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ORIGINAL ARTICLE

A dendroclimatological reconstruction of climate since AD 1700 in the Mt. Waddington area, British Columbia Coast Mountains, Canada

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Abstract

The radial growth characteristics of five high-elevation coniferous tree species were established from sites located within the southern British Columbia Coast Mountains, Canada. The sites are located on valley slopes ranging from 760 to 1860 m asl and were found close to the terminus of contemporary glaciers, predominantly occupying sites with southern and western aspects. Increment core samples were collected from *Pinus albicaulis* Engelmann (whitebark pine), *Abies lasiocarpa* [Hooker] Nuttall (subalpine fir), *Tsuga mertensiana* (Bongard) Carriere (mountain hemlock), *Pseudotsuga menziesii* (Mirbel) Franco (Douglas-fir), and *Chamaecyparis nootkatensis* (D. Don in Lambert) Spach (yellow-cedar). After a common radial growth response was detected within and between each species, species-specific master tree-ring chronologies were constructed to express the regional signal. Correlation analyses indicate that radial growth in this setting is negatively impacted by summer air temperature of the previous growth year, positively influenced by November air temperature of the previous growth year and air temperature of the current growing season (mostly July), and negatively influenced by larger than normal April 1 snowpack depths. These relationships were validated and models of temperature (January, July, summer) and snowpack (April 1) were developed back to the 17th century. Common modes of variability found occurring between 2 and 8 years, at approximately 20–23 years, and approximately 120 years are believed associated with North Pacific Ocean-atmospheric circulation systems (ENSO, PDO) and with perturbations in solar activity.

Keywords: Temperature and snowpack reconstruction; *Pinus albicaulis*; *Abies lasiocarpa*; *Tsuga mertensiana*; *Pseudotsuga menziesii*; *Chamaecyparis nootkatensis*

Introduction

Complex atmosphere – ocean forcing processes in the North Pacific Ocean and indeterminate feedback mechanisms have a marked influence on natural systems in Coastal Pacific North America (Cayan and Peterson, 1989). Over the past century abrupt spatial shifts in the position of the Aleutian Low and the varied influence of the El Niño Southern Oscillation on Pacific North America (e.g., Mantua et al., 1997; Gedalof and Smith, 2001a) had discernible impacts on streamflow (Moore and Demuth, 2001), glacier mass balance (Kovanen, 2003), and radial tree growth (Gedalof and Smith, 2001b; Peterson et al., 2002).

High-resolution archives of past climate fluctuations are required to detect and assess the long-term impact and significance of these climate-induced changes. In coastal British Columbia, the climate sensitivity of several long-lived tree species offers an opportunity to develop tree-ring records of environmental change that

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potentially span the last millennium. While previous dendroclimatological research in the surrounding region provides proxy records of changing environmental conditions in Washington and Oregon (Peterson and Peterson, 1994; Ettl and Peterson, 1995; Peterson et al., 2002) and on Vancouver Island (Smith and Laroque, 1996; Laroque and Smith, 1999, Zhang et al., 1999; Laroque, 2002), there are few existent high-resolution tree-ring-based reconstructions of changing environmental conditions in the southern British Columbia Coast Mountains (Desloges, 1987; Schweingruber, 1988; Briffa et al., 1992). The purpose of this paper is to present the findings of our dendroclimatological investigations in the Mt. Waddington area of southwestern British Columbia, Canada. Ring-width chronologies of five conifer species are used to develop air temperature and snowpack records that span the last three centuries.

Materials and methods

Study sites

Study sites were widely dispersed through the Homathko, Niut, Pantheon and Waddington Ranges (Fig. 1). Some of the highest peaks in British Columbia are found in this area, with Mt. Waddington reaching an elevation of 4019 m asl. Climatic conditions within the Homathko and Waddington Ranges are maritime in character with yearly precipitation total averaging 1677 mm and mean air temperature averaging 7.9 °C (1961–1990; Bella Coola, 52°22′N–126°41′W, 18 m asl). The Niut and Pantheon Ranges flank the Interior Plateau of British Columbia and the climate is continental in character with annual air temperatures ranging from 2.2 °C (1961–1990; Big Creek; 51°43′N–123°02′W, 1128 m asl) to 4.1 °C (1961–1990; Williams Lake; 52°11′N–122°03′W, 940 m asl). Annual mean precipitation totals range from 400 to 450 mm/year (Meteorological Service of Canada, 2002).

The forest cover of the Mt. Waddington area is dominated by subalpine fir (*Abies lasiocarpa* [Hooker] Nuttall) trees at higher elevations, except within the Niut and Pantheon Ranges where whitebark pine (*Pinus albicaulis* Engelmann) trees favour disturbed and rocky sites (Meidinger and Pojar, 1991). In the Homathko and Waddington Ranges, homogenous stands of mountain hemlock (*Tsuga mertensiana* (Bongard) Carriere) characterize most slopes, with Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) restricted to a few scattered south-facing sites. Higher elevation sites are characterized

