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Original article

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

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ABSTRACT

The growth of mountain hemlock trees in Pacific North America demonstrates a complex relationship to two or more seasonal environmental variables. In order to examine the radial growth response of mountain hemlock to subseasonal climate variables, ring-width and X-ray densitometric analyses were used to construct intra-annual dendroclimatic records. The intent was to highlight the difference between the dendroclimatic outcomes of standard ring-width analyses to those derived from density chronologies collected at high elevation locations in the British Columbia Coast Mountains. This study highlights the importance of using multiple tree-ring parameters to better define the complex growth behaviour in mountain hemlock trees for the construction of more robust proxy climate records. Tree-ring chronologies from three sites were used to describe the inherent climate-growth trends. Maximum tree-ring density values provided a robust data series for constructing site-specific proxy records of late-summer temperature. Annual ring-width measurements provided independent proxies of spring snowpack trends. Significant decreases in temperature and an increase in snowpack depth during the early 1700s and early 1800s coincides with documented PDO phases and Little Ice Age glacier advances. Identification of early and late growing season climate signals within mountain hemlock trees demonstrates the value of documenting the characteristics of multiple tree ring parameters in future dendroclimatic studies.

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 relationship to a single climate parameter (e.g. Wilson and Luckman, 2006; Youngblut and Luckman, 2008; Flower and Smith, 2010), the radial growth of trees in mountainous regions of Pacific North America frequently demonstrate complex relationships to two or more seasonal environmental parameters (Graumlich and Brubaker, 1986; Smith and Laroque, 1998; Laroque and Smith, 1999).

Montane forests in large areas of the British Columbia Coast Mountains are characterized by mature stands of mountain hemlock (*Tsuga mertensiana*) trees, interspersed with cohorts of Pacific silver fir (*Abies amabilis*), subalpine fir (*Abies lasiocarpa*) and yellow cedar (*Callitropsis nootkatensis*) (Brooke et al., 1970; Klinka and Chourmouzis, 2001). The radial growth of mountain hemlock trees in these settings typically demonstrates a positive response to increased summer air temperature (Gedalof and Smith, 2001a; Peterson and Peterson, 2001), and a negative response to seasonally persistent winter snowpacks (Smith and Laroque, 1998; Peterson and Peterson, 2001). In previous dendroclimatic studies, this complex growth behaviour prompted application of species-specific factor analyses (Gedalof and Smith, 2001b; Peterson and Peterson, 2001) and/or inter-species principal component analyses (Larocque and Smith, 2005) to elucidate a climate-response growth signal for the construction of robust proxy climate records. In order to improve upon these proxy reconstructions, specific attention needed 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.,

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2002), as their cells characteristically vary as a result of subseasonal environmental conditions (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 temperature (Parker and Henoch, 1971; Schweingruber et al., 1991; D'Arrigo et al., 1992; Briffa et al., 1992; Davi et al., 2002; Wood et al., 2011).

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

Study sites

Tree-ring samples were collected from mature mountain hemlock stands (200–400 years in age) located at three locations in southwestern British Columbia in July, 2010 (Fig. 1). Two sampling sites were located adjacent to M Gurr Lake in the central Coast Mountains near Bella Coola, British Columbia (Fig. 1). Maritime conditions characterize the local environment, with precipitation falling principally as snow from late-fall to early-spring (Burns and Honk, 1990). Site M Gurr Lake 1 (MGL1) is found within a mountain hemlock parkland, cohabited by yellow cedar and subalpine fir, located 200 m southeast of the lake on a gentle-to-steep southeast-facing slope at 1330 m asl (52°17′22″ Lat N, 126°53′37″ Long W; Fig. 1; Table 1). Site M Gurr Lake 2 (MGL2) is located within a closed stand of mature mountain hemlocks trees 1 km southwest of M Gurr Lake on a moderate south-facing slope at 1050 m asl (52°17′02″ Lat N, 126°54′22″ Long W; Fig. 1; Table 1).

Mountain hemlock trees at Cyprus Provincial Park in the southern Coast Mountains were sampled in 1983 on a south-east facing slope at 1110 m asl (49°25′12″ Lat N, 123°05′20″ Long W; Fig. 1; Table 1). Maritime conditions characterize the local environment, with Pacific silver fir, 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 on Vancouver Island were sampled in 1983 (49°29′47″ Lat N, 125°12′05″ Long W; Fig. 1; Table 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).

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.

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 programme by Schweingruber (1988) and Schweingruber et al. (1991). Between 20 and 22 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 programme (Schweingruber et al., 1991; 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).

At M Gurr Lake increment core samples were collected from mature trees without obvious disturbance. Increment borers (5 mm) were used to extract two cores per tree (90–180° apart) near breast height at MGL1 and MGL2. At the latter 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). Cores were transported to the University of Victoria Tree Ring Laboratory (UVTRL) where 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 using WinDENDRO™ (Ver. 2008g, Regent Instruments Inc., 2008).

