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Original article

An investigation of the snowpack signal in moisture-sensitive trees from the Southern Canadian Cordillera

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ABSTRACT

Variations in mountain snowpack in the western Canadian Cordillera have widespread and important impacts on ecosystems, environmental processes and socio-economic activities (e.g. water availability downstream). Historical records of snowpack generally span only the latter half of the 20th century offering a limited perspective on the causes and uniqueness of recently observed changes across the region. This paper explores the potential utility of a network of low elevation Douglas-fir (*Pseudotsuga menziesii)* and ponderosa pine (*Pinus ponderosa)* tree ring-width chronologies to reconstruct past snowpack variations. Correlation coefficients between the tree-ring chronologies and a set of snow water equivalent (SWE) records are calculated and mapped. Separate analyses were carried out for total ring-width (TRW) and partial-ring measurements (earlywood and latewood; EW and LW). A set of Adjusted LW chronologies was also developed; in these, the relationship between LW and the preceding EW width has been removed. The ring-width chronologies exhibit moderately strong relationships with SWE records from the western Canadian Cordillera and these relationships vary in sign across the region. Distinctive regional groups are identified where chronologies exhibit same-sign correlations with SWE, in possible accordance with the elevation and characteristics of the tree-ring chronology sample sites. The EW chronologies correlate more strongly and consistently with SWE records in regions where the growth relationship with SWE is negative. The LW chronologies, and particularly the Adjusted LW chronologies, exhibit a greater number of positive correlations with the set of SWE records. Collectively these results offer valuable insights for developing a targeted sampling and/or reconstruction strategy that can exploit these different relationships with SWE to generate more robust estimates of pre-instrumental snowpack for the region.

1. Introduction

Recent studies have documented changes in mountain snowpack and hydrology in western Canada and the adjacent United States. These changes, which include reduced spring snowpack, earlier spring runoff and increases in the rain:snow ratio, may be attributable to recent increases in temperature, particularly in late winter and spring, and, more notably at higher elevations, changes in precipitation observed across the region (e.g. Stewart et al., 2005; Hamlet et al., 2005; Mote et al., 2005; Barnett et al., 2008; Hidalgo et al., 2009; Pederson et al., 2011, 2013; Kapnick and Hall, 2012; Vincent et al., 2015).

Observations of snowpack from the Canadian Cordillera typically cover only the last 50 years or less. Longer records are required to improve our understanding of the range of natural variability, particularly at lower frequencies, and provide greater context for the recent changes. Many studies have documented linkages between indices representing large scale patterns of atmospheric and oceanic variability (e.g. the Pacific Decadal Oscillation and Pacific/North America Pattern) and observed records of surface climate and climate-related phenomena across the region, particularly for the winter season (e.g. Moore and McKendry, 1996; Brown and Goodison, 1996; Brown and Braaten, 1998; Bonsal et al., 2001; Shabbar and Skinner, 2004; Stahl et al., 2006; Watson et al., 2006; Fleming and Whitfield, 2010; Whitfield et al., 2010; Bonsal and Shabbar, 2011; Thorne and Woo, 2011; Shabbar and Yu, 2012). Interdecadal variations in these patterns approach the length of many of the shorter observed snowpack records (∼25 years)

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complicating studies that attempt to disentangle the cause(s) of recent snowpack declines (e.g., Stewart et al., 2005; Mote, 2006).

There have been numerous tree-ring based reconstructions of environmental variables that are controlled in part by winter snowpack including streamflow and glacier mass balance (e.g. Case and MacDonald, 2003; Lewis and Smith, 2004; Watson and Luckman, 2004a; Gedalof et al., 2004; Larocque and Smith, 2005a; Axelson et al., 2009; Hart et al., 2010; Sauchyn et al., 2011). Many of the streamflow reconstructions developed for British Columbia (B.C.; east of the Coast Ranges) and Alberta rely on chronologies from low-elevation moisture-sensitive sites where snowmelt water recharges soil moisture in spring. However, when evaluated on a monthly basis, many of the moisture-sensitive chronologies are most strongly sensitive to summer and spring precipitation (from the prior and current year) with weaker associations with winter precipitation (e.g., Watson and Luckman 2002). In this region, winter snowpack is an important control of streamflow over the water year (e.g. Watson and Luckman, 2005a, 2006) and spring/summer and winter precipitation are generally uncorrelated (not shown[1]). A more comprehensive investigation of the relationship between growth chronologies from moisture-sensitive trees and high elevation snowpack records from across the region may inform future reconstruction of streamflow in snowmelt dominated rivers.

Most glacier mass balance reconstructions in B.C. have been based on chronologies from high-elevation species whose growth is sensitive to both winter snowpack depth (negative association) and summer temperatures (positive association; Lewis and Smith, 2004; Larocque and Smith, 2005a). This mixed climate-growth signal is useful for reconstructing glacier mass balance where the combined strength of these seasonal signals improves the overall statistical relationship but it is not beneficial if one is trying to isolate the winter snowpack signal alone. Some estimates of winter mass balance (as opposed to net balance) for continental glaciers in the region have relied in part on the large-scale teleconnections between the winter climate of the area and variations in the Pacific Ocean climate system (e.g. Pederson et al., 2004). That is, in some instances, 'local' climate can be linked with the winter climate in 'remote' regions – and hence the winter climate related growth signal in appropriate chronologies – through their common association with large-scale variations in the Pacific Ocean. For example Watson and Luckman (2004a) relied in part on information derived from tree-growth chronologies from Alaska to provide information on winter climate for sites in the southern Canadian Rockies. However, this approach is not ideal because we do not know how stable such remote teleconnections are through time (e.g. McAfee, 2014). Identifying tree-ring chronologies from within the region that do exhibit a clear relationship with snowpack is important for expanding our understanding of past environmental changes and developing improved reconstructions of past streamflow and glacier mass balance.

The few published tree-ring based reconstructions of snowpack available for western Canada are mainly from the Coast Mountains and Vancouver Island. Larocque and Smith (2005b) developed a 300 year-long reconstruction of snowpack (April 1 snow water equivalent (SWE) records from Big Creek and Tatlayoko Lake) for the Mt. Waddington area of the B.C. Coast Mountains from a regional, high elevation subalpine fir chronology. Wood et al. (2011) used a total ring-width chronology from Douglas-fir and a mean ring density chronology from Englemann spruce to reconstruct October-March snowpack for Tatlayoko Lake back to 1730. East of the Coast Mountains, Wood and Smith (2013) reconstructed February snowpack back to 1780 for Golden, B.C. from total ring-width chronologies from subalpine fir and mountain hemlock sampled at high elevation sites in the Columbia Mountains. These reconstructions provide a valuable long-term perspective on snowpack variability at the local and possibly regional scale, explaining roughly 20–30% of the variance in the observed record.

An extensive set of tree-ring based snowpack reconstructions was developed recently for key basins in the U.S. Rockies (Pederson et al., 2011). The snowpack reconstructions for the northern reaches of the Columbia basin encompass part of the southern Canadian Cordillera and two Canadian tree-ring chronologies (high elevation subalpine larch) enter some of the reconstruction models. As with the studies from B.C. described above, these ring-width chronologies enter the reconstruction models negatively because, at these high elevation sites, deep snowpacks that persist late into spring are thought to reduce the period of cambial activity and therefore the width of annual rings (Gedalof et al., 2004; Lutz et al., 2012).

At sites farther south in the American Rockies (e.g. in the Colorado Basin) and the Pacific Northwest, selected lower elevation chronologies exhibit positive correlations with snowpack where the volume of water in the snowpack affects soil moisture availability, particularly during the early growing season (Woodhouse, 2003; Pederson et al., 2011; Lutz et al., 2012). This type of positive relationship with winter precipitation has not been as consistently or strongly identified or exploited in western Canada. For both negative and positive snowpack-growth relationships, extremes related to the limiting factor are better modelled than the opposite extreme: i.e. deep versus shallow snowpack when there is a negative relationship and less moisture versus more moisture when there is a positive relationship. The best approach for developing snowpack reconstruction models that capture both high and low snowpack extremes is therefore to incorporate chronologies that exhibit both types of relationships with snowpack (Pederson et al., 2011; Lutz et al., 2012).

Ring-width chronologies from Douglas-fir and ponderosa pine have been used to reconstruct snowpack in previous studies (e.g. Woodhouse, 2003; Pederson et al., 2011; Wood et al., 2011; Lutz et al., 2012). Separate earlywood (EW) and latewood (LW) width chronologies developed from Douglas-fir have proved sensitive to precipitation over different parts of the current/previous growing season (Meko and Baisan, 2001; Watson and Luckman, 2002; Díaz et al., 2002; Griffin et al., 2013). A network of moisture-sensitive Douglas-fir and ponderosa pine total ring-width (TRW) chronologies has previously been developed from low-mid elevation sites in the Fraser, Upper Columbia, Athabasca and Saskatchewan River watersheds of the southern Canadian Cordillera (Fig. 1; Watson and Luckman, 2001, 2002). Separate EW and LW chronologies are available for a subset of this network. Annual precipitation reconstructions developed using these chronologies have explored the spatial and temporal patterns of precipitation variations across the region over the past ~300 years (Watson and Luckman, 2004b, 2005b). However, these annual precipitation reconstructions were based primarily on strong tree-growth relationships with precipitation at valley floor stations over the summer period. Winter precipitation at these low elevation stations is not necessarily representative of cumulative snowpack at higher elevations. Winter snowpack is not equivalent to winter precipitation as it reflects a cumulative volume that is sensitive to both the total amount of precipitation received and temperatures in winter and spring. Recent work (Luce et al., 2013; Dettinger, 2014) suggests that different

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[1] Correlations were calculated between winter-spring and winter-summer precipitation for 77 stations in B.C. and Alberta (from the Adjusted and Homogenised Canadian Climate Dataset: http://ec.gc.ca/dccha-ahccd/Default.asp?lang=En&n=B1F8423A-1). All correlation coefficients were <0.35 and only 9/77 of the winter-spring and 8/77 of the winter-summer correlations were statistically significant at the $p \leq 0.05$ level. Correlation coefficients calculated between mean spring SWE (1936–1999) and these precipitation records over the current and previous summer were similar (current summer: 3/77 significant, prior summer 6/77 significant).