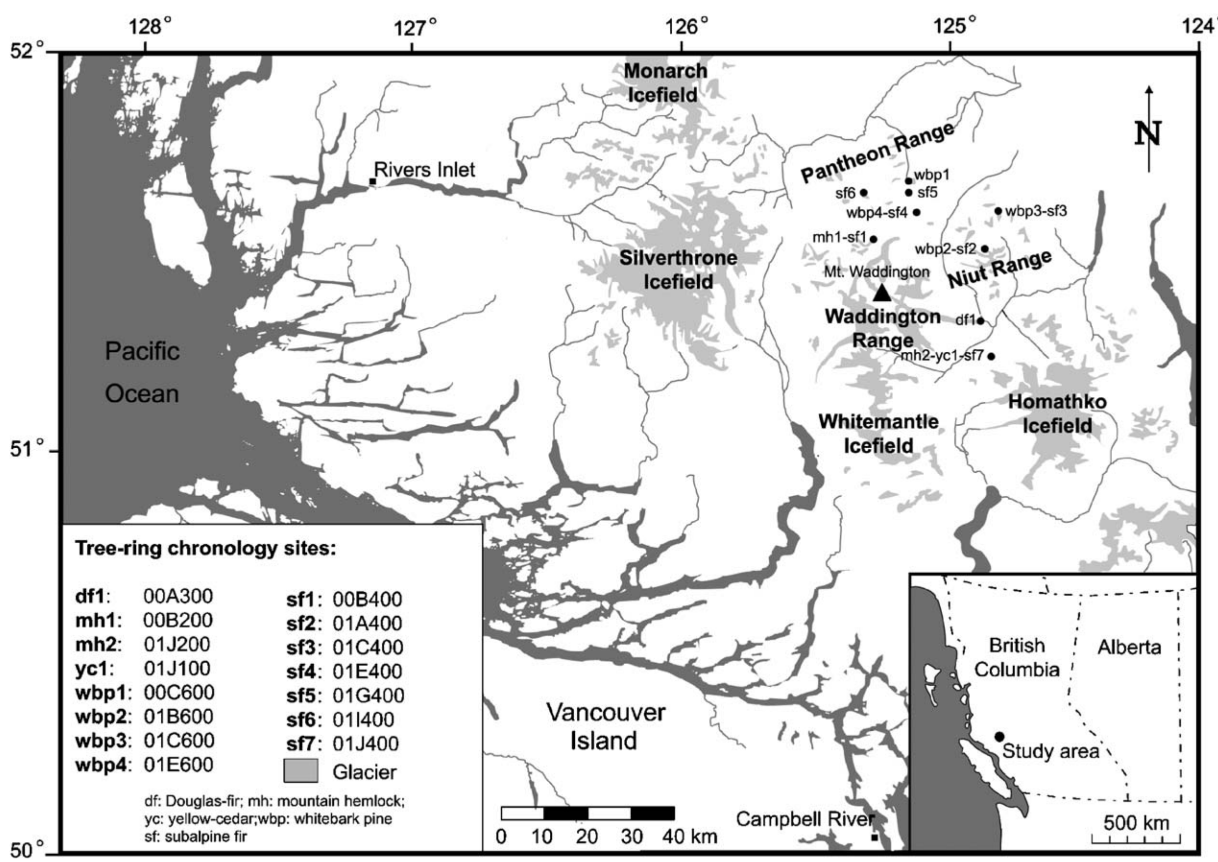

Fig. 1. Location of the samples site in the Mt. Waddington area.

Table 1. Summary of the tree-ring width chronologies developed in the Mt. Waddington area

Sample	Sp[a]	Loc[b]	Coordinates	Elev[c]	Asp[d]	*N*[e]	*r*[f]	MS[g]	AC[h]	Length[i]	Period 1[j]	SSS[k]	Period 2[l]
00A300	df	TG	51°19′N; 124°54′W	760	S	30(28)	0.504	0.185	0.862	442	1559–2000	12	1747–1999
00B400	sf	OG	51°29′N; 125°15′W	1500	SE	35(20)	0.575	0.209	0.774	357	1644–2000	7	1802–2000
00B200	mh	OG	51°29′N; 125°15′W	1400	S	37(19)	0.62	0.237	0.701	238	1762–1999	8	1835–1999
00C600	wbp	SG	51°39′N; 125°10′W	1800	SW	50(27)	0.495	0.213	0.856	812	1189–2000	9	1357–1999
01A400	sf	HG	51°31′N; 124°53′W	1830	W	37(20)	0.606	0.239	0.671	302	1700–2001	5	1743–2000
01B600	wbp	PG	51°30′N; 124°55′W	1860	SW	36(19)	0.531	0.215	0.826	594	1408–2001	8	1552–2000
01C400	sf	LG	51°35′N; 124°50′W	1770	W	38(20)	0.566	0.189	0.805	296	1705–2000	7	1728–2000
01C600	wbp	LG	51°35′N; 124°50′W	1770	W	32(17)	0.501	0.184	0.894	364	1637–2000	10	1679–2000
01E400	sf	EG	51°37′N; 125°07′W	1700	SE	36(19)	0.592	0.188	0.692	223	1778–2000	7	1818–2000
01E600	wbp	EG	51°37′N; 125°07′W	1700	SE	38(22)	0.495	0.195	0.839	280	1721–2000	10	1767–2000
01G400	sf	BG	51°38′N; 125°11′W	1720	SW	37(20)	0.6	0.224	0.713	319	1682–2000	6	1741–2000
01I400	sf	RG	51°36′N; 125°18′W	1800	SE	35(18)	0.566	0.181	0.776	372	1629–2000	7	1750–2000
01J100	yc	CG	51°14′N; 124°52′W	1600	SW	36(20)	0.515	0.272	0.807	354	1648–2001	11	1721–2000
01J200	mh	CG	51°14′N; 124°52′W	1600	SW	39(20)	0.639	0.293	0.689	341	1660–2000	8	1700–2000
01J400	sf	CG	51°14′N; 124°52′W	1600	SW	48(27)	0.579	0.237	0.773	359	1642–2000	6	1708–2000

Statistical data are from the output of programme COFECHA, preceding autoregressive modelling.

[a]Species: df: Douglas-fir, sf: subalpine fir, mh: mountain hemlock, wbp: whitebark pine, yc: yellow-cedar.

[b]Location: TG: Tiedemann Glacier, OG: Oval Glacier, SG: Siva Glacier, HG: Hope Glacier, PG: Pagoda Glacier, LG: Liberty Glacier, EG: Escape Glacier, BG: Byamee Glacier, RG: Ragnarok Glacier, CG: Cathedral Glacier.

[c]Elevation in metres.

[d]Aspect.

[e]*N* indicates the number of tree cores (or series) included in the master chronology. In brackets is the equivalent number of trees.

[f]Pearson's coefficient of correlation calculated between all series included in the master chronology.

[g]MS: mean sensitivity. Indicator of relative variation from 1-yearly ring width to another. Varies from 0 to 1, with increasing sensitivity.

[h]AC: autocorrelation coefficient of lag 1. It describes the importance of prior year growth in current year growth.

[i]Total number of years in the chronology.

[j]Total period covered by the chronology (in years AD).

[k]SSS: Subsample signal strength. Number of series needed to capture the theoretical population signal (SSS$\geqslant$0.80).

[l]Period where SSS$\geqslant$0.80 (in years AD).

by mixed stands of subalpine fir, mountain hemlock, whitebark pine, and yellow-cedar (*Chamaecyparis nootkatensis* (D. Don in Lambert) Spach) (Pojar and MacKinnon, 1994). Subalpine fir trees dominate at treeline sites throughout the region, except locally where harsh conditions favour the growth of whitebark pine.

Field collections

Increment core samples were collected in the summers of 2000 and 2001 from living trees at 15 sites (Fig. 1). Two increment cores extracted at breast height were collected from at least 20 trees per site. All sites are located on valley slopes close to the terminus of contemporary glaciers, predominantly occupying sites with southern and western aspects that range from 760 to 1860 m asl (Table 1). Most cores came from trees found growing at the local altitudinal limit of the forest cover, as previous research has shown high-elevation trees in this region are particularly sensitive to climatic fluctuations (Ettl and Peterson, 1995; Laroque, 2002). One low-elevation Douglas-fir stand (00A300) was sampled on a south-facing slope above Tiedemann Glacier along the eastern flank of the Waddington Range.