The 12 mm 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 with the blade angle adjusted to correct for non-perpendicular rings (Haygreen and Bowyer, 1996). Water and resin were removed by soaking the samples in an acetone Soxhet apparatus for 8 h (Schweingruber et al., 1978; Jensen, 2007). Each lathe was scanned perpendicular to the X-ray beam for 20-μs at 50-μm intervals with a 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 scanned digital X-ray images using WinDENDRO image analysis software (Ver. 2008g, Regent Instruments Inc., 2008).

Visual cross-dating of the 5 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). Density chronologies were visually compared and cross-dated to the 5 mm ring-width data to ensure correct dating. Narrow or non-perpendicular rings prevented precise measurement of the density parameters from the X-ray images (Polge, 1970; Schweingruber, 1988) and were discarded from further analysis.

The ring-width, maximum, mean and minimum density series were compiled into specific master chronologies. Chronologies were standardized using the dendrochonology programme ARSTAN by double-detrending each series (Holmes et al., 1986). First a negative exponential curve was applied to remove age-related growth trends (Kramer and Kozlowski, 1960; Cook and Kruisic, 2005) and second a smoothing spline with a 67% frequency cut off, preserving 50% of the variance in ring-width growth was used to reduce the influence of endogenous and exogenous disturbance (Cook, 1985). After detrending, standardized master chronologies were created using a robust biweighted mean to enhance the common signal found between all series (Cook, 1987). Residual chronologies were constructed using autoregressive modelling to remove low-order autocorrelation from the standardized data, this limits the influence growth from the previous has on the current growth year (Cook and Kruisic, 2005). Both standardized

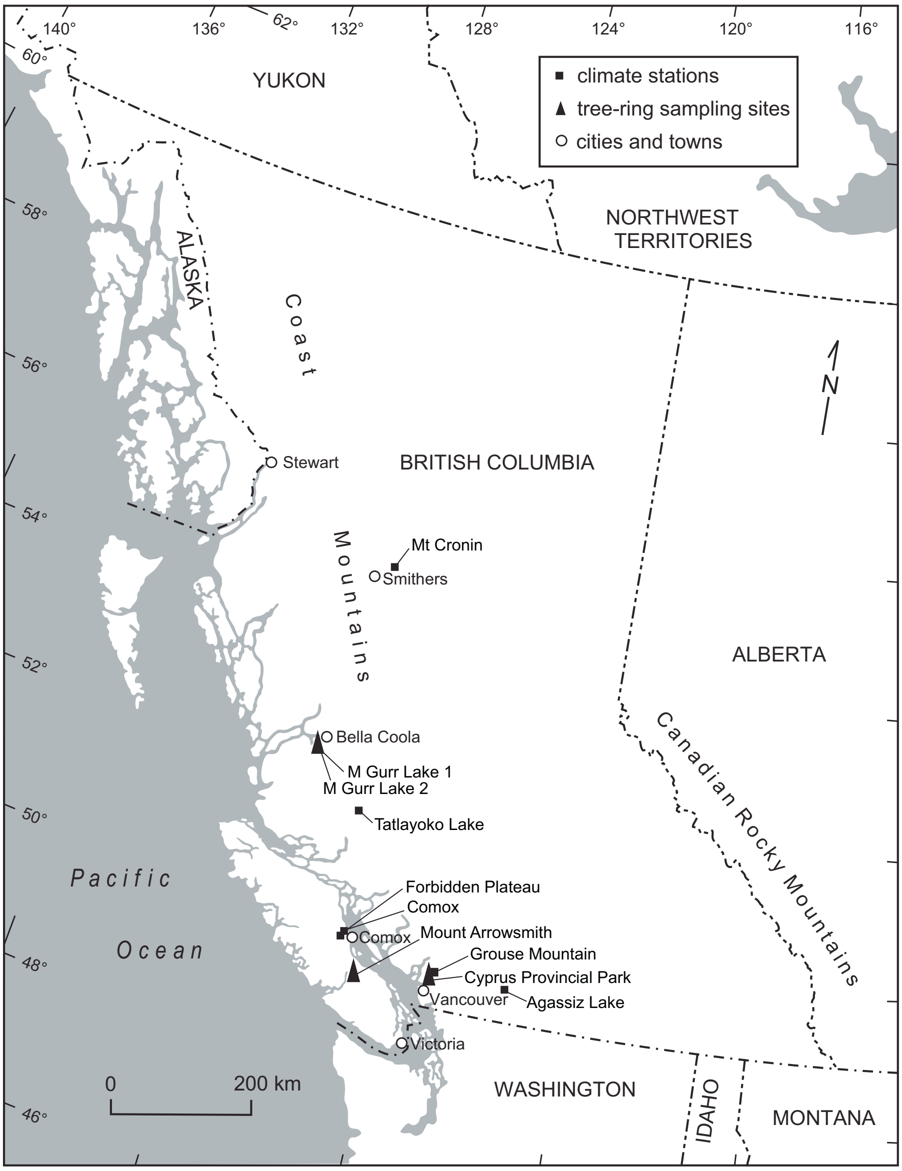

Fig. 1. Location of tree-ring width, density chronologies and climate stations in the British Columbia Coast Mountains, British Columbia, Canada.

and residual chronologies were used in this study. 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 Kruisic, 2005).