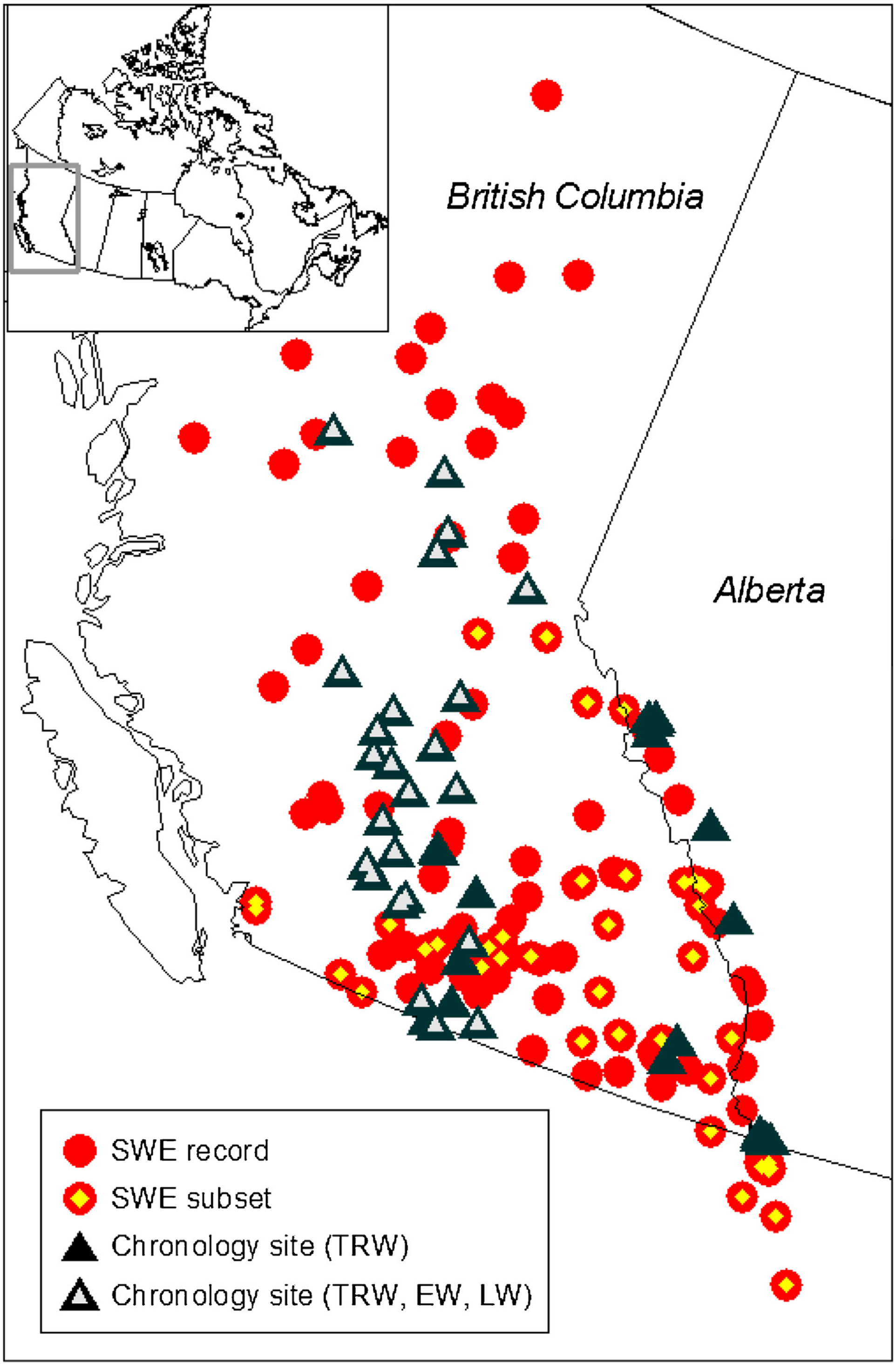

Fig. 1. Location of the tree-ring chronologies and snow water equivalent (SWE) records used in the study. The SWE subset records are those that cover a 'long' common period 1951–1999. Tree-ring chronology sample sites where total ring-width (TRW) plus separate earlywood (EW) and latewood (LW) chronologies are also available are shown.

trends may be observed in precipitation records from high and low elevation stations from the same area related to changes in the strength of zonal winds that in turn influence the strength of orographic effects. Furthermore, on average, the chronology sites are located at higher elevations (mean 910 m, range 400–1800 m) than the high quality precipitation records available for the region (mean 598 m, range 4–1397 m) and some of the chronologies are closer in elevation to nearby SWE stations (mean 1500 m) than precipitation records from valley floor stations. As such, the potential utility of these low elevation chronologies for reconstructing past variations in high elevation snowpack has not been explicitly explored.

To date only total ring-width parameters have been used to reconstruct snowpack variations in western North America: partial-width chronologies have not been used. In this study, the climate signal in the network of moisture-sensitive Douglas-fir and ponderosa pine chronologies from the southern Canadian

Cordillera is assessed against a set of high elevation snowpack records. The goals of the study are to explore systematically the snowpack-related signal in the network of low-mid elevation Douglas-fir and ponderosa pine tree-ring chronologies from the southern Canadian Cordillera. This evaluation will include an assessment of the spatial pattern in the sign and strength of snowpack-growth relationships across the region. We also explore the potential utility of separate EW- and LW-width chronologies for snowpack reconstruction.

2. Data and methods

Annual precipitation totals across the study area are controlled primarily by topography and the regional atmospheric circulation and air mass moisture content. Precipitation is greatest along the windward slopes of the Coast Ranges and can exceed 4000 mm per year on the western summits. East of the Coast Ranges, precipitation in the interior valleys of B.C., the deep Rocky Mountain trench and the leeward slopes of the Rockies is comparatively low due to rain shadow effects and the mean presence of a mid-tropospheric ridge in summer months. The driest areas of the interior valleys receive less than 300 mm of precipitation annually. Higher precipitation totals associated with orographic effects are found in the Columbia Mountain ranges and the windward slopes of the Rocky Mountains. Watson (2002) noted that, on average, valley floor sites across the southern Canadian Cordillera recorded maximum seasonal precipitation for summer and minimum for spring (31% and 20% of total precipitation respectively). Winter and fall precipitation each accounted for 24% of the annual total on average. As noted above, winter precipitation in this region is generally uncorrelated with spring and summer season precipitation (Watson and Luckman, 2006) reflecting differing controls of seasonal precipitation.

2.1. Tree-ring chronologies

The network of tree-ring data used in this study was sampled from open-grown, low to mid-elevation sites, irregularly spaced across the semi-arid interior valleys of the southern Canadian Cordillera. Forty *Pseudotsuga menziesii* (Douglas-fir) and thirteen *Pinus ponderosa* (ponderosa pine) chronologies were developed from 43 sites; chronologies from both species were collected from 10 of the sites (Fig. 1). Chronology development, quality and dendroclimatic potential are documented in Watson and Luckman (2001, 2002). The chronologies range in length from 123 to 696 years ending in the mid to late 1990s. Twenty-eight separate earlywood and latewood ring-width chronologies are available for 23 of the sites (23 Douglas-fir, 5 ponderosa pine; Fig. 1). Previous studies have demonstrated that the total ringwidth chronologies are sensitive to moisture conditions (primarily spring and summer precipitation) with slight differences in the seasonal timing of the signal identified for the two species. Greater differences in the seasonal timing of the strongest precipitation signal are observed for the partial ring-width parameters as one would expect based on differences in the timing of cell formation (Watson and Luckman, 2002, 2004b). In particular, a greater proportion of the LW than the EW chronologies correlate with winter precipitation (Watson and Luckman, 2002; see further discussion below) a finding which, in part, prompted this study.

Studies from the southwestern U.S. have enhanced the distinction between the climate signal identified in separate EW and LW width chronologies by removing the linear relationship between LW width and the EW that precedes it (Meko and Baisan, 2001; Stahle et al., 2009; Griffin et al., 2011). To assess the utility of this approach in this environment, each of the 28 LW chronologies were adjusted for their statistical relationship (or dependence) on EW. For each site chronology, LW width was regressed on EW width and the residual from this regression was used as an Adjusted LW chronology (Meko and Baisan, 2001; Stahle et al., 2009).

2.2. Snowpack records

A large set of snow water equivalent (SWE) records were assembled for use in exploring snowpack relationships with tree growth across the region (Fig. 1: Table 1). The Canadian records are from the Canadian Snow Data CD-ROM (2004 version, Meteorological Service of Canada, 2000). The records for Montana were obtained from the National Resources Conservation's Service (NRCS) anonymous ftp server (ftp.wcc.nrcs.usda.gov). The SWE records were checked for normality prior to their use in the correlation analysis (Table 1). A small number of missing values were replaced previously in the records used in the study by Watson et al. (2008) and in a subset of the records that cover the period 1951–1999 (a long common period) using simple linear regression with the closest stations. Missing values in the other records were not replaced.

These high elevation spring SWE records (104 of the 118 records are from sites > 1000 m) are for April 1st (within 7 days) for the Canadian stations and May 1st for the majority of the northern U.S. stations (selected for data availability). April 1 SWE generally approximates maximum seasonal snowpack in the study area and integrates a temperature and precipitation signal. The strongest correlations between mean regional spring SWE and climate records from across the region (see Supplemental information 1, Fig. S1) are with winter precipitation (positive relationship) and winter and spring temperatures (negative relationship). Mean spring SWE across the region is weakly associated with elevation ($r = 0.30$, $p < 0.05$, $n = 118$). This orographic effect is complicated by distance from the coast. Spring SWE exceeds 1000 mm at some of the more westerly sites and at high elevation wet sites in the Selkirks, Purcells and southern Rockies (Fig. 2). Lower mean spring SWE totals and lower elevation records are found in the central interior of B.C. (Fig. 2).

2.3. Methods

To evaluate relationships between tree growth and spring snowpack, simple Pearson's product-moment correlation coefficients were calculated over the maximum overlap between each pair of series and also over a common period (1951–1999). The common period is based upon a mean SWE record developed from a sub-set of the records that cover a 'long' common period (for details see Table 1; Supplementary information 2, Figs. S2 and S3). Comparison of chronology-SWE pairings on a site by site basis gives a better indication of the geographic pattern of relationships with SWE for each chronology than can be provided by exploring relationships with the spatially limited set of SWE records that cover the longer, common period. Relationships with the longer regional record of snowfall are used to confirm the nature of these relationships over a common period. The standard versions of the chronologies were used for the analyses presented in this study because there is persistence in both the snowpack and tree ring data. To assess the influence of serial correlation in the tree-ring and/or snowpack time series on the assessment of statistical significance, the significance of chronology-SWE relationships was evaluated following adjustment (i.e. reduction) of the degrees of freedom where significant ($p < 0.05$) first order autocorrelation is present in either or both series (Dawdy and Matalas, 1964).

Table 1
SWE records used in the study.

