TREE-RING BASED RECONSTRUCTIONS OF PRECIPITATION FOR THE SOUTHERN CANADIAN CORDILLERA

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Abstract. This paper reconstructs precipitation variability in the southern Canadian Cordillera over the past 3–400 years using dendroclimatological techniques. Fifty-three total ring-width (RW) chronologies, 28 earlywood (EW) and 28 latewood (LW) chronologies were developed from open-grown, low-elevation stands of *Pseudotsuga menziesii* (Douglas-fir) and *Pinus ponderosa* (ponderosa pine) across the southern Canadian Cordillera. RW, EW and LW chronologies from both species were used to develop 13 annual (prior July to current June) precipitation reconstructions across the region. The reconstructions range in length from 165 to 688 years, pass verification tests and capture 39–64% of the variance in the instrumental record. Coincident, prolonged intervals of dry conditions are estimated for the years: 1717–1732, 1839–1859, 1917–1941 and 1968–1979. Shorter dry intervals are identified between 1581–1586, 1626–1630, 1641–1653 1701–1708, 1756–1761, 1768–1772, 1793–1800, 1868–1875, 1889–1897 and 1985–1989. The historic drought of the 1920–1930s was the longest but not the most intense across this area in the last 300 years. Wet conditions occur in the majority of reconstructions for the years: 1689–1700, 1750–55, 1778–1789, 1800–1830, 1880–1890, 1898–1916 and 1942–1960. These data, in conjunction with data from adjacent areas, are used to provide the first maps of decadal precipitation anomalies for the region between 1700 and 1990.

1. Introduction

The utility of proxy records of palaeoclimatic conditions for placing the short instrumental record in a longer-term perspective is well documented (e.g., Bradley, 1999). Annually resolved proxy series such as those calibrated from tree-ring chronologies permit an assessment of the frequency, duration and, to a lesser degree, intensity of past climatic events (e.g., droughts) over hundreds of years. Networks of long, annually-resolved tree-ring chronologies are a particularly powerful tool for studying historical climatic variations as they afford temporal information about local climates (i.e., single-site chronologies and/or reconstructions) and can also document spatial patterns of variability through time.

Extensive networks of temperature sensitive ring-width and maximum density chronologies have been developed for the Northern Hemisphere (e.g., Briffa et al., 2001, 2002; Schweingruber et al., 1993; Schweingruber and Briffa, 1996) and

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Climatic Change **65:** 209–241, 2004.

have been used to explore temperature variability throughout the late Holocene. Past precipitation variability has received comparatively little attention. Although Cook et al. (1996, 1999) developed a network of tree-ring based Palmer Drought Severity Index (PDSI) reconstructions for the continental United States it does not extend into Canada and pre-20th century precipitation variability remains poorly documented north of the 49th parallel. Establishing a more detailed history of precipitation variability in Canada will yield a better understanding of the spatial and temporal scales of droughts across North America during the pre-instrumental period and provide documentation of large-scale precipitation anomalies prior to those documented by the instrumental record. The availability of both spatial and temporal information on past anomalies can help climatologists understand the scales and ultimately the mechanisms responsible for climatic variations that impact human endeavours. From a more regional perspective, a network of precipitation reconstructions for western Canada can establish the scale and historical frequency of droughts which are of great importance for effective water resource planning. Consider for example that more than ninety per cent of the electricity produced by B.C. Hydro is generated using water powered turbines (B.C. Hydro, 2002).

The majority of tree-ring work in western Canada has focussed on the development of temperature-sensitive chronologies and reconstructions from upper treeline sites (e.g., Luckman et al., 1997). However, given the tremendous impacts of dry conditions in the mountainous regions of western Canada and the adjacent Prairies on the national economy, much more work with moisture-sensitive sites and species is required. Recent work by St. George and Nielsen (2002) in Manitoba, Sauchyn et al. in Saskatchewan (Sauchyn and Beaudoin, 1998; Sauchyn and Skinner, 2001) and Case and MacDonald (1995) in the Rocky Mountain foothills of southwestern Alberta has provided important paleoclimatic information for individual sites but the regional representativeness of these reconstructions is not known.

Watson and Luckman (2001a) describe the development and dendrochronological characteristics of a network of *Pseudotsuga menziesii* (Douglas-fir) and *Pinus ponderosa* (ponderosa pine) tree-ring chronologies from low-elevation sites in the southern Canadian Cordillera. These new chronologies update and expand upon preliminary work conducted in the area by Schulman (1947), Fritts and colleagues in the 1960s (Drew, 1975; Fritts and Shatz, 1975) and Robertson and Jozsa (1988). The chronologies are well-correlated with annual precipitation (Watson and Luckman, 2002) and chronologies from both species have proven particularly useful for studying/reconstructing precipitation for sites in the United States (e.g., Woodhouse and Brown, 2001; Grissino-Mayer, 1996), southern British Columbia and Alberta (Watson, 1998; Watson and Luckman, 2001b) and Mexico (Stahle et al., 2000a).

This paper documents the development of a set of tree-ring based precipitation reconstructions for the southern Canadian Cordillera. The reconstructions are used to explore the length, frequency and severity of historical dry and wet periods in the southern Canadian Cordillera and their spatial extent. Comparisons with other precipitation and/or PDSI reconstructions from the Canadian Prairies and the adjacent U.S. examine the regional extent of these historical precipitation anomalies.

2. Materials and Methods

2.1. DATASETS

2.1.1. *Tree-Ring Chronologies*

Forty Douglas-fir and 13 ponderosa pine chronologies were developed from 43 open grown, low elevation sites in the southern Canadian Cordillera (Watson and Luckman, 2001a). The distribution of suitable chronology sites is controlled primarily by annual precipitation totals that predominantly reflect rainshadow effects across the region (Figure 1) and by the presence of numerous narrow ribbon lakes in southeastern British Columbia that preclude tree growth at many valley floor sites. For the stations used in this study, maximum monthly precipitation totals occur in June and July and minimum monthly totals generally occur in spring (March/April; Watson, 2002). The individual tree-ring series for each site were crossdated using standard procedures (Stokes and Smiley, 1968) and measured to the nearest 0.001 mm. The dated series were standardised and combined into site chronologies using the computer program ARSTAN (Cook, 1985). Standardisation involved dividing the raw ring-width measurements for each core by values derived from either a negative exponential curve, a negative linear trend line or a straight line fitted to each series. The chronologies range in length from 123 to 691 years and the average mean segment length for the 53 chronologies is 228 years (range: 96–391). Separate earlywood and latewood (EW and LW) chronologies were developed for a 28 chronology subset (23 Douglas-fir and 5 ponderosa pine) of these data from sites located west of the Rocky Mountain Trench. Earlywood cells are the first part of the annual growth ring to form during each growing season. In conifers they are thin-walled, light coloured, low density and have a large diameter. Latewood cells, which typically form later in the growing season, are darker, denser, smaller and have thicker cell walls. Further details on chronology development, characteristics and chronology-climate relationships are presented in Watson and Luckman (2001a, 2002).

2.1.2. *Precipitation Records*

Rehabilitated monthly precipitation (Mekis and Hogg, 1999) and homogenised monthly temperature records (Vincent, 1998; Vincent and Gullett, 1999) from the Historical Canadian Climate Database were provided by the Climate Research Branch of the Meteorological Service of Canada (MSC). These records have been rigorously corrected for inhomogeneities or bias related to changes in station location, exposure, instrument type and measurement procedures. The stations selected

