elevation sites within the mountain hemlock biogeoclimatic zone (MHZ) of coastal British Columbia. The intent was to compare dendroclimatic records derived from standard ring-width analyses to those derived from density chronologies. The MHZ spans montane regions of windward coastal mountain slopes from southern Alaska to northern California, a zone characterized by mild to cool winters and short growing seasons receiving moderate to high amounts of precipitation (Means, 1990; Meidinger and Pojar, 1991).

3.2 Study Sites

Tree-ring samples were collected from mature mountain hemlock stands (200-400 years in age) located at three sites in southwestern British Columbia (Figure 3.1). The

Figure 3.1: Location of study sites.

northernmost site is located adjacent to M Gurr Lake in the central Coast Mountains near Bella Coola, British Columbia (Figure 3.1). Maritime conditions characterize the local environment, with precipitation falling principally as snow from late-fall to early-spring (Kendrew and Kerr, 1955; Moore *et al.*, 2010). Tree-ring samples were collected from two close proximity stands. Site MGL1 is found within a mountain hemlock parkland, cohabited by yellow cedar *(Chamaecyparis nootkatensis*) and subalpine fir *(Abies lasiocarpa),* located 200 m southeast of the lake on a gentle-to-steep southeast-facing slope at 1330 m asl (Lat 52° 17’ 22” N, Long 126° 53’ 37” W; Figure 3.1; Table 3.1). Site MGL2 is located within a closed stand of mature mountain hemlock trees 1 km southwest of M Gurr Lake on a moderate south-facing slope at 1050 m asl (Lat 52° 17’ 02” N, Long 126° 54’ 22” W; Figure 3.1; Table 3.1).

Mountain hemlock trees at Cyprus Provincial Park in the southern Coast Mountains were sampled by Schweingruber (1988) on a south-east facing slope at 1110 m asl (Lat 49° 25’12” N, Long 123° 05’20” W; Figure 3.1; Table 3.1). Maritime conditions characterize the local environment, with Pacific silver fir (*Abies amabilis*), subalpine fir and yellow cedar trees cohabitating local slopes above 1000 m asl (Means, 1990; Meidinger and Pojar, 1991).

Mature mountain hemlock trees growing on a montane ridge at 1020 m asl on Mount Arrowsmith were sampled by Schweingruber (1988) in 1983 (Lat 49° 29’47” N, Long 125° 12’05” W; Figure 31.; Table 3.1). The site is characterized by prevailing westerly winds that bring moist air masses onshore, precipitating high amounts of snowfall during the fall-winter months (Hnytka, 1990).

Table 3.1: Mountain hemlock tree-ring chronology sampling locations.

Sampling Site	Data	Sampled	Latitude,Longitude	Elevation (m)
M Gurr Lake 1	rw	2010	52° 17’ 22”N, 126° 53’ 37” W	1330
M Gurr Lake 2	rw	2010	52° 17’ 02” N, 126° 54’ 22” W	1050
	MinD	2010	52° 17’ 02” N, 126° 54’ 22” W	1050
	MaxD	2010	52° 17’ 02” N, 126° 54’ 22” W	1050
Mount Arrowsmith	rw	1983	49° 29’47” N, 125° 12’05” W	1020
	MaxD	1983	49° 29’47” N, 125° 12’05” W	1020
Cyprus Provincial Park	rw	1983	49° 25’12” N, 123° 05’20” W	1110
	MaxD	1983	49° 25’12” N, 123° 05’20” W	1110

rw – ring width, MinD – minimum density, MaxD – Maximum density

3.3 Methods and Data

Increment cores were extracted from mature mountain hemlock trees for standard dendrochronological and denstiometric analysis. Site-specific ring-width and densitometric chronologies were constructed, and correlated with nearby instrumental records to build climate proxy models.

3.3.1 Tree-ring data

The ring-width and density chronologies from Cyprus Provincial Park and Mount Arrowsmith were collected as part of a broader regional sampling program by Schweingruber (1991). Between 10-12 trees were sampled at each site and processed following standard dendrochronological and densitometric techniques (Briffa *et al.*, 1992). Following presentation of the findings of this research program by Schweingruber *et al*. (1991) and Briffa *et al.* (1992), the ring-width, minimum and maximum density data was deposited for public use in the International Tree Ring Data Bank (ITRDB) (Grissino-Mayer, 1997).

Increment core samples were collected from mature trees without obvious disturbance or rot at two sites located close to M Gurr Lake in July, 2010. Five mm increment borers were used at both sites to extract two cores per tree (90°-180° apart) at breast height. At the MGL2, site a 12 mm increment borer was used to extract a third core for density analysis directly above a 5 mm borehole location. Care was taken to ensure the latter samples displayed perpendicular ring angles, an essential requirement for density analysis (Schweingruber, 1988; Schweingruber *et al.*, 1991).

All the cores were transported to the University of Victoria Tree Ring Laboratory (UVTRL) for analysis. The 5 mm cores were allowed to air-dry, mounted into grooved boards, and sanded to a 600-grit polish to distinguish ring boundaries. Digital images of the tree cores were processed using a high-resolution scanner with the ring-widths measured to the nearest 0.01 mm with WinDENDRO™ (Ver. 2008g, Regent Instruments Inc, 2008).

The 12 mm density cores were air-dried and glued flush to 2.5 mm wide fibre-board blocks for densitometric analysis. To reveal the radial surface of the core, a 2 mm thick lathe was cut using a Waltech high-precision twin-bladed saw (Haygreen and Bowyer, 1996) with the blade angle adjusted to correct for non-perpendicular rings. Water and resin was removed by soaking the samples in an acetone Soxhet apparatus for 8 hours (Schweingruber *et al.,* 1978; Jenson, 2007). Each lathe was scanned perpendicular to the x-ray beam for 20-μs at 50-μm intervals with the digital ITRAX scanning densitometer using a chromium x-ray tube maintained at 30 mA and 55 kV. Annual ring-width, minimum, and maximum density values were obtained by measuring the ITRAX scanned digital x-ray images using WinDENDRO image analysis software (Ver. 2008g, Regent Instruments Inc. 2008).

Visual cross-dating of the 5 and 12 mm ring-width data was completed following standard cross-dating protocols (Stokes and Smiley, 1968). COFECHA was used to quality check the cross-dating by examining correlations between 50-year segments with 25-year lags at a significance level of 0.01 (Holmes, 1983; Grissino-Mayer, 2001). Following this, the density chronologies were visually compared to the cross-dated 12 mm ring-width data to ensure correct dating. Where blurred x-ray images due to narrow or non-perpendicular rings prevented precise measurement of the density parameters (Polge, 1970; Schweingruber, 1988), the data was discarded from further analysis.