Site Name	Variable	Latitude	Longitude	Elev m	Start	End	Length	Subset
Summit Lake	April 1	58.65	124.72	1280	1964	2002	39	
Pink Mountain	April 1	57.03	122.52	1170	1964	2003	40	
Lady Laurier Lake	April 1	56.70	123.75	1460	1963	2003	41	
Pine pass	April 1	55.35	122.63	1430	1961	2003	43	
Morfee Mtn	April 1	55.42	123.05	1450	1968	2003	36	
Philip Lake	April 1	55.12	123.88	980	1963	2003	41	
Tsaydaychi Lake	April 1	55.42	124.77	1160	1963	2003	41	
Germansen (upper)	April 1	55.82	124.70	1500	1961	2003	43	
Fort St. James	April 1	54.48	124.15	810	1955	1997	43	
Burns Lake	April 1	54.23	125.73	800	1970	2002	33	
Mcleod Lake	April 1	54.93	122.88	980	1960	2000	41	
Pacific Lake	April 1	54.38	121.57	770	1963	2003	41	
Chapman Lake	April 1	54.88	126.73	1460	1965	2003	39	
McBride	April 1	53.30	120.32	1580	1950	2003	54	X
Nazko	April 1	53.02	123.65	1070	1957	2003	47	
Tahtsa Lake	April 1	53.57	127.63	1300	1952	2003	52	
Longworth	April 1	53.95	121.43	1740	1953	2003	51	
Prince George	April 1	53.87	122.68	690	1962	2003	42	
Skins Lake	April 1	53.77	125.98	880	1964	2003	40	
Barkerville	April 1	53.05	121.48	1520	1951	1999	49	X
Canoe River	April 1	52.82	119.20	1040	1938	2003	66	X
Yellowhead	April 1	52.90	118.55	1860	1950	2003	54	X
Horsefly Mountain	April 1	52.33	121.05	1550	1970	2003	34	
Puntzi Mountain	April 1	52.13	124.10	940	1970	2003	34	
Nigel Creek	April 1	52.20	117.08	1920	1968	2003	36	
Sunwapta Falls	April 1	52.55	117.65	1400	1968	2003	36	
Marmot-Jasper	April 1	52.80	118.08	1830	1970	2003	34	
Glacier	April 1	51.25	117.50	1250	1938	2003	66	X
Kicking Horse	April 1	51.43	116.35	1650	1947	2003	57	X
Field	April 1	51.38	116.52	1280	1939	2003	65	X
Mirror Lake	April 1	51.42	116.23	2030	1940	2003	64	X
Chateau Lawn	April 1	51.42	116.22	1740	1940	2003	64	X
Pipestone upper	April 1	51.43	116.17	1615	1937	2003	67	X
Bow River	April 1	51.42	116.18	1580	1937	2003	67	X
Marble Canyon	April 1	51.20	116.13	1520	1947	2003	57	X
Mount Revelstoke	April 1	51.03	118.15	1830	1947	2003	57	X
Tatlayoko Lake	April 1	51.60	124.33	1710	1952	1998	47	
Anglemont	April 1	51.00	119.18	1190	1956	2003	48	
Mount Timothy	April 1	51.90	121.27	1660	1961	2003	43	
Fidelity Mountain	April 1	51.23	117.70	1870	1963	2003	41	
Goldstream	April 1	51.70	118.43	1920	1963	2003	41	
Ptarmigan Hut	April 1	51.47	116.10	2190	1967	2003	37	
Sunshine Village	April 1	51.08	115.78	2230	1967	2003	37	
Sinclair Pass	April 1	50.67	115.97	1370	1936	2003	68	X
Revelstoke	April 1	50.98	118.22	560	1938	1995	58	
Ferguson	April 1	50.68	117.48	880	1938	2003	66	X
Aberdeen Lake	April 1	50.15	119.05	1310	1939	2003	65	X
Monashee Pass	April 1	50.08	118.50	1370	1949	2003	55	X
Postill Lake	April 1	50.00	119.23	1370	1950	2003	54	X
Pass Lake	April 1	50.85	120.50	870	1950	1998	49	
Porcupine Ridge	April 1	50.97	120.55	1830	1962	1998	37	
Tranquille Lake	April 1	50.93	120.55	1420	1952	1998	47	
McGillivray Pass	April 1	50.68	122.60	1800	1952	2003	52	
Tenquille Lake	April 1	50.53	122.93	1680	1953	2003	51	
Whiterocks Mountain	April 1	50.02	119.75	1830	1953	2003	51	
Pavilion	April 1	50.92	121.82	1230	1955	2003	49	
Lac Le Jeune	April 1	50.47	120.50	1370	1956	2003	48	
Barnes Creek	April 1	50.07	118.35	1620	1957	2003	47	
Whatshan Upper	April 1	50.20	118.03	1480	1958	2003	46	
Silver Star Mtn	April 1	50.37	119.05	1840	1959	2003	45	
Enderby	April 1	50.65	118.92	1900	1963	2003	41	
Bralorne	April 1	50.78	122.78	1450	1963	2003	41	
Esperon Creek Upper	April 1	50.08	119.75	1650	1966	2003	38	
Wilkinson S.Bush	April 1	50.20	114.55	1980	1963	2003	41	
Wilkinson S.Open	April 1	50.20	114.55	1980	1965	2003	39	
Highwood S. Bush	May 1	50.60	114.98	2210	1965	2003	39	
Mist Creek	May 1	50.52	114.83	1790	1968	2003	36	
Upper Elk River	April 1	49.98	114.92	1340	1948	2002	55	X
Fernie	April 1	49.50	115.05	1070	1938	1987	50	
Fernie East	April 1	49.50	115.03	1250	1951	2003	53	X
Kimberley	April 1	49.68	115.98	1160	1938	1995	58	
Sullivan Mine	April 1	49.72	116.02	1550	1946	2003	58	X
Moyie Mtn	April 1	49.25	115.77	1940	1969	1998	30	
Moyie Mtn—pillow*	April 1	49.25	115.77	1940	1972	2003	32	
Kimberley VOR- upper	April 1	49.57	116.08	2140	1969	2003	35	
Kimberley VOR—middle	April 1	49.57	116.05	1680	1969	2003	35	
Kimberley VOR—lower*	April 1	49.53	116.03	1370	1969	1996	28	

Table 1 (*Continued*)

Site Name	Variable	Latitude	Longitude	Elev m	Start	End	Length	Subset
Sandon	April 1	49.98	117.23	1070	1938	2003	66	X
Nelson	April 1	49.42	117.23	930	1938	2003	66	X
Gray creek—lower	April 1	49.62	116.68	1550	1948	2003	56	X
Gray creek—upper	April 1	49.62	116.65	1910	1969	2001	33	
Arrow Creek*	April 1	49.25	116.50	1620	1978	2001	24	
Char creek	April 1	49.10	116.95	1310	1965	2003	39	
Trout Creek	April 1	49.73	120.18	1430	1935	2003	69	X
Summerland Reservoir	April 1	49.82	120.02	1280	1935	2003	69	X
Graystoke Lake	April 1	49.98	118.87	1810	1971	2003	33	
McCulloch	April 1	49.78	119.20	1280	1939	2003	65	X
Mission Creek	April 1	49.95	118.95	1780	1939	2003	65	X
Brookmere	April 1	49.82	120.87	980	1945	2003	59	X
Dog Mountain	April 1	49.38	122.97	1080	1945	2003	59	X
Pallisaide Lake	April 1	49.45	123.03	880	1946	2002	57	X
Lightning Lake	April 1	49.05	120.85	1220	1947	2003	57	X
Old Glory Mtn	April 1	49.15	117.92	2130	1948	1982	35	
Klesilkwa	April 1	49.13	121.30	1130	1947	2003	57	X
Greyback Reservoir	April 1	49.62	119.42	1550	1953	2003	51	
Koch Creek	April 1	49.72	117.98	1860	1959	2002	44	
Lost Horse Mtn	April 1	49.28	120.13	1920	1960	2003	44	
Missezula Mtn	April 1	49.67	120.53	1550	1960	2003	44	
Hamilton Hill	April 1	49.50	120.78	1490	1960	2003	44	
Carmi	April 1	49.50	119.08	1250	1963	2003	41	
Isintok Lake	April 1	49.55	119.97	1680	1965	2003	39	
Big White Mountain	April 1	49.72	118.93	1680	1966	2003	38	
Allison Pass	April 1	49.73	114.60	1980	1963	2003	41	
West Castle Bush	April 1	49.28	114.37	1520	1967	2003	37	
Weasel divide	May 1	48.96	114.76	1661	1939	1999	61	X
Iceberg Lake	May 1	48.83	113.72	1707	1922	2003	82	X
Ptarmigan Lake	May 1	48.83	113.72	1770	1951	2003	53	X
Mineral Creek	May 1	48.77	113.82	1219	1939	2003	65	X
Mount Allen	May 1	48.77	113.68	1737	1922	2003	82	X
Piegan pass	May 1	48.76	113.69	1676	1922	2001	80	X
Desert Mtn	May 1	48.41	113.96	1707	1939	1999	61	X
Marias Pass	May 1	48.32	113.36	1600	1936	2003	68	X
Josephine Lower	May 1	48.78	113.67	1490	1955	2003	49	
Stahl Creek Peak	April 1	49.52	115.43	1838	1961	2003	43	
Stahl Creek Peak Pillow	April 1	49.52	115.43	1838	1961	2003	43	
Flattop Pillow	April 1	48.80	113.85	1920	1970	2003	34	
Goat Mountain	May 1	47.65	112.91	1921	1939	1999	61	X
Stemple pass	May 1	46.88	112.48	2012	1939	1999	61	X

Notes. An X indicates that the SWE record is used in the longer subset mean series. Correlations with tree-ring chronologies are not presented for the three SWE records identified with an asterisk. The time series are normally distributed as evaluated using the Kolmogorov–Smirnov test.

3. Results and discussion

In the following sections, we provide results of the correlation analyses between the tree-ring chronologies and SWE records. We discuss possible explanations for the patterns that emerge based on knowledge of the physical aspects of the sample sites while considering the context for these results based on similar relationships documented in the published literature.

3.1. SWE-TRW correlations

Table 2 summarizes correlations between the 53 TRW chronologies and the set of 115[2] SWE records calculated over their maximum paired overlaps (i.e. the time period varies; see also Fig. S4). In this table, correlation coefficients are binned according to strength and sign. For each chronology the maximum correlation[3] with an individual SWE record is listed along with the total number of positive and negative correlations. The chronologies are sorted from highest positive to highest negative correlations. Thirty eight of the 53 total ring-width chronologies correlate significantly with at least one of the SWE records (Table 2; Fig. S5) but the number of significant correlations ($p \leq 0.05$) for each chronology can be quite high (average 9; maximum 61) which may reflect the strong low-frequency coherence of snowpack across the region (Watson et al., 2008; see also Supplemental information 2). From this list, it is clear that some of the chronologies are positively associated with snowpack while others correlate negatively. This table and Fig. 3 also demonstrate that, in general, the highest positive correlations are with chronologies sampled at low elevations while the highest negative relationships are generally with chronologies sampled at higher elevations.

The maximum statistically significant correlations ($p \leq 0.05$) of SWE with each of the total ring-width chronologies are mapped in Fig. 4a. Four distinct and coherent regional groupings emerge with chronology-SWE relationships of consistent sign. The spatial extent and location of the groupings as well as the sign of relationships probably reflect characteristics of the chronology sites related to topography and local climate. When correlations between the total ring-width chronologies and the mean SWE record over a common period are plotted the same four regional groupings emerge (Fig. 4b).