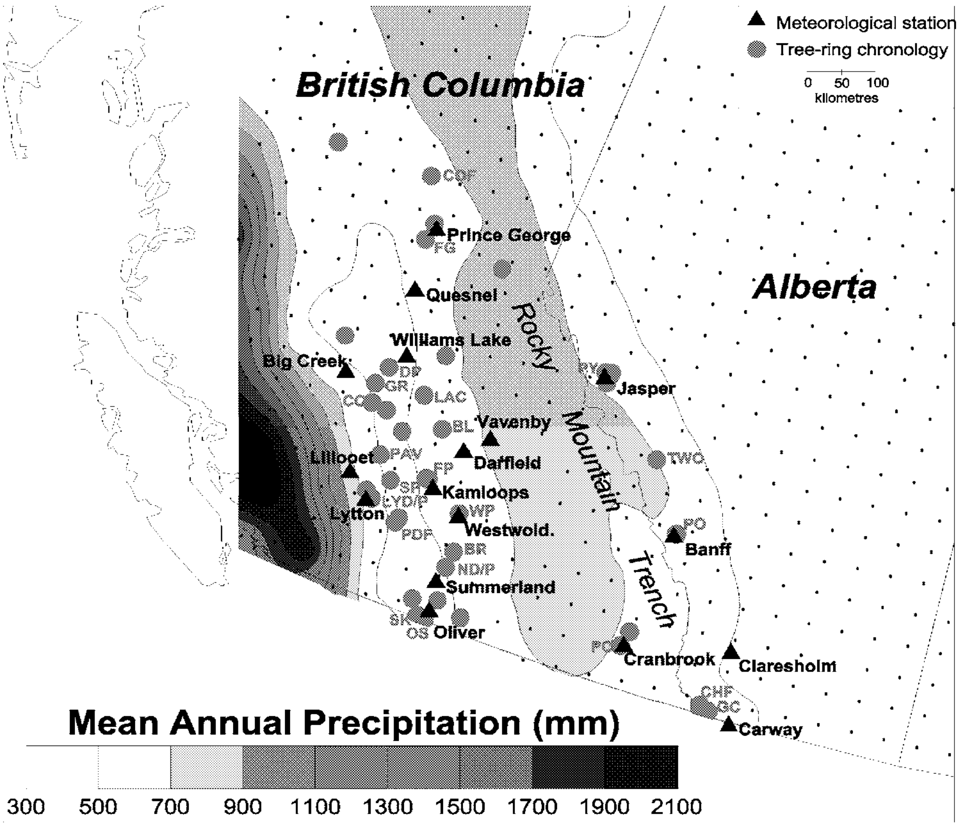


Figure 1. Mean annual precipitation in southern British Columbia and Alberta. The map also shows the location of the tree-ring chronology sites and meteorological stations used in this study. Mean annual precipitation (July–June: 1896–1998) is calculated from the CANGRID datapoints (small black dots) in the region. Chronology codes are displayed for those chronologies used as predictors in precipitation reconstructions. The species is Douglas-fir unless identified as (ponderosa) pine. **FG** = Fort George, **COF** = Coffeepot, **LAC** = Lac La Hache, **DP** = Deer Park, **GR** = Gang Ranch, **CC** = Churn Creek, **BL** = Bridge Lake, **FP** = Fritts pine, **LYP** = Lytton pine, **LYD** = Lytton, **PAV** = Pavilion Lake, **PDF** = Patriot, **SPP** = Spatsum pine, **WP** = Westwold pine, **BR** = Bald Range, **ND** = Naramata, **NP** = Naramata pine, **OS** = Osoyoos, **SK** = Skemeoskaunkin, **PY** = Pyramid Lake, **TWO** = Two o'clock Creek, **PO** = Powerhouse, **PC** = Perry Creek, **CHF** = Chief Mountain, **GC** = Golf Course. For details of sites and meteorological records see Watson and Luckman (2001a, 2002).

for use in this analysis (Figure 1) are mainly valley floor sites and represent the longest and highest quality climate records available for this region (Watson and Luckman, 2002). In addition, MSC provided a gridded dataset (50 km resolution) of monthly precipitation totals for Canada developed using an optimal interpolation method (Milewska and Hogg, 2001; Zhang et al., 2000). Data for each grid-point extend back to 1896 and were developed using the network of rehabilitated precipitation records described above.

2.2. RECONSTRUCTION STRATEGY

The network of moisture-sensitive Douglas-fir and ponderosa pine chronologies are used to develop a set of precipitation reconstructions for selected meteorological records from the southern Canadian Cordillera. The best statistical relationships consistently occur between chronologies and precipitation records from the most proximal meteorological station (generally from within the same valley; Watson and Luckman, 2002) and therefore single-station reconstructions were developed to examine the temporal and spatial patterns of precipitation variability. The natural distribution of suitable sample sites resulted in the clustering of chronologies near several valley floor meteorological stations (Figure 1). The configuration and number of the reconstructed records depended primarily on the quality and length of the available precipitation records and on the distribution of chronology sites and meteorological stations (Figure 1). Only those chronologies that were proximal to and displayed strong statistical relationships with the precipitation record from the station were included as potential predictors (Watson, 2002; Watson and Luckman, 2002).

The Douglas-fir chronologies ($n = 40$) tend to correlate most highly with pJuly–June precipitation* (i.e., precipitation totals for the 12-month period previous July to June of the year of growth) whereas maximum correlations for the thirteen ponderosa pine chronologies are generally with pAugust–July totals (Watson and Luckman, 2002). However, the differences between chronology-precipitation correlations for the two annualisations are small and not significant. Therefore, all reconstructions are of total precipitation over the 12-month period from prior July to current June (i.e., the period of maximum correlation for the majority of chronologies). This enables comparison of the same parameter across the entire region. Moreover, as the reconstructions involve independent predictors (the chronologies are uniquely assigned to climate stations) comparison of the precipitation reconstructions provides a means of verifying temporal variability (i.e., identifying common wet and/or dry intervals).

Stepwise multiple linear regression analysis was used to generate the models that were used to produce precipitation estimates. Total ring-width and, where available, earlywood and latewood chronologies were considered as candidate predictors of precipitation. Chronologies for years t, $t - 1$ and $t + 1$ were also included as predictors to model lagged growth effects. Only those chronologies that exhibited a statistically significant ($p < 0.05$) contemporaneous (i.e., year t) correlation with the annual precipitation record were included as potential predictors in a stepwise regression model. This reduces the number of predictors and the likelihood of problems with interpretation due to the effects of multicolinearity and with variance inflation. The variance inflation factor (VIF) was also used as a guide to identify the optimum model (Fox, 1997).

* See Watson and Luckman (2002) for a detailed assessment of the relationships between the chronologies and monthly, seasonal and annual climate data.

A split-period procedure was used to generate independent estimates of precipitation that could be used to evaluate the quality of the models developed for each precipitation record. The period of instrumental record for each station was split in half with the model generated for the first half being verified on the second half and vice versa. This standard approach assesses the temporal stability of the modelled relationship. The verification statistics used include the Pearson's product-moment correlation coefficient, the Reduction of Error (RE) statistic, the Coefficient of Efficiency (CE) and the sign test (see Cook et al., 1994; Fritts, 1976, 1991; Fritts et al., 1990). Residuals from the full regression model were evaluated for normality using the Kolmogorov-Smirnov (K-S) test and for 1st order serial correlation using the Durbin-Watson D statistic.

3. Results

3.1. CALIBRATION AND VERIFICATION OF THE RECONSTRUCTION MODELS

3.1.1. *Traditional Calibration and Verification of the Reconstructed Time Series*

Thirteen annual (pJuly–June) precipitation reconstructions were developed for meteorological stations* in southern British Columbia and southwestern Alberta. Nine full reconstruction models have multiple R values of $\geq$0.70 (range 0.64 to 0.81; Table I, Figure 2). Explained variance (adjusted R^2) ranges from 39 to 64% and over half of the models account for >50% of the variance in the instrumental records with which they were calibrated. The models appear to capture low and higher frequency trends over the calibration period (Figure 2) as the majority pass verification (Table I). The majority of reconstructions also pass verification tests calculated with independent data generated using the 'leave-one-out method' (Gordon, 1982) and with first-differenced time series (Watson, 2002). These results are of comparable quality to those from precipitation and PDSI reconstructions in the United States (e.g., Woodhouse and Overpeck, 1998) and western Canada (Case and MacDonald, 1995; Watson and Luckman, 2001b; Robertson and Jozsa, 1988; Sauchyn and Beaudoin, 1998; Sauchyn and Skinner, 2001).

3.1.2. *Evaluation of the Models*

Latewood chronologies were available as potential predictors for eight of the reconstruction models and entered as the most heavily weighted predictors in six (Table II). Four of the latewood chronologies used to develop the reconstructions were transformed using a base-10 log to remove positive skew (Table II). The latewood chronologies have less autocorrelation and are less dependent on precipitation from the previous year than the total ring-width or earlywood chronologies

* Two reconstructions (North Thompson – combined Kamloops, Vavenby and Darfield; and Waterton Lakes – combined Claresholm and Carway) are of precipitation series generated for combined meteorological stations because the calibration results are superior to those for individual station models. The records were combined using a technique outlined in Jones and Hulme (1996).

Table I

Calibration and verification results for the 13 annual precipitation reconstructions

Model	Calibration					Verification				
	Years	SE[a]	R	R^2_{adj}	D-W *d*[b]	Period	*r*	RE[c]	CE	Sign test
Prince George (1780–1996)[d]										
Early[e]	1914–1954	83.67	0.71	0.48	1.42	1955–1996	0.45	0.54	**–0.42**	**26/16**
Late	1955–1996	82.54	0.46	0.17	1.69	1914–1954	0.70	0.48	**–0.19**	2.73
Full	1914–1996	88.60	0.70	0.47	**1.33**					
Williams Lake (1571–1996)										
Early	1949–1972	51.46	0.82	0.62	1.38	1973–1996	0.76	0.28	0.07	18/6
Late	1973–1996	41.95	0.88	0.74	2.36	1949–1972	0.77	0.36	0.18	20/4
Full	1949–1996	54.28	0.78	0.59	**1.02**					
Big Creek (1561–1996)										
Early	1905–1941	54.81	0.56	0.25	1.92	1942–1977	0.70	0.46	0.35	**22/14**
Late	1942–1977	50.13	0.71	0.46	2.04	1905–1941	0.55	0.33	0.15	25/12
Full	1905–1977	52.57	0.64	0.39	2.04					
North Thompson (1686–1996)[f]										
Early	1914–1954	36.88	0.74	0.51	2.19	1955–1996	0.62	0.46	0.31	32/10
Late	1955–1996	44.73	0.63	0.34	1.64	1914–1954	0.41	0.24	0.02	30/11
Full	1914–1996	39.27	0.69	0.45	1.79					
Lytton (1468–1996)										
Early	1927–1959	73.78	0.67	0.43	1.70	1960–1991	0.82	0.59	0.59	28/4
Late	1960–1991	61.62	0.82	0.67	1.76	1927–1959	0.67	0.32	0.31	25/8
Full	1927–1991	69.11	0.74	0.54	1.75					
Lillooet (1640–1996)										
Early	1918–1956	49.26	0.74	0.49	2.19	1957–1994	0.71	0.55	0.48	29/9
Late	1957–1994	63.57	0.74	0.50	1.90	1918–1956	0.69	0.53	0.39	29/10
Full	1918–1994	56.17	0.74	0.52	2.02					
Westwold (1830–1996)										
Early	1922–1959	57.53	0.62	0.34	1.65	1960–1996	0.76	0.51	0.51	29/8
Late	1960–1996	46.55	0.77	0.57	1.82	1922–1959	0.61	0.24	0.24	29/9
Full	1922–1996	52.54	0.68	0.45	1.66					
Summerland (1704–1996)										
Early	1909–1951	39.70	0.83	0.67	2.09	1952–1994	0.54	0.36	0.21	30/13
Late	1952–1994	48.40	0.64	0.36	1.85	1909–1951	0.73	0.41	0.30	**27/16**
Full	1909–1994	46.03	0.73	0.52	1.68					
Oliver (1720–1996)										
Early	1925–1960	40.46	0.84	0.68	2.29	1961–1995	0.82	0.55	0.36	30/5
Late	1961–1996	41.30	0.83	0.66	1.44	1925–1960	0.84	0.56	0.37	29/7
Full	1925–1996	44.77	0.81	0.64	1.60					

