

The dendroclimatic signal in Douglas-fir and ponderosa pine tree-ring chronologies from the southern Canadian Cordillera

Emma Watson and Brian H. Luckman

Abstract: A network of 53 ring-width chronologies has been developed from low-elevation stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco, $n = 40$) and ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws., $n = 13$) in the southern Canadian Cordillera. Relationships between the chronologies and monthly, seasonal, and annualized climatic parameters (precipitation, temperature, and Palmer Drought Severity Index (PDSI)) were investigated using correlation analyses. The results indicate that tree growth at the sites is most strongly related to water availability during the growing season months. Although the response of the two species is similar, Douglas-fir show a slightly stronger correlation with seasonalized precipitation for the prior year and early summer whereas ponderosa pine correlate most strongly with current year and late (July) summer precipitation. Maximum correlations for both species occur with annual precipitation totals. The precipitation signal is slightly weaker in the more northerly Douglas-fir chronologies in British Columbia and the higher elevation sites in southwestern Alberta. Correlations with available PDSI records are generally comparable with those from precipitation variables, but the limited number of PDSI records and the availability of more proximal and better correlated precipitation records indicated that annual (summer-summer) precipitation totals provide the best possibilities to develop regional, moisture-related proxy climate records from these data. Analysis of earlywood and latewood chronologies for 28 sites (mainly Douglas-fir) indicates that earlywood width is most consistently and strongly correlated with precipitation in the previous summer (July and August), and latewood width is more strongly related to precipitation in the current summer (June and July). The results of these analyses demonstrate considerable potential for reconstructing annual (and (or) summer) precipitation for sites across the region.

Résumé : Un réseau de 53 séries dendrochronologiques a été mis en place à partir de peuplements de Douglas (*Pseudotsuga menziesii* (Mirb.) Franco, $n = 40$) et de pin ponderosa (*Pinus ponderosa* Dougl. ex P. & C. Laws., $n = 13$) situés à basse altitude dans le Sud de la Cordillère canadienne. Des analyses de corrélation ont été utilisées pour rechercher des relations entre les chronologies et des paramètres climatiques mensuels, saisonniers et annuels (précipitation, température et indice Palmer de gravité de la sécheresse (IPGS)). Les résultats montrent que la croissance des arbres dans ces sites est étroitement corrélée avec la disponibilité en eau pendant les mois de la saison de croissance. Bien que la réponse des deux espèces soit similaire, le Douglas montre une corrélation légèrement plus forte avec les précipitations saisonnières de l'année précédente et du début de l'été alors que le pin ponderosa montre une corrélation plus forte avec les précipitations de l'année courante et celles de la fin de l'été (juillet). Pour les deux espèces, les corrélations maximales sont observées avec la précipitation annuelle totale. Le signal dû à la précipitation est légèrement plus faible dans les séries dendrochronologiques de Douglas les plus au nord en Colombie-Britannique et celles des sites les plus élevés du Sud-Ouest de l'Alberta. Les corrélations observées avec les données disponibles d'IPGS sont généralement comparables avec celles obtenues à partir des précipitations, mais le nombre limité de données d'IPGS ainsi que la disponibilité de mesures de précipitation plus proches des sites et mieux corrélées montrent que la précipitation annuelle totale (d'été à été) fournit les meilleures possibilités de développement de variables climatiques régionales reliées à l'humidité. Une analyse des chronologies de bois initial et final pour 28 sites (surtout du Douglas) montre que la largeur du bois initial est plus fortement corrélée avec les précipitations de l'été précédent (juillet et août) alors que la largeur du bois final est plus fortement corrélée avec les précipitations de l'été en cours (juin et juillet). Les résultats de ces analyses démontrent un potentiel considérable à reconstituer la précipitation annuelle (ou de l'été) pour des sites de la région.

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Introduction

Most of the dendroclimatic research conducted in the southern Canadian Cordillera has focussed on temperature-sensitive, upper tree line sites using alpine larch (*Larix lyallii* Parl.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and whitebark pine (*Pinus albicaulis* Engelm.) (e.g., Luckman et al. 1997; St. George and Luckman 2001;

Wilson and Luckman 2002; Colenutt 2000; Youngblut 1999). Studies of the low-elevation montane dryland species (Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.)) were conducted in the mid-1940s (Schulman 1947) and in the 1960s (Drew 1975). However, few subsequent studies have explored the climate signal in these trees within the dry regions of southwestern Canada. Prior to 1998, only two precipitation reconstructions had been developed in the Canadian Cordillera: a short 181-year record using Douglas-fir at Banff (Robertson and Jozsa 1988) and a longer reconstruction based on limber pine (*Pinus flexilis* James) in the Rocky Mountain Foothills of southwestern Alberta (Case and MacDonald 1995). In 1997, we collected Douglas-fir and ponderosa pine chronologies from 13 sites in the southern Cordillera, updating most of the Laboratory of Tree-Ring Research (LTRR, University of Arizona, Tucson, Ariz.) records. These chronologies were used to develop high-quality, annual (summer–summer) precipitation reconstructions for six meteorological stations across the region (Banff, Jasper, Cranbrook, Kamloops, Penticton, and Westwold; Watson 1998; Watson and Luckman 2001a). Subsequently we have developed an expanded network of 40 Douglas-fir and 13 ponderosa pine chronologies across the full range of both species in the southern Cordillera (Watson and Luckman 2001b).

In this paper, we explore and document the relationships between these chronologies and instrumental climate records (precipitation, temperature, and Palmer Drought Severity Index (PDSI)) from across the region. Specifically our objectives are to (i) compare climate – tree ring relationships for the two species growing at the same site, and (ii) determine if relationships between ring width and climate variables are similar across the range of these species. Demonstrating that observed spatial variations among tree ring series across this region (Watson and Luckman 2001b) are related to local climate controls (rather than site-related, ecological factors) is an essential prerequisite to the reconstruction of spatial patterns of paleoclimate. Recent studies at the southern range of these species in the southwestern U.S.A. and Mexico have demonstrated that earlywood (EW) and latewood (LW) widths are related to precipitation in different seasons (Stahle et al. 2000; Meko and Baisan 2001). We therefore present a separate analysis to examine the nature of the climate signal in EW and LW ring-width chronologies from a subset of these sites.

Methods

Tree-ring data

Fifty-three tree-ring chronologies (40 Douglas-fir and 13 ponderosa pine) were developed from 43 sites, which extend from the Canada–U.S. border to sites near the northern limits of the species range (Table 1, Fig. 1). The chronologies were sampled over the 1997–2000 period and vary from 123 to 691 years in length. The sites are unevenly distributed throughout the dry interior valleys located between the east slope of the Coastal Ranges and the east slope of the Rocky Mountains. The primary criteria for site selection were the geographical distribution of sites, their accessibility, the

presence of old trees, and the absence of obvious disturbance. Sites were also targeted based on their proximity to meteorological stations with long, high-quality precipitation records. As the goal of the project was to select sites across the full range of both species in the area of study, no attempt was made to control systematically for variations in elevation, slope, aspect, and other ecological factors between sites. Generally, the sites sampled were open grown with a grassy understory, which often included big sagebrush (*Artemisia tridentata* Nutt.) or rabbit-brush (*Chrysothamnus* spp.). Ponderosa pine is common on warmer, drier sites in the southern interior of British Columbia (particularly south-facing rocky outcrops; British Columbia Ministry of Forests 1998) and reaches its northern limit between Clinton and Williams Lake in the Fraser Valley and around Barriere in the North Thompson River valley. Douglas-fir extends northwards beyond Prince George where it is found in association with Engelmann spruce and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.). The sample depth of the chronologies ranges from 8 to 28 trees at each site (average 16) with replicate cores from each tree. The average number of trees required to reach an expressed population signal (EPS) value of 0.85 (Wigley et al. 1984) is 8.3. Further details about the chronologies and sample sites are given in Table 1 and in Watson and Luckman (2001b).

Previous studies (e.g., Stahle et al. 1998; Meko and Baisan 2001) have demonstrated that measurements of the earlywood (EW) and latewood components (LW) of annual rings from Douglas-fir and ponderosa pine can contain different climatic signals that are related to differences in the timing of cell formation. Earlywood and latewood measurements were made for a subset of these sites concentrated in the western half of the network (Table 1, Fig. 1). Both Douglas-fir and ponderosa pine generally exhibit an abrupt colour transition as well as a distinctive change in cell lumen size between EW and LW cells. These changes were used to identify the boundary between EW and LW cells visually during measurement (see Stahle et al. 2000, pp. 294–295). The computer program ARSTAN (Cook 1985) was used to standardize individual series by fitting a modified negative exponential curve, a linear trend line of negative slope, or a horizontal line through the mean of the raw ring-width series. The series were then divided by the value of the curve and averaged together to produce the mean indexed chronology for each site.

Climate data

The meteorological records used for climate calibration studies must undergo rigorous analyses for quality control to remove any effects associated with changes of station location or measurement procedures (Metcalf et al. 1997). In this study, we used rehabilitated monthly precipitation (Mekis and Hogg 1999) and homogenized monthly temperature records (Vincent 1998; Vincent and Gullett 1999) from the Historical Canadian Climate Database, recently developed by the Climate Research Branch of the Meteorological Service of Canada (MSC). The stations selected (Table 2, Fig. 1) are mainly valley floor sites and represent the longest and highest quality climate records available for this region. The limited number of missing monthly values in the re-

Table 1. Location and characteristics of the tree-ring chronologies (listed north–south) in the network.