The chronologies in the southwestern portion of the study area (oriented NW-SE; Region 1 in Fig. 4a) were sampled at low elevation sites (mean elevation $\sim$625 m) in the most arid part of the southern Canadian Cordillera. Annual precipitation totals at valley floor stations in this region can be less than 300 mm and

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[2] Correlation results for the three shortest SWE records are not presented (see Table 1).

[3] Note that, given the variable lengths of the SWE records, the highest correlation reported for each chronology is not necessarily the most statistically significant (i.e. has the lowest p value).

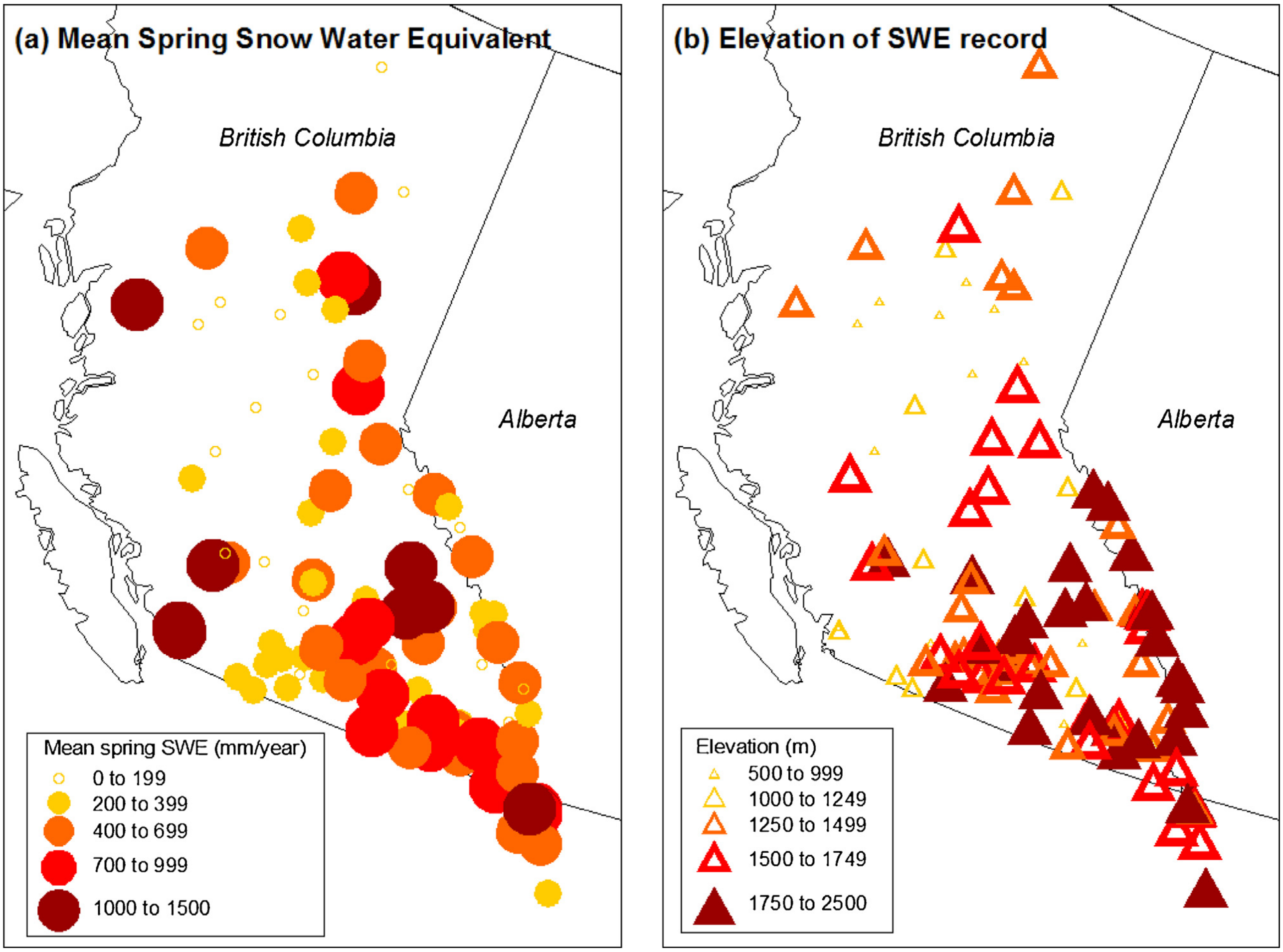

Fig. 2. Characteristics of the SWE records (a) Mean spring SWE calculated for the full length of each record (period of record varies) and (b) elevation (m) of SWE sites used in the study.

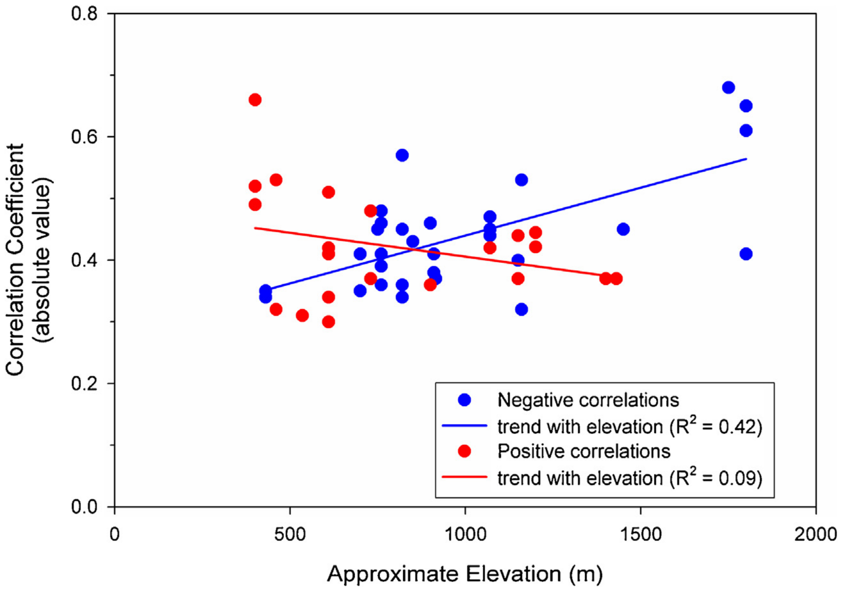

Fig. 3. Relationships between maximum chronology-SWE correlation strength (as listed in Table 2) and chronology elevation. Chronologies are grouped according to the sign of their maximum correlation with SWE; chronologies with maximum correlations that are negative and positive are shown in blue and red respectively.

Table 2
Summary of correlation coefficients calculated between the 53 total ring-width chronologies and the 115 SWE records.(For interpretation of the references to colour in this table, the reader is referred to the web version of this article.)

Chronology	Elev (m)	-0.61 to -0.70	-0.51 to -0.60	-0.41 to -0.50	-0.31 to -0.40	-0.21 to -0.30	-0.11 to -0.20	-0.10 to -0.00	0.00 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	Max corr.	Max Sig corr.	#Neg	#Pos
Spatsum DF	400	0	0	0	0	0	0	2	1	10	30	29	33	9	1	**0.66**	**0.66**	2	113
Merritt DF	820	0	0	0	0	1	1	10	11	11	39	32	9	1	0	**0.57**	**0.57**	12	103
Lillooet DF	460	0	0	0	0	1	0	4	19	33	30	24	1	3	0	**0.53**	**0.53**	5	110
Spatsum PP	400	0	0	0	0	0	1	0	5	14	44	44	6	1	0	**0.52**	**0.52**	1	114
Lytton PP	610	0	0	0	0	0	0	3	21	31	36	16	7	1	0	**0.51**	**0.51**	3	112
Skemeoskaunkin DF	400	0	0	0	0	0	5	17	20	32	31	8	2	0	0	**0.49**	**0.49**	22	93
Perry Creek DF	760	0	0	0	0	2	1	7	16	29	40	14	6	0	0	**0.48**	**0.48**	10	105
Pyramid Lake DF	1200	0	0	0	0	1	3	7	21	27	34	17	5	0	0	**0.44**	**0.44**	11	104
Patrtiot DF	730	0	0	0	0	2	9	12	30	31	25	5	1	0	0	**0.44**	**0.44**	23	92
Prairie de la Vache DF	1150	0	0	0	0	1	4	15	28	32	23	10	2	0	0	**0.43**	**0.43**	20	95
Maligne Canyon DF	1200	0	0	0	0	0	4	5	29	25	37	14	1	0	0	**0.42**	**0.42**	9	106
Wasa Lake DF	610	0	0	0	1	0	12	20	39	27	11	4	1	0	0	**0.42**	**0.42**	33	82
Bald Range PP	1070	0	0	0	0	0	0	11	19	34	41	9	1	0	0	0.42		11	104
Lytton DF	610	0	0	0	0	0	1	10	22	22	39	20	1	0	0	**0.41**	**0.41**	11	104
Churn Creek DF	910	0	0	0	0	0	7	24	23	27	26	8	0	0	0	**0.38**	**0.38**	31	84
Lake Annette DF	1150	0	0	0	0	0	6	11	32	33	26	7	0	0	0	**0.37**	**0.37**	17	98
Powerhouse DF	1430	0	0	0	0	4	10	20	30	32	14	5	0	0	0	**0.37**	**0.37**	34	81
Two o'clock Creek DF	1400	0	0	0	0	4	18	34	30	14	10	5	0	0	0	**0.37**	**0.37**	56	59
Patriot PP	730	0	0	0	0	5	13	20	40	25	9	3	0	0	0	0.37		38	77
Westwold DF	900	0	0	0	1	13	26	38	27	8	1	1	0	0	0	0.36		78	37
Osoyoos DF	610	0	0	0	1	7	21	35	33	14	4	0	0	0	0	0.34		64	51
Lillooet PP	460	0	0	0	0	0	1	11	36	35	27	5	0	0	0	0.32		12	106
Pavilion Lake DF	1160	0	0	0	0	1	11	20	34	34	14	1	0	0	0	0.32		32	83
Keremeos DF	535	0	0	0	0	5	13	22	37	26	11	1	0	0	0	0.31		40	75
Prince George DF	610	0	0	0	0	2	6	16	51	33	5	2	0	0	0	0.30		24	91
Naramata PP	430	0	0	0	1	7	18	33	45	8	3	0	0	0	0	**-0.34**	**-0.34**	59	56
Merritt PP	820	0	0	0	2	9	23	40	27	13	1	0	0	0	0	-0.34		74	41
Naramata DF	430	0	0	0	2	14	20	30	27	11	11	0	0	0	0	-0.35*	**0.29**	66	49
Fritts PP	700	0	0	0	4	17	37	26	19	9	3	0	0	0	0	**-0.35**	**-0.35**	84	31
Kettle River DF	760	0	0	0	4	24	33	26	22	6	0	0	0	0	0	-0.36		87	28
Gang Ranch DF	820	0	0	0	0	7	18	28	40	15	7	0	0	0	0	-0.36		53	62
Deer Park DF	915	0	0	0	1	4	16	29	41	18	5	1	0	0	0	**-0.37**	**-0.37**	50	65
Horsefly Lake DF	760	0	0	0	2	5	26	36	33	11	1	1	0	0	0	**-0.39**	**-0.39**	69	46
Pinchi Lake DF	1150	0	0	0	1	9	34	36	23	9	3	0	0	0	0	-0.40		80	35
Fort George DF	700	0	0	1	3	13	22	33	35	8	0	0	0	0	0	**-0.41**	**-0.41**	72	43
Lac la Hache DF	910	0	0	1	9	20	27	32	24	2	0	0	0	0	0	**-0.41**	**-0.41**	89	26
Kettle River PP	760	0	0	1	7	25	31	29	19	2	0	1	0	0	0	-0.41		93	22
Lost Horse Creek DF	1800	0	0	1	1	13	36	31	31	2	0	0	0	0	0	**-0.41**	**-0.41**	82	33
Bull Canyon DF	910	0	0	1	0	7	19	27	43	9	7	2	0	0	0	**-0.41**	**-0.41**	54	61
Tranquille PP	850	0	0	3	12	35	34	22	9	0	0	0	0	0	0	-0.43*	**-0.42**	106	9
Tranquille DF	850	0	0	2	2	29	28	25	22	6	1	0	0	0	0	**-0.43**	**-0.43**	86	29
Indian Meadows DF	1070	0	0	2	9	24	28	31	18	3	0	0	0	0	0	**-0.44**	**-0.44**	94	21
Chief Mountain DF	1450	0	0	2	4	17	46	21	18	7	0	0	0	0	0	-0.45*	**-0.42**	90	25
Shuttleworth Creek PP	820	0	0	1	2	17	16	44	26	7	2	0	0	0	0	**-0.45**	**-0.45**	80	35
Coffeepot DF	750	0	0	0	0	5	15	53	34	6	2	0	0	0	0	-0.45		73	42
Clinton DF	1070	0	0	2	11	49	36	13	4	0	0	0	0	0	0	**-0.45**	**-0.45**	111	4
Dome Creek DF	760	0	0	0	3	24	45	28	13	1	1	0	0	0	0	-0.46*	**-0.37**	100	15
Westwold PP	900	0	0	5	22	35	36	11	5	1	0	0	0	0	0	**-0.46**	**-0.46**	109	6
Clinton PP	1070	0	0	6	17	39	38	11	4	0	0	0	0	0	0	**-0.47**	**-0.47**	111	4
Bridge Lake DF	1160	0	3	11	34	35	21	9	2	0	0	0	0	0	0	**-0.53**	**-0.53**	113	2
Ruby Ridge DF	1800	1	2	23	24	30	16	15	3	1	0	0	0	0	0	-0.61		111	4
Golf Course DF	1800	3	10	26	27	29	11	6	1	2	0	0	0	0	0	**-0.65**	**-0.65**	112	3
Mt. Crandell DF	1750	1	8	26	25	16	19	13	5	2	0	0	0	0	0	-0.68*	**-0.50**	108	7
																	SUM	3015	3083