Instrumental climate data

Instrumental records from long-term climate stations located in close proximity to M Gurr Lake (Tatlayoko Lake, AD 1895–1983), Cyprus Provincial Park (Agassiz, AD 1895–1983) and Mount Arrowsmith (Comox, AD 1936–1983) were used in correlation analyses to discern any site-specific climate-radial growth relationships (Table 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, AD 1969–2010), Cyprus Provincial Park (Grouse Mountain, AD 1950–1983) and Mount Arrowsmith (Forbidden Plateau, AD 1958–1983) was obtained from the Government of British Columbia River Forecast Centre (BC RFC, 2010) (Table 2). Gridded air temperature anomaly data (Lat 50–55° N and Long 125–130° W) compiled by the Climatic Research Unit (1900–2010) was

Table 1
Mountain hemlock tree-ring chronology sampling locations.

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

rw – ring width; MinD – minimum density; MaxD – maximum density.

Table 2
Climate station locations and metadata.

Station (m asl)	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

employed to test for significant regional temperature relationships (CRU, 2010).

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 and seasonal variables in the current and previous year of tree-ring growth. Only relationships demonstrating statistically significant correlations were used, and for this purpose only those will be discussed further. 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 (R_v). A 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 (Fritts, 1976). Statistically significant correlations, strong r^2 values, and positive RE statistics proved model adequacy and were 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.

Results

Tree-ring chronologies

Three chronology sets were constructed from increment cores collected at M Gurr Lake: ring-width chronologies developed from cores collected at MGL1 and MGL2; and, a maximum density chronology developed from cores collected at MGL2 (Table 3). Forty-two series from 22 trees at MGL1 were used to create a site ring-width chronology (r = 0.64) spanning 329 years (1623–2010) (Table 3; Fig. 2). Fifty-three series from 29 trees were used to develop the MGL2 ring-width chronology (r = 0.61) spanning 388 years (1623–2010) (Table 3, Fig. 2). Maximum (r = 0.41) density chronologies for MGL2 were constructed from 23 series spanning 310 years (1700–2009) (Table 3; Fig. 2).

The ITRDB records compiled by Schweingruber (1988) in Cyprus Provincial Park include ring-width (r = 0.62) and maximum (r = 0.49) density chronologies spanning 571 years (1413–1983) (Table 3, Fig. 2). The ITRDB chronologies from Mount Arrowsmith compiled by Schweingruber (1988) include ring-width (r = 0.50), and maximum density chronologies (r = 0.72) from 28 series spanning a 355-year interval (1629–1983) (Table 3; Fig. 2).

Two independent master regional chronologies were constructed by crossdating the ring-width and maximum density data from the sampling sites. While the chronologies span a 598-year interval from 1413 to 2010, the ring-width (r = 0.48) chronology has an EPS cut off point at 1570 and the maximum density (r = 0.49) chronology has EPS cut off point at 1645 (Tables 3 and 4).

Dendroclimatic correlations

Significant relationships were revealed between distinct instrumental climate variables and individual residual ring-width, standardized ring-width and density chronologies (Figs. 3 and 4). The tree-ring width chronologies from all sites exhibit statistically significant correlation values to spring snowpack (Fig. 3). No statistically significant relationship existed between minimum or maximum density chronologies and spring snowpack. Significantly stronger correlation values for March 1 snowpack at Mt Cronin exist to the standardized ring-width chronology from MGL1 (r = −0.70) when compared to the standardized ring-width chronology from MGL2 (r = −0.57), highlighting the importance of tree ring sample site selection (Fig. 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 significantly negatively correlated to the April 1 Forbidden Plateau snowpack record (r = −0.49) (Fig. 3).

Maximum density values display stronger correlations to summer temperature records at all three sites than do the ring-width chronologies (Fig. 4). Significant positive correlations exist between the Cyprus Provincial Park residual maximum density chronology and the maximum July–August temperature at Agassiz (r = 0.47) (Fig. 4). The Mount Arrowsmith residual maximum density chronology displays a significant correlation to maximum June–August temperatures (r = 0.69) at Comox. The MGL2 residual maximum density chronology has a strong significant correlation to maximum July temperatures (r = 0.54) at Tatlayoko Lake (Fig. 4).

The regional ring-width and maximum density chronologies display distinct correlations to different portions of the summer growing season. The regional standardized ring-width chronology positively correlates to mid-summer (June–July) gridded air temperature anomalies (r = 0.47) (Fig. 4). The regional standardized maximum density chronology displays strongest positive relationships to late-summer (July–August) gridded air temperature anomalies (r = 0.46) (Fig. 4).

Table 3
Summary statistics for individual and regional chronologies.