Site name	Species ^a	Latitude	Longitude	Approximate elevation (m)	Aspect
1. Pinchi Lake	DFa	54°41'N	124°31'W	1150	S–SW
2. Coffeepot	DFa	54°27'N	122°42'W	750	N
3. Prince George	DFa	53°55'N	122°45'W	610	S
4. Dome Creek	DFa	53°43'N	121°00'W	760	Variable
5. Fort George	DFa	53°41'N	122°47'W	700	Variable
6. Maligne Canyon	DF	52°57'N	117°57'W	1200	S
7. Pyramid Lake	DF	52°56'N	118°05'W	1200	S
8. Lake Annette	DF	52°56'N	117°58'W	1150	W
9. Prairie de la Vache	DF	52°48'N	117°58'W	1150	W
10. Horsefly Lake	DFa	52°22'N	121°19'W	760	E
11. Bull Canyon	DFa	52°05'N	123°24'W	910	S
12. 2 O'Clock Creek	DF	52°04'N	116°25'W	1400	E
13. Deer Park	DFa	51°56'N	122°17'W	760–1070	E
14. Lac La Hache	DFa	51°46'N	121°23'W	910	W
15. Gang Ranch	DFa	51°40'N	122°24'W	820	Variable
16. Bridge Lake	DFa	51°27'N	120°45'W	1160	Variable
17. Churn Creek	DFa	51°25'N	122°17'W	910	N
18. Indian Meadows	DFa	51°24'N	121°57'W	1070	Variable
19. Clinton	DFa	51°13'N	121°29'W	1070	Variable
20. Clinton	PPa	51°13'N	121°29'W	1070	Variable
21. Powerhouse	DF	51°12'N	115°31'W	1430	W
22. Pavilion Lake	DFa	50°50'N	121°41'W	1160	S–SW
23. Tranquille	DF	50°46'N	120°39'W	850	S
24. Tranquille	PP	50°46'N	120°39'W	850	S
25. Fritts	PP	50°46'N	120°36'W	700	NW
26. Spatsum	DFa	50°34'N	121°17'W	370–430	W
27. Spatsum	PP	50°34'N	121°17'W	370–430	W
28. Westwold	DF	50°30'N	119°45'W	900	S
29. Westwold	PP	50°30'N	119°45'W	900	S
30. Lytton2	DFa	50°20'N	121°38'W	460	W
31. Lytton2	PPa	50°20'N	121°38'W	460	W
32. Lytton	DFa	50°15'N	121°28'W	610	N
33. Lytton	PPa	50°15'N	121°28'W	610	N
34. Patriot	DFa	50°09'N	120°49'W	700–760	S–SE
35. Patriot	PP	50°09'N	120°49'W	700–760	S–SE
36. Merritt	DFa	50°05'N	120°51'W	820	S–SE
37. Merritt	PP	50°05'N	120°51'W	820	S–SE
38. Bald Range	PPa	50°00'N	119°33'W	1070	Variable
39. Wasa Lake	DF	49°47'N	115°45'W	610	E
40. Naramata	DF	49°46'N	119°35'W	430	W
41. Naramata	PP	49°46'N	119°5'W	430	W
42. Perry Creek	DF	49°34'N	115°50'W	760	E
43. Shuttleworth Creek	PP	49°20'N	119°28'W	820	S
44. Keremeos	DFa	49°14'N	119°56'W	460–610	SW
45. Kettle River	DFa	49°13'N	118°56'W	760	E
46. Kettle River	PPa	49°13'N	118°56'W	760	E
47. Ruby Ridge ^b	DF	49°08'N	114°00'W	1800	SW
48. Crandell Moutain ^b	DF	49°05'N	113°59'W	1800	E
49. Golf course ^b	DF	49°04'N	113°54'W	1750	E
50. Lost Horse Creek ^b	DF	49°05'N	113°54'W	1750	E
51. Chief Moutain ^b	DF	49°05'N	113°48'W	1450	W
52. Skemeoskaunkin	DF	49°03'N	119°43'W	400	W
53. Osoyoos	DFa	49°02'N	119°33'W	610	N–NW

^aDF, Douglas-fir; PP, ponderosa pine. Sites designated DFa or PPa have earlywood, latewood, and total ring-width chronologies.

^bChronology provided by M. Colenutt (see Colenutt and Luckman 2000). Site numbers are those used for chronology sites in Fig. 1. Further details of chronologies are given in Watson and Luckman (2001b).

Fig. 1. Location of meteorological stations and tree-ring chronologies used in this study. The identification of chronology sites and meteorological stations are given in Tables 1 and 2, respectively.



cords from set B and the National Climate Data Archive (Table 2) were replaced with estimates derived by linear regression analyses with data from highly correlated, proximal station(s). Double-mass plots (Kohler 1949) of seasonal data were used to assess the homogeneity of the precipitation records from set B and the National Archive. They indicate that no significant inhomogeneities exist in these less rigorously corrected precipitation records.

Numerous dendroclimatic studies have found that tree-ring-width chronologies from arid – semi-arid sites in the United States are related to both precipitation and temperature variables (Fritts 1974). The PDSI (Palmer 1965) is a measure of meteorological drought that incorporates precipitation, potential evapotranspiration, antecedent soil moisture, and runoff (Oladijo 1985). Because of the combined effect of both precipitation and temperature on the availability of moisture for tree growth, several researchers have found that reconstructions of spring and (or) summer PDSI are superior to those of precipitation alone (e.g., Stahle and Cleaveland 1988). PDSI is conceptually appealing because the values

are standardized and correspond to “levels” of drought severity (Alley 1984). Many successful PDSI reconstructions have been developed from tree-ring chronologies in the United States (e.g., Cook et al. 1996, 1999; Stahle et al. 1988). PDSI data developed by Walter Skinner of the Climate Research Branch of the MSC were available for a subset of these stations (Table 2, Fig. 1).

Analytical methods

Principal component and correlation analyses of the relationships between these tree-ring chronologies (Watson and Luckman 2001b) reveal local and regional patterns of spatial variability. For the reconstruction of past climates it is critical to demonstrate that these variations reflect climate variability between sites rather than differences in the response of these species to climate, i.e., that the climate signal preserved in these tree-ring records is essentially similar across the area of investigation. Assessment of this signal is therefore carried out on a site-by-site basis by evaluating the relationships between the standardized total (RW), earlywood

Table 2. Location, elevation, and length of the meteorological records used in this study.

No.	Station name	Latitude	Longitude	Elevation (m)	Precipitation records	Temperature records	PDSI records	Annual precipitation (mm)
1	Fort St James	54°27'N	124°15'W	695	1895–1996	1895–1998	1895–1998	459
2	Burns Lake	54°14'N	125°46'W	704	1949–1990	1950–1998	1950–1998	527
3	Prince George	53°53'N	122°40'W	676	1913–1996	1912–1998	1913–1998	633
4	Wistaria	53°49'N	126°13'W	863	1926–1996	1926–1995	—	451
5	Edson	53°35'N	116°28'W	921	1920–1993	1914–1995	1920–1995	564
6	Entrance	53°23'N	117°41'W	991	—	1917–1998	—	—
7	McBride	53°16'N	120°09'W	722	1922–1962 ^a	—	—	529
8	Barkerville	53°02'N	121°35'W	1265	1895–1996	1896–1995	1896–1998	1049
9	Quesnel	53°02'N	122°31'W	545	1895–1996	1895–1998	1895–1998	541
10	Jasper	52°53'N	118°04'W	1061	1936–1995	1916–1994 ^b	1953–1995	382
11	Williams Lake	52°11'N	122°04'W	940	1936–1996	—	—	495
12	Big Creek	51°40'N	123°04'W	1175	1904–1977 ^c	—	—	326
13	Vavenby	51°35'N	119°47'W	447	1913–1996	1913–1997	1913–1998	442
14	Lake Louise	51°25'N	116°10'W	1524	1915–1994 ^b	—	—	666
15	Darfield	51°18'N	120°11'W	390	1913–1996	—	—	460
16	Banff	51°11'N	115°34'W	1389	1895–1994	1895–1995	1895–1994	511
17	Ashcroft	50°44'N	121°17'W	305	1924–1979 ^a	—	—	200
18	Kamloops	50°42'N	120°27'W	346	1896–1996	1895–1998	1896–1998	302
19	Lillooet	50°40'N	121°55'W	198	1917–1996 ^c	—	—	353
20	Westwold	50°29'N	119°45'W	617	1921–1996	1921–1996 ^a	—	376
21	Lytton	50°14'N	121°35'W	258	1926–1991	—	—	487
22	Vernon	50°14'N	119°12'W	482	1900–1996	1900–1996	1900–1996	422
23	Kelowna	49°58'N	119°23'W	428	1899–1996	—	—	363
24	Claresholm	49°56'N	113°45'W	1045	1913–1996	—	—	424
25	Wasa	49°49'N	115°38'W	930	1924–1996	—	—	417
26	McCulloch	49°48'N	119°12'W	1250	1924–1994	—	—	669
27	Cranbrook	49°36'N	115°47'W	939	1909–1996	1909–1998	1910–1998	418
28	Summerland	49°34'N	199°39'W	455	1908–1994	1907–1995	1908–1994	307
29	Pincher Creek	49°31'N	114°00'W	1189	—	1895–1995	—	—
30	Penticton	49°28'N	119°36'W	344	1908–1996	1907–1996 ^a	—	341
31	Princeton	49°28'N	120°31'W	700	1901–1996	1895–1998	1901–1998	369
32	Beaverdell	49°25'N	199°06'W	780	1939–1975 ^c	—	—	504
33	Hedley	49°21'N	120°04'W	517	1905–1996	—	—	327
34	Keremos	49°13'N	119°49'W	435	1921–1996	1920–1996 ^a	—	268
35	Oliver	49°11'N	119°33'W	297	1924–1996	—	—	300
36	Caldwell	49°10'N	113°38'W	1278	1911–1990	—	—	656
37	Mountain View	49°08'N	113°38'W	1311	1913–1996	—	—	675
38	Creston	49°06'N	116°31'W	597	1912–1996	1912–1998	1913–1998	549
39	Warfield	49°06'N	117°45'W	606	1928–1996	1928–1995	1929–1998	708
40	Grasmere	49°04'N	114°04'W	869	1919–1986 ^c	—	—	435
41	Carway	49°00'N	113°22'W	1352	1914–1996	1914–1998	1915–1998	546

Note: Station numbers are those used to identify stations in Fig. 1. Data are primarily from the Historical Canadian Climate Database precipitation data from set A (Mekis and Hogg 1999) and temperature data (Vincent and Gullet 1999). All PDSI data were developed by W. Skinner of the Meteorological Service of Canada, Environment Canada. Jasper PDSI data were developed from daily as opposed to monthly data.