Notes. Correlations are calculated over the maximum overlap for each chronology-SWE pairing and are listed according to the maximum chronology-SWE correlation (i.e. highest positive to highest negative correlation). DF and PP are Douglas-fir and Ponderosa pine. Elev(m) is the approximate elevation of the tree-ring width chronology. Max corr. is the maximum correlation with SWE identified for each chronology. Bold values are statistically significant ($p \leq 0.05$) following adjustment of degrees of freedom for autocorrelation in the chronology and/or SWE time series. * indicates that, although the maximum correlation is not significant, there is at least one significant correlation with a SWE record. Max Sig corr. is the maximum statistically significant ($p \leq 0.05$) correlation following adjustment of degrees of freedom for autocorrelation in the chronology and/or SWE time series. #NEG and #POS gives the total number of correlations (total of 115) that are positive and negative; these are summed at the bottom of the column.

are amongst the driest in Canada. Additionally, a greater proportion of annual precipitation falls as snow in this region.[4] Pederson et al. (2011) noted that, in certain settings, the amount of water available to trees in the growing season is related to the amount of water in the snowpack from the previous winter. Lutz et al. (2012) indicate that, in certain environments, Douglas-fir and ponderosa pine growth can be limited by low water availability that can be related, in part, to snowpack depth. The positive relationship between tree-growth at these sites and snowpack is consistent with these findings. Although they are higher in absolute elevation, the Douglas-fir chronologies sampled in the Rocky Mountains and near Cranbrook in the adjacent Rocky Mountain Trench also exhibit

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[4] The proportion of total precipitation which falls in winter is higher at two of the stations from this dry region of interior B.C., (Lytton and Lillooet 42 and 31%, respectively) than in records from elsewhere in the southern Cordillera (average is 24%; Watson, 2002).

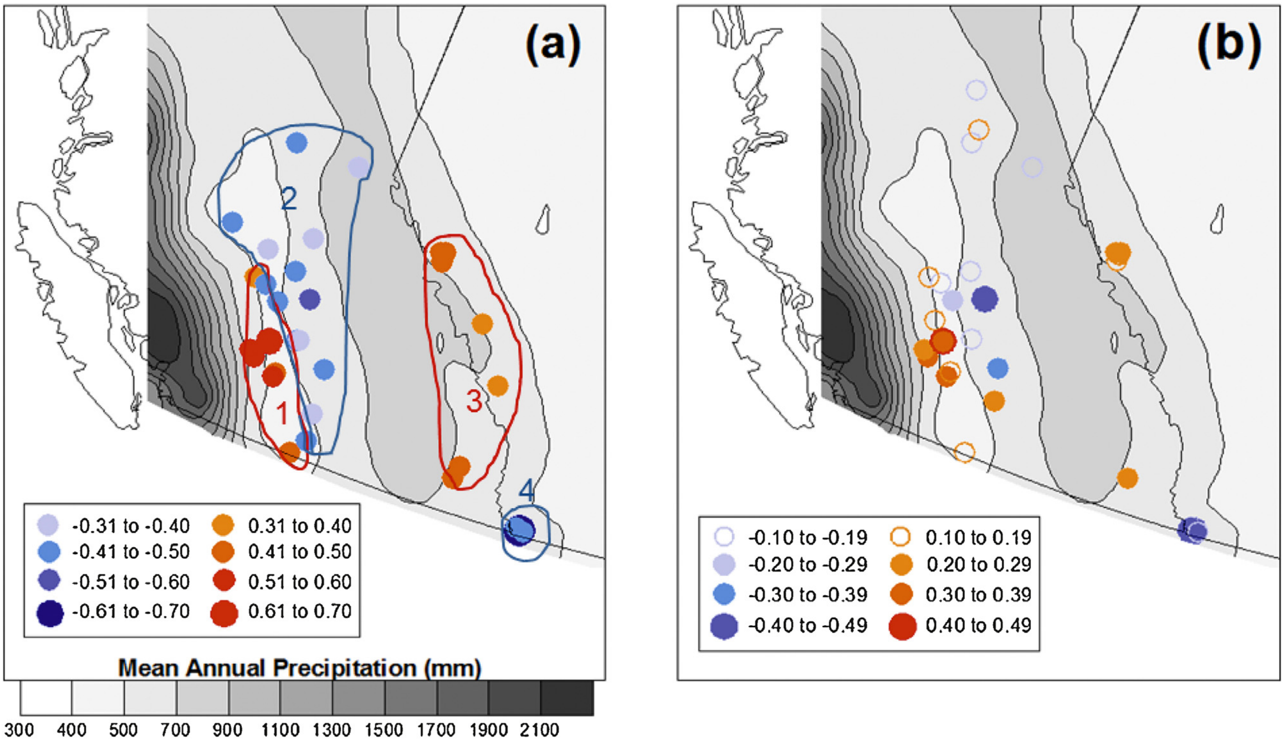

Fig. 4. (a) Maximum statistically-significant correlations (following adjustment for autocorrelation) between total ring-width chronologies and SWE records calculated over the maximum overlap for each pair. (38 of 53 chronologies correlate significantly with at least one of the 115 SWE records). The circles show the location of the tree-ring chronologies and the size and colour of the circle indicates the strength and sign of the relationship with the SWE record. (b) Correlation coefficients between the total ring-width chronologies and the SWE subset record mean (see Supplemental information 2) over the period 1951–1999. Mean annual precipitation across the region is presented in shaded greyscale (see Watson, 2002 for details).

positive correlations with a number of SWE records (Region 3 in Fig. 4a). The significant correlations in Region 3 are with SWE records that are concentrated along the continental divide (not shown).

The tree-ring chronologies in Region 2 (Fig. 4a) exhibit primarily negative correlations with the SWE records indicating that deeper (shallower) snowpacks are associated with narrower (wider) annual rings. These chronologies are found to the east and north of Region 1 where conditions are wetter and the chronologies were sampled at a slightly higher elevation (mean ~850 m). Watson and Luckman (2001, 2002) found that these chronologies, particularly the more northern ones, tended to have a weaker relationship with spring, summer and annual precipitation and a weaker common signal and lower mean sensitivity values than the average for the network chronologies. Mean spring SWE and SWE station elevation (Fig. 2) are also lower in this region and there are fewer SWE records (Fig. 1).

The five highest elevation chronologies (mean elevation ~1720 m) in this study were sampled in Waterton Lakes National Park. These Douglas-fir chronologies (Region 4, Fig. 4a) also exhibit negative correlations with a broad set of SWE records. This negative relationship probably reflects the detrimental influence of deeper snowpacks on the initiation of growing season at these sites. Littell et al. (2008) report that at some high-elevation plots in the Pacific Northwest, Douglas-fir growth is limited by factors associated with subalpine tree growth including higher snowpack which can persist into early summer, shortening the growing season. The Waterton chronologies, similar to those in Region 2, exhibit lower correlations with summer and annual precipitation and had a weaker common signal, lower mean sensitivity and higher first order autocorrelation than other sites in the network (Watson and Luckman, 2001, 2002)—these attributes are characteristic of more temperature sensitive, subalpine chronologies. Watson and Luckman (2002) noted that these chronologies correlated more strongly with temperatures from the previous summer (negative relationship) than precipitation in any month. There is a strong trend of increasing growth in these chronologies since the 1970s that may relate to increasing temperatures and declining snowpack in the region.

It should be noted that, Regions 1 and 2 (Fig. 4a) contain a mix of both Douglas-fir and ponderosa pine chronologies indicating that species-specific responses do not appear to be the main factor governing the strength and direction of the TRW-SWE relationship. Where there are co-located chronologies (5 sites), they exhibit similar correlations (both sign and strength) with the SWE records.