Site	Data	Interval (years AD)	# trees	# years	Mean series correlation	Mean sensitivity[a]
M Gurr Lake 1	rw	1682–2010	22	329	0.64	0.31
M Gurr Lake 2	rw	1623–2010	28	388	0.61	0.26
	MinD	1700–2009	22	310	0.41	0.09
	MaxD	1700–2009	22	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	102	598	0.48	0.23
	MaxD	1413–2010	73	598	0.49	0.07

rw – ring width; MinD – minimum density; MaxD – maximum density.
[a] 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.

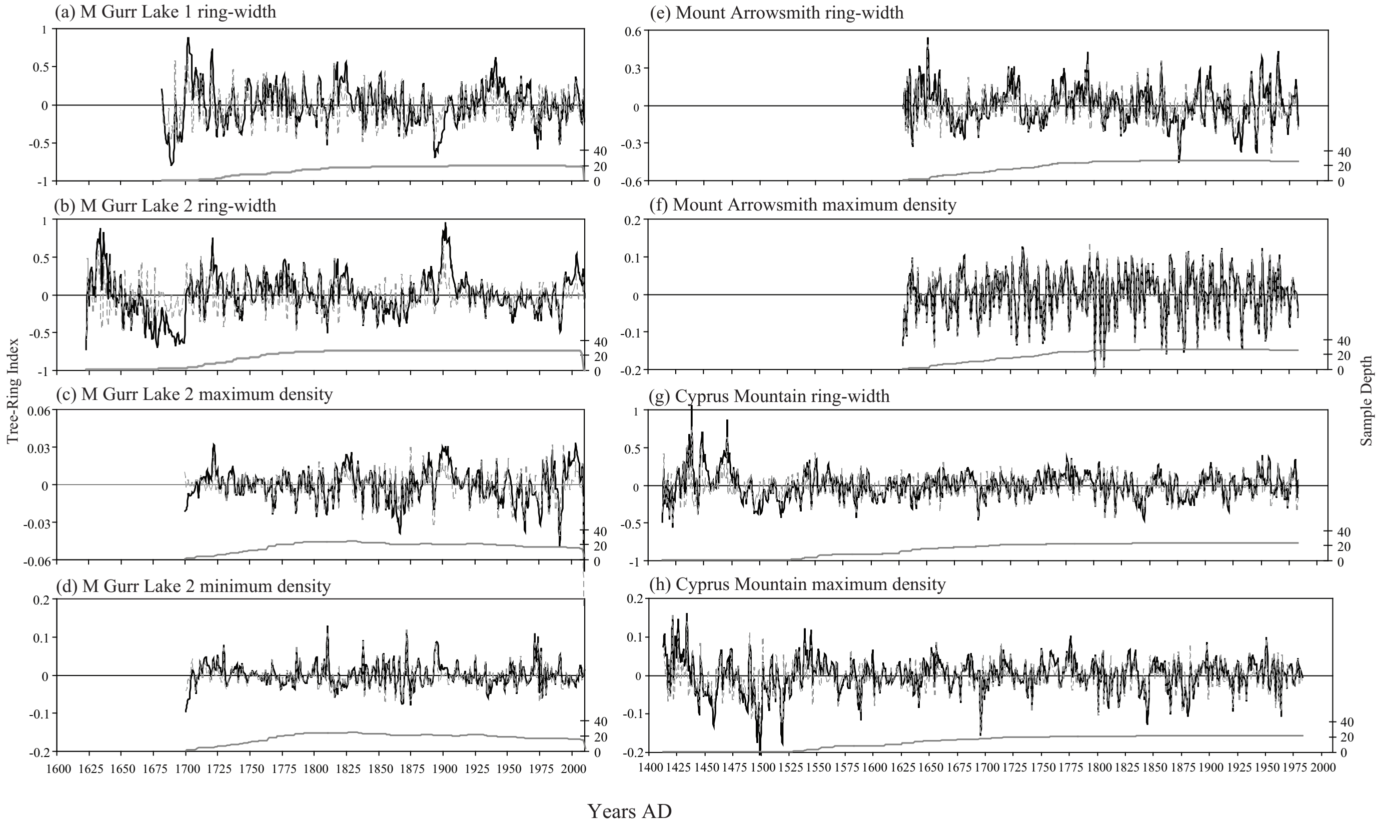

Fig. 2. Standardized and residual master tree-ring indices. Solid black lines represent the standardized chronologies. Grey dashed lines represent the residual chronologies. Grey solid lines indicate sample depth.

Table 4
Summary statistics for climate reconstructions.