Table I

(Continued)

Model	Calibration					Verification				
	Years	SE[a]	R	R^2_{adj}	D-W d[b]	Period	r	RE[c]	CE	Sign test
Jasper (1630–1996)[g]										
Early	1937–1966	59.71	0.70	0.45	1.95	1967–1995	0.73	0.56	0.52	23/6
Late	1967–1995	45.26	0.76	0.54	1.92	1937–1966	0.68	0.47	0.44	24/6
Full	1937–1995	52.33	0.72	0.51	1.93					
Banff (1307–1996)[h]										
Early	1896–1944	53.93	0.82	0.65	2.09	1945–1994	0.69	0.49	0.36	36/14
Late	1945–1994	56.39	0.70	0.45	2.17	1896–1944	0.81	0.64	0.57	35/14
Full	1896–1994	55.79	0.77	0.57	2.04					
Cranbrook (1746–1996)[i]										
Early	1910–1953	77.17	0.74	0.52	2.42	1954–1996	0.69	0.38	0.16	29/14
Late	1954–1996	60.49	0.72	0.53	2.56	1910–1953	0.68	0.38	0.25	30/14
Full	1910–1996	73.37	0.71	0.49	2.19					
Waterton Lakes (1673–1996)[j]										
Early	1915–1955	110.96	0.55	0.27	1.52	1956–1996	0.68	0.57	0.46	28/13
Late	1956–1996	75.92	0.72	0.49	**2.71**	1915–1955	0.54	0.38	0.29	31/10
Full	1915–1996	93.73	0.64	0.40	1.94					

[a] SE is the standard error of the estimate given in mm.
[b] Bolded Durbin-Watson D (D-W d) statistic values indicate that the residuals display statistically significant serial correlation.
[c] RE is Reduction of Error statistic and CE is the Coefficient of Efficiency.
[d] The full length of each reconstructed series.
[e] Early and Late models are for a split period verification.
[f] North Thompson is a regional series incorporating records from Kamloops, Vavenby and Darfield.
[g] This reconstruction is of similar statistical quality (adjusted R^2 increased from 50% to 51%) and is 38 years longer than the pAJ reconstruction in Watson and Luckman (2001b) and uses an additional chronology.
[h] Reconstruction presented in Watson and Luckman (2001b).
[i] This reconstruction uses different predictors over a longer calibration period and is almost 50 years longer than that in Watson and Luckman (2001b).
[j] Waterton Lakes is a regional precipitation record combining the records from Claresholm and Carway.
All correlation coefficients and sign test results are statistically significant ($p < 0.05$) except those bolded. Negative RE and CE values are also bolded.

(Watson and Luckman, 2002) and therefore probably enter the regression models because their persistence characteristics are more similar to those of the climate records. Earlywood chronologies have a very similar climate signal to total ring-width chronologies (Watson and Luckman, 2002) and only enter the models for Williams Lake and Lillooet (year $t - 1$). All reconstruction models except Lytton include at least one lagged variable (11 models include a negatively lagged variable and four include a positive lag; Table II).

Table II
Variables and standardized regression coefficients used in the 13 precipitation reconstruction models

	ew/lw	Beta coefficients			
		Variable 1	Variable 2	Variable 3	Variable 4
Prince George	X	**Fort George $LW_{log\ 10}$ 0.587**	**Coffeepot M1 0.206**		
Williams Lake	X	**Lac La Hache LW 0.458**	**Lac La Hache EW M1 –0.332**	**Deer Park 0.356**	
Big Creek	X	**Gang Ranch $LW_{log\ 10}$ 0.591**	Gang Ranch M1 –0.378	**Churn Creek LW P1 0.227**	
North Thompson	X	**Bridge Lake LW 0.505**	Fritts Pine M1 –0.493	**Fritts Pine 0.474**	
Lytton	X	**Lytton Pine $LW_{log\ 10}$ 0.737**			
Lillooet	X	**Lytton 0.541**	**Pavillion P1 0.290**	**Patriot EW M1 0.358**	**Spatsum Pine M1 –0.230**
Westwold	X	**Westwold Pine 0.579**	**Bald Range M1 –0.366**		
Summerland		**Naramata 0.626**	Naramata M1 –0.193	**Naramata Pine 0.208**	
Oliver	X	**Osoyoos $LW_{log\ 10}$ 0.527**	**Skemeoskaunkin P1 0.429**		
Jasper		**Pyramid Lake 0.577**	**Two o'Clock Creek M1 0.287**		
Banff		**Powerhouse 0.754**	**Powerhouse M1 –0.192**	**Powerhouse P1 0.160**	
Cranbrook		**Perry Creek 0.754**	Perry Creek M1 –0.192		
Waterton Lakes		**Chief Mountain 0.532**	**Golf Course M1 0.209**		

Predictor variables that are significantly ($p < 0.05$) correlated with the dependent variable in a simple correlation analysis are boldfaced. **X** in the ew/lw column indicates that earlywood and latewood chronologies were available as potential predictors for the regression model. $_{log\ 10}$ indicates that the chronology was transformed using a base-10 logarithm. Total ring-width chronologies are used unless specified **EW** or **LW** (earlywood and latewood chronologies respectively). Lagged chronology inputs are indicated as **M1** (year $t-1$) and **P1** (year $t+1$).

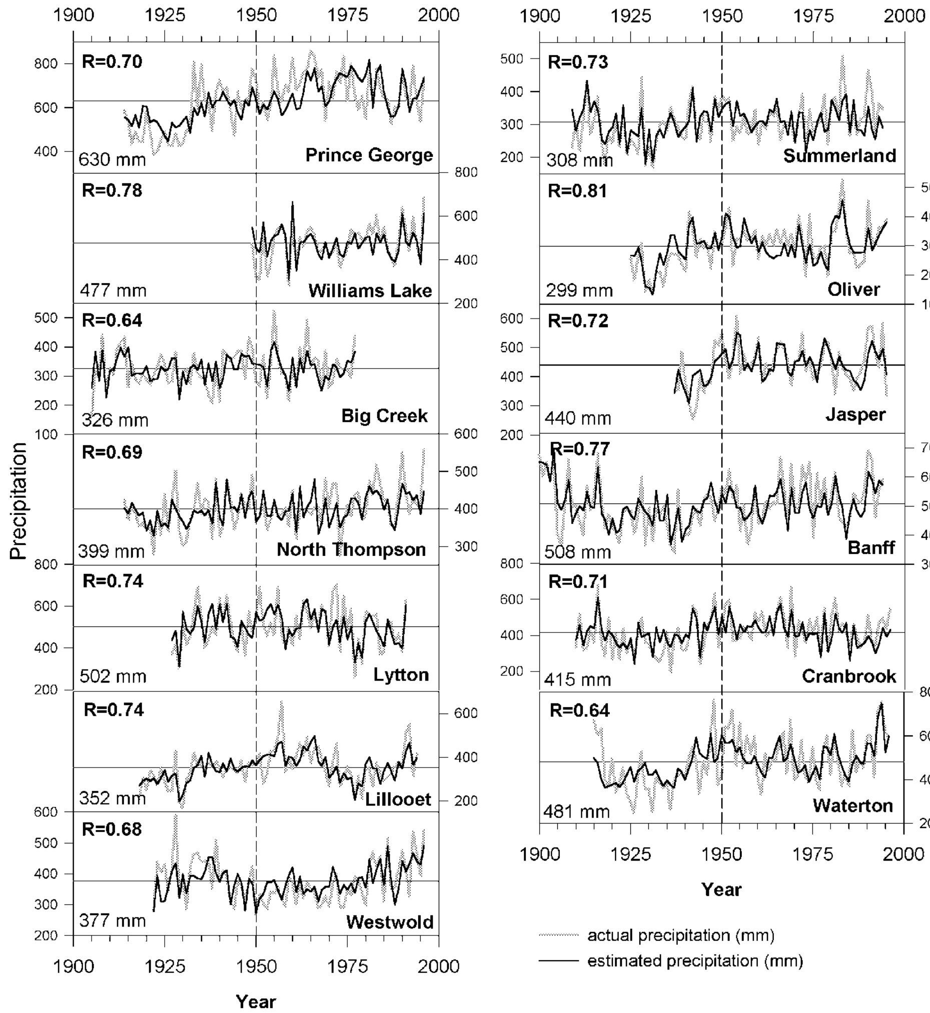


Figure 2. Comparison of actual (grey) and reconstructed (black) annual (pJuly–June) precipitation for each of the 13 meteorological records over the calibration interval. The mean of the instrumental record is given in the bottom left corner of each plot and shown as a horizontal line. Multiple *R* values for the full calibration models are presented in the upper left corner of each plot.