The 5 mm ring-width, maximum, mean and minimum density series were compiled into site-specific master chronologies. Each chronology was first detrended (standardized) with the ITRDB program ARSTAN using a negative exponential curve to remove age-related growth trends (Kramer and Kozlowski, 1960; Cook and Kruisic, 2005). A second smoothing spline was applied with a 67% frequency cut off, preserving 50% of the variance in ring-width growth to reduce the influence of endogenous and exogenous disturbance (Cook, 1985). Express Population Signal (EPS) values were calculated and chronologies were truncated when the signal strength fell below 0.80 (Wigley *et al.*, 1984; Fowler and Boswijk, 2003; Cook and Krusic, 2005).

3.3.2 Instrumental climate data

Instrumental records from long-term climate stations located in close proximity to M Gurr Lake (Tatlayoko Lake, #1088015), Cyprus Provincial Park (Agassiz, #1100120) and Mount Arrowsmith (Comox, #1021830) were used for correlation analysis to discern any site-specific climate-radial growth relationships (Table 3.2). Monthly temperature data for each station was accessed from the Adjusted Homogenized Canadian Climate Database (AHCCD, 2010). Long-term snowpack data relevant to M Gurr Lake (Mt Cronin, #4B08), Cyprus Provincial Park (Grouse Mountain, #3A01) and Mount Arrowsmith (Forbidden Plateau, #3B01) was obtained from the Government of British Columbia River Forecast Centre (BC RFC, 2010) (Table 3.2). Gridded air temperature anomaly data (Lat 50°-55° N and Long 125°-130° W) compiled by the Climatic Research

Table 3.2: Climate station locations and metadata.

Station	**Type**	**ID**	**Years**	**Latitude,Longitude**	**Elevation (m asl)**
Tatlayoko Lake	Meteorologic	1088015	1931-2009	51° 40’ N, 124°24’ W	870
Agassiz	Meteorologic	1100120	1894-1983	49° 18’ N, 121° 48; W	15
Comox	Meteorologic	1021830	1936-1983	49° 42’ N, 124° 54’ W	26
Mt Cronin	Snow survey	4B08	1969-2010	54° 55’ N, 126° 48’ W	1491
Grouse Mountain	Snow survey	3A01	1950-1983	49° 23’ N, 123° 04’ W	1126
Forbidden Plateau	Snow survey	3B01	1958-1983	49°39’ N, 125° 12’ W	1110

Unit (AD 1900-2010) was employed to test for significant regional temperature relationships (CRU, 2010).

3.3.3 Dendroclimatic correlations and reconstructions

Correlations between standardized/residual master tree-ring chronologies and monthly climate variables were obtained using SPSS (Ver. PASW Statistics 18). Pearson's R correlation coefficients were determined for monthly variables in the current and previous year of tree-ring growth. Proxy reconstructions were developed using the most statistically significant ($p \leq 0.05$) relationships, with the chronologies treated as the explanatory variable and the instrumental climate data as the response variable. The leave-one-out method was chosen as the calibration tool best able to verify the tree-ring models over the duration of the temporally limited instrumental records (Gordon, 1982). Individual linear regression models were computed for the entire length of the instrumental period. Each model had one year removed over the entire calibration period, with the residual used to predict a value for the missing year. The predicted values were subsequently merged into an independent climate record and compared to the instrumental climate record to verify the strength of the reconstruction (Rv). A rigorous reduction of error (RE) statistic was computed as an additional model quality check (Fritts, 1976). The RE statistic provides a highly sensitive measure of reliability with positive RE values indicating that the regression model has enough skill for reconstructions to be made with the particular model (Fritts, 1976). Coefficient of determination (r^2) statistic was calculated to quantify the success of the reconstruction. Statistically significant correlations, strong r^2 values, and positive RE statistics proved model adequacy and was used for climate proxy reconstruction.

The reconstructed dendroclimatic records were standardized as deviations from the instrumental mean. This approach produced climate anomaly records allowing for cross-chronology comparisons among the proxy models. Years that strongly deviated from the mean were recorded.

3.4 Results

The mountain hemlock master ring-width and density chronologies were examined to determine their relationship to localized and regional climate variables. Only those relationships with statistically significant correlations are discussed.

3.4.1 Tree-ring chronologies

Two chronology sets were constructed from increment cores collected at M Gurr Lake: ring-width chronologies developed from cores collected at MGL1 and MGL2; and, minimum and maximum density chronologies developed from cores collected at MGL2 (Table 3.3). Forty-two series from 22 trees at MGL1 were used to create a site ring-width chronology (r = 0.64) spanning 329 years (AD 1623-2010) (Table 3.3; Figure 3.2). Fifty-three series from 29 trees were used to develop the MGL2 ring-width chronology (r = 0.61) spanning 388 years (AD 1623-2010) (Table 3.3, Figure 3.2). Minimum (r = 0.42) and maximum (r = 0.41) density chronologies for MGL2 were constructed from 23 series spanning 310 years (AD 1700-2009) (Table 3.3; Figure 3.2).

The ITRDB records compiled by Schwiengruber (1988) from Cyprus Provincial Park site include ring-width (r = 0.62) and maximum (r = 0.49) density chronologies spanning 571 years (AD 1413-1983) (Table 3.3, Figure 3.2). The ITRDB chronologies from Mount Arrowsmith compiled by Schwiengruber (1988) include ring-width (r =

Table 3.3: Summary statistics for individual and regional chronologies.

Stie	Data	Interval (yrs AD)	# cores	# years	Mean Series Correlation	Mean Sensitivity[1]
M Gurr Lake 1	rw	1682-2010	42	329	0.64	0.31
M Gurr Lake 2	rw	1623-2010	53	388	0.61	0.26
	MinD	1700-2009	23	310	0.41	0.09
	MaxD	1700-2009	23	310	0.42	0.07
Mount Arrowsmith	rw	1629-1983	28	355	0.50	0.20
	MaxD	1629-1983	28	355	0.72	0.09
Cyprus Provincial Park	rw	1413-1983	23	571	0.62	0.21
	MaxD	1413-1983	23	571	0.49	0.06
Regional	rw	1413-2010	104	598	0.48	0.23
	MaxD	1413-2010	74	598	0.49	0.07

rw – ring width, MinD – minimum density, MaxD – Maximum density
[1]Measures the amount of variation between the annual rings with intermediate values ranging between 0.20-0.29 and highly sensitive values represented by values above 0.30.