3.2. SWE correlations with EW, LW and Adjusted LW chronologies

Table 3 summarizes correlations between the 28 EW, LW and Adjusted LW chronologies and the set of 115 SWE records calculated over their maximum paired overlaps (i.e. the time period varies). There are notable differences in the overall number and sign of the correlation coefficients with SWE computed for the EW and LW chronologies (Table 3). Regardless of the strength or statistical significance, the EW chronologies show a greater number of negative than positive correlations while the LW chronologies show a greater number of positive than negative correlations (Table 3). Mapping of either (i) the maximum statistically significant correlations between the 28 EW and LW chronologies and the SWE dataset, as was done for TRW in Fig. 4a, or (ii) the prevailing sign of the correlations (Table 3) identifies two regions corresponding to Regions 1 and 2 of Fig. 4 (not shown). Nine of the EW chronologies show statistically significant negative correlations with at least one SWE record. Only three of the LW chronologies exhibit statistically significant negative correlations with a SWE record (these three chronologies are located in Region 2).

Table 3
Summary of correlation coefficients calculated between the 28 (a) earlywood (b) latewood and (c) adjusted latewood ring-width chronologies and the 115 SWE records.(For interpretation of the references to colour in this table footnote, the reader is referred to the web version of this article.)

(a)	Earlywood Chronology	Elev (m)	-0.61 to -0.70	-0.51 to -0.60	-0.41 to -0.50	-0.31 to -0.40	-0.21 to -0.30	-0.11 to -0.20	-0.10 to -0.00	0.00 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	Max corr.	Max Sig corr.	#Neg	#Pos
	Spatsum DF	400	0	0	0	0	0	0	2	0	15	28	36	30	3	1	**0.63**	**0.63**	2	113
	Lillooet DF	460	0	0	0	1	0	2	10	32	33	24	10	3	0	0	**0.47**	**0.47**	13	102
	Lillooet PP	460	0	0	0	0	0	2	8	32	38	28	7	0	0	0	**0.36**	**0.34**	10	105
	Keremeos DF	535	0	0	0	0	2	16	20	38	27	11	1	0	0	0	-0.30		38	77
	Lytton PP	610	0	0	0	0	0	0	3	22	33	34	14	8	1	0	**0.51**	**0.51**	3	112
	Osoyoos DF	610	0	0	0	1	14	24	34	34	7	1	0	0	0	0	-0.32		73	42
	Lytton DF	610	0	0	0	0	0	3	13	17	34	35	13	0	0	0	**0.39**	**0.39**	16	99
	Prince George DF	610	0	0	0	0	2	9	34	48	19	3	0	0	0	0	0.22		45	70
	Fort George DF	700	0	0	1	6	23	29	39	15	2	0	0	0	0	0	-0.43		98	17
	Patriot DF	730	0	0	0	0	0	12	13	31	33	21	4	1	0	0	**0.42**	**0.42**	25	90
	Coffeepot DF	750	0	0	0	4	9	42	42	14	4	0	0	0	0	0	-0.37*	**-0.29**	97	18
	Kettle River DF	760	0	0	0	13	22	26	29	19	5	1	0	0	0	0	-0.37		90	25
	Horsefly Lake DF	760	0	0	1	0	8	33	42	25	5	1	0	0	0	0	**-0.42**	**-0.42**	84	31
	Kettle River PP	760	0	0	1	9	24	31	27	19	3	1	0	0	0	0	-0.43		92	23
	Dome Creek DF	760	0	0	0	6	25	48	23	11	1	1	0	0	0	0	-0.37		102	13
	Merritt DF	820	0	0	0	0	1	1	9	10	12	37	35	9	1	0	**0.59**	**0.59**	11	104
	Gang Ranch DF	820	0	0	0	0	7	19	29	41	13	6	0	0	0	0	-0.29		55	60
	Churn Creek DF	910	0	0	0	0	0	7	22	26	31	25	4	0	0	0	**0.38**	**0.38**	29	86
	Lac la Hache DF	910	0	0	3	9	26	27	33	16	1	0	0	0	0	0	**-0.44**	**-0.44**	98	17
	Bull Canyon DF	910	0	0	0	1	5	17	32	38	14	6	2	0	0	0	**-0.39**	**-0.39**	55	60
	Deer Park DF	915	0	0	0	1	8	17	28	40	20	0	1	0	0	0	**-0.39**	**-0.39**	54	61
	Bald Range PP	1070	0	0	0	0	0	0	9	20	35	40	10	1	0	0	0.42*	**0.34**	9	106
	Clinton PP	1070	0	0	5	12	42	38	13	5	0	0	0	0	0	0	**-0.44**	**-0.44**	110	5
	Indian Meadows DF	1070	0	0	2	10	28	25	33	14	3	0	0	0	0	0	**-0.45**	**-0.45**	98	17
	Clinton DF	1070	0	0	5	14	48	35	11	2	0	0	0	0	0	0	**-0.48**	**-0.48**	113	2
	Pinchi Lake DF	1150	0	0	0	3	10	30	41	22	7	2	0	0	0	0	-0.37		84	31
	Pavillion DF	1160	0	0	0	0	2	18	20	32	28	13	2	0	0	0	0.32		40	75
	Bridge Lake DF	1160	0	2	16	30	38	17	10	1	1	0	0	0	0	0	**-0.53**	**-0.53**	113	2
																	SUM	SUM	1657	1563

(b)	Latewood Chronology	Elev (m)	-0.61 to -0.70	-0.51 to -0.60	-0.41 to -0.50	-0.31 to -0.40	-0.21 to -0.30	-0.11 to -0.20	-0.10 to -0.00	0.00 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	Max corr.	Max Sig corr.	#Neg	#Pos
	Spatsum DF	400	0	0	0	0	0	0	3	4	7	19	38	30	13	1	**0.61**	**0.61**	3	112
	Lillooet DF	460	0	0	0	0	0	1	2	6	27	36	22	14	7	0	**0.59**	**0.59**	3	112
	Lillooet PP	460	0	0	0	0	3	9	26	43	29	5	0	0	0	0	-0.28		38	77
	Keremeos DF	535	0	0	0	0	0	9	9	27	32	30	6	2	0	0	0.42		18	97
	Lytton PP	610	0	0	0	0	0	3	3	18	40	31	11	8	1	0	**0.51**	**0.51**	6	109
	Osoyoos DF	610	0	0	0	0	2	5	13	41	31	17	6	0	0	0	**0.40**	**0.40**	20	**95**
	Lytton DF	610	0	0	0	0	0	2	9	18	29	32	18	7	0	0	**0.46**	**0.46**	11	104
	Prince George DF	610	0	0	0	0	1	2	9	20	46	29	5	3	0	0	**0.43**	**0.43**	12	103
	Fort George DF	700	0	0	0	0	3	15	27	40	27	3	0	0	0	0	-0.30		45	**70**
	Patriot DF	730	0	0	0	0	1	6	14	22	37	25	9	1	0	0	**0.42**	**0.42**	21	94
	Coffeepot DF	750	0	0	0	0	2	7	22	57	22	3	1	1	0	0	**0.40**	**0.41**	31	**84**
	Horsefly Lake DF	760	0	0	0	0	8	23	37	29	13	4	1	0	0	0	0.35		68	47
	Kettle River PP	760	0	0	0	4	13	34	30	29	4	1	0	0	0	0	-0.32		81	34
	Dome Creek DF	760	0	0	0	3	9	40	32	24	6	1	0	0	0	0	-0.34		84	31
	Kettle River DF	760	0	0	0	1	7	26	37	34	8	2	0	0	0	0	-0.34		71	44
	Merritt DF	820	0	0	0	0	1	3	6	21	13	36	27	7	1	0	0.51*	**0.50**	10	105
	Gang Ranch DF	820	0	0	0	0	3	9	25	40	24	14	0	0	0	0	0.34		37	78
	Bull Canyon DF	910	0	0	0	1	5	18	20	50	11	9	1	0	0	0	**-0.37**	**-0.37**	44	71
	Churn Creek DF	910	0	0	0	0	0	7	17	35	26	20	7	3	0	0	**0.43**	**0.43**	24	91
	Lac la Hache DF	910	0	0	0	3	10	23	41	29	8	1	0	0	0	0	-0.33		77	38
	Deer Park DF	915	0	0	0	0	2	6	33	40	25	6	3	0	0	0	**0.34**	**0.34**	41	74
	Bald Range PP	1070	0	0	0	0	0	1	8	28	31	41	6	0	0	0	0.38		9	106
	Clinton DF	1070	0	0	0	3	13	42	38	17	2	0	0	0	0	0	-0.33		96	19
	Indian Meadows DF	1070	0	0	0	3	10	29	33	29	10	1	0	0	0	0	-0.35		75	40
	Clinton PP	1070	0	0	1	9	27	33	32	12	0	1	0	0	0	0	-0.46*	**-0.38**	102	13
	Pinchi Lake DF	1150	0	0	0	0	0	7	28	49	17	10	4	0	0	0	**0.39**	**0.39**	35	**80**
	Pavillion DF	1160	0	0	0	0	1	4	17	34	41	16	2	0	0	0	0.37		22	93
	Bridge Lake DF	1160	0	1	8	17	32	29	15	12	1	0	0	0	0	0	-0.51*	**-0.50**	102	13
																	SUM	SUM	1186	2034