Laboratory analysis

Samples were returned to the University of Victoria Tree-Ring Laboratory (UVTRL) where they were air dried, glued to slotted wood mounting boards, and sanded with progressively finer sand paper. A WinDENDRO™ (Version 6.1b) digital tree-ring image processing and measuring system (Guay et al., 1992) and a Velmex-type stage were used to measure the annual ring increments to the nearest 0.01 mm.

The tree-ring measurements were visually crossdated using narrow marker years and were quality checked using the International Tree-Ring Data Bank Library (ITRDBL) software program COFECHA (Holmes, 1999). Verification was based on 50-year dated segments with 25-year lags, significant at a 99% critical level of correlation of 0.320 (Fritts, 1976). Low-frequency variance was removed by filtering with a cubic smoothing spline having a 50% cutoff of 32 years. An autoregressive model was fit to the data to remove any persistence within the smoothed series and a log-transformation was performed in order to produce more equal ring measurements. Segments that were not significantly correlated were re-measured, corrected and/or deleted to account for radial growth anomalies arising from the inclusion of missing or false rings or operator error.

Standardized chronologies were constructed with the program ARSTAN (version 6.04P; Cook and Holmes, 1986) and incorporated a double-detrending approach. First, a negative exponential curve, a linear regression, or a horizontal line passing through the mean was used to remove any age-growth trends (Fritts, 1976). Following this, the series were detrended a second time to reduce the impact of non-climatic factors on radial growth (e.g., competition and defoliation) with a smoothing spline having a common level of 67% frequency-response cutoff to ensure that little low-frequency variance was lost in estimating and removing the growth trend (Cook et al., 1990). In order to limit the effect of past radial growth on the current year's growth, we employed an autoregressive model of order determined by the Akaike Information Criterion (AIC) value (e.g. Stahle et al., 1998; Fekedulegn et al., 2002) and limited any further analysis to the AR residuals to limit any non-climatic influence on tree-growth.

Climate reconstruction

To examine the contribution of climatic parameters to tree-ring width variance, correlation analyses were undertaken between annual radial growth and historical climate data. Climate data from meteorological stations at Big Creek (Lat. 51°43′N, Long. 123°02′W; 1904–1984 [1904–1977 for precipitation data]) and Tatlayoko Lake (Lat. 51°40′N, Long. 124°24′W; 1930–1997) were obtained from the Environment Canada, Homogenized Canadian Climate Data set.[1] These stations are positioned along the eastern flanks of the Coast Mountains and were considered more representative than climate records from the longer but more maritime Bella Coola and more continental Williams Lake stations. A simple averaging function was computed to establish regional monthly temperature and precipitation data, thereby reducing the influence of local and extreme climate anomalies in the station climate records. Historical snow survey data for Big Creek (April 1, 1970–2000) and Tatlayoko Lake (April 1, 1952–1998) were obtained at the British Columbia Ministry of Sustainable Resource Management website.[2]

Standardised tree-ring indices were compared to monthly climate data (precipitation, temperature, snowpack) to calculate Pearson's coefficients of correlation. A partial correlation analysis was also undertaken to reject any spurious relationships. The significant variables ($p \leqslant 0.05$) were then combined with the ring-width indices to reconstruct a time series predicting past climate. Linear regression was used to establish the relationships between the predictant (climate) and predictor (tree-ring width index) on the last half of the historical climate series. The relationships were verified using the first half (independent variable) of the observed climate data, and the verified relationships were used to produce proxy climate data from tree-ring chronologies. Standard statistical tests were computed to assess the goodness of fit of the regression and the prediction efficiency of the model. Because the number of series within our chronologies diminishes with time, the tree-ring index chronologies and climate models present increased variability in the early portion of the data. The subsample signal strength (SSS) values (program ARSTAN) provide a statistical tool useful for determining the number of sample replications needed to capture the theoretical population signal of tree-ring variation. SSS values above 0.80 were used to identify a cutoff year in the chronologies, above which there was sufficient sample robustness to reconstruct a reliable time series (Wigley et al., 1984).

A wavelet analysis was completed to determine the dominant modes of variability in time within the climate reconstructions (Torrence and Compo, 1998; Laroque, 2002; Gray et al., 2003). These analyses were undertaken at the interactive website developed by Torrence and Compo.[3] A Morlet wavelet function with a significance level of 5% was applied using a red-noise process of lag-1 autoregression, as this non-orthogonal approach allows for increased precision on the periodic scale (Torrence and Compo, 1998). To overcome any time-related errors at the beginning and the end of the series, the extremities were padded with zeros to limit the edge effects.

Dendrochronological characteristics

A total of 537 radial series from 316 trees (144 subalpine fir, 85 whitebark pine, 39 mountain hemlock, 28 Douglas-fir, 20 yellow-cedar) were used in our analyses (Table 1). The chronology statistics are comparable to those from other high-elevation sites in coastal British Columbia (Laroque, 2002; Zhang and Hebda, 2004). Series correlation values range from 0.495 (whitebark pine) to 0.639 (mountain hemlock) and mean sensitivity values vary from 0.293 (mountain hemlock) to 0.184 (whitebark pine). High first-order autocorrelation coefficients before detrending indicate that the low sensitivity values are attributable to lag effects that, in

[1]http://www.cccma.bc.ec.gc.ca/hccd/data/access_data.html.
[2]http://srmwww.gov.bc.ca/aib/wat/rfc/archive/historic.html.
[3]http://paos.colorado.edu/research/wavelets/.