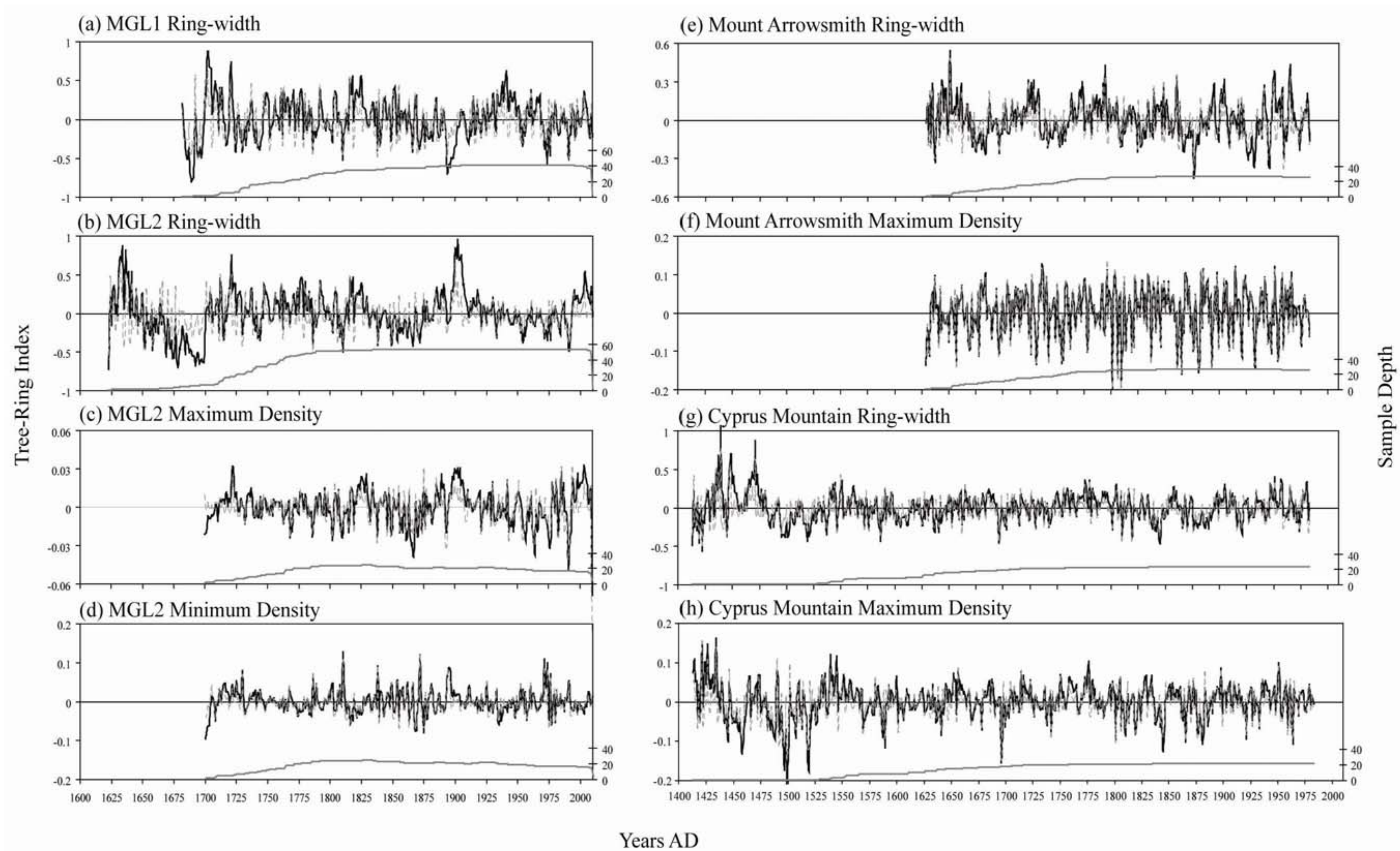

Figure 3.2: Standardized and residual master tree-ring indices. Solid black lines represent the standardized chronologies. Grey dashed lines represent the residual chronologies. Grey solid lines indicate sample depth.

0.50) and maximum density chronologies (r = 0.72) from 28 series spanning a 355-year interval (AD 1629-1983) (Table 3.3; Figure 3.2).

Two independent master regional chronologies were constructed using ring-width and maximum density data from the four sampling sites. While the chronologies span a 598-year interval from AD 1413 to 2010, the ring-width (r = 0.48) chronology has an EPS cut off point at AD 1570 and the maximum density (r=0.49) chronology has EPS cut off point at AD 1645 (Tables 3.3 and 3.4).

3.4.2 Dendroclimatic correlations

Significant relationships were found between individual residual and standardized ring-width and density chronologies, and distinct instrumental climate variables (Figure 3.3). The ring-width chronologies from all sites display statistically significant correlations to monthly spring snowpack (Figure 3.3). Statistically significant relationships were not found between the minimum, mean or maximum density chronologies and snowpack data. Stronger correlation values for March 1 snowpack at Mt Cronin exist to the standardized ring-width chronology from MGL1 (r = -0.57) when compared to the standardized ring-width chronology from MGL2 (r = -0.70), highlighting the importance of site selection (Figure 3.3). Significant negative correlations exist between the Cyprus Provincial Park standardized ring-width chronology and the May 1 Grouse Mountain snowpack (r = -0.58). Similarly, the Mount Arrowsmith residual ring-width chronology was negatively correlated to the April 1 Forbidden Plateau snowpack record (r = -0.49) (Figure 3.3).

Maximum density displays stronger correlations to summer temperature records at all three sites than do the ring-width chronologies (Figure 3.4). Significant positive

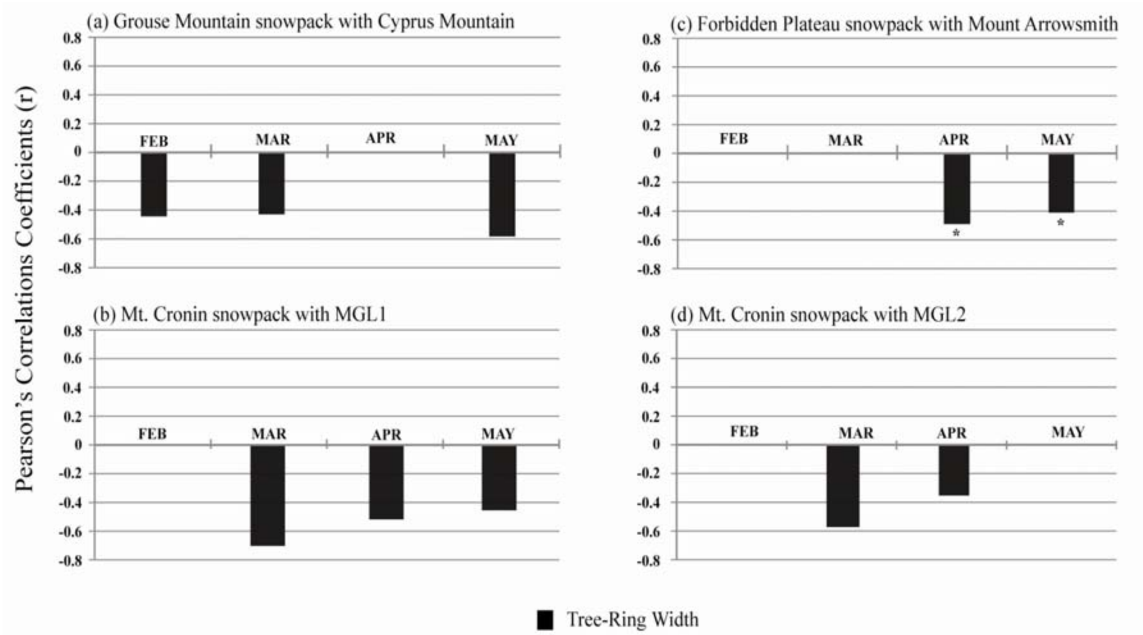

Figure 3.3: Significant Pearson's correlation coefficients between master tree ring width chronologies and climate records ($p \leq 0.05$). Correlations marked by an * represent residual chronologies.