(c)	Adjusted Latewood Chronology	Elev (m)	-0.61 to -0.70	-0.51 to -0.60	-0.41 to -0.50	-0.31 to -0.40	-0.21 to -0.30	-0.11 to -0.20	-0.10 to -0.00	0.00 to 0.10	0.11 to 0.20	0.21 to 0.30	0.31 to 0.40	0.41 to 0.50	0.51 to 0.60	0.61 to 0.70	Max corr.	Max Sig corr.	#Neg	#Pos
	Spatsum DF	400	0	0	0	0	1	0	11	28	38	25	11	1	0	0	**0.44**	**0.44**	12	103
	Lillooet DF	460	0	0	0	0	0	2	5	12	38	29	17	9	3	0	**0.57**	**0.57**	7	108
	Lillooet PP	460	0	0	9	15	35	38	13	5	0	0	0	0	0	0	**-0.39**	**-0.39**	**110**	5
	Keremeos DF	535	0	0	0	0	0	0	12	31	25	31	16	0	0	0	**0.39**	**0.39**	12	103
	Lytton PP	610	0	0	0	2	13	34	42	21	3	0	0	0	0	0	0.24		**91**	24
	Osoyoos DF	610	0	0	0	0	0	0	4	17	37	30	24	3	0	0	**0.48**	**0.48**	4	**111**
	Lytton DF	610	0	0	0	0	4	7	9	43	30	16	6	0	0	0	**0.39**	**0.39**	20	95
	Prince George DF	610	0	0	0	0	0	2	4	17	43	30	18	1	0	0	**0.43**	**0.43**	6	109
	Fort George DF	700	0	0	0	0	0	1	2	29	36	31	14	1	1	0	**0.53**	**0.53**	3	**112**
	Patriot DF	730	0	0	0	0	0	7	17	34	34	19	4	0	0	0	**0.39**	**0.39**	24	91
	Coffeepot DF	750	0	0	0	0	0	1	10	21	41	37	3	2	0	0	**0.48**	**0.48**	11	**104**
	Horsefly Lake DF	760	0	0	0	0	1	19	19	39	23	9	3	2	0	0	**0.41**	**0.41**	39	**76**
	Kettle River PP	760	0	0	0	0	4	17	40	30	20	4	0	0	0	0	-0.26		61	54
	Dome Creek DF	760	0	0	0	1	5	11	30	27	27	11	3	0	0	0	0.37*	**-0.34**	47	**68**
	Kettle River DF	760	0	0	0	0	3	11	38	38	16	8	1	0	0	0	0.34		52	**63**
	Merritt DF	820	0	0	0	1	8	10	12	37	32	14	1	0	0	0	**-0.35**	**-0.35**	31	84
	Gang Ranch DF	820	0	0	0	0	0	0	20	38	36	17	3	1	0	0	**0.46**	**0.46**	20	95
	Bull Canyon DF	910	0	0	0	0	0	11	27	45	26	6	0	0	0	0	0.28		38	77
	Churn Creek DF	910	0	0	0	0	1	9	25	37	27	13	3	0	0	0	**0.33**	**0.33**	35	80
	Lac la Hache DF	910	0	0	0	0	1	1	11	31	34	28	6	3	0	0	**0.47**	**0.47**	13	**102**
	Deer Park DF	915	0	0	0	0	0	4	17	27	42	13	11	1	0	0	**0.43**	**0.43**	21	94
	Bald Range PP	1070	0	0	0	0	1	4	22	42	32	13	1	0	0	0	0.31		27	88
	Clinton DF	1070	0	0	0	0	0	1	15	41	42	12	3	1	0	0	**0.42**	**0.42**	16	**99**
	Indian Meadows DF	1070	0	0	0	0	0	1	17	39	44	12	2	0	0	0	**0.40**	**0.40**	18	**97**
	Clinton PP	1070	0	0	0	0	0	10	27	49	22	6	1	0	0	0	0.39		37	**78**
	Pinchi Lake DF	1150	0	0	0	0	0	0	12	17	39	36	9	2	0	0	**0.44**	**0.44**	12	**103**
	Pavillion DF	1160	0	0	0	0	0	3	17	41	36	12	5	1	0	0	**0.42**	**0.42**	20	95
	Bridge Lake DF	1160	0	0	0	0	5	19	37	36	10	7	1	0	0	0	0.35		61	54
																	SUM	SUM	848	2372

Notes. Correlations are calculated over the maximum overlap for each chronology-SWE pairing and are listed by elevation (low to high). For abbreviations see Table 2. The bold red values in the #POS and bold blue values in the #NEG columns in this Table (b) and (c) identifies chronologies for which the correlations with the SWE records are a different sign to those for their EW counterparts.

The correlation coefficients calculated between the Adjusted LW chronologies and the SWE records (Table 3c) are, in total, more frequently positive than those with the EW or LW chronologies (Table 3b). Examination of the maximum statistically significant correlations for the 28 LW and Adjusted LW chronologies (Table 3b and c) reveal that for LW, 12 of the 15 statistically significant maximum correlations are positive (mean correlation 0.46); for Adjusted LW, 18 of the 21 statistically significant maximum correlations are positive (mean correlation 0.44). Thus, although the maximum significant correlations are similar in strength, these results suggest that removing the dependence of LW-width on the preceding EW-width does improve the seasonal distinction in the climate signal that can be identified in separate sub-annual ring with measurement series from this environment.

Spatially, the tree growth relationships with SWE are generally similar for TRW, EW and LW (i.e. essentially the same two broad regions are identified regardless of RW parameter). However, as noted above, where the relationship between tree growth and snowpack is positive (as in Region 1), this relationship is slightly stronger and more broadly consistent for the LW chronologies. Additionally, some of the chronologies that exhibited a negative response to SWE for their EW and TRW components, switched to positive relationships when correlations were calculated for the LW component (Table 3b). When the Adjusted LW chronology results are examined (Table 3c), the chronology-SWE correlations are more generally positive and the two ‘regional groupings’ identified for EW, and to a lesser extent LW, are no longer evident. LW cells form later in the growing season (studies of Douglas-fir in the Pacific Northwest indicate that latewood transition occurs by mid-July on average; Grotta et al., 2005; Renniger et al., 2006) and may therefore more strongly reflect the link with snow melt and its effect on soil moisture in the current growing season. As noted above, Region 1 is particularly dry and winter precipitation accounts for a greater proportion of the annual total; snowmelt may therefore represent a more important source of moisture for trees in this region.

When the relationship between tree growth and snowpack is negative (as in Region 2), this relationship is stronger and more broadly consistent for the EW chronologies. Previous studies (Watson and Luckman, 2002) have demonstrated that the set of EW chronologies used in this study are most strongly related to climate conditions in the previous year (most strongly prior July-August precipitation and prior July temperature). As such, on average, EW growth is unlikely to be facilitated by the volume of water available in the snowpack that accumulates in the winter that precedes the current growth year. However, the negative correlations reported in this study for generally coherent regions suggest, as reported elsewhere in the literature, that at certain sites/environments, higher snowpacks can delay growth initiation (narrower EW). The EW chronologies may be more sensitive to this type of growth limitation since EW is formed in spring.

4. Summary and conclusion

In this paper we explore relationships between a network of Douglas-fir and ponderosa pine ring-width chronologies and snowpack (i.e. SWE records) across the southern Canadian Cordillera. This is the most comprehensive analysis of growth–snowpack relationships for the region. Mapping of the maximum statistically significant correlations between the total ring-width chronologies and snowpack revealed four distinct groupings of chronologies within which the sign of the relationship was remarkably consistent. Both the set of tree-ring chronologies and SWE records are unevenly spaced across the region (e.g. the SWE records are concentrated most densely in the southern part of the region) and are sampled at different elevations. As such, the number, pattern and strength of significant correlations identified for each chronology may in part reflect horizontal and/or vertical distances from the SWE stations. However, despite this complication, the sign of chronology-SWE correlations is remarkably consistent within these broadly-defined regions suggesting that broadscale chronology location/site characteristics control the sign of the relationship.

Two groups of chronologies exhibit positive relationships with snowpack depth: (1) the chronologies located in the dry valleys of southwestern B.C and (2) the Douglas-fir chronologies from the Rocky Mountains and the Rocky Mountain trench. Positive relationships with snowpack have been identified previously for more southerly locations (e.g. the Colorado Rockies and PNW) but these are the first statistically significant, broadly replicated positive relationships with snowpack that have been reported for the Canadian Cordillera. Negative relationships with snowpack were identified for the higher elevation Douglas-fir chronologies from Waterton Lakes and from a group of chronologies located in central B.C. Conditions at these sites are wetter and cooler and it is hypothesized that deeper snowpack limits the length of the growing season at these sites.

Separate analyses were also conducted on a smaller subset of these chronologies for which EW and LW chronologies were available. Similar analyses for the EW and LW chronologies identified essentially the same broad regions where the relationships with SWE were the same sign. The Adjusted LW chronologies however exhibited more consistently positive correlations with SWE and were, as one would expect, more distinct from the EW and TRW results for the same chronologies. The EW chronologies display a slightly stronger negative growth relationship with SWE than the LW and Adjusted LW chronologies. The LW, and Adjusted LW chronologies in particular, exhibit a stronger predominantly positive growth relationship with snowpack. These differences likely reflect differences in the seasonal timing of cell formation and climate window ‘seen’ by the ring parameter measured. The EW chronologies correlate most strongly with climate conditions from the previous summer and are unlikely to be affected by snowpack volume during the dormant period. However, the negative relationship with winter snowpack suggests that EW growth (spring) is limited by deep snowpacks which delay the start of the growing season in spring. In contrast, the LW and Adjusted LW chronologies demonstrate the highest correlations with climate conditions during the current growth year suggesting that they may be more sensitive to water availability from snowpack during the current growth year. More studies of the growth phenology of these species in this environment are needed to confirm these relationships.

The relationships detailed in this paper suggest that these chronologies have potential for the development of reconstructions of winter snowpack. The relationships with SWE are, in some cases, quite strong (maximum statistically significant correlations between $\pm 0.29 - 0.66$; Table 2) and are broadscale, reflecting the coherence of snowpack variability across the region. Extreme conditions related to the limiting factor are better modelled in dendroclimatic reconstructions than the opposite extremes. In the case of snowpack reconstructions, this means that deep snowpack is better modelled than shallow snowpack when there is a negative relationship and that years with less moisture are better modelled than wetter years when there is a positive relationship. The results reported herein demonstrate that both positive and negative relationships can be found with SWE. Using a set of chronologies that exhibit both relationships with SWE as potential predictors should yield reconstructions with a better approximation of high and low snowpack extremes. The LW and Adjusted LW chronologies have a different response to SWE than the EW and TRW chronologies; these different signals may be useful for maximizing skill in future reconstructions of snowpack for the region. Many of the chronologies also correlate with spring and/or summer precipitation over parts of the previous or current growing season. Careful attention must therefore be given to ensuring that any future snowpack reconstruction developed using these data account for this mixed signal.

Although the present paper focuses on an exploration of the relationships between snowpack records and growth in moisture-sensitive chronologies it is noted that, since spring temperatures influence both snowpack depth and tree growth, temperature-sensitive chronologies may also be useful predictors of past snowpack. Preliminary analyses reveal that some of the existing temperature sensitive chronologies available for the region do correlate negatively with snowpack. This suggests that a broader set of both moisture and temperature sensitive chronologies, which record different aspects of the SWE-climate relationship, may complement each other in the generation of snowpack reconstructions for the region.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.dendro.2016.03.008.

References

Axelson, J.N., Sauchyn, D.J., Barichivich, J., 2009. New reconstructions of streamflow variability in the South Saskatchewan River Basin from a network of tree ring chronologies, Alberta, Canada. Water Resour. Res. 45, W09422, http://dx.doi.org/10.1029/2008WR007639.

Barnett, T.P., Pierce, D.W., Hidalgo, H.G., Bonfils, C., Santer, B.D., Das, T., Bala, G., Wood, A.W., Nozawa, T., Mirin, A.A., Cayan, D.R., Dettinger, M.D., 2008. Human-induced changes in the hydrology of the western United States. Science 319, 1080–1083.

Bonsal, B., Shabbar, A., 2011. Large-scale climate oscillations influencing Canada, 1900–2008. Canadian Biodiversity: Ecosystem Status and Trends, 2010, Technical Thematic Report No. 4. Canadian Council of Resource Ministers, Ottawa, iii +15pp. http://www.biodivcanada.ca/.

Bonsal, B.R., Shabbar, A., Higuchi, K., 2001. Impacts of low frequency variability modes on Canadian winter temperature. Int. J. Climatol. 21, 95–108.

Brown, R.D., Braaten, R.O., 1998. Spatial and temporal variability of Canadian monthly snow depths, 1946–1995. Atmos. Ocean 36, 37–45.

Brown, R.D., Goodison, B.E., 1996. Interannual variability in reconstructed Canadian snow cover, 1915–1992. J. Clim. 9, 1299–1318.