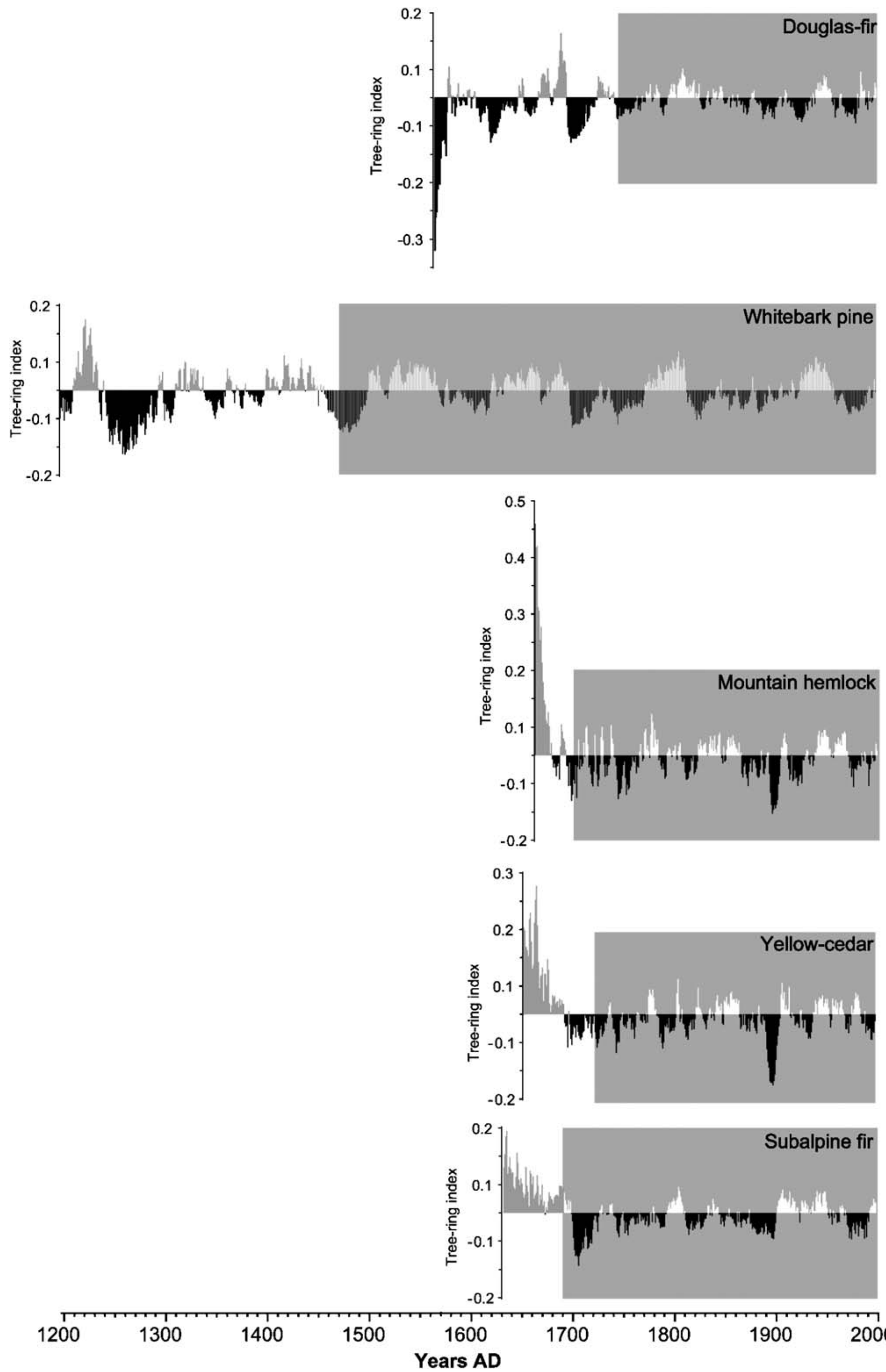

Fig. 2. Spline smoothed ring-width indices. Bars in black: below-average tree-ring index. Bars in white and grey: above-average tree-ring index. The grey rectangle corresponds to the period when SSS$\geqslant$0.80. Douglas-fir: 1747–1999, whitebark pine: 1469–2000, mountain hemlock: 1700–2000, yellow-cedar: 1721–2000, and subalpine fir: 1690–2000.

the case of whitebark pine, persist for as long as 5 years (e.g., Hansen-Bristow et al., 1990).

Most of the 15 site chronologies are limited to the interval from approximately 1650–1700 AD to present, with the longest chronology coming from a stand of whitebark pine at Siva Glacier (AD 1189–2000, 812 years) (Fig. 2). The whitebark pine chronologies collectively record a significant reduction in ring-width growth from 1694 to 1700 that corresponds to the formation of narrow rings in 1695 in Douglas-fir; 1699

Table 2. Principal component loadings for tree-ring width chronologies and total variance explained by each component

Chronologies	Species[a]	PC1	PC2	PC3
01C400	sf	0.857	0.111	0.202
01I400	sf	0.855	0.195	0.122
01A400	sf	0.789	0.308	0.245
01G400	sf	0.779	0.250	0.333
00B400	sf	0.732	0.448	0.017
01J400	sf	0.686	0.524	0.036
01E400	sf	0.503	0.426	0.246
00A300	df	0.432	0.153	0.135
01J200	mh	0.317	0.850	0.104
01J100	yc	0.208	0.802	0.261
00B200	mh	0.300	0.779	0.080
00C600	wbp	−0.025	0.014	0.870
01B600	wbp	0.243	0.221	0.815
01E600	wbp	0.233	0.193	0.776
01C600	wbp	0.273	0.073	0.730
Variance explained (%)		48.2	13.7	7.8

[a]Species: df: Douglas-fir, sf: subalpine fir, mh: mountain hemlock, wbp: whitebark pine, yc: yellow-cedar.

and 1701 in whitebark pine; 1697, 1703, and 1706 in mountain hemlock; 1696, 1697, and 1699 in yellow-cedar; and 1701 in subalpine fir. This period was followed by an interval of above-average growth until 1740, when radial growth was again suppressed before a decade of enhanced growth from 1775 to 1785. Several decades of fluctuating periods of reduced and enhanced radial growth were followed by an extended episode of suppressed growth from 1810 to 1905. Over the last century radial growth increments remained below the long-term average until the 1940s, when above average rates of growth were recorded. A decade or so of enhanced growth was followed by reduced growth until 1994.

A principal component analysis (PCA) shows that 48.2% of the variance in tree-ring width is represented by subalpine fir and Douglas-fir trees (Table 2). Mountain hemlock and yellow-cedar trees contribute in the PC2 loadings, explaining 13.7% of the total variance. Finally, 7.8% of the variance is contained in the PC3, which corresponds to the whitebark pine domain. Pearson's correlation coefficients performed on residual series also indicate that there is significant inter-species correspondence between the radial growth trends of mountain hemlock and subalpine fir (0.471) (Table 3). In contrast, the radial growth of the one Douglas-fir chronology included within our study is more divergent.

Dendroclimatological relationships

The 15 chronologies were averaged into five species-specific chronologies (Fig. 2). The climate-radial growth response of the five tree species was examined with respect to monthly temperature and precipitation data. While we did consider the varied impact and potential response to minimum, maximum, and mean air temperatures, no significant growth response differences were detected and our observations focus solely on the relationships established with mean monthly air temperatures. As for total monthly precipitation, a few significant correlation coefficients were observed but no consistency is shown between the climate stations as a result of a weak regional signal. This result shows clearly that precipitation is not the main climate factor influencing tree growth in the area.