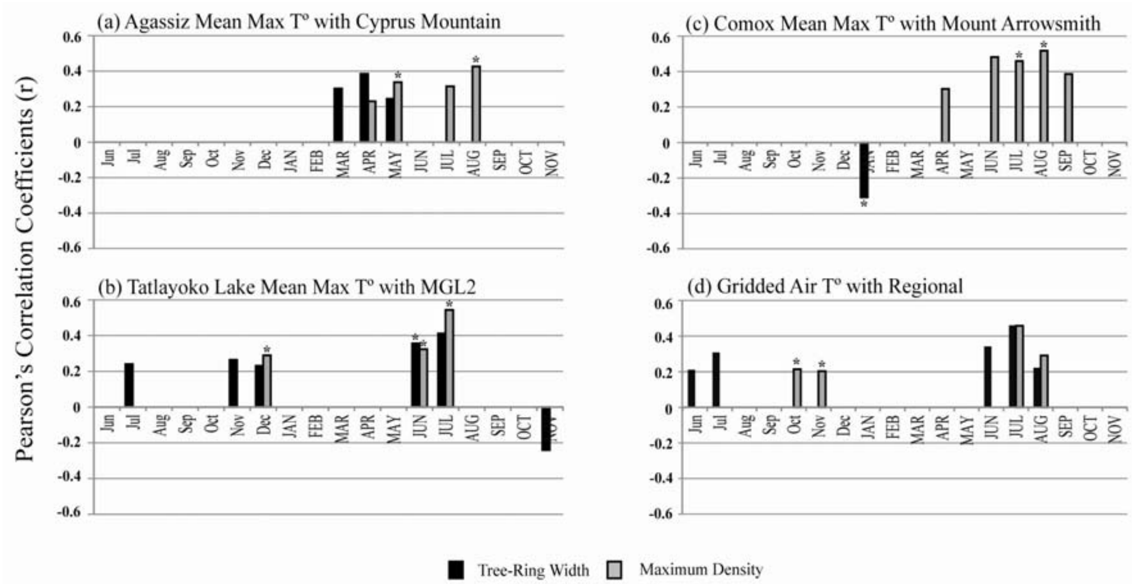

Figure 3.4: Significant Pearson's correlation coefficients between master tree ring width and maximum density chronologies and climate records (p≤0.05). Months in lower case represent months from preceding year of growth. Correlations marked by an * represent residual chronologies.

correlations exist between the Cyprus Provincial Park residual maximum density chronology and the maximum July–August temperature (r = 0.47) at Agassiz (Figure 3.4). The Mount Arrowsmith maximum density residual chronology displays a significant correlation to maximum June–August temperatures (r = 0.69) at Comox (Figure 3.4). The MGL2 maximum density residual chronology has the strongest significant correlation to maximum July temperatures(r = 0.54) at Tatlayoko Lake (Figure 3.4).

The regional ring-width and maximum density chronologies display distinct correlations to different portions of the summer growing season. The regional ring-width chronology positively correlates to mid-summer (June-July) gridded air temperature anomalies (r = 0.47) (Figure 3.4). The maximum density chronology displays strongest positive relationships to late-summer (July-August) gridded air temperature anomalies (r = 0.46) (Figure 3.4).

3.4.3 Proxy climate reconstructions

Both ring-width and maximum density chronologies were used to develop independent proxy records of climate and snowpack. The strong site correlations between maximum density and summer temperature allowed for the reconstruction of a Tatlayoko July temperature record, an Agassiz July-August temperature proxy, and a June-August temperature record for Comox (Table 3.4). Significant correlations between the ring-width chronologies to historic snowpack data allowed for the reconstruction of a proxy record of March 1 snow depth at Mt Cronin, May 1 snow depth at Grouse Mountain, and April 1 snowpack depth at Forbidden Plateau (Table 3.4).

All the reconstructions demonstrate adequate R^2 values and positive RE statistics (Table 3.4). Visualization of the calibration period shows the ability of the models to

Table 3.4: Summary statistics for climate reconstructions.

Climate Variable	Chronologies	r	Rv	r^2	RE	Record duration	EPS[1]
Tatlayoko July Max T°	MGL2 MaxD*	0.54	0.51	0.30	0.26	1700-2009	1785
Agassiz July-Aug Max T°	Cyprus MaxD*	0.47	0.44	0.22	0.19	1413-1983	1645
Comox June-Aug Max T°	Arrowsmith MaxD*	0.69	0.64	0.48	0.41	1626-1983	1680
Gridded Jun-July air T°	Regional rw	0.47	0.44	0.22	0.19	1413-2009	1570
Gridded July-Aug air T°	Regional MaxD	0.46	0.42	0.21	0.17	1413-2009	1645
Cronin March snowpack	MGL1 rw	0.70	0.67	0.49	0.44	1682-2010	1730
Grouse Mtn. May snowpack	Cyprus rw	0.58	0.52	0.34	0.26	1413-1983	1570
Forbidden April snowpack	Arrowsmith rw*	0.49	0.38	0.24	0.13	1705-1983	1730

rw – ring width, MaxD – Maximum density, MGL1 and 2 – M Gurr Lake sampling sites
* – residual chronology
[1]Date that the EPS drops below 0.80 due to decreased sample depth.

represent the instrumental climate data (Figure 3.5). Of note is the tendency for the models to underestimate the actual data, indicating that the tree-ring models are not completely successful at representing the actual annual variability (Figure 3.5).

The proxy models of summer temperature explain between 22-48% of the variability over the instrumental period (Table 3.4). The reconstructions demonstrate comparable temporal trends, with the greatest synchrony shown between Mount Arrowsmith and Cyprus Provincial Park (Figure 3.6). The intervals with cooler-or warmer-than-average temperatures correspond with those modeled by previous reconstructions of temperature in this region (Gedalof and Smith, 2001b; Larocque and Smith, 2005a).