Case, R.A., MacDonald, G.M., 2003. Tree ring reconstructions of streamflow for three Canadian prairie rivers. J. Am. Water Resour. Assoc. 39, 703–716.

Díaz, S.C., Therrell, M.D., Stahle, D.W., Cleaveland, M.K., 2002. Chihuahua (Mexico) winter-spring precipitation reconstructed from tree rings, 1647–1992. Clim. Res. 22, 237–244.

Dawdy, D.R., Matalas, N.C., 1964. Statistical and probability analysis of hydrologic data. Part III: analysis of variance, covariance and time series. In: Chow, V.T. (Ed.), Handbook of Applied Hydrology: a Compendium of Water-resources Technology. McGraw-Hill, pp. 8. 68–8.90.

Dettinger, M., 2014. Impacts in the third dimension. Nat. Geosci. 7, 166–167.

Fleming, S.W., Whitfield, P.H., 2010. Spatiotemporal mapping of ENSO and PDO surface meteorological signals in British Columbia, Yukon, and southeast Alaska. Atmos. Ocean 48, 122–131.

Gedalof, Z., Peterson, D.L., Mantua, N.J., 2004. Columbia River flow and drought since 1750. J. Am. Water Resour. Assoc. 40, 1579–1592.

Griffin, D., Meko, D.M., Touhcan, R., Leavitt, S.W., Woodhouse, C.A., 2011. Latewood chronology development for summer-moisture reconstruction in the US Southwest. Tree-Ring Res. 67, 87–101.

Griffin, D., Woodhouse, C.A., Meko, D.M., Stahle, D.W., Faulstich, H.L., Carrillo, C., Touchan, R., Castro, C.L., Leavitt, S.W., 2013. North American monsoon precipitation reconstructed from tree-ring latewood. Geophys. Res. Lett. 40, http://dx.doi.org/10.1002/grl.50184.

Grotta, A.T., Gartner, B.L., Radosevich, S.R., Huso, M., 2005. Influence of red alder competition on cambial phenology and latewood formation in Douglas-fir. IAWA J. 26, 309–324.

Hamlet, A.F., Mote, P.W., Clark, M.P., Lettenmaier, D.P., 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. J. Clim. 18, 4545–4561.

Hart, S.J., Smith, D.J., Clague, J.J., 2010. A multi-species dendroclimatic reconstruction of Chilko River streamflow British Columbia, Canada. Hydrol. Process. 24, 2752–2761.

Hidalgo, H.G., Das, T., Dettinger, M.D., Cayan, D.R., Pierce, D.W., Barnett, T.P., Bala, G., Mirin, A., Wood, A.W., Bonfils, C., Santer, B.D., Nozawa, T., 2009. Detection and attribution of streamflow timing changes to climate change in the western United States. J. Clim. 22, 3838–3855.

Kapnick, S., Hall, A., 2012. Causes of recent changes in western North American snowpack. Clim. Dyn. 38, 1885–1899.

Larocque, S.J., Smith, D.J., 2005a. ‘Little Ice Age’ proxy glacier mass balance records reconstructed from tree rings in the Mt Waddington area British Columbia Coast Mountains, Canada. Holocene 15, 748–757.

Larocque, S.J., Smith, D.J., 2005b. A dendroclimatological reconstruction of climate since AD 1700 in the Mt. Waddington area British Columbia Coast Mountains, Canada. Dendrochronologia 22, 93–106.

Lewis, D., Smith, D., 2004. Dendrochronological mass balance reconstruction Strathcona Provincial Park, Vancouver Island, British Columbia, Canada. Arctic Antarctic Alpine Res. 36, 598–606.

Littell, J.S., Peterson, D.L., Tjoelker, M., 2008. Douglas-fir growth in mountain ecosystems: water limits tree growth from stand to region. Ecol. Monogr. 78, 349–368.

Luce, C.H., Abatzoglou, J.T., Holden, Z.A., 2013. The missing mountain water: slower westerlies decrease orographic enhancement in the Pacific Northwest, USA. Science 342, 1360–1364.

Lutz, E., Hamlet, A.F., Littell, J.S., 2012. Paleoreconstruction of cool season precipitation and warm season streamflow in the Pacific Northwest with applications to climate change assessments. Water Resour. Res. 48, W01525, http://dx.doi.org/10.1029/2011wr010687.

McAfee, S.A., 2014. Consistency and the lack thereof in Pacific Decadal Oscillation impacts on North American winter climate. J. Clim. 27, 7410–7431.

Meko, D.M., Baisan, C.H., 2001. Pilot study of latewood-width of conifers as an indicator of variability of summer rainfall in the North American monsoon region. Int. J. Climatol. 21, 697–708.

Meteorological Service of Canada, 2000. Canadian Snow Data CD-ROM. CRYSYS Project, Climate Processes and Earth Observation Division, Meteorological Service of Canada, Downsview, Ontario, January 2000. ftp://ccrp.tor.ec.gc.ca/pub/RBrown.

Moore, R.D., McKendry, I.G., 1996. Spring snowpack anomaly patterns and winter climate variability British Columbia, Canada. Water Resour. Res. 32, 623–632.

Mote, P.W., Hamlet, A.F., Clark, M.P., Lettenmaier, D.P., 2005. Declining mountain snowpack in western North America. Bull. Am. Meteorol. Soc. 86, 39–49.

Mote, P.W., 2006. Climate-driven variability and trends in mountain snowpack in western North America. J. Clim. 19, 6209–6220.

Pederson, G.T., Fagre, D.B., Gray, S.T., Graumlich, L.J., 2004. Decadal-scale climate drivers for glacial dynamics in Glacier National Park, Montana, USA. Geophys. Res. Lett. 31, L12203, http://dx.doi.org/10.1029/2004gl019770.

Pederson, G.T., Gray, S.T., Woodhouse, C.A., Betancourt, J.L., Fagre, D.B., Littell, J.S., Watson, E., Luckman, B.H., Graumlich, L.J., 2011. The unusual nature of recent snowpack declines in the North American Cordillera. Science 333, http://dx.doi.org/10.1126/science.1201570.

Pederson, G.T., Betancourt, J.L., McCabe, G.J., 2013. Regional patters and proximal causes of the recent snowpack decline in the Rocky Mountains, U.S. Geophys. Res. Lett. 40, http://dx.doi.org/10.1002/grl.50424.

Renniger, H.J., Gartner, B.L., Grotta, A.T., 2006. No correlation between latewood formation and leader growth in Douglas-fir saplings. IAWA J. 27, 183–191.

Sauchyn, D., Vanstone, J., Perez-Valdivia, C., 2011. Modes and forcing of hydroclimatic variability in the Upper North Saskatchewan River Basin since 1063. Can. Water Resour. J. 36, 205–218.

Shabbar, A., Skinner, W., 2004. Summer drought patterns in Canada and the relationship to global sea surface temperatures. J. Clim. 17, 2866–2880.

Shabbar, A., Yu, B., 2012. Intraseasonal Canadian winter temperature responses to interannual and interdecadal Pacific SST modulations. Atmos. Ocean 50, 109–121, http://dx.doi.org/10.1080/07055900.2012.657154.

Stahl, K., Moore, R.D., McKendry, I.G., 2006. The role of synoptic-scale criculation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada. Int. J. Climatol. 26, 541–560, http://dx.doi.org/10.1002/joc.1268.

Stahle, D.W., Cleaveland, M.K., Grissino-Mayer, H.D., Griffin, R.D., Fye, F.K., Therrell, M.D., Burnette, D.J., Meko, D.M., Villanueva-Diaz, J., 2009. Cool- and warm-season precipitation reconstructions over western New Mexico. J. Clim. 22, 3729–3750.

Stewart, I.T., Cayan, D.R., Dettinger, M.D., 2005. Changes toward earlier streamflow timing across western North America. J. Clim. 18, 1136–1155.

Thorne, R., Woo, M.-K., 2011. Streamflow response to climatic variability in a complex mountainous environment: Fraser River Basin British Columbia, Canada. Hydrol. Process. 25, 3076–3085.

Vincent, L.A., Zhang, X., Brown, R.D., Feng, Y., Mekis, E., Milewska, E.J., Wan, H., Wang, X.L., 2015. Observed trends in Canada’s climate and influence of low-frequency variability modes. J. Clim. 28, 4545–4560.

Watson, E., Luckman, B.H., 2001. The development of a moisture-stressed tree-ring chronology network for the southern Canadian Cordillera. Tree-Ring Res. 57, 149–168.

Watson, E., Luckman, B.H., 2002. The dendroclimatic signal in Douglas-fir and ponderosa pine tree-ring chronologies from the southern Canadian Cordillera. Can. J. For. Res. 32, 1858–1874.

Watson, E., Luckman, B.H., 2004a. Tree-ring based mass-balance estimates for the past 300 years at Peyto Glacier Alberta, Canada. Quat. Res. 62, 9–18.

Watson, E., Luckman, B.H., 2004b. Tree-ring based reconstructions of precipitation for the southern Canadian Cordillera. Clim. Change 65, 209–241.

Watson, E., Luckman, B.H., 2005a. An exploration of the controls of pre-instrumental streamflow using multiple tree-ring proxies. Dendrochronologia 22, 225–234.

Watson, E., Luckman, B.H., 2005b. Spatial patterns of preinstrumental moisture variability in the southern Canadian Cordillera. J. Clim. 18, 2847–2863.

Watson, E., Luckman, B.H., 2006. Long hydroclimate records from tree-rings in western Canada: potential, problems and prospects. Can. Water Resour. J. 31, 205–228.

Watson, E., Luckman, B.H., Yu, B., 2006. Long-term relationships between reconstructed seasonal mass balance at Peyto Glacier, Canada and Pacific sea surface temperatures. Holocene 16, 783–790.

Watson, E., Pederson, G.T., Luckman, B.H., Fagre, D.B., 2008. Glacier mass balance in the northern U.S. and Canadian Rockies: paleo-perspectives and 20th century change. In: Orlove, B., Weigand, E., Luckman, B.H. (Eds.), Darkening Peaks: Glaciers, Science and Society. University of California Press, pp. 139–151.

Watson, E., 2002. Tree-Ring Based Reconstructions of Precipitation in the Southern Canadian Cordillera. Unpublished Ph. D. Dissertation. University of Western Ontario, London, Canada.

Whitfield, P.H., Moore, R.D., Fleming, S.W., Zawadzki, A., 2010. Pacific Decadal Oscillation and the Hydroclimatology of Western Canada—review and prospects. Can. Water Resour. J. 35, 1–28.

Wood, L.J., Smith, D.J., 2013. Climate and glacier mass balance trends from AD 1780 to present in the Columbia Mountains British Columbia, Canada. Holocene 23, 739–748.

Wood, L.J., Smith, D.J., Demuth, M.N., 2011. Extending the Place Glacier mass-balance record to AD 1585, using tree rings and wood density. Quat. Res. 76, 305–313.

Woodhouse, C.A., 2003. A 431-Yr reconstruction of western Colorado snowpack from tree rings. J. Clim. 16, 1551–1561.