^aData are from the National Climate Data Archive.

^bData are from Luckman and Seed (1995).

^cData are from Mekis and Hogg (1999) set B.

(EW), and latewood (LW) ring-width chronologies and local climate records using simple Pearson product-moment correlation coefficients. These were calculated between each chronology and the full length of record (mean temperatures, total precipitation, and PDSI) from selected meteorological stations over monthly, seasonal, and annual windows. Calculations were limited to correlations with the two “closest” stations. In addition to straight-line distance, elevation and

topography were considered when selecting the most appropriate meteorological stations for analysis. This approach is physically realistic given the high spatial variability of precipitation in mountain areas because chronologies are more likely to be related to local rather than distant precipitation amounts. Chronologies may be correlated with more distant precipitation records, but such teleconnections reflect correlations between precipitation patterns (which may vary in

Table 3. Summary characteristics of the 10 co-located Douglas-fir and ponderosa pine chronologies.

Site name	Species ^a	Mean sensitivity	SD	AC(1)	Mean r_{mt}	Mean r_{wt}	Mean r_{bt}	No. trees for EPS = 0.85
Clinton	DF	0.24	0.28	0.41	0.58	0.73	0.58	4.2
Clinton	PP	0.20	0.27	0.55	0.58	0.75	0.57	4.3
Tranquille	DF	0.32	0.36	0.33	0.57	0.76	0.57	4.3
Tranquille	PP	0.26	0.33	0.58	0.59	0.85	0.56	4.5
Spatsum	DF	0.29	0.36	0.54	0.54	0.82	0.52	5.2
Spatsum	PP	0.24	0.34	0.66	0.64	0.85	0.63	3.4
Westwold	DF	0.23	0.26	0.38	0.59	0.93	0.55	4.6
Westwold	PP	0.18	0.25	0.56	0.40	0.71	0.39	9.0
Lillooet	DF	0.21	0.24	0.38	0.42	0.74	0.40	8.5
Lillooet	PP	0.19	0.22	0.48	0.43	0.61	0.42	7.8
Lytton	DF	0.25	0.28	0.40	0.46	0.73	0.44	7.1
Lytton	PP	0.26	0.31	0.55	0.49	0.89	0.46	6.8
Patriot	DF	0.31	0.31	0.37	0.57	0.81	0.56	4.4
Patriot	PP	0.27	0.32	0.48	0.40	0.76	0.38	9.2
Merritt	DF	0.26	0.28	0.40	0.52	0.82	0.51	5.4
Merritt	PP	0.17	0.22	0.57	0.52	0.71	0.52	5.3
Naramata	DF	0.22	0.25	0.47	0.55	0.83	0.53	5.0
Naramata	PP	0.22	0.25	0.43	0.36	0.69	0.34	10.9
Kettle River	DF	0.20	0.30	0.60	0.48	0.75	0.47	6.5
Kettle River	PP	0.17	0.26	0.65	0.45	0.77	0.44	7.4
Mean DF		0.25	0.29	0.43	0.53	0.79	0.51	5.52
Mean PP		0.22	0.28	0.55	0.49	0.76	0.47	6.85

Note: Mean sensitivity (Fritts 1976) and standard deviation (SD) values are calculated over the common period (1790–1996) for all 20 chronologies. r_{mt} , r_{wt} , and r_{bt} are the overall, within-tree, and between-tree mean correlations calculated over the 20th century (1900–1996) where there is maximum replication. AC(1) is the lag 1 serial correlation coefficient (1790–1996). The expressed population signal (EPS) is a measure of the statistical quality of a tree-ring chronology. Values ≥ 0.85 are considered desirable for dendroclimatic work (see Briffa 1995; Wigley et al. 1984; Briffa and Jones 1990). The final column presents the number of trees required to attain an EPS of 0.85 based on the r_{bt} values in the adjacent column.

^aDF, Douglas-fir; PP, ponderosa pine.

time; Cook et al. 1999) rather than the direct linkage between precipitation and tree growth.

This paper seeks to explore the spatial variability in the strength of chronology–climate relationships. Examination of these patterns is complicated by inherent limitations in the data available for analysis:

(1) The meteorological stations are not at the chronology sites and are at variable distances (horizontally and vertically) from the chronology sites.

(2) Differences in the strength and timing of correlations with climate between sites may reflect differences between growth conditions at the tree-ring sites rather than their location within the network.

(3) The instrumental records may be of varying quality.

(4) Differences in the strength of correlations may reflect differences in the period of time over which they were calculated.

(5) The closest precipitation, temperature, and PDSI records to each chronology site may differ because fewer temperature and PDSI records are available (Table 2).

(6) The chronology response to climate may differ with species.

All of these factors may influence the results of the subsequent analyses. Some of these factors may be assessed by subsampling the chronology data set (e.g., assessing the climate signal from chronologies of different species growing

at the same site), but others must remain as uncontrolled sources of variability in the relationships.

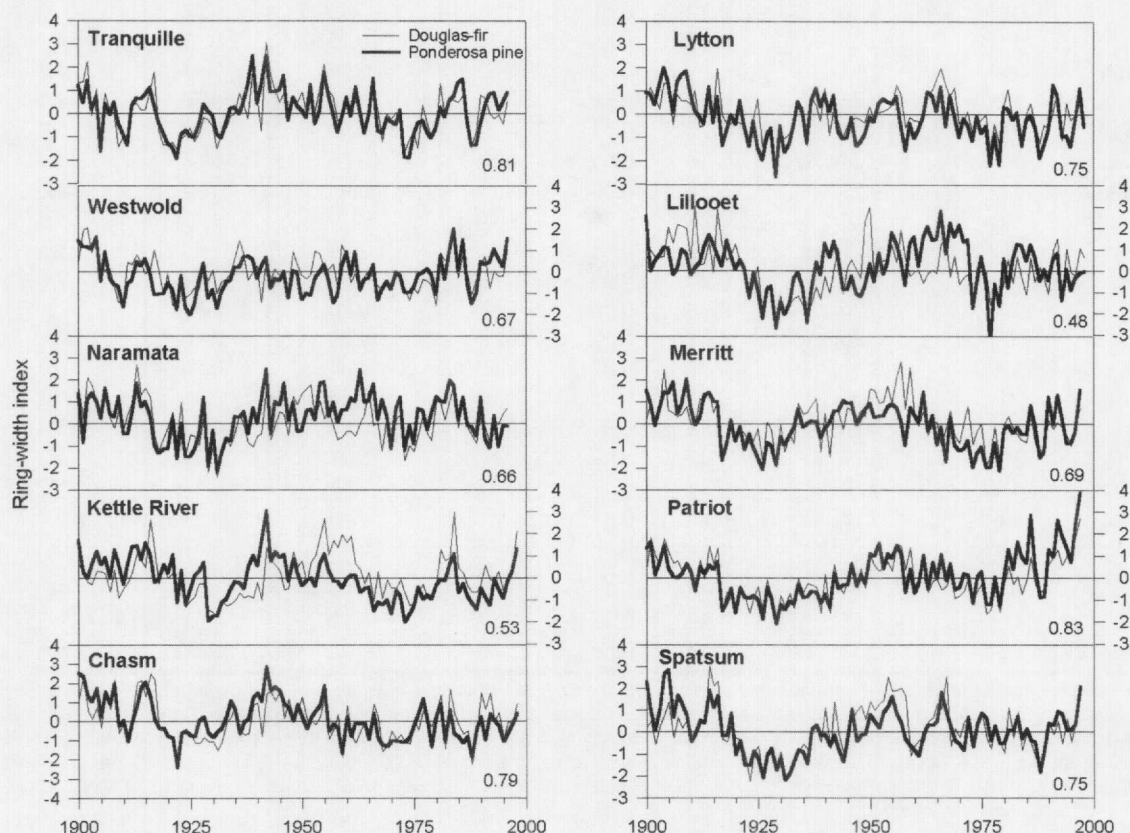
Chronology–climate relationships

Presentation of the results of the analysis of the climate signal in these 53 tree-ring chronologies is broken down into four major sections that utilize different data sets. The first section compares the climate signal in Douglas-fir and ponderosa pine chronologies from trees growing at the same site. The second section evaluates correlations between monthly climate records and the 40 Douglas-fir ring-width chronologies. Investigations then establish the best seasonal or annual correlations with ring widths in the Douglas-fir and ponderosa pine chronologies. Finally, differences between the climate signal in separate EW and LW chronologies from the same trees are evaluated. These analyses are presented sequentially and the major findings are discussed before proceeding to the next section.