The snowpack proxies explain from 24-49% of the variability over the instrumental period (Table 3.4). Snowpack depth fluctuates throughout the period of record, with little synchrony apparent between the three study sites. The Mount Arrowsmith reconstruction shows little variability, likely due to the limited duration of the instrumental snowpack record available for calibration (Figure 3.7; Table 3.2). The Mount Arrowsmith and Cyprus Provincial Park reconstructions follow similar trends throughout the record. The snowpack record from the Mt Cronin site displays little similarity to other two sites, likely due to station data location and/or site-specific factors.

The proxy climate models derived from the regional ring-width and density data, explain, respectively 22% and 21% of the gridded temperature anomaly records (Table 3.4). With the exception of a significant rise in temperature around AD 1900 recorded by the regional ring-width chronology, both models display comparable intervals of cooler- and warmer-than-average intervals over their duration (Figure 3.8). These trends are

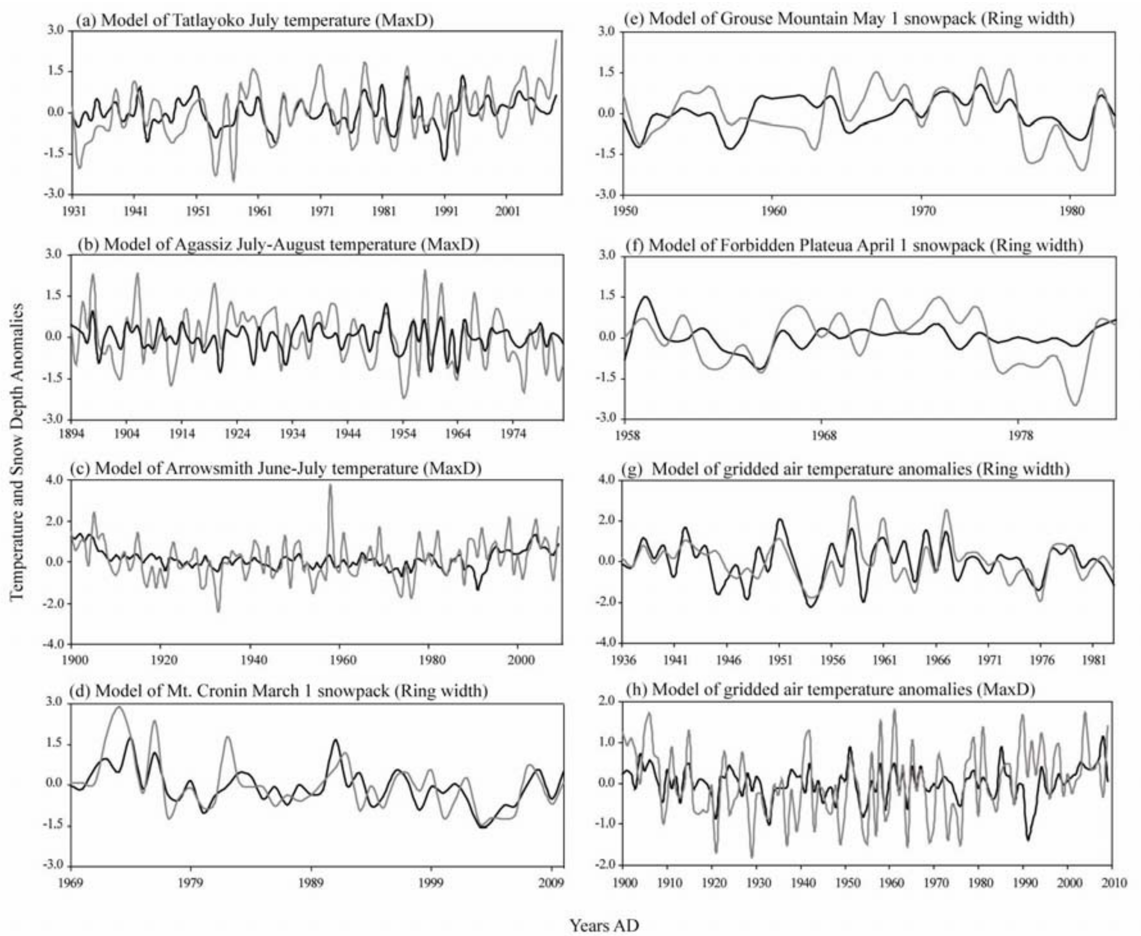

Figure 3.5: Comparison between reconstructed (black line) and instrumental data (grey line) records for all sampling sites during the calibration period. Parentheses indicate which parameter was used.