Climate variable	Chronologies	r	R_v	r^b	RE	Record duration	EPS[b]
Tatlayoko July Max T°	MGL2 MaxD[a]	0.54	0.51	0.30	0.26	1700–2009	1985
Agassiz July–August Max T°	Cyprus MaxD[a]	0.47	0.44	0.22	0.19	1413–1983	1645
Comox June–August Max T°	Arrowsmith MaxD[a]	0.69	0.64	0.48	0.41	1626–1983	1680
Gridded June–August air T°	Regional rw	0.47	0.44	0.22	0.19	1413–2009	1570
Gridded July–August 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	1682–2009	1730
Grouse May snowpack	Cyprus rw	0.58	0.52	0.34	0.26	1413–1983	1570
Forbidden April snowpack	Arrowsmith rw[a]	0.49	0.38	0.24	0.13	1705–1983	1730

R_v – correlation coefficient statistics for verification period; rw – ring width; MaxD – maximum density.
[a] Residual chronology
[b] Date that the EPS drops below 0.80 due to decreased sample depth.

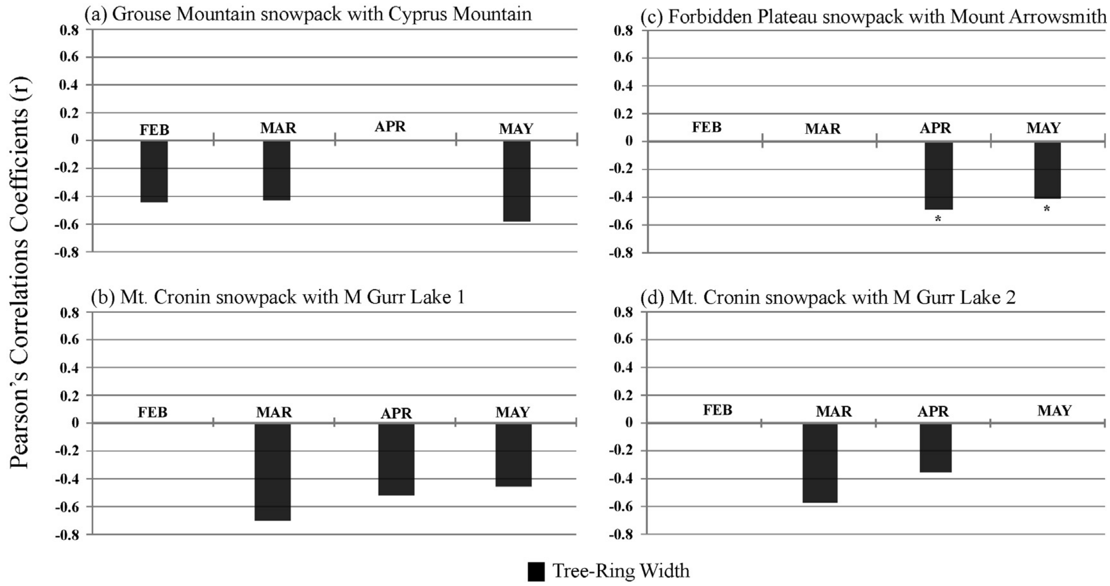

Fig. 3. Significant Pearson's correlation coefficients between master tree ring width chronologies and climate records ($p \leq 0.05$). Correlations marked by an * represent residual chronologies.

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 Lake July temperature record, an Agassiz Lake July–August temperature record, and a Comox June–August temperature record (Table 4). Significant correlations between the ring-width chronologies to historic snowpack data allowed for the reconstruction of a proxy record of March 1 snowpack at Mt Cronin, May 1 snowpack at Grouse Mountain, and an April 1 snowpack at Forbidden Plateau (Table 4). All of the reconstructions demonstrate strong r^2 values and positive RE statistics (Table 4). Visualization of the calibration period shows the ability of the model to represent the instrumental climate data (Fig. 5). Of note is the tendency for the models to underestimate the instrumental data, indicating that the tree-ring models are not completely successful at representing the measured annual variability (Fig. 5). This underestimation is responsible for some of the unexplained instrumental variability not captured by the tree-ring proxy records and results in a modest reconstruction of the representative climatic station. 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.