The residuals from all thirteen models do not differ significantly from the theoretical normal distribution and a visual inspection of various plots of the residuals reveal no major violations of the assumptions of the general linear model (Draper and Smith, 1981). However, the residuals from the full reconstruction models from Prince George and Williams Lake display statistically significant ($p < 0.05$) positive autocorrelation (as determined by the Durbin-Watson *d* statistic, Table I; Draper and Smith, 1981). The positive autocorrelation in the residuals from the Williams Lake full reconstruction model is related to an interval of overprediction that dominates the early part of the record and is not considered to be a major problem. The positive autocorrelation in the regression residuals for the Prince George model occurs because a significant pattern of lower-frequency variability in the instrumental data is not well-modelled by the predictor chronologies (Figure 2). Variability at decadal timescales in this reconstruction should therefore be interpreted with caution (Watson, 2002). The pronounced variability in mean conditions in the Prince George instrumental record* also caused the model to fail the CE verification test in both the early and late period. Another notable feature is that the Waterton Lakes reconstruction model captures low frequency variations well throughout the entire instrumental period but tracks higher frequency variability more closely in the second half of the record (Figure 2; Table I; Watson, 2002).

3.1.3. *Reproducibility of Spatial Patterns of Correlation*

The standard calibration and verification procedures shown in Table I examine the strength of relationships between actual and reconstructed time series of data. In this study, we are also interested in the spatial patterns of precipitation and it is important to establish whether the relationships between the reconstructed precipitation records mimic those found in the instrumental record. The degree to which the reconstructions reflect the 'true' spatial variability of precipitation across the region was evaluated by comparing the matrix of correlations between the estimated precipitation records with the matrix for the instrumental precipitation records computed over the calibration interval for each model. Overall the correlation matrices are very similar (Watson, 2002) – correlation coefficients are of similar magnitude (differences exceed ± 0.20 in only eight of 78 cases and 53% of the differences are $< \pm 0.10$) and in both matrices the maximum correlation pairings are the same (generally with the most proximal record). Three broad regions (a northern, southern and eastern region) with similar variability are also evident in both matrices.

The regional representativeness of individual precipitation records can be assessed by determining the spatial field of correlations with records over a broad area. Figure 3a shows correlations between each of the 13 instrumental precipitation records (pJuly–June) used in calibration and the 50 km resolution CANGRID dataset over the early calibration period (see Table I) for each reconstruction. Figure 3b shows the equivalent patterns of correlation calculated between the 13 reconstructed precipitation records derived from the late period models and the CANGRID dataset over the early period. Comparison of these matched figures provides additional verification for the reconstructions by demonstrating their ability to replicate spatial patterns found in the instrumental records. The general patterns of correlations with the gridded dataset are very similar for each pair of instrumental and reconstructed precipitation records (Figure 3). High correlation and congruence coefficients (Richman, 1986; Cook et al., 1999) between each pair of

* The mean in the first half of the Prince George record (564.28 mm) is significantly different ($p < 0.05$) than the mean in the latter half of the record (694.07 mm).

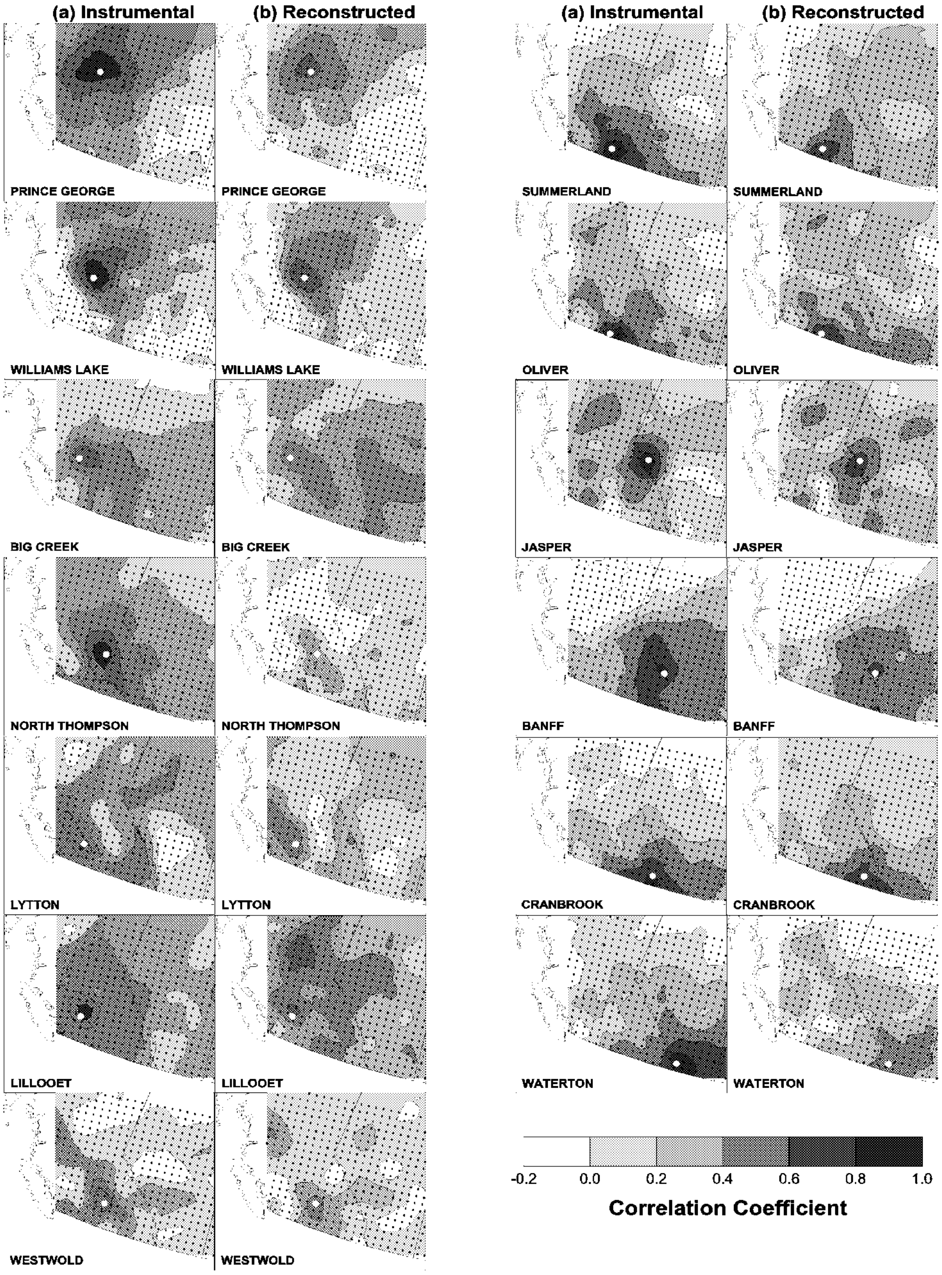


Figure 3. Contoured correlation patterns between pJuly–June precipitation for each of the thirteen meteorological records (white circles) and grid point data from the CANGRID dataset. The correlation patterns for both instrumental and reconstructed precipitation records were calculated over the early calibration interval (see Table I). The reconstructed values used are derived from regression models developed from independent data over the late calibration interval for each reconstruction (see Table I).

maps confirm this finding (Table IIIa). Similar results are found when the analyses are repeated over the late calibration interval (Table IIIb). As would be anticipated given the loss of variance inherent in regression modelling, correlations with the gridded dataset are generally higher with the instrumental precipitation records than with the reconstructed series (Table III).

In general, the regions of maximum correlations for each station tend to be confined to individual mountain ranges and rarely straddle the Rocky Mountain Trench. These maps demonstrate that, collectively, these reconstructions are correlated with precipitation over much of the southern Cordillera including the region of higher precipitation in east-central British Columbia within which no chronologies (and therefore no reconstructions) were developed (Figure 1). This suggests that, although the reconstructions are developed for individual meteorological stations, they provide information on historical precipitation variability across a broad area.

3.2. THE PRECIPITATION RECONSTRUCTIONS

The thirteen precipitation reconstructions range in length from 167 to 688 years (Table IV). They are shown over their full length in Figure 4, arranged as two north-south sequences on either side of the Rocky Mountain Trench. The subsample signal strength (SSS; Wigley et al., 1984; Briffa and Jones, 1990) provides an indication of the reliability of the early part of each reconstruction where sample depth can be comparatively low (Figure 4).

These reconstructions may be assessed at several spatial and temporal scales. The presentation and discussion of these results will begin with a discussion of their general characteristics followed by a regional grouping of the reconstructions and results of correlations with reconstructions from adjacent areas. The discussion will end with a summary that integrates results over the southern cordillera and adjacent areas.