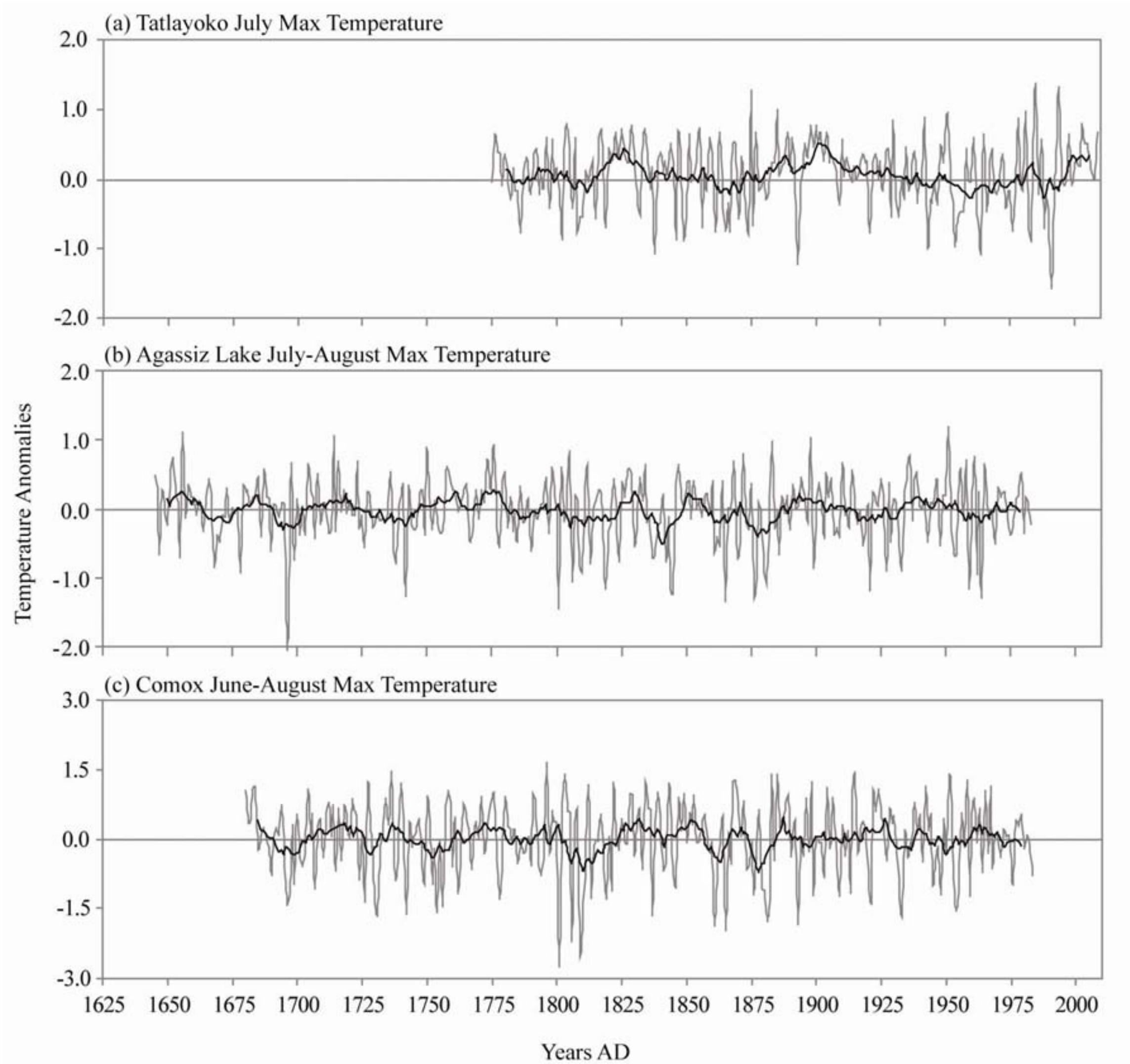

Figure 3.6: Proxy temperature reconstructions at the three study sites. Grey lines are annual values, with the black lines showing the 10-year running mean.

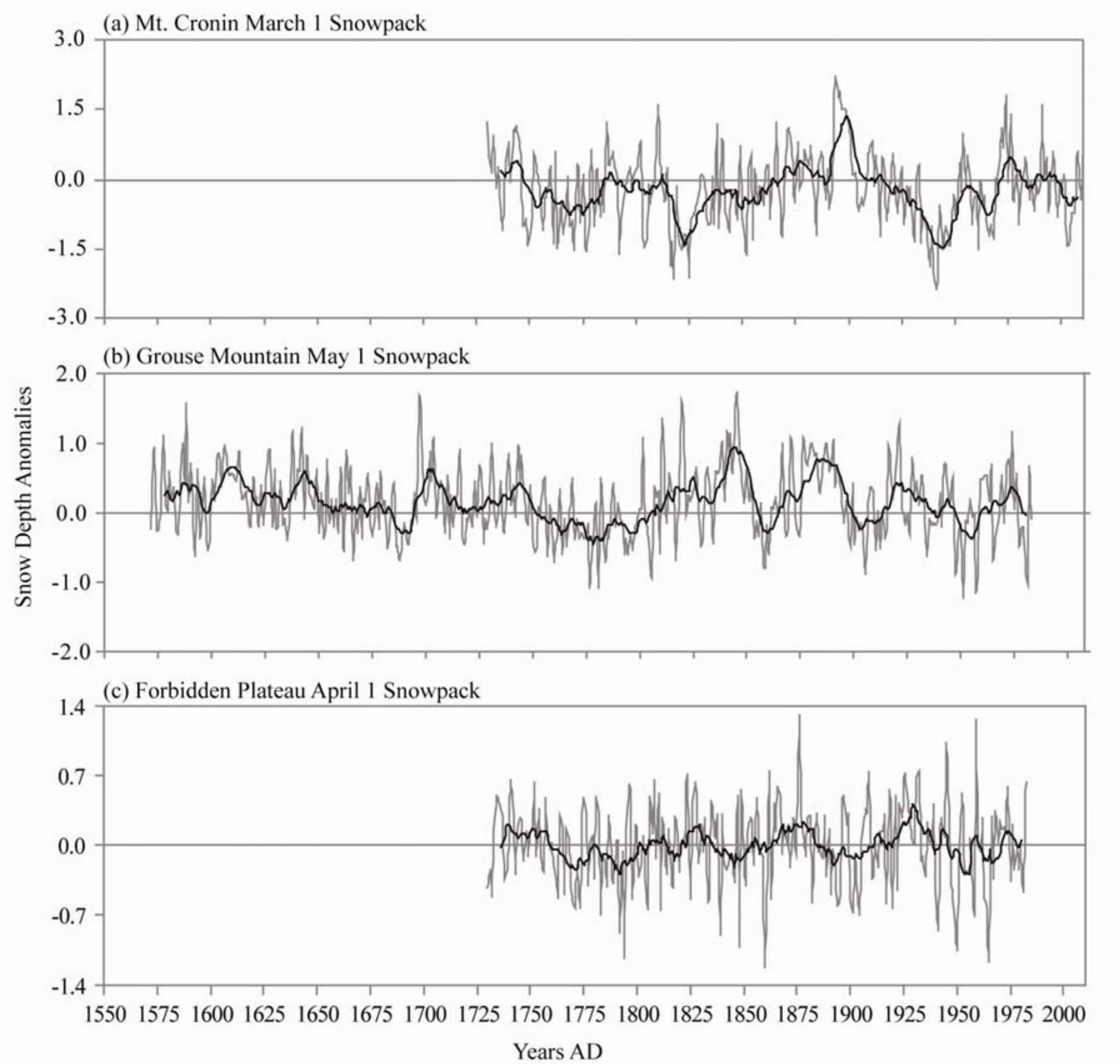

Figure 3.7: Reconstruction of early spring snowpack records at the three study sites. Grey lines are annual reconstructed values. Black lines display the 10-year running mean.