Douglas-fir growth is significantly correlated to July and November air temperatures of the previous growth year, and late-winter/early spring air temperatures of the current growth year (Fig. 3). Warm temperatures in the previous July potentially cause either increased evapotranspiration, water loss, reduced nutrient storage and foliage efficiency in the following year or they hasten cone initiation and production which redirects resources away from cambium development (Klinka and Spelchtna, 1998; Zhang et al., 1999). While the positive relationship between November air temperature and radial growth may reflect an extended opportunity for bud development and nutrient storage in the previous year (Fritts, 1976; Zhang et al., 1999), warm air temperatures in late February/early-March may significantly extend the local growing season on this south-facing slope (Zhang and Hebda, 2004). These temperature relationships are distinct from the precipitation-related limitations to Douglas-fir growth previously reported for high-elevation coastal sites in British Columbia (Laroque, 2002; Luckman et al., 2002).

Above average summer air temperature is shown to enhance radial growth of whitebark pine in the Mt. Waddington area (Fig. 3). Similar findings in Idaho (Perkins and Swetnam, 1996) and eastern British Columbia (Youngblut, 2003) point to the role that warm air temperatures may play in accelerating needle maturation and enhanced photosynthesis (Schmidt and Lotan, 1980). The negative relationship between previous November air temperatures and whitebark pine radial growth is possibly related to accelerated bud hardening and the reduced opportunity for nutrient storage. Despite the significance of the climate-radial growth relationships shown in Fig. 3, the dendroclimatological potential of whitebark pine remains problematic due to its susceptibility to disease and insect infestation (McCaughey and Schmidt, 1990; Peterson et al., 1990; Goheen et al., 2002), and the lack of high-frequency variability in its radial growth (Perkins and Swetnam, 1996; Youngblut, 2003).

Radial growth in mountain hemlock is significantly correlated with previous July, January and current July air temperatures (Fig. 3). Woodward et al. (1994) and

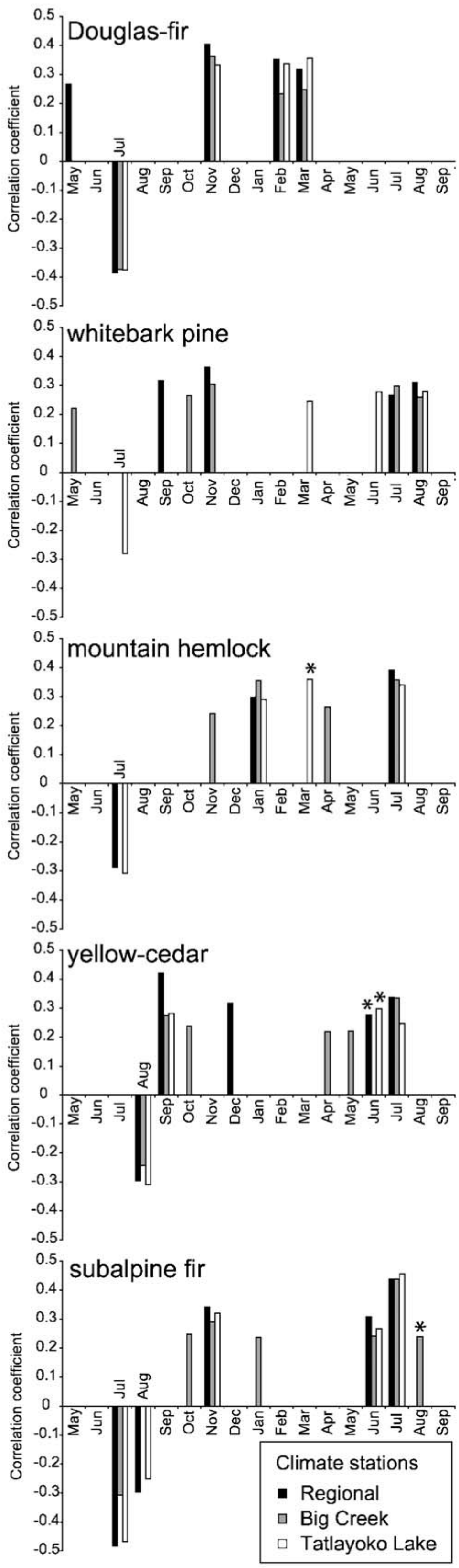

Fig. 3. Significant Pearson's correlation coefficients between regional tree-ring chronologies and mean temperature ($p \leqslant 0.05$). Asterisks indicate possible spurious relationships as determined by partial correlation analysis.

Peterson and Peterson (2001) have shown that July air temperatures have a direct impact on cone production, water availability and, ultimately, radial growth. Warmer than normal air temperatures in January enhance the survivability of vegetative buds through the winter, leading to an increase in a tree's photosynthetic potential. The radial growth of mountain hemlock trees was also shown to be negatively correlated (−0.451) with the April 1 snowpack depth in the Mt. Waddington area. Deep spring snowpacks negatively influence radial growth by diminishing the duration of seasonal cambial activity (Gedalof and Smith, 2001a; Peterson and Peterson, 2001; Laroque, 2002).

The relationship of yellow-cedar radial growth to climate was investigated at a single site. A significant negative relationship to the previous August and September highlights the impact of extreme late-summer air temperatures (Fig. 3). While air temperatures in July positively influence radial growth, these can be offset by deep April 1 snowpacks that reduce the duration of the growing season (Laroque and Smith, 1999; Laroque et al., 2001).

A significant negative relationship between subalpine fir and air temperature in the previous summer has been reported to correspond to greater foliage mass and enhanced cambial development (Ettl and Peterson, 1995). The positive relationship to warmer fall air temperatures may signal the impact of an extended period of nutrient storage, leading to enhanced radial growth in the following growing season (Peterson and Peterson, 1994; Ettl and Peterson, 1995). Similar to mountain hemlock and yellow-cedar, the radial growth of subalpine fir is negatively correlated to April 1 snowpack depth ($r = -0.436$). The response to July air temperature is the most pervasive (Villalba et al., 1994; Parish et al., 1999; Spelchtna et al., 2000; Luckman et al., 2002). While the role above average air temperature in July will play is influenced by cone production or reduced water availability in the previous year (Woodward et al., 1994; Ettl and Peterson, 1995; Parish et al., 1999), the role higher than normal air temperatures play in enhancing radial growth is well documented and, at least in part, relates to the role these conditions have on

Table 3. Pearson's correlation coefficients obtained for regional tree-ring width chronologies

	df	wbp	mh	yc	sf
df		0.183	0.189	0.150	0.184
wbp	0.183		0.242	0.267	0.296
mh	0.189	0.242		0.336	0.471
yc	0.150	0.267	0.336		0.330
sf	0.184	0.296	0.471	0.330	

df: Douglas-fir, wbp: whitebark pine, mh: mountain hemlock, yc: yellow-cedar, sf: subalpine fir.
All correlations are significant at 95% confidence level.