3.2.1. *General Characteristics and Extreme Values*

The mean precipitation in nine of the reconstructed series is not significantly different from the reconstructed mean over the period of instrumental record (Table IVa). However, mean reconstructed precipitation over the pre-calibration period is significantly lower ($p < 0.05$) than the calibration period mean at Prince George and Banff and both reconstructions estimate precipitation as above the full-record mean since ~1945 (Figure 4). Contrarywise, at Lytton and Lillooet, mean reconstructed precipitation over the calibration interval is significantly lower ($p < 0.05$) than that of the pre-instrumental period of the reconstructions. Both of these records show very dry conditions during the 1920s-1940s and from the late 1970s through 1990s (Figure 4).

Each precipitation estimate is assigned the calendar year of the last six months of the reconstructed annual period (pJuly–June). This is not ideally suited to a

Table III

Comparison of the pattern of correlations between the instrumental and reconstructed precipitation records from each of the 13 meteorological stations and CANGRID precipitation data (Figure 3) over the early (A) and late (B) calibration interval for each station (see Table I)

	(a)		(b) Mean correlation		(c) Percent >0.40	
	r	*cc*	Instrumental	Reconstructed	Instrumental	Reconstructed
(A) Early period						
Prince George	0.965	0.930	0.33	0.15	41	15
Williams Lake	0.923	0.955	0.23	0.18	23	16
Big Creek	0.656	0.930	0.26	0.32	18	26
North Thompson	0.339	0.572	0.34	0.07	28	0
Lytton	0.909	0.930	0.26	0.18	21	5
Lillooet	0.621	0.946	0.35	0.39	35	42
Westwold	0.616	0.781	0.12	0.12	5	2
Summerland	0.752	0.908	0.25	0.24	21	8
Oliver	0.857	0.946	0.24	0.27	18	16
Jasper	0.657	0.900	0.26	0.27	19	17
Banff	0.986	0.980	0.25	0.18	42	31
Cranbrook	0.937	0.940	0.19	0.22	19	13
Waterton	0.847	0.904	0.25	0.15	21	10
MEAN	0.774	0.894	0.26	0.21	24	16
(B) Late period						
Prince George	0.359	0.822	0.29	0.23	21	12
Williams Lake	0.451	0.800	0.30	0.29	38	33
Big Creek	0.805	0.717	0.07	0.22	6	7
North Thompson	0.867	0.921	0.24	0.19	23	21
Lytton	0.909	0.938	0.10	0.11	16	10
Lillooet	0.882	0.876	0.01	0.05	5	7
Westwold	0.939	0.965	0.19	0.18	19	15
Summerland	0.828	0.874	0.22	0.13	19	10
Oliver	0.921	0.913	0.18	0.04	13	10
Jasper	0.682	0.845	0.24	0.16	12	8
Banff	0.796	0.846	0.17	0.13	9	12
Cranbrook	0.887	0.905	0.13	0.10	13	8
Waterton	0.937	0.920	0.11	0.17	16	16
MEAN	0.789	0.865	0.17	0.15	16	13

(a) Correlation (r) and congruence coefficients (cc) (Richman, 1986; Cook et al., 1999) are calculated between each pair of maps in Figure 3 for the 415 gridpoints. (b) Mean correlation coefficients calculated between all CANGRID precipitation datapoints ($n = 415$) and instrumental and reconstructed precipitation series for each of the 13 sites (i.e., the mean value for all points in each correlation map in Figure 3). (c) The percentage of these 415 correlations for the instrumental and reconstructed series that exceed 0.40. This 0.40 cutoff provides a measure of the regional extent of the core area of strong correlations with each station (see Figure 3). It is a useful guide as to whether the strength (not just the shape) of the patterns seen in the instrumental and reconstructed plots is similar.

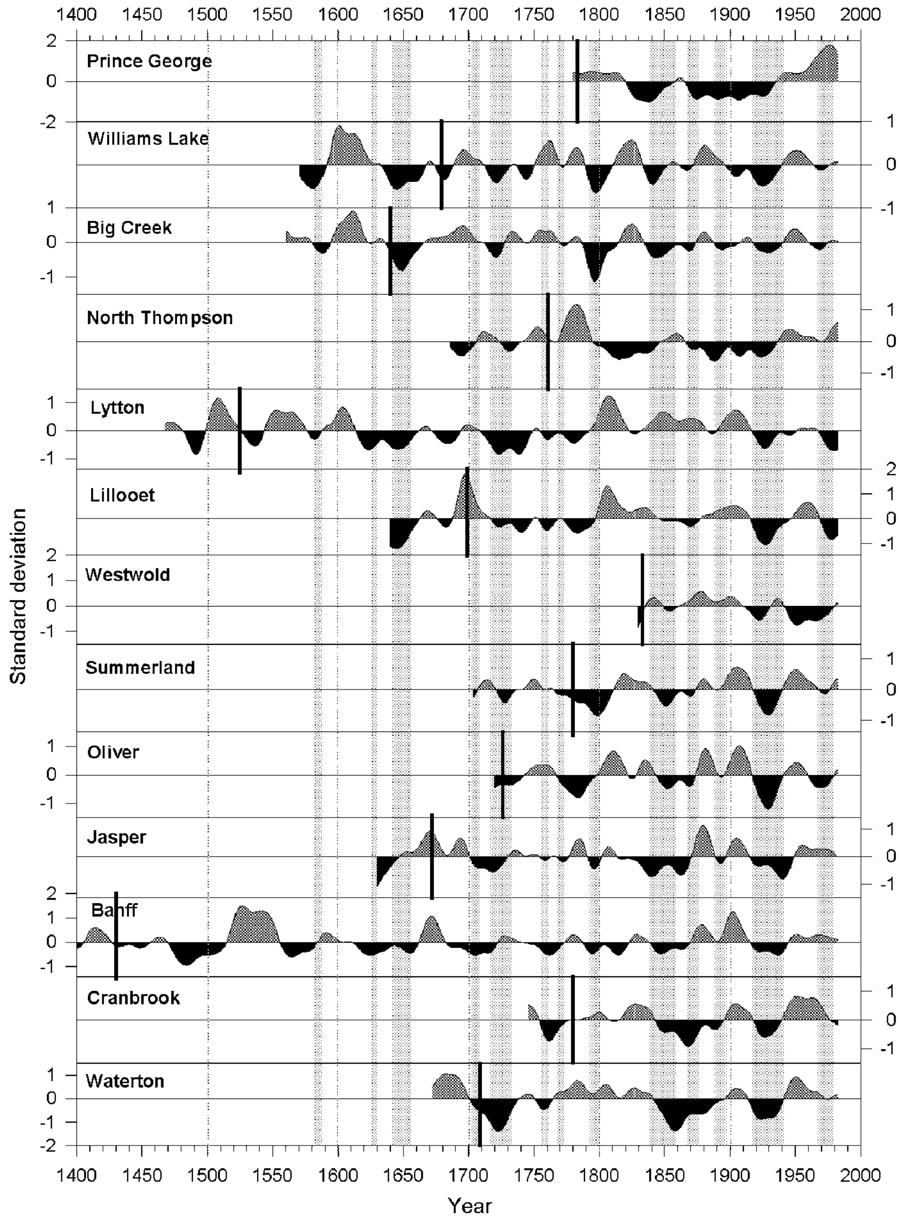


Figure 4. Low frequency variation in the annual precipitation reconstructions for the southern Canadian Cordillera. All series are expressed in standard deviation units from their long-term mean and are smoothed with a 25-year spline. The thick vertical black line in each reconstruction indicates the first year for which the subsample signal strength (SSS; Wigley et al., 1984; Briffa and Jones, 1990) value of the shortest chronology used in the reconstruction is ≥ 0.85 (Watson, 2002). The vertical shading highlights intervals >4 years in duration when below mean annual precipitation is identified in the majority of the available reconstructions (at least 60% prior to 1700 and >50% post 1700) based on the annual series (see Table VI, below).

Table IVa

Summary characteristics of the 13 annual (pJuly–June) precipitation reconstructions: general characteristics

Reconstruction	Start	Start SSS	Adj. R^2	S.E. (mm)	Mean (mm)		Std. deviation	
					Calib.	Full	Calib.	Full
Prince George	1780	1783	0.47	88.6	629.9 [a]	585.8	85.5	83.8
Williams Lake	1571	1679	0.59	52.5	477.2	468.1	66.4	82.4
Big Creek	1561	1640	0.39	52.6	326.2	326.8	43.0	50.4
North Thompson	1686	1761	0.45	39.3	399.1	392.8	36.7	40.1
Lytton	1468	1525	0.54	69.1	502.3 [a]	526.3	74.9	87.5
Lillooet	1640	1699	0.52	56.2	351.8 [a]	369.4	60.3	70.6
Westwold	1830	1833	0.45	52.5	376.6	383.0	47.9	44.9
Summerland	1704	1780	0.52	46.0	308.4	305.4	48.1	47.1
Oliver	1720	1726	0.64	44.8	299.7	309.2	60.3	63.7
Jasper	1630	1672	0.51	52.3	439.6	440.0	53.8	57.4
Banff	1307	1430	0.57	55.8	508.0 [a]	493.2	65.2	65.5
Cranbrook	1746	1780	0.49	73.4	415.3	408.9	72.6	65.3
Waterton	1673	1709	0.40	93.7	480.7	471.6	77.2	71.9

Start SSS indicates the earliest year for which SSS is >0.85 in the shortest chronology used in each reconstruction. S.E. is the standard error of the estimate in mm. Std. deviation is the standard deviation of the reconstructed series over the calibration interval (Calib.) and the full length of the reconstruction (Full).