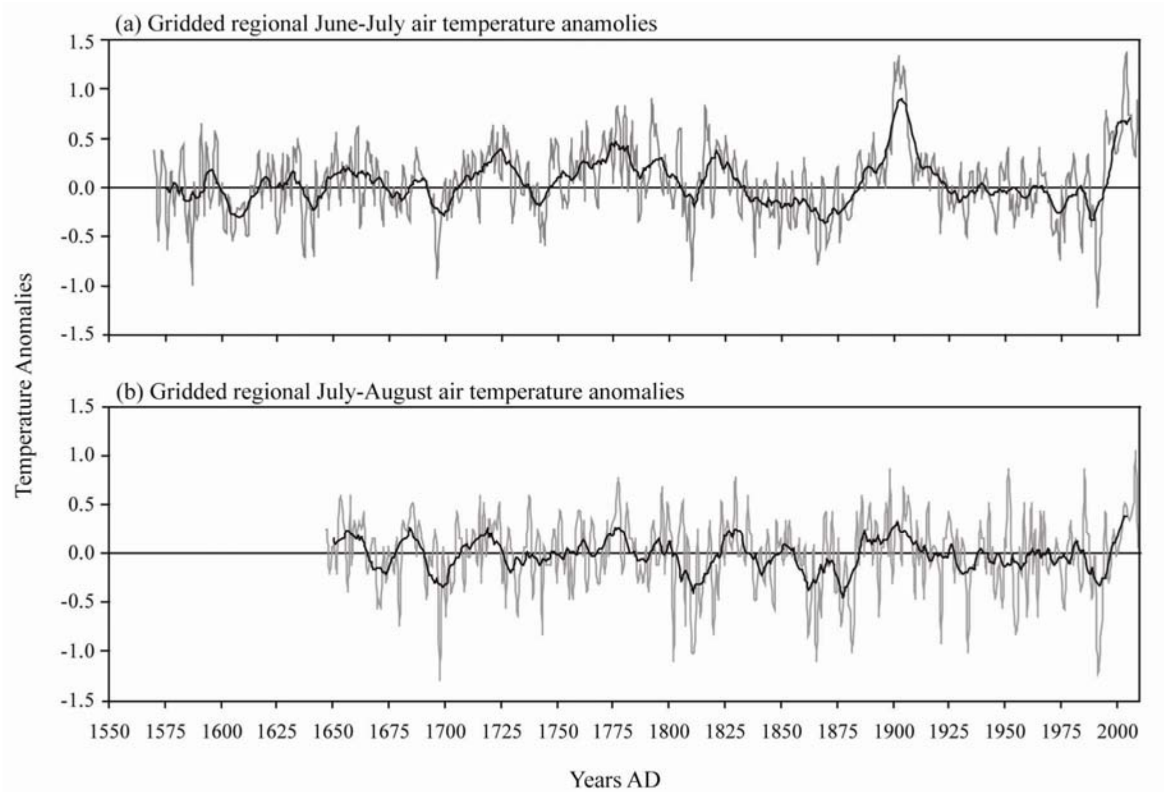

Figure 3.8: Reconstructions comparing: (a) tree-ring width; and, (b) tree-ring maximum density to gridded air temperature anomalies. Grey lines are the actual reconstructions while the black lines represent a 10-year running mean of the data.

comparable to those found in previous dendroclimatic research over the past 350-450 years in this region (Gedalof and Smith, 2001b; Laroque, 2002; Larocque and Smith, 2005a).

3.5 Discussion

Tree-rings provide robust opportunities for describing pre-instrumental environmental conditions (Fritts, 1976; Schweingruber *et al.*, 1978; Beeckman, 1993). Ring-width growth is dependent upon seasonal periclinal cell division and enlargement occurring in the cambial region (Larson, 1994; Lachaud *et al.*, 1999), whereas ring-width density is primarily determined by cell-wall thickness, an anatomical alteration that begins in late-summer once cell division and enlargement cease (Polge, 1970). The seasonal partioning of these activities means that ring-width measurements should better capture early-season climate variability, with late-season density changes better correlating to end-of-growing season climates (Wimmer and Graber, 2000; Davi *et al.*, 2002; Frank and Esper, 2005; Tuovien, 2005).

These investigations demonstrate that measurements of mountain hemlock maximum annual tree-ring density provide robust data series for reconstructing proxy records of late summer temperature. Complimentary measurements of the annual ring-width increment shows that this metric can be interpreted to provide an independent proxy of spring snowpack trends.

Maximum ring density consistently showed a strong positive correlation to summer temperature (Figure 3.4). Based upon previous research, it is assumed that this relationship reflects the impact of longer and/or warmer growing seasons on cell wall thickness (Schweingruber *et al.*, 1988; Vaganov, 1996; Tuvinen, 2005). While the Mount

Arrowsmith maximum density chronology was shown to be related to early-season temperature (June), this relationship is likely due to the early arrival of spring conditions and a lengthened growing season at this particular site (Conkey, 1986).

The negative correlation between ring-width and spring snowpack is a reflection of the physiological impact of seasonal snowpacks (Laroque and Smith, 1999; Gedalof and Smith, 2001b; Larocque and Smith, 2005a). During springs when deep snowpacks linger into the growing season, they reduce soil temperatures, plant respiration and bud development (Hansen-Bristow, 1986; Peterson and Peterson, 2001). During growing seasons when these conditions prevail, the annual increment of ring-width growth is reduced and a negative correlation to snowpack results (Smith and Laroque, 1998; Gedalof and Smith 2001b).

The significant correlation between selected tree-ring parameters and climate, as well as their assumed physiological relationships, provided a rationale for developing station-specific proxy climate/snowpack records and a regional temperature anomaly reconstruction. As Figure 3.6 shows, common patterns of variability exist among the air temperature reconstructions. The Cyprus Provincial Park and Mount Arrowsmith reconstructions have the strongest synchronicity, with the M Gurr Lake reconstruction displaying similar long-term trends but reduced annual variability. The reconstructions indicate that during the early-1700s air temperatures were below average, with above average growing season temperatures characterizing the 1760s to 1780s. Average temperatures rapidly decrease to lower than average values in the early-1800s, afterwhich two decades of higher than average temperatures characterize the 1820s to 1830s. Following this, temperatures drastically declined in the mid-1800s until the late-1800s with a rise around the early-1900s and little temperature variation until the present (Figure 3.6).

The three snowpack reconstructions display only limited similarity (Figure 3.7), almost certainly reflecting the variability of winter snowfall trends in the mountains of coastal British Columbia (Mote, 2003, 2006). Generally, spring snowpacks at Grouse Mountain are higher than average in the early-1700s, and mid-1700s. All three sites show lower than average snowpack depths during the late-1700s. Forbidden Plateau and Grouse Mountain show above average snowpacks during the early-1800's, with Mt. Cronin shifting to lower-than-average snowpack depths from AD 1800-1825. During the mid to late-1800's all sites exhibit above average snowpack depths. During the early-1900's and continuing to the mid-1950's snowpack depths are lower-than-average. The Mt. Cronin snowpacks follow a general decline until the mid-1950's where average snowpack depths occur until the present. Grouse Mountain and Forbidden Plateau snowpacks increased in the early 1900's, until the AD 1930's when snowpack declined to below average levels until present (Figure 3.7).

Significant correlations between the gridded air temperature anomaly data and the ring-width and maximum density chronologies provided a basis for constructing regional temperature models. The ring-width chronology displayed the strongest correlation to June-July air temperature anomalies and is better able to describe trends in early-season temperatures when the majority of cambial cell construction occurs (Fritts, 1976). In contrast, the density chronology displayed strong correlations to late-summer temperature anomalies when cell wall thickening is underway.

Taken together, the regional models provide both seasonal and subseasonal insights into temperature variability in coastal British Columbia from AD 1575-1650 to present. The June-July model illustrates that early season temperatures were depressed in AD 1600, afterwhich both models indicate temperatures in the summer growing season to be higher-than-average by the late-1600s before dropping to below average temperatures by AD 1700. Following this decline, summer growing season temperatures oscillated to warmer-than-average intervals in the early-1700s and again in the late-1700s. Cooler-than-average periods characterize the early-1800s and warmer-than-average periods occur in the mid-1800s. Average temperatures declined in the late-1800’s and rose again by AD 1900, afterwhich yearly temperature variations have remained relatively stable until the present (Figure 3.8). The increase in temperature by AD 1900 is best associated with the ring-width model (Figure 3.8), suggesting that the extended growing period implicit in the model is associated with warmer early-season temperatures.