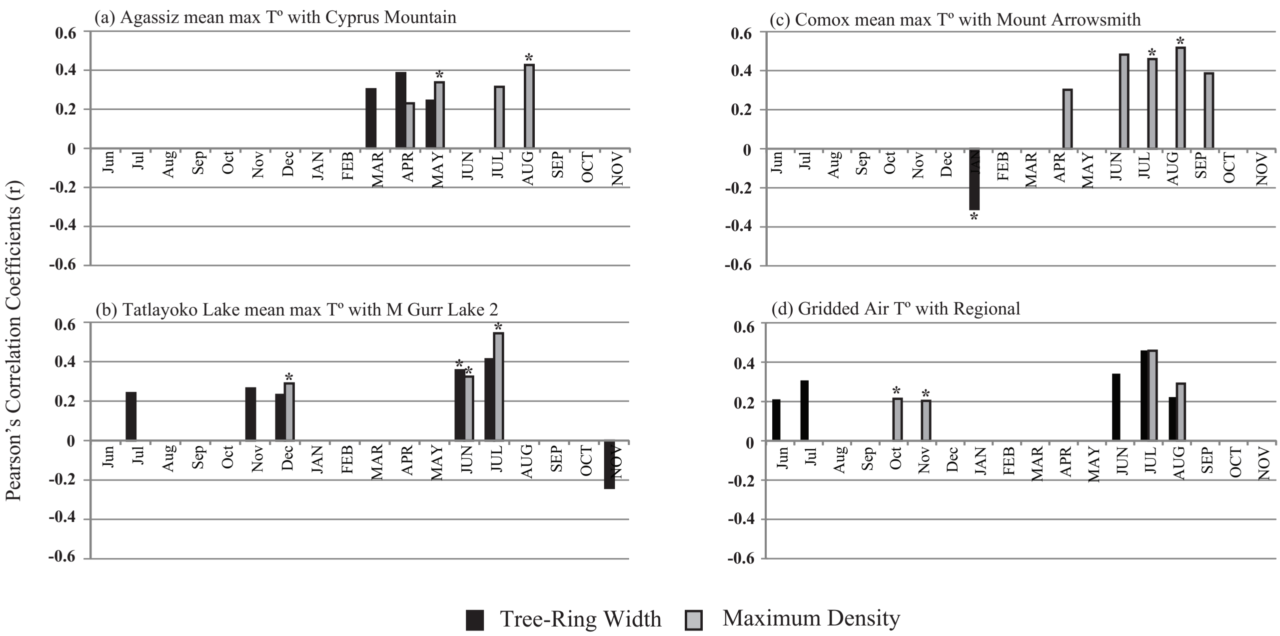

Fig. 4. Significant Pearson's correlation coefficients between master tree ring width and maximum density chronologies and climate records ($p \leq 0.05$). Months in lower case represent months from preceding year of growth. Correlations marked by an * represent residual chronologies.