Table 4. Percentage of tree-ring width variance explained by climate

Station	df	wbp	mh	yc	sf
Mean temperature and total precipitation					
Big Creek	47.1	50.7	51.5	52.6	70.9
Tatlayoko Lake	57.5	46.6	59.4	55.6	67.0
Regional	47.6	48.2	52.4	43.8	63.7
Minimum temperature and total precipitation					
Big Creek	42.2	50.8	46.4	42.1	66.3
Tatlayoko Lake	50.3	38.9	59.4	48.6	51.1
Regional	59.0	46.9	47.6	41.3	57.6
Maximum temperature and total precipitation					
Tatlayoko Lake	57.0	46.6	60.8	57.0	72.5

The values were extracted from the response function analysis performed by program PRECON.
df: Douglas-fir, wbp: whitebark pine, mh: mountain hemlock, yc: yellow-cedar, sf: subalpine fir.

melting lingering snowpacks and lengthening the growing season (Peterson and Peterson, 1994; Ettl and Peterson, 1995).

Dendroclimatic reconstruction

The radial growth response of the five master tree-ring chronologies to variations in air temperature, precipitation and snowpack depth provided a rationale for using these relationships to develop proxy-climate records (Table 4). We have carefully examined these correlations and identified six statistically significant regression functions performed on the second half of the data sets between: mountain hemlock and January mean temperature ($r = 0.322$); subalpine fir and April 1 snowpack depth ($r = 0.457$); subalpine fir and previous July mean temperature ($r = 0.546$); mountain hemlock and July mean temperature ($r = 0.365$); subalpine fir and July

Table 5. Climate model statistics

Variables reconstructed	r^a	r^b	Period[b]	Equation	Species[c]	
(A) *Regression analysis*						
January mean temp.	0.322	0.103	1944–1984	$y = 10.984x–22.29$	mh	
April 1 snowpack	0.457	0.209	1975–1998	$y = –83.795x + 168.52$	sf	
Previous July mean temp.	0.536	0.288	1965–1998	$y = –3.663x + 17.388$	sf	
July mean temp. (mh)	0.365	0.133	1944–1984	$y = 3.77x + 9.73$	mh	
July mean temp. (sf)	0.556	0.309	1964–1997	$y = 3.852x + 9.925$	sf	
Summer mean temp.	0.346	0.120	1944–1984	$y = 2.747x + 9.7$	mh	
Variables reconstructed	r^d	Reduction of error[e]	*t*-value	Sign-products[f]	Negative1st diff.[g]	Period[b]
(B) *Calibration*						
January mean temp.	0.324**	0.1048*	1.6585	16	11*	1944–1984
April 1 snowpack	0.467**	0.2178*	2.2854*	11	7	1975–1998
Previous July mean temp.	0.530**	0.2809*	2.2448*	8*	8*	1965–1998
July mean temp. (mh)	0.357**	0.1271*	1.8215*	16	12*	1944–1984
July mean temp. (sf)	0.545**	0.2966*	0.8373	7*	9*	1964–1997
Summer mean temp.	0.343**	0.1177*	2.1611*	18	12*	1944–1984
Variables reconstructed	*r*	Reduction of error	*t*-value	sign-product	Negative 1st diff	Period[h]
(C) *Validation*						
January mean temp.	0.359**	0.1252*	1.2150	16	13*	1904–1943
April 1 snowpack	0.354**	0.1991*	0.382	5*	8	1952–1974
Previous July mean temp.	0.413**	0.1698*	0.6929	10*	7*	1931–1964
July mean temp. (mh)	0.377**	0.0973*	2.3302*	17	10*	1904–1943
July mean temp. (sf)	0.393**	0.1474*	1.7426*	13	10*	1930–1963
Summer mean temp.	0.331**	0.0145	1.6994*	18	12*	1904–1943

Calibration and verification statistical values were computed using program VERIFY (Lawrence and Grissino-Mayer, 2001).
[a]Pearson's correlation coefficient.
[b]Represents the period included in the calibration (second half of the total number of years in the historical climatic record).
[c]sf: subalpine fir, mh: mountain hemlock.
[d]Period where SSS$\geqslant$0.80 (in years AD).
[e]Reduction of error: measures the association between estimated and actual values (Fritts, 1976).
[f]Sign-products test: measures the direction and magnitude of the departures in estimated and actual values (Fritts, 1976).
[g]Negative first-difference test: measures only the direction of the departures from 1 year to the next in the two series.
[h]Represents the period included in the verification (first half of the total number of years in the historical climatic record).
*Significant at 95% confidence level.
**Significant at 97.5% confidence level.

mean temperature ($r = 0.556$); and, mountain hemlock and summer (June, July, August) mean temperature ($r = 0.346$) (Table 5). Explaining between 10% and 31% of the measured variations in radial growth, the related calibration and verification statistics are detailed in Table 5. The temperature and snowpack models derived from these relationships are presented in Fig. 4, with the proxy July mean temperature record having been calculated from an average of those independently developed for subalpine fir and mountain hemlock. Whereas the other species responded significantly to summer temperature (Fig. 3), none of the relationships led to statistically valid models.

Although the duration of the living whitebark pine chronologies (594 and 812 years) offered the potential for developing lengthy climate models, these series are highly autocorrelated and typically include locally missing rings. High correlation and high mean sensitivity values and low autocorrelation confer subalpine fir and mountain hemlock advantages in climate modelling. Whereas yellow-cedar and Douglas-fir were found to be valuable species in modelling past climate (Zhang et al., 1999; Laroque, 2002), they have a limited importance in our study because of the low number of chronologies sampled which most likely enhance the noisy signal reported.