Comparison of the climate signal in Douglas-fir and ponderosa pine

Douglas-fir and ponderosa pine were targeted for sampling because both species have proven useful in previous precipitation reconstruction work in the United States (e.g., Grissino-Mayer 1996; D'Arrigo and Jacoby 1991) and Canada (Watson and Luckman 2001a; Watson 1998; Robertson

Fig. 2. Time-series plots of standard Douglas-fir and ponderosa pine chronologies (1900 – ca. 1997; i.e., the period of instrumental record) for trees growing at the 10 sites with mixed stands. Correlation coefficients between each pair of chronologies are presented in the bottom right-hand corner of each plot. The chronologies were converted to standardized anomalies over their common period to facilitate comparison.



and Jozsa 1988). However, although the growth of both species is sensitive to precipitation, it is important to establish whether the climate signal differs in detail between the two species. Ten of the 43 sites sampled in the network supported mixed stands of Douglas-fir and ponderosa pine (Table 3). These co-located chronologies were used to evaluate differences in the tree-ring characteristics and climatic signal between the two species.

Results

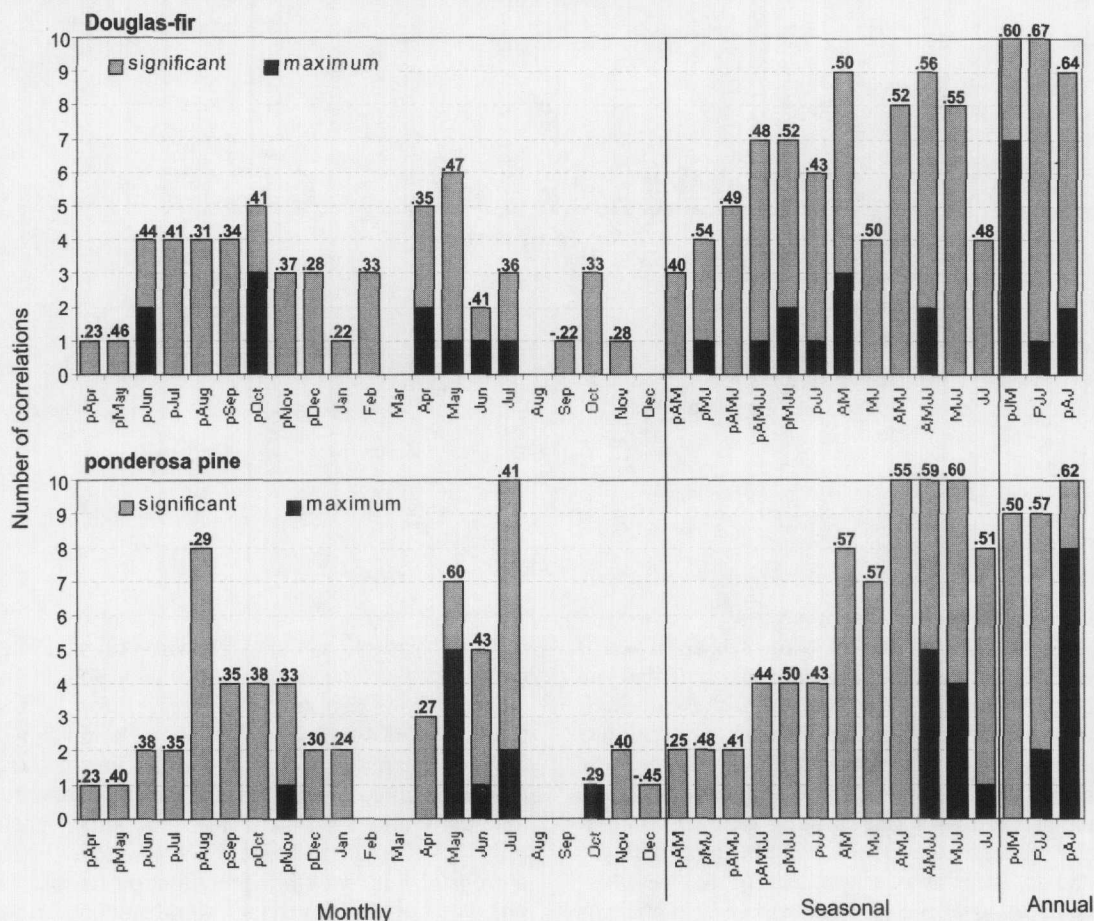
Mean summary statistics for the paired chronologies are presented in Table 3. Two-tailed independent sample *t* tests indicate that six of the mean pairings are not significantly different at the 0.05 level. However, the mean first-order autocorrelation value for ponderosa pine is significantly higher than that for the Douglas-fir chronologies ($p < 0.05$). Three of the 10 ponderosa pine chronologies also require a much greater number of trees (>9) to attain an EPS of 0.85. The paired chronologies show similar patterns of ring-width variation during the 20th century (Fig. 2). Correlation coefficients between the two records (Fig. 2) exceed 0.66 for all sites except Lillooet and Kettle River, although both species at these two sites correlate equally well with the other chronologies in this analysis. Visual comparison of these site chronologies with nearby chronologies of both species (Figs. 1 and 2, Table 1) suggests that local factors may have influenced the growth of the ponderosa pine chronologies from Kettle River (anomalously low growth in the middle to late

1950s) and Lillooet (exceptionally wide rings in the mid-1960s). Douglas-fir in interior British Columbia is known to suffer from infestations of the Douglas-fir tussock moth (*Orgyia pseudotsugata* (McDunnough)) and Douglas-fir beetle (*Dendroctonus pseudotsugae* (Hopk.)) (British Columbia Ministry of Forests 1995; Schmitz and Gibson 1996). The similarity in the chronologies of both species from the majority of sites (Fig. 2) is encouraging evidence that the ring-width records of these Douglas-fir stands do not appear to show major differential impacts of insect infestation during the 20th century.

Differences in the climate signal between the two species were evaluated by comparing statistically significant correlations ($p < 0.05$) calculated between the co-located chronologies and total monthly precipitation, mean monthly temperatures, and monthly PDSI. Ninety-six percent of the correlations between the chronologies and monthly precipitation are positive. The overall pattern of significant monthly correlations is similar for both species with the most notable differences being the greater numbers of statistically significant correlations exhibited by the ponderosa pine chronologies in the current spring–summer (May, June, and July) and in prior August (Fig. 3). Eight of the 10 ponderosa pine chronologies exhibit their maximum correlation with monthly precipitation during current May–July, and all 10 are significantly correlated with July precipitation.

Chronology correlations with seasonal and annual precipitation variables are higher than those with monthly precipita-

Fig. 3. Correlations between precipitation variables and Douglas-fir and ponderosa pine ring-width chronologies from trees at the same site. Shaded bars indicate the number of statistically significant ($p < 0.05$) correlations for each species (maximum 10) with monthly, seasonal, and annualized precipitation totals from the closest meteorological station. The solid bars indicate the number of chronologies that exhibit their maximum correlation with precipitation with that month, season, or annualization. The maximum statistically significant correlation coefficient for each analysis is given above each column.



tion totals (Fig. 3). The Douglas-fir chronologies exhibit a greater number of significant correlations with seasonalized precipitation from the year prior to growth than the ponderosa pine chronologies. There are few differences between the two species in the timing and number of significant correlations for the current season and annual totals (Fig. 3). However, maximum correlations with annual precipitation for the Douglas-fir generally occur with prior June–May (7 of 10) whereas 8 of the 10 ponderosa pine chronologies correlate most highly with prior August–July precipitation (Fig. 3). However, correlations between each chronology and precipitation in the three annual periods are never significantly different ($p < 0.05$). The overall means of the statistically significant correlations with precipitation (monthly, seasonal, and annual) are similar for both species (Douglas-fir, $r = 0.35$; ponderosa pine, $r = 0.36$).

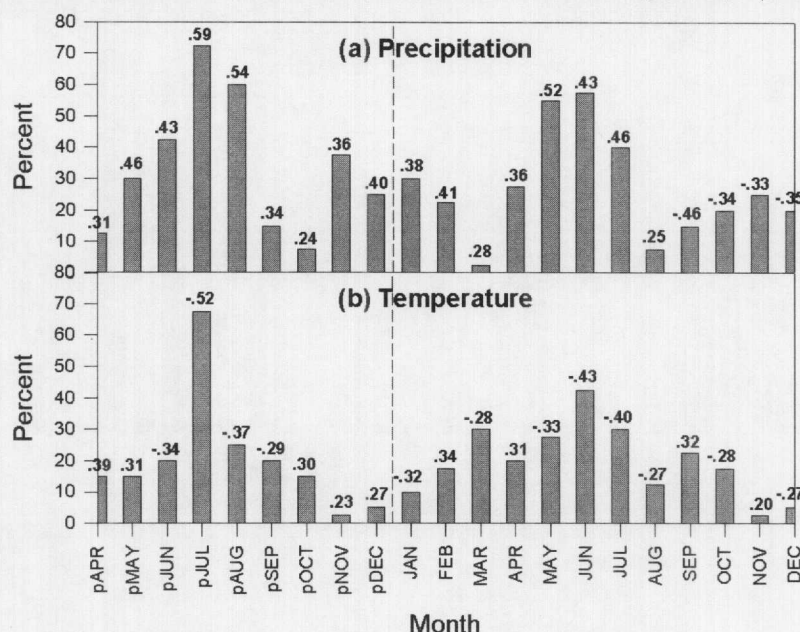
The majority of chronology–temperature correlations are negative and generally weaker (only 12% exceed $|0.30|$ and none are $>|0.33|$) and less numerous than those with monthly precipitation. Correlations between the 10 co-located chronologies and monthly PDSI are all positive and consistently higher than those with monthly temperature or precipitation. Monthly PDSI values represent conditions over a longer time period than a single month and are, there-

fore, more appropriately compared with the seasonal and annual precipitation results. In most cases, chronology pairs are significantly correlated with PDSI in the same months. Notable exceptions are Kettle River and Lillooet (the two sites with the lowest between-species correlations, Fig. 2). The mean correlations with PDSI over all months are similar for the two species (Douglas-fir, $r = 0.31$ ($n = 122$) and ponderosa pine, $r = 0.30$ ($n = 107$)).