[a] Indicates that the mean of the reconstructed record over the calibration interval is significantly different ($p < 0.05$) than the mean of both the entire reconstruction and the reconstruction prior to the calibration period.

discussion of conditions in individual years because it spans equal parts of two adjacent calendar years. There is also a relatively large statistical uncertainty associated with individual precipitation estimates (the 2 S.E. confidence limit averages ±28% of the full series mean value; Tables I and IV). Nevertheless, extreme annual values common to a number of these independent reconstructions can be viewed with more credibility. Table IVb shows the five most extreme dry and wet years in all reconstructions over the 1700–1996 period. The most commonly identified extreme dry year is 1869 which is found in six reconstructions spread across the entire region. Several other extreme years are common to more than one reconstruction, namely, 1929 (4), 1759 and 1793 (3) and 1760, 1764, 1783, 1790, 1931 and 1977 (2; Table IV). Apart from 1869 and 1977 these extreme years are grouped in three periods; 1759–1764, 1783–1793 and 1929–1931. This latter period corresponds with the well-documented drought that affected much of western North America. The most extreme 10-year periods identified in nine of the reconstructions are in broad correspondence with these periods (Table IVb).

Table IVb

Summary characteristics of the 13 annual (pJuly–June) precipitation reconstructions: extreme values

Reconstruction	Driest years post-1700					Wettest years post-1700					Extreme years		Decades post-1700	
	1	2	3	4	5	1	2	3	4	5	Dry	Wet	Driest	Wettest
Prince George	1837	1906	1828	1872	1842	1981	1984	1976	1966	1990	5	0	1869–1878	1972–1981
Williams Lake	***1869***	1741	1790	1919	1959	1762	1960	1828	1766	1788	8	5	1790–1799	1758–1967
Big Creek	1800	1790	***1869***	**1793**	1796	1990	1828	1820	1778	1700	9	9	1791–1800	1819–1828
North Thompson	***1869***	1905	1705	1886	1768	1785	***1900***	1773	1792	1966	10	4	1901–1910	1780–1789
Lytton	1739	1759	1929	1977	1760	1803	1845	1806	1772	1805	5	48	1734–1743	1803–1812
Lillooet	1759	1740	1929	1977	1760	1806	1804	1805	1802	1803	2	11	1923–1932	1802–1811
Westwold	1950	***1869***	1922	1947	1988	1996	1879	1986	1832	***1900***	1	0	1943–1952	1872–1881
Summerland	1929	1783	1931	***1869***	1924	1763	1752	1913	1819	1942	0	2	1795–1804	1898–1907
Oliver	1931	1783	1930	1929	1787	1906	1832	1885	1983	1878	0	2	1925–1934	1876–1885
Jasper	1941	**1793**	1794	1853	1757	1789	1787	1881	1882	1901	0	12	1937–1946	1874–1883
Banff	**1793**	1764	1706	1759	1831	1904	***1900***	1901	1898	1902	6	0	1757–1766	1897–1906
Cranbrook	1926	1985	***1869***	1764	1944	1916	1801	1750	1966	1948	0	0	1756–1765	1945–1954
Waterton	1720	1726	1856	1857	1727	1994	1993	1787	1947	1981	17	0	1718–1727	1987–1996

The five driest and wettest years after 1700 are listed. Boxes and differences in font indicate years common to 3 or more reconstructions. The 'extreme years' columns list the number of years in each reconstruction that fall outside the range defined by the maximum and minimum reconstructed value during the calibration period. The final two columns identify the driest and wettest ten year periods during the 1700–1996 period for each reconstruction. More extreme decades occur prior to 1700 in the Williams Lake (1641–1650 dry, 1618–1627 wet); Big Creek (1608–1617 wet), Lillooet (1642–1651 dry, 1693–1702 wet) and Banff (1476–1485 dry, 1521–1530 wet) records.

The temporal pattern of extreme wet years is not as coherent as that of extreme dry years: only two years (1900 and 1966) are common to three reconstructions (Table IVb). However, roughly half of the extreme wet years are concentrated in the intervals 1801–1850 and 1951–present and correspond with periods of above normal precipitation in the majority of reconstructions (Figure 4). They are not isolated wide rings. Over half of the reconstructions show their wettest decades in the last quarter of the 19th century (5 records) or during the 20th century (Table IVb).

In many cases the extreme values reconstructed for the 20th century are of similar magnitude to those seen over the full length of the reconstructions (i.e., the 20th century extremes are not frequently exceeded; Table IVb). However, some stations appear to have experienced more frequent and greater extremes for some periods prior to the 20th century (e.g., 20 years in the 1500s at Lytton are reconstructed wetter than the wettest year for the period of instrumental record).

3.2.2. *Regional Groupings of the Reconstructions*

Examination of Figure 4 reveals strong similarities between several reconstructions and these are confirmed by correlation analyses calculated between the reconstructions over their maximum paired intervals (Table Va). The reconstructions can be grouped into three fairly distinct geographical sub-regions. These sub-regions are related to differences in topography and climate: they are similar to groupings identified from the 53 original ring-width chronologies (Watson and Luckman, 2001b), the CANGRID dataset of gridded instrumental precipitation records (pJuly–June, 1900–1996; not shown) and in a principal components analysis (PCA) of the 13 reconstructions over the 1830–1996 common interval (Watson, 2002).

The four most northerly chronologies (Prince George, Williams Lake, Bull Canyon and North Thompson) correlate significantly with each other (except the Prince George and Bull Canyon pairing; Table Va). However, the smoothed version of these series (Figure 4) shows that, although all four reconstructions are quite similar over the 20th century, the Prince George-North Thompson reconstructions show different patterns than the Big Creek-Williams Lake chronologies prior to 1900.

The largest grouping contains the five most southerly reconstructions in British Columbia (Lytton, Lillooet, Westwold, Summerland and Oliver). The Lytton and Lillooet sites are only 15 km apart and the reconstructions correlate highly ($r = 0.57$) and compare well visually except for ca. 1850–1880 (Figure 4). Lytton and Lillooet also correlate quite well with Summerland and Oliver ($r = 0.16$–0.39). The reconstructions for Oliver and Summerland are very similar ($r = 0.58$): the most notable difference is that the dry interval at the end of the 18th century continues into the 19th century in the Summerland reconstruction. The short Westwold reconstruction also correlates with Summerland ($r = 0.44$) and Oliver ($r = 0.30$) and shows the double peaks of wetter conditions centred at approximately 1880 and 1900 (Figure 4). These double peaks are also found in the reconstructions from Jasper and Banff, the Rocky Mountain Foothills (Case and MacDonald, 1995) and

Table V

Correlation matrices for precipitation/drought reconstructions from western Canada/U.S.

(a)	PG	WL	BC	NT	LY	LI	WE	SU	OL	JA	BA	CR	WA
Prince George (P)G)	–	0.16		**0.34**									0.19
Williams Lake (WL)	217	–	**0.61**	**0.52**	0.21	0.16	0.22	0.28	0.17	**0.33**	0.20	0.18	0.12
Big Creek (BC)	217	426	–	**0.44**	0.15	0.25	**0.32**	**0.33**	0.24	0.29	0.25	0.15	0.19
North Thompson (NT)	217	311	311	–			**0.45**	**0.35**	0.18	0.12	0.26	0.24	0.12
Lytton (LY)	217	426	436	311	–	**0.57**		0.16	0.23	0.15		0.20	
Lillooet (LI)	215	355	355	309	355	–		0.28	**0.39**	0.25	0.20	**0.30**	0.23
Westwold (WE)	167	167	167	167	167	165	–	**0.44**	**0.30**		0.18		
Summerland (SU)	215	291	291	291	291	291	165	–	**0.58**	0.17	0.25	**0.33**	0.15
Oliver (OL)	216	276	276	276	276	275	166	275	–		0.22	0.28	0.13
Jasper (JA) v	216	366	366	310	366	355	166	291	276	–	**0.41**	0.22	**0.30**
Banff (BA)	215	424	434	309	527	355	165	291	275	365	–	**0.47**	**0.35**
Cranbrook (CR)	217	251	251	251	251	249	167	249	250	250	249	–	**0.38**
Waterton (WA)	217	324	324	311	324	322	167	291	276	323	322	251	–

(b)	PG	WL	BC	NT	LY	LI	WE	SU	OL	JA	BA	CR	WA
Lake Athabasca 1										0.17			
Lake Athabasca 2	–0.16					0.18				0.17	0.24	0.22	
Lake Athabasca 3													
Foothills	–0.14	0.11	0.18	0.12		0.25	0.22	0.26	0.21	0.18	**0.47**	**0.41**	**0.30**
Prairie					0.15	0.12					0.16	0.18	
Winnipeg							0.17				0.16	0.21	
GP 8		0.20	0.12	0.14	0.11	0.18	0.24	0.28	0.28		0.19	0.23	
GP 9		0.12	0.12	0.21	0.19	0.22	0.24	**0.35**	**0.39**		0.21	**0.32**	
GP 16		0.23	0.28	**0.36**	0.24	**0.30**	**0.37**	**0.49**	**0.40**	0.14	**0.37**	**0.47**	0.21
GP 17		0.12	0.15	0.25	0.20	0.24	**0.33**	**0.42**	**0.38**		**0.35**	**0.49**	0.16
GP 25			0.17	0.25	0.17	0.14	0.27	**0.31**	0.30	0.13	**0.33**	**0.47**	0.23
GP 26	–0.18	0.18	0.25	0.16		0.16	0.17	**0.35**	**0.35**	0.13	**0.33**	**0.40**	0.22

(a) Correlation between reconstructions for the southern Cordillera. Correlations calculated over the maximum interval of overlap between the reconstructions are presented in the top half of the matrix. The number of years of common period is shown in the bottom half of the matrix. Horizontal and vertical lines within the matrix identify regional groupings of the reconstructions. (b) Correlations between the 13 reconstructions and other tree-ring based records of moisture availability from surrounding sites calculated for the maximum overlap between each pair. Sources for these records are given in Figure 5. In both (a) and (b) only statistically significant ($p < 0.05$) correlation coefficients are presented. Correlations greater than 0.30 are boldfaced and values that exceed 0.40 are also boxed.

the PDSI reconstructions from the northwestern United States (Cook et al., 1999; see Figure 5 below). However, the dry conditions seen in both the instrumental and reconstructed series from Westwold during the period 1940–1980 appear to be local and are not seen in any other reconstruction (Figures 2 and 4).