These proxy records provide complimentary high-resolution perspectives on changing climates for the last three centuries. Periods of cooler-than-average air temperatures (July and January) are shown to have occurred in 1696–1708, 1716–1727, 1731–1736, 1742–1765, 1787–1792, 1811–1823, 1848–1851, 1867–1904,

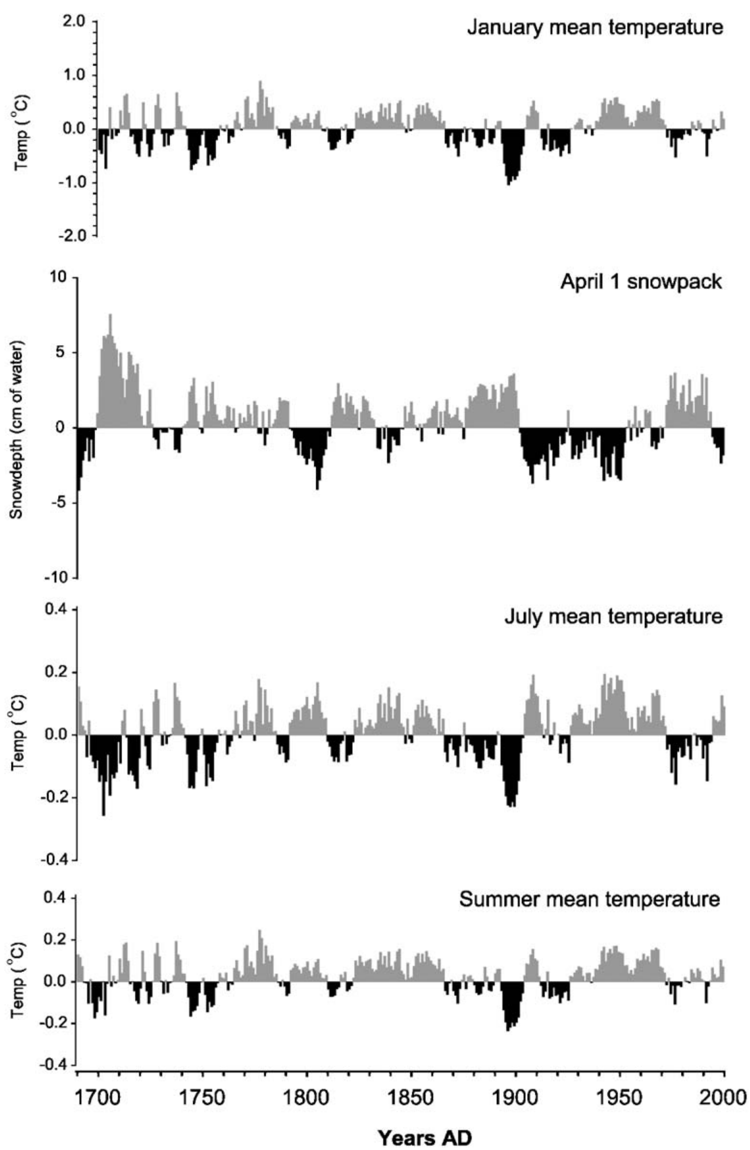

Fig. 4. Proxy climate models reconstructed for the Mt. Waddington area (bars in black: below-average; bars in grey: above-average).

1914–1926, 1934–1938, and 1973–1994 (Fig. 4). Reconstructed April 1 snowpack records suggest that above-average snow depths distinguished the winters of 1701–1727, 1742–1792, 1813–1839, 1848–1902, and 1954–1994. Collectively, these proxy indices suggest that the Mt. Waddington area was characterized by cool-wet conditions from 1701–1708, 1716–1727, 1735, 1742–1765, 1787–1792, 1813–1823, 1848–1851, 1867–1902, 1926, and 1973–1994.

Cyclic nature of tree growth and proxy-climate records

Wavelet analyses provide insights into recurrent variability within a time series that has changed in strength and frequency (Gedalof and Smith, 2001b; Rigozo et al., 2001). A visual examination of the 800 year-long whitebark pine index chronology suggests that it retains inherent radial growth trends (Fig. 2). A wavelet analysis confirmed this, appearing to highlight a dominant mode of variability at about 120 years and a minor component of variability of less than 8 years (Fig. 5). Much of the interval showing the 120-year old variability mode appears in the crosshatched region and therefore interpretation should be cautious. Previous researchers have noted that periodic radial growth trends similar to these are an artifact of the influence of broad-scale climate forcing mechanisms such as El Niño/Southern Oscillation and the Pacific Decadal Oscillation operating at the sub-regional to regional scale (Briffa et al., 1992; Stahle et al., 1998; Gedalof and Smith, 2001b; Laroque, 2002).

To gain some appreciation for the mechanisms affecting climate in the Mt. Waddington area and the resultant radial growth trends, wavelet analyses were performed on our derived records of air temperature and snowpack depth (Fig. 2). All the reconstructions share similar modes of variability: high frequency at less than 8 years and medium frequency at 23–25 years (Fig. 6).

Variability modes shorter than 8 years are found in most existent dendroclimatological reconstructions from this region (Wiles et al., 1998; Laroque, 2002). They are believed associated with the El Niño/Southern Oscillation (ENSO) (Stahle et al., 1998) that brings warm/dry conditions and enhances radial growth.

The 20–23-year mode of variability coincides with the recurrent influence of the Pacific Decadal Oscillation (PDO) on climate in western North America (Hare and Francis, 1994; Mantua and Hare, 2002). Similar frequencies have been reported in tree-ring series throughout the region (Wiles et al., 1998; Gedalof and Smith, 1999; Biondi, 2000; Peterson et al., 2002). The PDO is a long-lived El Niño-like pattern of Pacific climate variability characterized by alternating regimes of warm and cool sea surface temperatures in the North Pacific (Zhang et al., 1997). The positive phase (warm) of the PDO results in warmer, drier winters with below average snowpacks. Conversely, the negative phase (cool) of the PDO is associated with increased winter storminess, cooler air temperatures, increased precipitation, and greater snowpack depths. Our

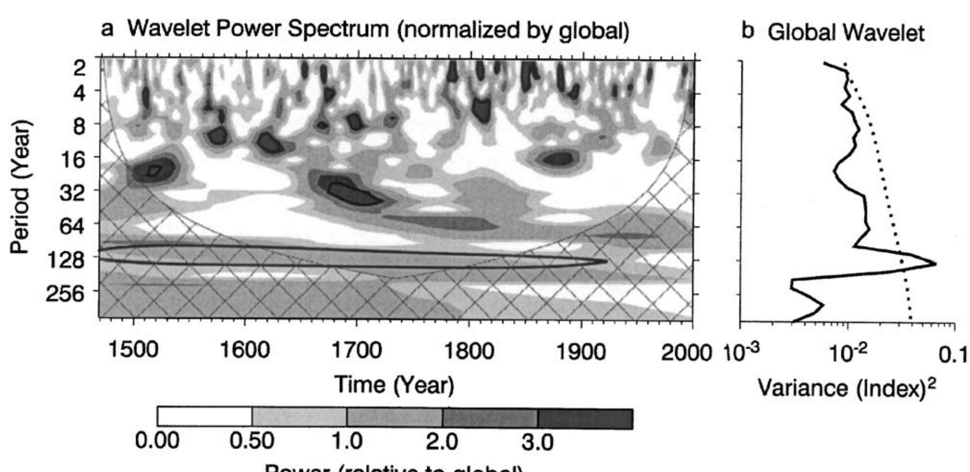

Fig. 5. Wavelet power spectrum (a) and global wavelet (b) showing the significant modes of variability in the whitebark pine tree-ring index series (SSS $\geqslant$ 0.80). The wavelet power spectrum uses a Morlet wavelet function. The left axis corresponds to the Fourier period (in year). The contour levels represent 75%; 50%; 25%; and 5% of the wavelet power. The thick contours indicate significant modes of variance at 95% confidence using red-noise (AR lag-1) background spectrum. The crosshatched region corresponds to the cone of influence, where zero-padding has reduced the variance. The dashed line in the global wavelet indicates 95% confidence level.