Periods of cooler-than-average and warmer-than-average temperature in the proxy records generally correspond to years of higher-than-average and lower-than-average snowpack, respectively. The interrelatonship between these two climate variables, as well as their apparent cyclity, suggests that ocean-atmospheric teleconnections like those described by the Pacific Decadal Oscillation (PDO)(Mantua and Hare, 2002) influence climate trends and thus, mountain hemlock growth in coastal British Columbia. Of note are the significant decreases in air temperature and increases in snowpack during the early-1700s and early-1800s shown in Figures 3.6 and 3.7. These intervals coincide with significant negative PDO shifts described by Gedalof and Smith (2001a) and notable

Little Ice Age glacier advances described in this region (Larocque and Smith, 2003, 2005b; Allen and Smith, 2007; Koehler and Smith, 2011).

3.6 Conclusion

This research employs a network of mountain hemlock chronologies to describe climate trends in the south western British Columbia Coast Mountains over the last 500 years. Standardized ring-width chronologies were used, in conjunction with density chronologies, to discern the influence of early- and late-growing season conditions on the radial growth characteristics of mountain hemlock trees found at three high elevation sites. Identification of these subseasonal climate signals allowed for construction of better-defined site-specific growing season air temperature and spring snowpack models, as well as the presentation of regional temperature anaomaly models extending from AD 1575 to present.

Chapter 4 – Conclusion

4.1 Thesis Summary

The primary goal of this research was to build an extended mountain hemlock tree-ring chronology spanning beyond the duration of living trees in southern British Columbia. The intent was to use this extended chronology to describe the character of climate changes over the last millennia. A secondary goal was to utilize the outcome of this chronology development, in concert with companion densitometric analyses, to investigate subseasonal climate signals contained within the annual tree-rings of mountain hemlock trees.

An extended chronology spanning the last 785 years was constructed from samples collected from living mountain hemlock trees and coarse woody debris (CWD) salvaged from the bottom of a high-elevation subalpine lake. This multi-century regional tree-ring chronology was used to model a gridded June-July air temperature anomaly record describing climate variations in the southern Coast Mountains and Vancouver Insular Mountains since AD 1225. Wavelet analysis revealed a low-frequency trend within the proxy record that has been displayed in other millennia long chronologies collected in the British Columbia Coast Mountains. This finding suggests long-term trends in the radial growth of mountain hemlock trees in this region may be governed, in part, by a long-term cycle attributed to solar irradiance. This climate-induced forcing of tree growth is presumed to primarily reflect a physiological relationship between tree-ring growth and growing season temperatures.

An extended pre-historic, snow avalanche chronology was constructed based upon the CWD removed from M Gurr Lake and living trees surrounding the lake. Snow avalanche events were determined from CWD kill dates and from the reaction wood initiation dates recorded in the living trees and within the CWD samples. At M Gurr Lake it was determined that low-magnitude avalanche events occurred in the winters of AD 1713-1714, 1764-1765, 1792-1793, 1914-1915, 1925-1926 and 1940-1941. High-magnitude snow avalanche events responsible for transporting woody detritus into M Gurr Lake occurred in the winters of AD 1502-1503 and 1869-1868.

An examination of the subseasonal radial growth response of mountain hemlock trees in the southern Coast Mountains was completed using archived data and increment core samples collected at M Gurr Lake. Standardized ring-width chronologies were used in tandem with density chronologies to distinguish the influence of early- and late-season climates on the radial growth of mountain hemlock trees. It was shown that the total ring-width was negatively correlated with early-season snowpacks, whereas maximum ring density was correlated with late-summer (July-August) temperatures. These relationships were described and used to model intra-annual proxy climate records that present long-term site-specific records of snowpack and temperature trends. Additional analyses were undertaken in an attempt to develop an understanding of climate changes over the concurrent length of regional chronologies. A regional ring-width chronology was constructed and used to develop a proxy gridded June-July air temperature anomaly record. Similarly a regional maximum density chronology was constructed and used to model a proxy record of gridded July-August air temperature anomalies. Considered together the various proxy climate records developed in this thesis consistently illustrate that, cooler-than-average and warmer-than-average temperatures correspond to years of higher-than-average and lower-than-average snow pack, respectively.

4.2 Research limitations

a) Dating the extended tree-ring chronology:

The construction of the extended tree-ring chronology was conducted without the use of radiocarbon dating. This dating method could have provided an additional verification tool to ensure that appropriate dates were assigned to the undated floating CWD chronologies.

b) Avalanche return intervals:

Due to the nature of this sampling technique and sample depth, it was not possible to construct an avalanche return interval. Avalanche return intervals are of particular importance as they assist in the prediction and preparation of future avalanches events.

4.3 Research recommendations

b) Site location and sampling using SCUBA diving methods:

Sample site location requires consideration when conducting this type of research. Using SCUBA diving as a research methodology presents a challenge that requires particular attention. Elements requiring consideration include the need:

- to locate an accessible high elevation lake site where cold-water conditions preserve the CWD and where tree rings show sufficient annual variability to allow for cross-dating.

- to safely SCUBA dive. High-elevation scientific diving brings with it a high-degree of risk that limits the length of time that a diver can stay submerged. This restriction limits the number of samples that can be collected within short-time spans.
- to develop sampling protocols that do not prohibit the removal of large boles from lake bottoms. The weight and size of such waterlogged samples prevents their extraction by shoreline-based ropes and winches.

c) Densitometric analysis

While densitometry provides an opportunity to describe intra-annual relationships to subseasonal climate fluctuations, several issues require consideration:

- complications arise when sampling density chronologies; notably that having the correct ring angle is crucial for ensuring useful x-ray images. Care must be taken during sampling, and during sample preparation, to ensure that the ring cross-sections are horizonal throughout the sample length.
- trees with exceptionally narrow perimeter rings, like mountain hemlock trees, typically result in x-ray images where it is difficult to discern the boundaries between early- and late-wood. This issue can be somewhat alleviated when ancient trees are sampled, by including younger cohort trees with large perimeter rings in the sample.

4.4 Future Research

This research provided new insights into our understanding of climate variations in coastal British Columbia over the last millennia. Research should now focus on efforts to:

- continue the development of a regional high-elevation mountain hemlock tree ring chronology in western British Columbia that extend beyond the length recorded in this research.
- further explore the complex response of mountain hemlock trees to multiple seasonal environmental parameters through the use of intra-annual density measurements.

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