The final grouping is composed of the four most easterly reconstructions (Jasper, Banff, Cranbrook and Waterton). All four of these reconstructions correlate significantly ($p < 0.05$: Table Va) with one another but low frequency plots of the reconstructions (Figure 4) clearly demonstrate a subdivision into northern (Banff-Jasper) and southern groups (Cranbrook-Waterton), although Cranbrook differs from the others in the late 20th century.

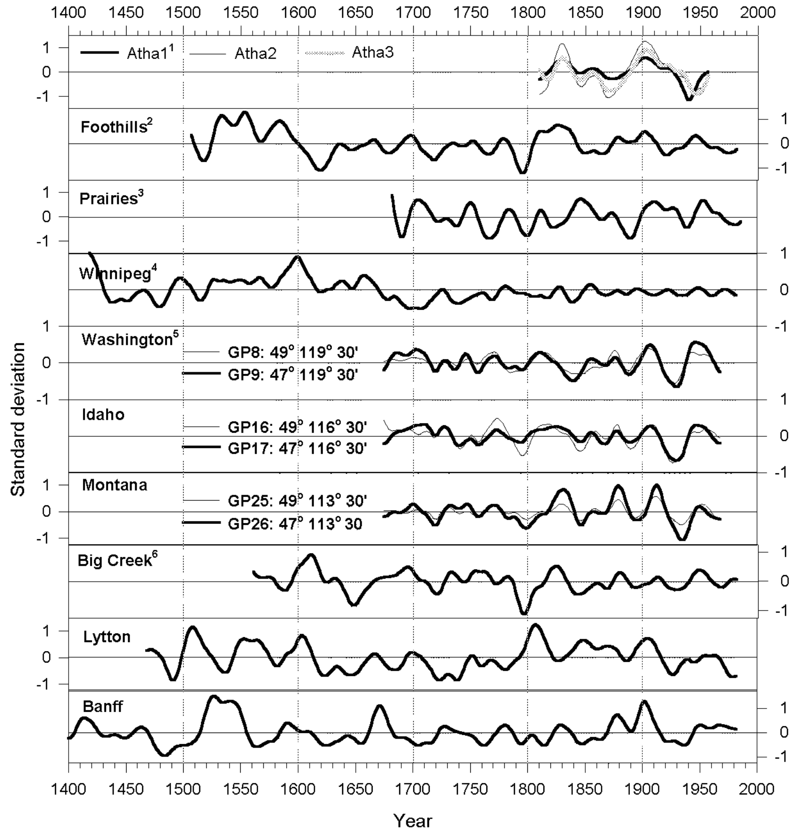


Figure 5. Time series plots of tree-ring based reconstructions of moisture conditions for western Canada and the northwestern United States. All series have been converted to z-scores over their full length and smoothed with a 25-year filter. The vertical shading highlights the region-wide dry intervals >4 years identified in Table VI. Notes: [1] lake level reconstructions for Lake Athabasca developed from white spruce for three time periods (Atha1 is May 21–30, Atha2 is July 11–20 and Atha3 is September 21–30; Stockton and Fritts, 1973); [2] annual precipitation reconstruction (pAugust–July for a combined Fort Macleod and Calgary record) using limber pine (Case and MacDonald, 1995); [3] annual precipitation reconstruction (pAugust–July) for Maple Creek, Saskatchewan utilising white spruce from the Cypress Hills (Sauchyn and Beaudoin, 1998); [4] Winnipeg annual (pAugust–July) precipitation reconstructed from bur oak (St.George and Nielsen, 2002); [5] June–August PDSI reconstructions for selected grid points (GPs) in the network developed by Cook et al. (1999); www.ngdc.noaa.gov/paleo/pdsi.html); [6] The longest reconstructions from the three major sub-regions identified in this study (Big Creek, Lytton, and Banff) are presented for comparison.

Correlations calculated between the reconstructions over their full length (Table Va) are similar to those over the calibration interval (Watson, 2002) indicating that the relationships between the reconstructions (and therefore any regions identified) appear to be stable over the past 2–5 centuries. However, the strength of the relationships between the reconstructions has varied over shorter intervals (Watson, 2002).

3.2.3. *Correlations with Other Reconstructions*

The regional coherence of the 13 reconstructions presented in this paper is explored by comparison with available reconstructions of moisture related variables from adjacent areas of western Canada and the United States. Table Vb reports the results of correlation analyses between these annual records and Figure 5 presents smoothed time series plots of representative reconstructions from the three regions and records from adjacent areas. The comparative data used are reconstructed lake levels from Lake Athabasca, annual precipitation reconstructions for the Rocky Mountain Foothills and Canadian Prairies plus summer PDSI reconstructions from the United States (see caption, Figure 5).

All of the reconstructions developed in this paper correlate significantly ($p < 0.05$) with at least three of the tree-ring based measures of moisture conditions from surrounding sites (Table Vb). Maximum correlations are positive (except those with Prince George) and generally occur with the most proximal series. These results indicate that the reconstructions presented herein are consistent with most previous studies from adjacent areas and can therefore be utilised to assemble a coherent regional picture of past climate variability. The correlations with lake level reconstructions from Lake Athabasca are weak but several of the reconstructions do correlate with the summer (July 11–20) lake level reconstruction (Lake Athabasca 2, Table Vb).⋆ The majority of reconstructions correlate significantly with the PDSI reconstructions from the United States and the annual precipitation reconstruction from the foothills of the Rocky Mountains (Table Vb). The 'Prairies' precipitation reconstruction correlates weakly with the Banff and Cranbrook reconstructions (Table Vb), the other regional reconstructions ($r = 0.14$ with Foothills, $r = 0.08$ with Winnipeg) and the closest PDSI grid points from the network developed by Cook et al. (1999). These poor correlations may reflect problems with the reconstruction itself or real differences in precipitation regimes and moisture sources east of the continental divide (Knox and Lawford, 1990; Richman and Lamb, 1987).

3.3. LARGE SCALE SPATIAL AND TEMPORAL PATTERNS

The previous analyses have demonstrated that dry (wet) periods are reconstructed at a number of different spatial scales across the study area. Local variability is demonstrated by individual or adjacent pairs of reconstructions but coherent variability is also shown at sub-regional and, more rarely, regional scales when coincident extended dry (wet) intervals affect much of the region (Figure 4). In this final section longer term intervals of common dry (wet) conditions are identified and discussed in the context of reconstructions from surrounding sites. This approach permits the exploration and documentation of both spatial and temporal patterns of extended drought across the region. Evaluation of patterns at these longer timescales is important because spatially extensive, long-term droughts can

⋆ Lake Athabasca is over 900 km from the study area and the reconstructions utilise white spruce.

have major economic and social impacts and may be related to large scale features of the atmospheric circulation.

3.3.1. *Development of Regional Wet/Dry Indices*

The annual wet–dry index (Figure 6) is a simple time series developed to explore the spatial extent and duration of dry and wet periods across the study region. It is based on the 13 unfiltered annual reconstructions and is defined as the percentage of the reconstructions in each year that have precipitation below the mean of each reconstructed record. The wet/dry series shown in Figure 6a is truncated at 1700 when sample depth falls below 8 reconstructions rendering the regional series a much less effective measure of spatial extent. Spatially extensive dry (wet) years are defined as those with >50% of the reconstructions below (above) the mean. Prior to 1700 similar years may be tentatively identified based on a higher threshold (>60%). Dry (wet) intervals are defined as periods of >4 consecutive dry (wet) years. The annual wet–dry index does not measure the severity of wet/dry events and therefore separate series were created to summarise the percentage of reconstructions with precipitation estimates > +1 (wet) and < −1 (dry) standard deviation from the mean of the full length of the reconstruction (Figures 6b,c).