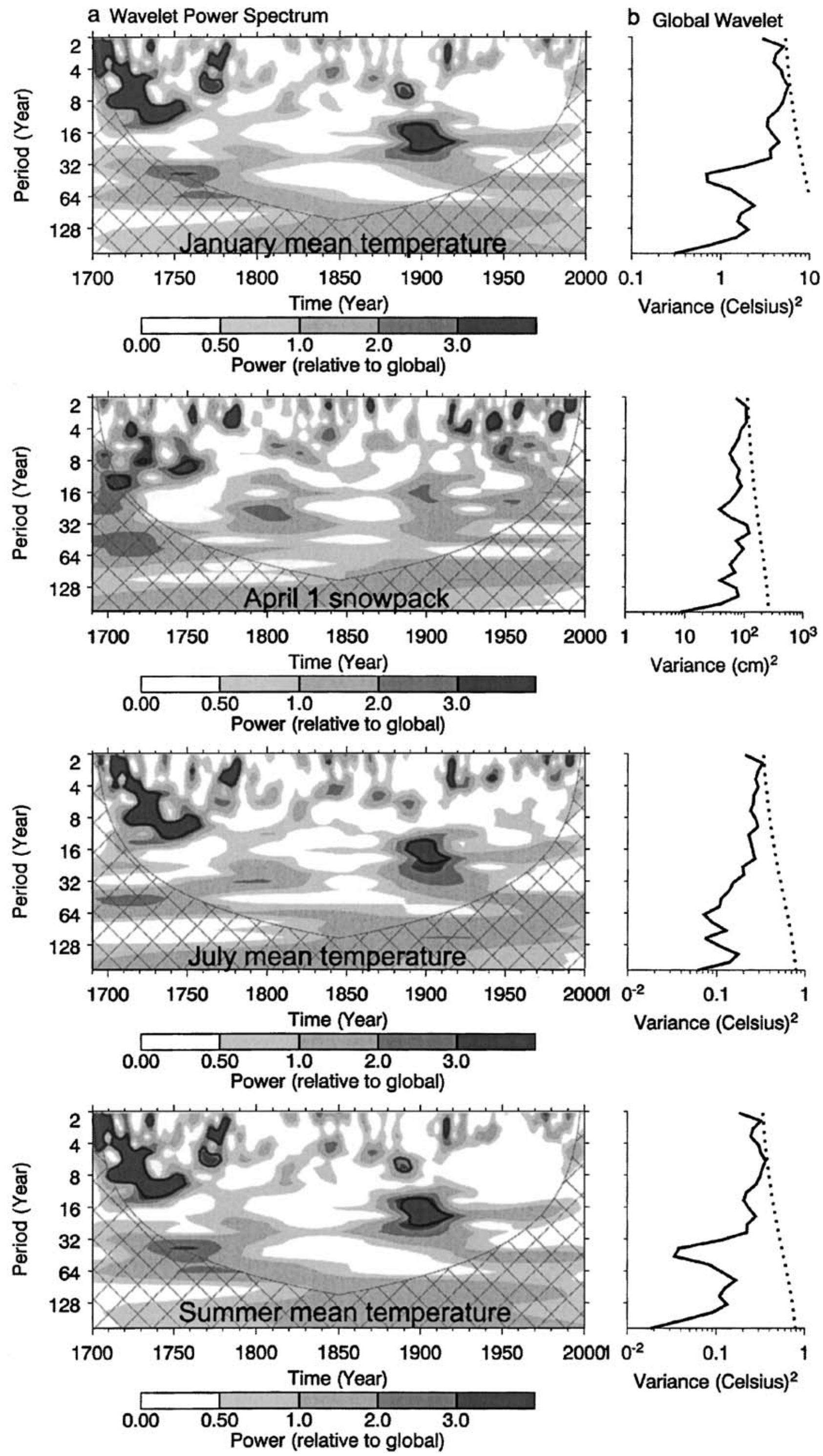

Fig. 6. Wavelet power spectrum (a) and global wavelet (b) showing the significant modes of variability in the reconstructed temperature and snowpack series (SSS $\geqslant$ 0.80). The wavelet power spectrum uses a Morlet wavelet function. The left axis corresponds to the Fourier period (in year). The contour levels represent 75%; 50%; 25%; and 5% of the wavelet power. The thick contours indicate significant modes of variance at 95% confidence using red-noise (AR lag-1) background spectrum. Crosshatched regions correspond to the cones of influence, where zero-padding has reduced the variance. The dashed line in the global wavelet indicates 95% confidence level.

dendroclimatological analyses indicate these fluctuating climate states lead to intervals of enhanced radial growth (positive PDO phase) and reduced radial growth (negative PDO phase).

The 120-year mode of variability expressed within the whitebark pine tree-ring series is similar to that reported within millennia-long tree-ring chronologies from Vancouver Island (Laroque, 2002). While uncommon in other proxy climate records, several studies have associated century-scale cyclicity to solar forcing (Yu and Ito, 1999; Domack et al., 2001; Neff et al., 2001). Given that prior research suggests that small changes in solar activity bring about pervasive climate shifts that oscillate from colder to warmer (Shindell et al., 2001), it may be that the century long trends demonstrated within whitebark pine reflect persistent solar perturbations.

Conclusion

The radial growth characteristics of five high-elevation coniferous tree species were established from treeline sites located within the southern British Columbia Coast Mountains. Dendroclimatological analyses undertaken using historical climate data suggest their radial growth is significantly affected by seasonal air temperature and spring snowpack depth. Whereas principal component analysis showed that radial growth was species-specific, the overall growth trends of all five species are strongly correlated. This finding suggests they share a common regional response to climate that is especially well expressed by the radial growth of subalpine fir and mountain hemlock.

These climate-radial growth relationships were used to build proxy models of January, July, summer temperature, and April 1 snowpack depths extending from AD 1700 to present. These indices highlight cyclic periods of cool-snowy conditions that have modes of variability shorter than 8 years, approximately 20–23 years in duration, and approximately 120 years in length.

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