Discussion

Similarities between the two species in statistical characteristics (Table 3) and ring-width variability at interannual and longer time scales (Fig. 2) are encouraging evidence that growth responds to similar limiting factors (i.e., their ring-width records possess a similar climatic signal). Both species exhibit strong, predominantly positive relationships with PDSI and precipitation (especially with seasonal and annual precipitation totals) and weaker negative correlations with temperature. However, the distribution of maximum correlations with monthly and particularly annual precipitation suggests that the Douglas-fir chronologies respond to precipitation earlier in the year than do the ponderosa pine chronologies. This difference may be attributable to the fact that Douglas-fir needles are fully grown and photo-

Fig. 4. The percentage of Douglas-fir chronologies ($n = 40$) showing significant correlations ($p < 0.05$) with (a) monthly precipitation totals and (b) monthly mean temperature from one of the two most proximal meteorological stations. The value above each column indicates the maximum correlation with each month. The 95% confidence limit varies but is generally $>|0.25|$.



synthetically active early in the growing season whereas needles in ponderosa pine are not fully formed until later in the growing season (Fritts 1976). Therefore, the chronologies from the two species may each contribute some unique information to a climatic reconstruction. However, these slight differences may also introduce complications to the analysis of spatial patterns of ring width – climate relationships, especially because the ponderosa pine chronologies are concentrated in the southwestern part of the network. Douglas-fir occurs at 40 of the 43 sites sampled, so analysis of the spatial patterns of response is restricted to the Douglas-fir chronologies.

Correlations between the Douglas-fir chronologies and monthly climate records

The nature of the climate signal within and across the chronology network was investigated through correlation analyses between monthly climatic parameters (precipitation and PDSI) and ring width of the 40 Douglas-fir chronologies. This permits a rapid assessment of the commonality of the climate signal in these chronologies. A strong common signal is an important indication that the chronologies are responding to the same climatic parameter(s) in the same way and that a useful network of reconstructions may be developed to explore the variability of the climatic parameter across the region through time.

Results

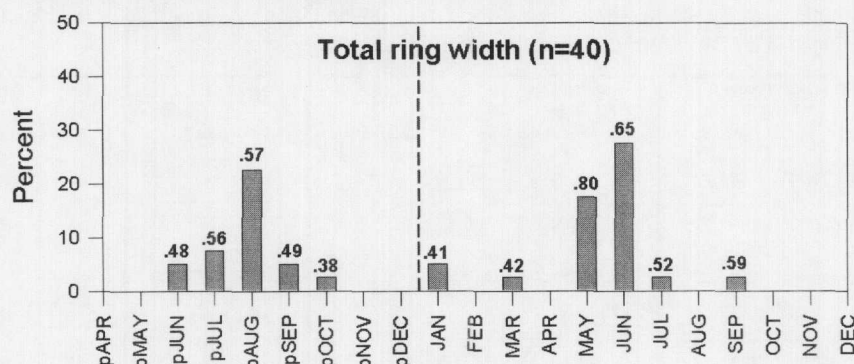
Precipitation

Eighty-nine percent of the correlations between the 40 Douglas-fir ring-width chronologies and total monthly precipitation from the closest meteorological stations are positive, indicating that overall wet (dry) conditions result in

wide (narrow) annual growth rings. These positive correlations are consistent with many previous studies using conifers from semi-arid sites (e.g., Fritts 1976; Watson and Luckman 2001a) and reflect the relationship between precipitation and soil moisture levels. Current-year September, November, and December are the only months when negative correlations considerably outnumber positive correlations. Although individual chronologies can be highly correlated with monthly precipitation (as high as 0.59; Fig. 4a), 90% of the significant monthly correlation coefficients are <0.40 .

Many chronologies correlate significantly with precipitation in the winter and summer prior to the growing season and current spring–summer (Fig. 4a). The largest percentages of the chronologies are significantly correlated with prior June, July, and August precipitation (43, 73, and 60%, respectively). Maximum precipitation for most of the meteorological stations in Table 2 generally occurs in June–July with minima during February–April. In the current year, the majority of chronologies are significantly correlated with precipitation in spring (May and June). This indicates that for the majority of chronologies, ring-width variation is controlled by precipitation near the end of the prior growing season and by moisture availability in the spring of the year of growth. On average, about 30% of the chronologies are also positively correlated with winter precipitation (prior November to current February), which may indicate that snowier winters lead to greater soil moisture recharge in spring. Unfortunately, these chronologies are scattered throughout the network and show no coherent spatial or elevational pattern. The distribution of statistically significant correlations with monthly precipitation for the 10 ponderosa pine chronologies (Fig. 3) more closely resembles the pattern of Douglas-fir correlations in Fig. 4a (based on 40

Fig. 5. The percentage of Douglas-fir ring-width chronologies ($n = 40$) that exhibit their maximum correlation with PDSI in each month. The value above each column is the maximum correlation with each month.



chronologies) than it does the summary based on the 10 co-located Douglas-fir chronologies (Fig. 3).

Temperature

Many studies have documented statistically significant inverse correlations between ring-width chronologies developed from arid–semi-arid site conifers and temperature during summer months (e.g., Fritts 1974). Seventy-two percent of the statistically significant ($p < 0.05$) correlations between monthly mean temperatures from proximal stations and the 40 ring-width chronologies are negative. Negative correlations prevail during growing season months (mainly May–July) indicating that high temperatures, which increase evaporative losses and water stress, are detrimental to tree growth. Conversely, lower temperatures, which reduce evaporation, are beneficial to tree growth. Positive correlations predominate for some months outside the current growing season including February, September and previous April, May, and October. Chronology–temperature correlations are generally lower than those with precipitation (Fig. 4) and partially reflect the inverse relationship between precipitation and temperature in the region. The chronologies appear to have a narrower window of response to mean monthly temperatures (Fig. 4b) than monthly precipitation (Fig. 4a) particularly in the prior summer. There are also far fewer statistically significant correlations with winter temperatures than with winter precipitation.

The correlations with monthly mean temperatures are of consistent sign and magnitude to those seen for other chronologies from similar dry regions (e.g., Case and MacDonald 1995). However, the five RW chronologies from the Waterton region are more highly correlated with temperature during previous July and August (r values range from -0.39 to -0.52) than they are with precipitation in any month. Such negative correlations with prior summer temperatures are characteristic of many upper tree line, temperature sensitive chronologies (e.g., Ettl and Peterson 1995; Wilson and Luckman 2002; St. George and Luckman 2001). The differences in signal in these Waterton chronologies may be related to the fact that they are the highest elevation sites in the network (1450–1800 m; Table 1).

Palmer Drought Severity Index (PDSI)

Ring-width chronologies are significantly correlated with PDSI records in almost all months because considerable

month-to-month persistence is incorporated in the derivation of the PDSI (coefficient for the previous month is 0.897; see Hu and Wilson (2000) for details). The pattern of maximum correlations between the 40 chronologies and monthly PDSI is similar to that for precipitation (not shown) with the greatest number correlations concentrated in the previous and current summers (Fig. 5). The median correlation for the 40-chronology data set is 0.47, with coefficients ranging as high as 0.80 (between May PDSI at Jasper and the Pyramid Lake RW chronology; Fig. 5). The monthly PDSI correlations are consistently higher than those for monthly precipitation or temperature because the PDSI values actually represent conditions integrated over several months. For example, correlation coefficients between June PDSI and annual precipitation range from 0.60 to 0.87 for prior July to current June and from 0.68 to 0.88 for a prior August to current July annualization (based on 17 meteorological stations in Table 2). Correlations between the PDSI records and monthly temperature for years t and $t - 1$ are predominantly negative but weak, and few are significant at the 0.05 level.

Correlations between Douglas-fir and ponderosa pine ring-width chronologies and seasonal and annual climate records

Radial tree growth (i.e., ring width) often correlates more highly with seasonal precipitation totals than with individual monthly values. Based on the monthly analyses above, the relationships between the chronologies and proximal precipitation and PDSI records were evaluated over several monthly combinations for the current and prior growth years (Table 4). Previous studies (e.g., Duvick and Blasing 1981; Stockton and Meko 1983; Case and MacDonald 1995) have demonstrated that RW chronologies from semi-arid sites can be used to develop well-verified reconstructions of total annual precipitation over an interval that encompasses part of the current and previous year's climate data. Such correlations are successful because radial growth in any year (i.e., the annual ring) in moisture-stressed trees is often related to a climatic window that includes part of the previous and current summers. Six annual reconstructions have previously been developed from chronologies in the current data set (Watson 1998; Watson and Luckman 2001a). Based on these results, correlations were calculated between the ring-width

Table 4. (A) Correlations between the 53 total ring-width chronologies and three precipitation annualizations, plus maximum correlations with monthly precipitation and monthly and (or) seasonal PDSI where correlations are calculated using the same meteorological station for each climate variable and (B) the maximum correlation with precipitation and (or) PDSI variables for each chronology where correlations are calculated with data from the closest meteorological station.