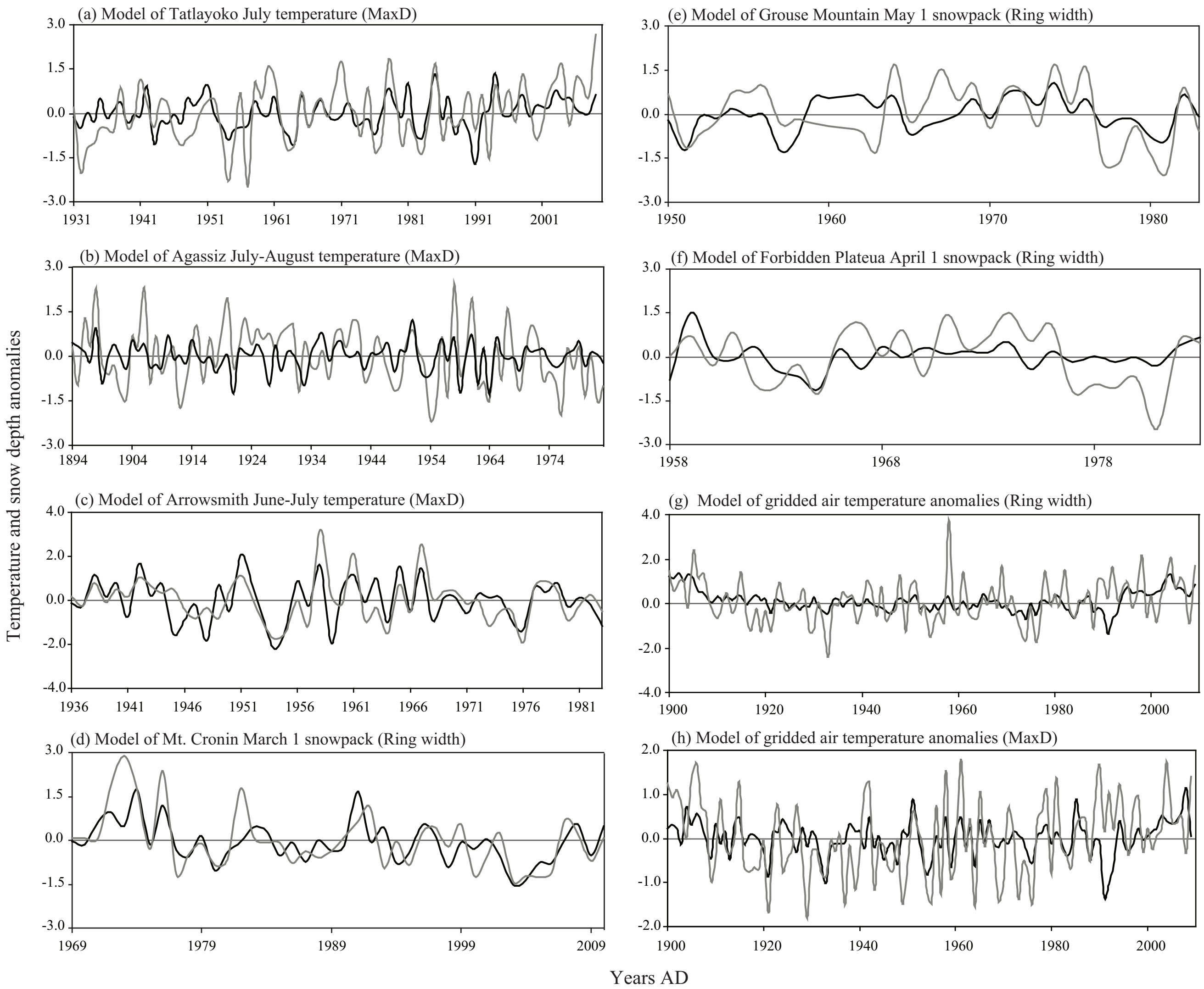

Fig. 5. Comparison between reconstructed (black line) and instrumental data (grey line) records for all sampling sites during the calibration period. Parentheses indicate which parameter was used.

The proxy models of summer temperature explain between 22 and 48% of the variability over the instrumental period (Table 4). As Fig. 6 shows, common patterns of variability exist among the air temperature reconstructions. The Agassiz Lake and Comox reconstructions have the strongest synchronicity, with the Tatlayoko Lake reconstruction displaying similar long-term trends but reduced annual variability (Fig. 6). The reconstructions indicate that during the early 1700s growing season temperatures were below the long-term 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, after which two decades of higher than average temperatures characterize the 1820s to 1830s. 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 (Fig. 6). The intervals with cooler -or warmer-than-average temperatures correspond with those modelled by previous reconstructions of temperature in this region (Gedalof and Smith, 2001a; Larocque and Smith, 2005).

Maximum ring density consistently showed a strong positive correlation to summer temperature (Fig. 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; Tuovinen, 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 snowpack proxies explain from 24 to 49% of the variability over the instrumental period (Table 4). Snowpack depth fluctuates throughout the period of record, with little synchrony apparent between the three study sites (Fig. 7), almost certainly reflecting the variability of winter snowfall trends in the mountains of coastal British Columbia (Mote, 2003, 2006). The Mount Arrowsmith reconstruction shows little variability, likely due to the limited duration of the instrumental snowpack record available for calibration (Fig. 7; Table 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 the station's northern and inland proximity in relation to the Cyprus Provincial Park and Mount Arrowsmith snowpack stations.

Generally, spring snowpacks at Grouse Mountain are deeper than average in the early 1700s and mid-1700s. All three sites show

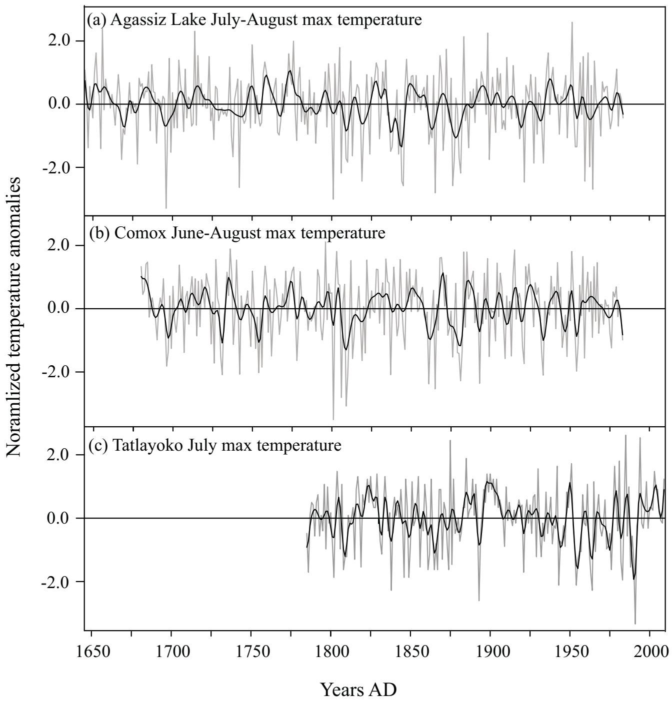

Fig. 6. Proxy temperature reconstructions at the three study sites. Grey lines are annual values, with the black lines showing smoothed data using a cubic smoothing spline. All chronologies are normalized to the common period.

lower than average snowpack depths during the late 1700s. Forbidden Plateau and Grouse Mountain show above average snowpack depths during the early 1800s, with Mt Cronin shifting to lower-than-average snowpack depths from 1800 to 1825. During the mid to late 1800s all sites exhibit above average snowpack depths. During the early 1900s and continuing to the mid-1950s snowpack depths are lower-than-average. The Mt Cronin snowpack depths follow a general decline until the mid-1950s where average snowpack depths occur until the present. Grouse Mountain and Forbidden Plateau snowpack depths increased in the early 1900s,