(A)	Annual Precip.				Max. Seasonal				Max. PDSI				(B)	Max.	Climate			
Douglas-fir	pJM	pJJ	pAJ	Station	r	Season	Station	r	Season	Station	Douglas-fir	r	variable	Season	Station			
Pinchi Lake	0.07	0.18	0.18	2	0.46	AMJJ	2	0.59	Sep	2	Pinchi Lake	0.59	PDSI	Sep	2			
Coffeepot	0.49	0.50	0.45	3	0.44	AMJJ	3	0.56	JJA	3	Coffeepot	A	0.56	PDSI	JJA	3		
Prince George	0.30	0.34	0.26	3	0.25	pJJ	3	0.31	Jun	3	Prince George	A	0.34	Precip	pJJ	3		
Dome Creek	0.21	0.20	0.14	8	0.37	pMJJ	8	0.34	pJul	8	Dome Creek	0.42	Precip	MJJ	7			
Fort George	0.56	0.58	0.52	3	0.57	AM	3	0.59	Jun	3	Fort George	A	0.59	PDSI	Jun	3		
Maligne Canyon	0.55	0.61	0.63	10	0.55	AMJJ	10	0.76	MJJ	10	Maligne Canyon	A	0.76	PDSI	MJJ	10		
Pyramid Lake	0.60	0.64	0.65	10	0.53	AMJJ	10	0.80	May	10	Pyramid Lake	A	0.80	PDSI	May	10		
Lake Annette	0.53	0.59	0.57	10	0.42	AMJJ	10	0.50	May	10	Lake Annette	A	0.59	Precip	pJJ	10		
Prairie de la Vache	0.59	0.60	0.56	10	0.47	AMJ	10	0.79	Jun	10	Prairie de la Vache	A	0.79	PDSI	Jun	10		
Horsefly Lake	0.40	0.38	0.37	9	0.29	pMJJ	9	0.35	pAug	9	Horsefly Lake	A	0.40	Precip	pJM	9		
Bull Canyon	0.50	0.49	0.47	9	0.33	pJJ	9	0.41	pAug	9	Bull Canyon	0.52	Precip	pAJ	12			
Two o'clock Creek	0.59	0.59	0.52	16	0.39	pAMJJ	16	0.53	May	16	Two o'clock Creek	0.60	Precip	pJM	10			
Deer Park	0.50	0.49	0.43	13	0.39	pMJJ	13	0.54	pAug	13	Deer Park	0.62	Preicp	pJJ	11			
Lac la Hache	0.43	0.32	0.26	18	0.46	pMJJ	18	0.43	pAug	18	Lac la Hache	0.61	Precip	pJJ	11			
Gang Ranch	0.31	0.28	0.18	18	0.34	pMJJ	18	0.39	pAug	18	Gang Ranch	0.57	Precip	pJM	12			
Bridge Lake	0.50	0.46	0.45	13	0.49	pAMJJ	13	0.57	pAug	13	Bridge Lake	A	0.57	PDSI	pAug	13		
Churn Creek	0.29	0.22	0.16	18	0.36	pMJJ	18	0.31	pAug	18	Churn Creek	0.49	Precip	pJM	12			
Indian Meadows	0.34	0.30	0.21	18	0.45	pMJJ	18	0.44	pAug	18	Indian Meadows	0.44	PDSI	pAug	18			
Chasm	0.28	0.26	0.17	18	0.43	pMJJ	18	0.43	pAug	18	Chasm	0.43	PDSI	pAug	18			
Powerhouse	0.64	0.70	0.61	16	0.50	AMJJ	16	0.58	MJJ	16	Powerhouse	A	0.70	Precip	pJJ	16		
Pavilion Lake	0.32	0.22	0.18	18	0.48	pMJJ	18	0.41	pJul	18	Pavilion Lake	0.64	Precip	pJM	19			
Tranquille	0.51	0.51	0.49	13	0.40	AMJJ	13	0.48	MJJ	13	Tranquille	A	0.51	Precip	pJJ	13		
Spatsum	0.21	0.10	0.09	18	0.34	pJJ	18	0.27	pJul	18	Spatsum	0.51	Precip	pJM	19			
Westwold	0.35	0.26	0.21	18	0.36	pJJ	18	0.25	pSep	18	Westwold	0.50	Precip	pJM	20			
Lillooet	0.29	0.26	0.24	31	0.31	pMJJ	31	0.32	May	31	Lillooet	0.46	Precip	pJM	19			
Lytton	0.32	0.28	0.30	31	0.20	pMJJ	31	0.19	pSep	31	Lytton	0.62	Precip	pAJ	19			
Patriot	0.48	0.45	0.48	31	0.39	pMJ	31	0.48	MJJ	31	Patriot	0.60	Precip	pJM	19			
Merritt	0.42	0.38	0.41	31	0.22	pMJ	31	0.33	May	31	Merritt	0.53	Precip	pAJ	19			
Wasa Lake	0.55	0.57	0.58	27	0.44	AMJJ	27	0.58	MJJ	27	Wasa Lake	A	0.58	Precip	pAJ	27		
Naramata	0.60	0.67	0.64	28	0.56	AMJJ	28	0.62	MJJ	28	Naramata	A	0.67	Precip	pJJ	28		
Perry Creek	0.67	0.68	0.66	27	0.44	AMJ	27	0.60	Jun	27	Perry Creek	A	0.68	Precip	pJJ	27		
Keremeos	0.49	0.44	0.37	28	0.41	pMJJ	28	0.51	pAug	28	Keremeos	A	0.51	PDSI	pAug	28		
Kettle River	0.37	0.33	0.25	28	0.35	pMJJ	28	0.39	pSep	28	Kettle River	0.49	Precip	pJM	35			

Table 4 (concluded).

(A)										
Ruby Ridge	0.35	0.38	0.36	38	0.42	AMJ	38	0.47	JJ	38
Mt. Crandell	0.35	0.35	0.30	41	0.23	pMJJ	41	0.36	May	41
Golf Course	0.36	0.39	0.38	38	0.49	AMJ	38	0.54	JJA	38
Lost Horse Creek	0.38	0.45	0.45	41	0.42	MJJ	41	0.42	Jun	41
Chief Mountain	0.50	0.51	0.47	41	0.43	pMJJ	41	0.44	pSep	41
Skemeoskaunkin	0.57	0.55	0.47	28	0.45	pMJJ	28	0.56	May	28
Osoyoos	0.57	0.56	0.43	28	0.48	pJJ	28	0.51	Jun	28
ponderosa pine										
Chasm	0.20	0.22	0.20	18	0.34	MJ	18	0.33	pAug	18
Tranquille	0.35	0.39	0.40	13	0.37	JJ	13	0.43	pSep	13
Fritts	0.34	0.41	0.43	13	0.37	JJ	13	0.44	pSep	13
Spatsum	0.21	0.20	0.21	18	0.19	pJJ	18	0.27	pJul	18
Westwold	0.34	0.39	0.40	18	0.36	pJJ	18	0.33	pSep	18
Lillooet	0.24	0.22	0.24	31	0.13	pAMJ	31	0.20	pSep	31
Lytton	0.31	0.31	0.35	31	0.15	pMJJ	31	0.20	Jul	31
Patriot	0.46	0.45	0.51	31	0.43	JJ	31	0.50	JJ	31
Merritt	0.25	0.27	0.32	31	0.42	MJJ	31	0.40	JJ	31
Bald Range	0.42	0.42	0.44	28	0.21	AMJJ	28	0.37	MJJ	28
Naramata	0.43	0.56	0.62	28	0.60	MJJ	28	0.62	MJJ	28
Shuttleworth Creek	0.54	0.61	0.65	28	0.57	AMJJ	28	0.64	MJJ	28
Kettle River	0.26	0.33	0.36	28	0.40	MJJ	28	0.35	MJJ	28

(B)					
Ruby Ridge	0.48	Precip	MJJ	24	
Mt. Crandell	0.40	Precip	pJJ	40	
Golf Course	0.54	PDSI	JJA	38	
Lost Horse Creek	0.54	Precip	pJJ	40	
Chief Mountain	0.58	Precip	MJJ	24	
Skemeoskaunkin	0.73	Precip	pJM	35	
Osoyoos	0.67	Precip	pJM	35	
ponderosa pine					
Chasm	0.49	Precip	MJJ	12	
Tranquille	0.43	PDSI	pSep	13	
Fritts	0.44	PDSI	pSep	13	
Spatsum	0.45	Precip	pAJ	19	
Westwold	0.57	Precip	pJJ	20	
Lillooet	0.51	Precip	pJJ	21	
Lytton	0.68	Precip	pAJ	21	
Patriot	0.57	Precip	pAJ	19	
Merritt	0.53	Precip	pAJ	19	
Bald Range	A	0.44	Precip	pAJ	28
Naramata	A	0.62	Precip	pAJ	28
Shuttleworth Creek	0.67	Precip	pAJ	35	
Kettle River	0.59	Precip	MJJ	32	

Note: In Table 4A, the maximum correlation for each chronology is highlighted. All maximum correlations are statistically significant ($p = 0.05$). Chronologies are listed from north to south for each species. The station number refers to the meteorological stations identified in Table 2. The annualizations used are pJM (previous June to current May), pJJ (previous July to current June), pAJ (previous August to current July). AM, MJ, AMJ, AMJJ, and JJ are April–May, May–June, April–June, April–July, and June–July, respectively. In Table 4B, the designation A next to the chronology name indicates that the meteorological station used is the same as that in Table 4A. The station identified in the right-hand column is the station with the highest correlation coefficient. Grey shading indicates that the maximum correlation has increased but is with the same variable (i.e., precipitation). Black boxes indicate that the maximum correlation has increased from that shown in Table 4A but that the most highly correlated variable has changed from PDSI to precipitation.

chronologies and various annualizations of proximal precipitation records.

Results

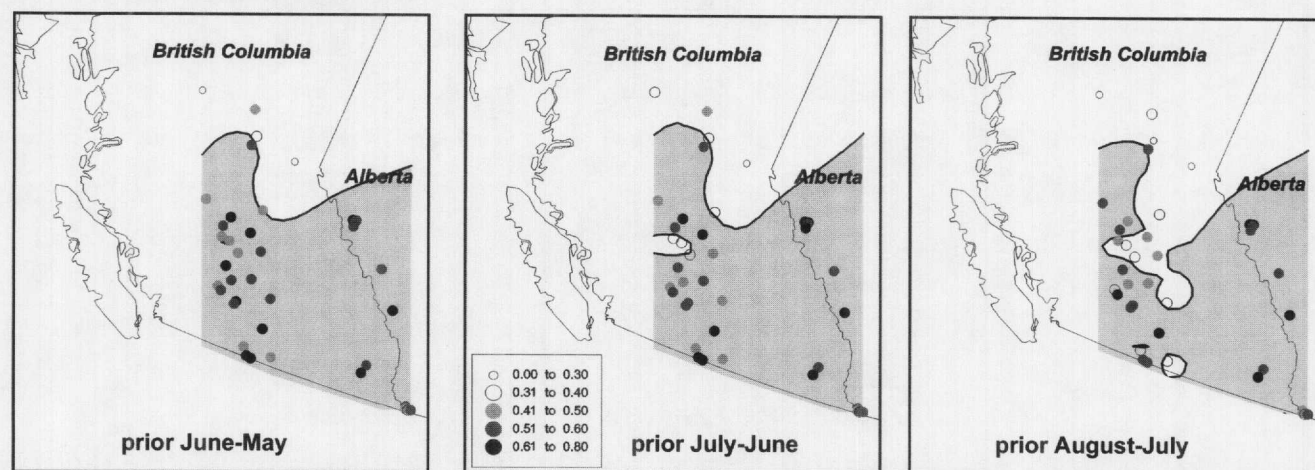
Comparison of correlations with precipitation and PDSI

Correlations between the 53 ring-width chronologies and seasonal and annual variables from the same meteorological station are presented in Table 4A. Mean maximum correlations are similar for the two species (Douglas-fir, $r = 0.57$; ponderosa pine, $r = 0.54$). Roughly equivalent numbers of the 40 Douglas-fir chronologies are most highly correlated with precipitation variables (seasonal or annual) and PDSI. The majority of the ponderosa pine chronologies exhibit their maximum correlation with precipitation (10 precipitation : 3 PDSI). However, the actual differences between the

maximum correlations with PDSI and precipitation for each chronology are minimal (in 85% of the 53 cases the two correlation coefficients differ by <0.10). This suggests that either variable could effectively be used to reconstruct precipitation-related patterns from most of these sites and there is little comparative advantage in using PDSI.

The current network of PDSI measurements was developed for sites that have both long precipitation and temperature records corrected by the MSC (Mekis and Hogg 1999; Vincent and Gullet 1999). In this region, the MSC data set contains more precipitation than temperature or PDSI records, and for many of the tree-ring sites, the closest high-quality climate record is only for precipitation variables. Therefore, the precipitation analyses reported in Table 4A were repeated using data from the most proximal precipitation record for 36 of the chronologies (Table 4B). The ring-

Fig. 6. The spatial patterns of correlation between annual precipitation and Douglas-fir ring width. Three annualizations are shown for the most proximal precipitation station to each of the 40 chronology sites (see Table 4B). The bold 0.45 isoline defines the lower quartile of statistically significant correlations.



width precipitation correlations increased for 83% of these cases with an average increase of 0.15 and 40% increasing by >0.15 . In this revised analysis (Table 4B), the maximum correlations for each chronology occur most often with annual (66%) and seasonal (9%) precipitation, and only 25% of the chronologies are most highly correlated with PDSI. There are only six cases in which the correlation with PDSI from a more distant site exceeds the maximum correlation from a seasonalized precipitation parameter at a more proximal site. These results indicate (as one might expect in mountain environments) that tree ring – climate relationships improve when more proximal meteorological records are used. Therefore, given the greater availability of high-quality precipitation records and their greater propinquity to the tree-ring sites, better quality proxy climate records (in terms of percentage of variance explained in calibration) can generally be derived for precipitation variables than for PDSI. There is no advantage to be gained by using PDSI measures, as in many cases, there are better correlations with more proximal precipitation records.

Maximum correlations for the Douglas-fir and ponderosa pine chronologies (Table 4B) occur mainly with annual precipitation. The range of correlation coefficients with annual precipitation is similar for the two species (Douglas-fir, $r = 0.34$ – 0.73 ; ponderosa pine, $r = 0.45$ – 0.68 ; Table 4B), but the maximum correlations occur with precipitation totals for slightly different annualizations: prior June–May or prior July–June for Douglas-fir and prior August to current July for the ponderosa pine chronologies. In many cases, however, chronology–precipitation correlations are not dramatically different with the three annual periods.

The correlations described above assess covariation between the chronologies and climate data at both high and low frequencies. First-difference series (Cook 1992) were generated for records identified as the maximum chronology–climate pairings in Table 4B (not shown) to assess the correlations independently of any common low frequency trends in these series. Although the first-differenced correlations were lower in the majority of cases, there is a similar pattern and range of correlation coefficients using the unfiltered and first-differenced series. This indicates that

most of the significant chronology–climate correlations occur over a range of frequencies.

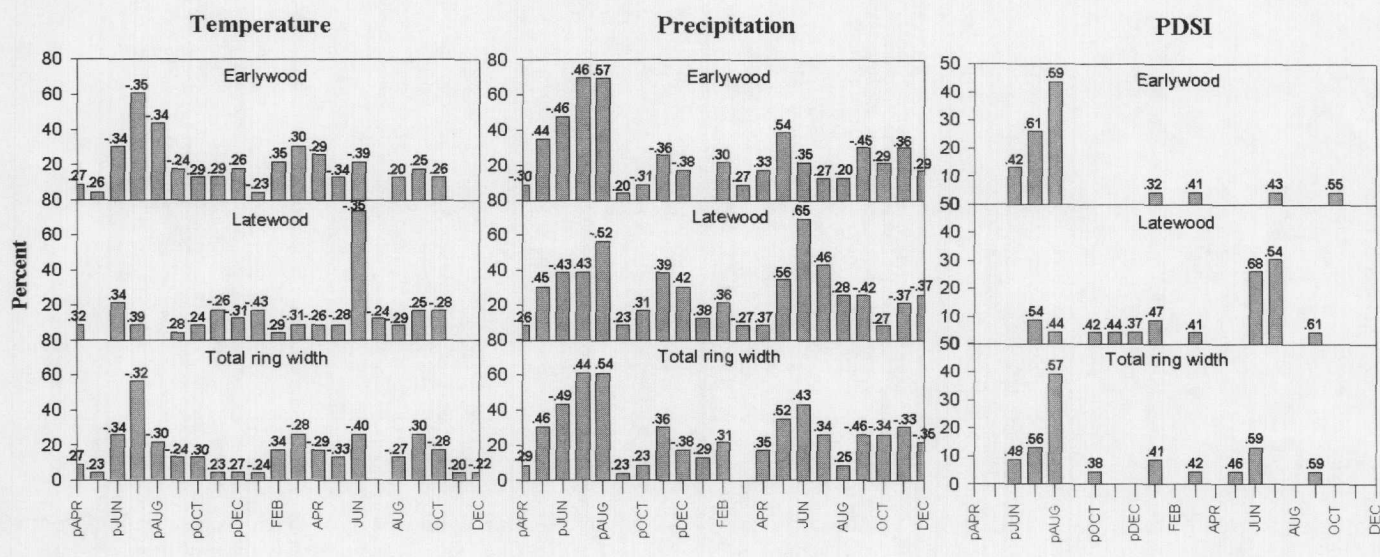
Spatial patterns in chronology–climate relationships

Examination of the annual precipitation signal in Douglas-fir appears to show some systematic variation across its range particularly as it approaches its northern limit (Fig. 6). These differences are not unexpected because the more northerly stands were less open and more diverse with isolated Douglas-fir growing in mixed stands including western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.), and subalpine fir. The two most northerly chronologies (Pinchi Lake and Coffeepot) are most highly correlated with PDSI (Table 4B). The Pinchi Lake and Dome Creek chronologies have weak or nonsignificant correlations with annual precipitation but are correlated with seasonal precipitation; unlike the majority of chronologies they are not correlated with precipitation in the prior growing season.

The maximum correlation coefficients for each chronology (the highlighted values in Table 4B) range from 0.34 to 0.80. The two lowest maximum chronology–climate correlations are both in the northern area, Prince George ($r = 0.34$) and the comparatively wet site adjacent to Horsefly Lake ($r = 0.40$, Table 4B). Fifty percent of the maximum seasonal correlations lie between 0.51 and 0.62 for Douglas-fir and 0.49 and 0.59 for ponderosa pine. The highest correlations are between the Maligne Canyon, Pyramid Lake, and Prairie de la Vache chronologies and Jasper PDSI. Although these sites are within 10 km of the climate station, the correlations with Jasper are based on the shortest PDSI record (1953–1995); correlations between the Jasper chronologies and annual precipitation are also considerably higher during this interval than over the full length of record (1936–1995).

In this study, the chronologies with a strong common signal (higher between-tree correlations) tend to correlate well with climate variables. However, several chronologies along the Fraser River (Churn Creek, Indian Meadows, Gang Ranch, and Clinton) have a strong common signal (Watson and Luckman 2001b) but weak correlations with climate that probably reflect their comparatively greater distances (~55–

Fig. 7. Significant correlations ($p < 0.05$) between earlywood, latewood, and total ring-width Douglas-fir chronologies and total monthly precipitation, mean temperature, and PDSI. Bar height represents the percentage of the chronologies ($n = 23$) showing statistically significant correlations with each climate variable from one of the two most proximal meteorological stations. The maximum correlation is shown above each column. The 95% confidence limit varies but is generally met by correlations $>|0.25|$.