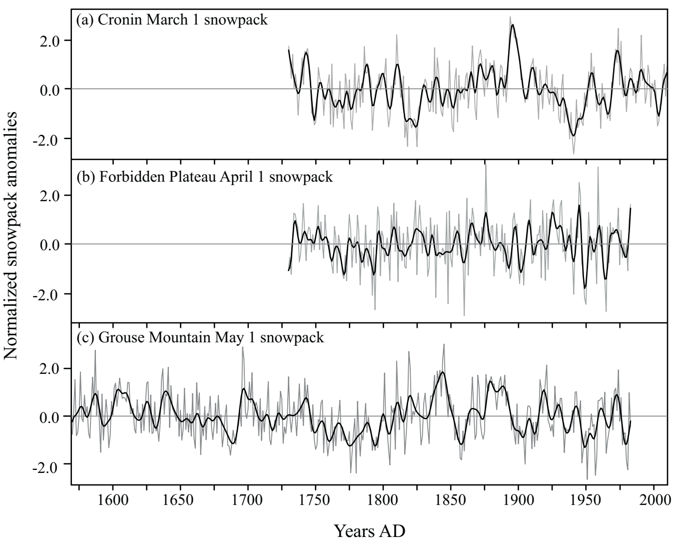

Fig. 7. Reconstruction of early spring snowpack records at the three study sites. Grey lines are annual reconstructed values. Black lines show the smoothed data using a cubic smoothing spline. All chronologies are normalized to the common period.

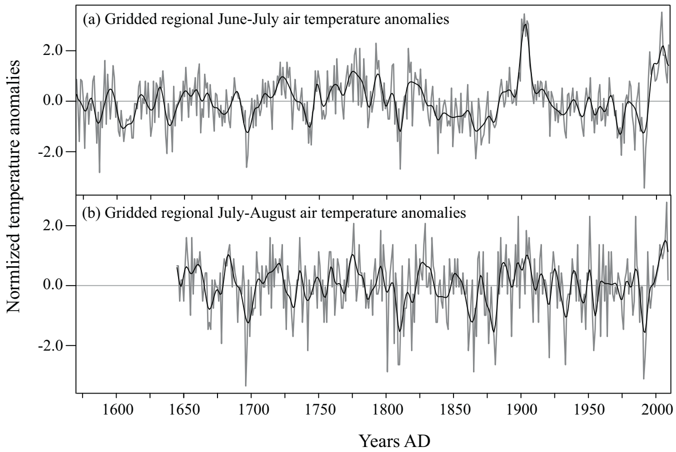

Fig. 8. Reconstructions comparing: (a) tree-ring width; and, (b) tree-ring maximum density to gridded air temperature anomalies. Grey lines are the actual reconstructions while the black lines represent the smoothed data using a cubic smoothing spline. All chronologies are normalized to the common period.

until the 1930s when snowpack declined to below average levels until present (Fig. 7).

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 4). With the exception of a significant rise in temperature around 1900 recorded by the regional ring-width chronology, both models display comparable intervals of cooler- and warmer-than-average intervals over their duration (Fig. 8). These trends are comparable to those found in previous dendroclimatic research spanning the last 350–450 years in this region (Gedalof and Smith, 2001b; Laroque and Smith, 2003; Larocque and Smith, 2005).

The regional models provide both seasonal and subseasonal insights into temperature variability in coastal British Columbia from 1575 to 1650 to present. The June–July model illustrates that early season temperatures were depressed in 1600, after which 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 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 1800s and rose again by 1900, after which yearly temperature variations have remained relatively stable until the present (Fig. 8). The increase in temperature by 1900 is best associated with the ring-width model (Fig. 8), suggesting that the extended growing period implicit in the model is associated with warmer early-season temperatures.

Discussion

Ring-width and density parameters

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 partitioning 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 Grabner, 2000; Davi et al., 2002; Frank and Esper, 2005; Tuovinen, 2005). Our investigations demonstrate that measurements of mountain hemlock maximum annual tree-ring density provide robust data series for reconstructing proxy records of late summer temperature. Complementary measurements of the annual ring-width increment show that this metric can be interpreted to provide an independent proxy of spring snowpack trends.

Proxy climate reconstructions

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, 2001a; Larocque and Smith, 2005). 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).

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.

The timing of cooler-than-average and warmer-than-average temperature in the proxy records 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 Figs. 6 and 7. These intervals coincide with significant negative PDO shifts described by Gedalof and Smith (2001b) and notable Little Ice Age glacier advances in this region (Larocque and Smith, 2003; Allen and Smith, 2007; Koehler and Smith, 2011), which has previously been recognized by a period of highly ranked volcanic eruptions index (VAI) presumably influenced by the combination of volcanic eruptions and sunspot minima (Briffa et al., 1998; Robertson et al., 2001). While 20th century warming has been detected in most tree-ring reconstructions in western North America (Luckman and Wilson, 2005; D'Arrigo et al., 2006), the snowpack and summer maximum temperatures from this study better describe ocean-atmospheric teleconnection climate forcing mechanisms like the PDO (Gedalof and Smith, 2001b; Hart et al., 2010; Whitfield et al., 2010; Starheim et al., 2012).

Conclusion

This research employs a network of mountain hemlock chronologies to describe climate trends in the 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 growing 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 1575 to present.

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