125 km) from the closest meteorological stations. The Tranquille and Fritts chronologies also display low correlations with the instrumental precipitation record from Kamloops (Table 4). This may be related to the concentration of variance at high frequencies in the Kamloops precipitation record (Watson 1998).

Evaluation of the climate signal in the earlywood and latewood chronologies

Separate EW and LW chronologies were developed for 23 Douglas-fir and 5 ponderosa pine chronologies concentrated in the western half of the network (Table 1, Fig. 1). Correlation analyses were used to evaluate possible differences in the precipitation signal in EW and LW chronologies of Douglas-fir and ponderosa pine in British Columbia.

Results

Statistically significant ($p < 0.05$) correlations between monthly precipitation records and 23 EW, LW, and RW Douglas-fir chronologies are summarized in Fig. 7. It is immediately apparent that the EW and LW chronologies are most strongly correlated with precipitation during different years. Seventy percent of the LW chronologies are significantly correlated with current June precipitation. Maximum correlations for 16 of the 23 LW chronologies are with spring-summer (April–August) precipitation in the year of growth with the greatest number in June (not shown). A greater percentage of the LW chronologies are also correlated with winter precipitation (November–February).

The EW chronologies are most consistently correlated with previous June, July, and August precipitation (Fig. 7), and the greatest number of maximum correlations are with prior August. Unlike the LW chronologies, comparatively few EW chronologies are significantly correlated with precipitation in the current summer. This suggests that moisture

conditions late in the growing season (July–August) have a strong influence on the EW component of the growth ring in the following year.

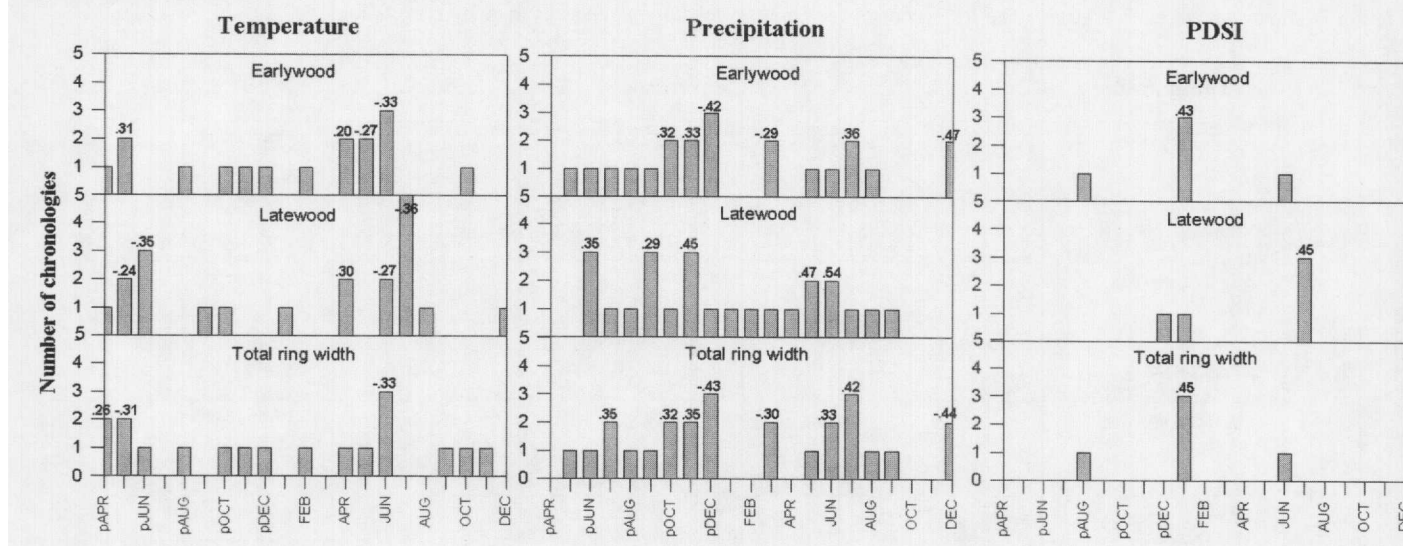
In the RW subset (Fig. 7), the pattern of significant correlations with precipitation most resembles that of the EW chronologies, with the greatest percentage of chronologies significantly correlated with previous July and August precipitation. This would be expected considering that earlywood accounts for 75–80% of the annual ring. The correlation pattern for RW in Fig. 7 differs slightly from that shown for the full data set (Fig. 4a) because this subset of chronologies is clustered in the western and northern parts of the network (Table 1; Watson and Luckman 2001b).

Most EW and RW chronologies are correlated with June–August temperatures of the previous year, and about 20% are also correlated with temperatures in current March–June (Fig. 7). Seventy-four percent of the LW chronologies are significantly correlated with June temperatures but the correlations are weak, never exceeding -0.35 . Although the LW chronologies correlate most frequently with June temperature and precipitation, the significant correlations with current summer precipitation cover a much broader window (May–August; Fig. 7).

The 23 EW and RW chronologies are most consistently and strongly correlated with PDSI in previous July and August, whereas the LW chronology correlations are consistently highest with June and July PDSI of the growth year (Fig. 7). Maximum correlations for the full 40 Douglas-fir RW chronology data set are more heavily concentrated in current May, June, and July (Fig. 5).

The distribution of statistically significant correlations between the five EW, LW, and RW ponderosa pine chronologies and monthly temperatures, precipitation, and PDSI is shown in Fig. 8. The ponderosa pine distribution for the LW chronologies is similar to that for the 23 Douglas-fir chro-

Fig. 8. The number of significant correlations ($p < 0.05$) between the five ponderosa pine earlywood, latewood, and total ring-width chronologies and total monthly precipitation, mean temperature, and PDSI. Maximum correlations are shown for months with >1 significant correlation.



nologies for temperature and PDSI (Fig. 7) with consistent correlations with current summer. However, the pattern of significant correlations between the EW and RW ponderosa pine chronologies and the three climate parameters lack the significant correlations with prior summer conditions.

Discussion

The results presented in the previous section indicate that the EW and LW Douglas-fir chronologies contain different climate signals. However, the nature of the differences are somewhat unexpected. Studies in Mexico (Stahle et al. 1998, 1999) have documented relationships between EW and winter – early spring precipitation. Latewood ring-width chronologies from the southwestern United States have been used to explore the variability of summer precipitation (the North American monsoon: Meko 2000; Meko and Baisan 2001). Although the LW chronologies discussed in this study show a strong summer signal, the EW chronologies lack the winter–spring signal demonstrated for chronologies further south and are most strongly correlated with precipitation at the end of the previous growing season. These differences are probably related to differences in the length and timing of the growing season between the subtropical U.S.–Mexico and the southern Canadian Cordillera. They may also reflect the differences in the proportion of winter precipitation that falls as snow, i.e., most winter precipitation does not penetrate the ground and become available to trees until after spring snowmelt.

Previous reconstructions of precipitation in southern Canada (Case and MacDonald 1995; Watson and Luckman 2001a; Watson 1998; Sauchyn and Beaudoin 1998) have used total ring-width chronologies to develop models that hind cast annual (summer–summer) precipitation. The results presented above suggest that separate EW and LW chronologies can be used to develop precipitation reconstructions for current summer alone using Douglas-fir with LW of the current year and EW from the following year as predictors. The results in Figs. 7 and 8 suggest that these parameters are both related to the same season although with

slightly different windows. LW chronologies reflect conditions during June and July, and EW chronologies relate to the previous July and August.

Summary and conclusions

Douglas-fir and ponderosa pine in the southern Canadian Cordillera exhibit predominantly positive correlations with monthly (mainly summer) precipitation and PDSI and weaker negative correlations with mean monthly temperatures. Maximum correlations for both species are generally with annual precipitation totals seasonalized as prior June–May, prior July–June, and prior August–July with values ranging from 0.34 to 0.73. There are slight differences in the seasonal window of response registered by the Douglas-fir and ponderosa pine chronologies: Douglas-fir is more strongly correlated with prior June–May or prior July–June, and ponderosa pine with prior August–July. Although correlations with PDSI have often been used as preferred indicators of drought stress, our results indicate that in these environments, correlations between ring width and annual or seasonal precipitation totals are marginally better than those with PDSI from the same station. Moreover, our results indicate that proximity to the climate station is a significant control of the strength of the climate – tree ring relationships. Therefore, given the greater availability of precipitation records in this region (and their greater proximity to chronology sites), reconstruction of annualized precipitation totals will probably provide the best representation of the spatial patterns of drought in this region.

There is little coherent geographical variation in the relationship between the precipitation records and tree-ring chronologies. The main sources of variability appear to be the separation between the tree-ring and meteorological sites and local conditions that influence either tree growth or the meteorological record at individual locations. However, there is some evidence that the more northerly Douglas-fir

sites and those at higher elevations in the Waterton Lakes area have a weaker precipitation signal.

Douglas-fir and ponderosa pine contain distinctly different climate signals in the EW and LW components of the annual ring. EW widths in Douglas-fir correlate most highly with precipitation in the latter half of the previous summer, whereas variability in LW width is more closely related to precipitation in the current spring–summer. The strong relationship between the LW-width chronologies and summer precipitation suggest that it may be possible to reconstruct both summer and annual precipitation totals.

The strong precipitation signal in these chronologies confirms the potential of using these species for the reconstruction of past precipitation and drought assessment shown in more limited studies by Watson and Luckman (2001a). Moreover the lack of major spatial variation in the nature of the climate signal retained in these chronologies indicates that a network of high-quality annual precipitation reconstructions can be developed using chronologies from either Douglas-fir or ponderosa pine.

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