Figure 7 presents maps of western Canada showing estimates of moisture conditions by decade from 1700–1989. These maps utilise all of the reconstructions developed in this paper plus available data for western Canada and PDSI reconstructions from the adjacent United States (Cook et al., 1999). The moisture estimates are based on PDSI, annual precipitation, and summer lake levels and are expressed in standard deviation units based on the 1700–1989 period where possible. In the southern Canadian Cordillera, annual precipitation totals (summer–summer) correlate highly with summer PDSI values (Watson and Luckman, 2002) and reconstructions of the two parameters are therefore comparable. These maps allow the magnitude and sign of decadal anomalies to be compared and give some indication of the spatial consistency and extent of longer term dry and wet periods.

3.3.2. *Dry Intervals*

Since 1700 there have been 54 periods when below normal precipitation was reconstructed for >50% of the reconstructions for one or more consecutive years (mean length = 3 years; mode = 1 year). Fourteen dry periods are identified that are greater than four years in length (Table VI). The most prolonged and spatially extensive period is the well-documented drought in the early 20th century (Figures 6a, 7). On average 75% of the reconstructions show dry conditions during the period 1917–1941 that includes the longest and most extensive interval of severe drought conditions (Figure 6b). This drought appears to be less severe and persistent in the reconstructions from the northwestern part of the study region and to have been more severe slightly later in the most easterly reconstructions (Jasper, the Prairies and the two PDSI reconstructions from Montana; Figures 4 and 5). The PDSI reconstructions from the northwestern United States (Cook et al.,

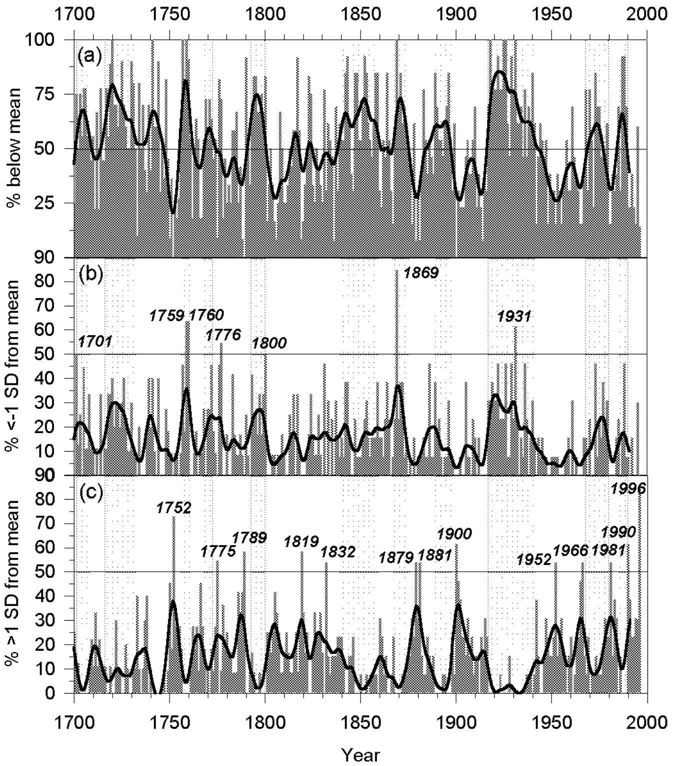
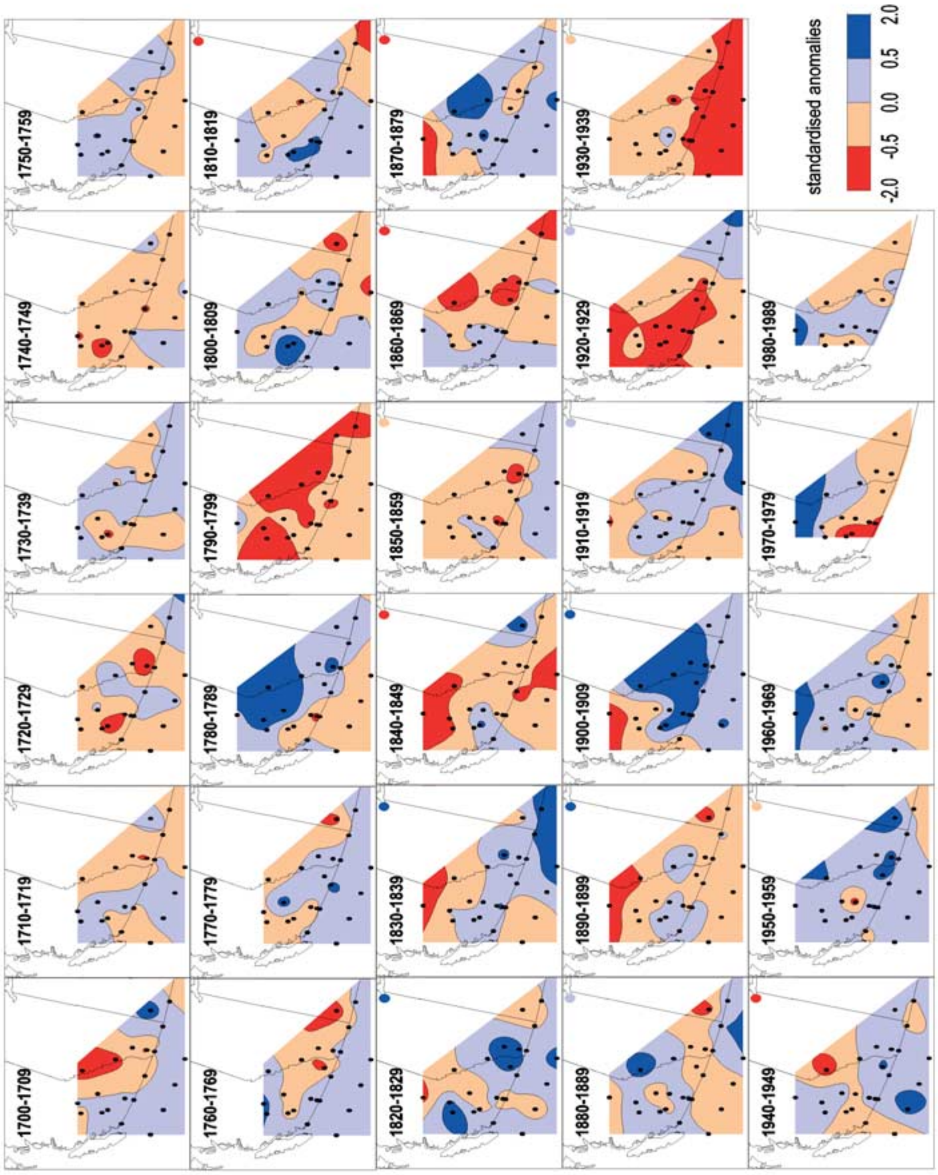


Figure 6. Summary of the spatial extent of dry and wet anomalies across southern B.C. and southwestern Alberta from 1700–1996. (a) The annual wet–dry index shows the percentage of reconstructions with a below normal precipitation estimate in each year. (b) Percentage of reconstructions with precipitation estimates more than one standard deviation below the reconstructed mean in each year. (c) Percentage of reconstructions with precipitation estimates more than one standard deviation above the reconstructed mean in each year. Years when >50% of the available reconstructions are > one standard deviation from the mean are identified. The heavy black line in all figures is a 10-year spline. The vertical grey bars indicate the extended dry periods identified in Table VI.

1999; Figures 5 and 7) indicate that this drought is the most severe and one of the most prolonged droughts to have occurred over the last three centuries. However, it is reconstructed as the driest period in only three of the new reconstructions (Jasper, Oliver and Lillooet, Figure 4, Table IVb). These records indicate that the intensity of the drought of the 1920–1930s is not unprecedented in this region as many individual records from the Southern Cordillera reconstruct droughts of similar or greater magnitude as frequently as once or twice per century. However, it is the most prolonged and spatially extensive dry interval reconstructed for the region: only the dry conditions reconstructed for the shorter event in the 1790s appear to be as extensive as those of the 1920s-1930s (Figure 7; Table IVb). Two shorter intervals of extensive dry conditions are reconstructed in the 20th century – 1968–1979, when all but the Prince George reconstruction showed dry years, and


1700-1709
1710-1719
1720-1729
1730-1739
1740-1749
1750-1759
1760-1769
1770-1779
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1790-1799
1800-1809
1810-1819
1820-1829
1830-1839
1840-1849
1850-1859
1860-1869
1870-1879
1880-1889
1890-1899
1900-1909
1910-1919
1920-1929
1930-1939
1940-1949
1950-1959
1960-1969
1970-1979
1980-1989
standardised anomalies
-2.0 -0.5 0.0 0.5 2.0

Figure 7.

1985–1989 (Table VI). Both of these intervals are seen in the instrumental records (Figure 2).

Three spatially extensive dry intervals occurred in the 19th century; 1839–1859, 1868–1875 and 1889–1897 (Table VI). During the 1839–1859 interval dry conditions are reconstructed as most severe for the more southerly and easterly reconstructions (plus the Winnipeg and Foothills reconstructions; Figure 5) and are most severe in the 1840s (Figure 7). This corresponds with dry conditions seen across much of the western Great Plains of the United States (Woodhouse et al., 2002; Cook et al., 1999) although the more westerly Lytton (and to a lesser extent Lillooet) reconstructions show wetter conditions at this time (Figure 4). The 1868–1875 drought corresponds with low lake levels reconstructed for Lake Athabasca (Stockton and Fritts, 1973) centred around 1868 (Figure 5). 1869 is the most common, severely dry year (Figure 6b) and the 1869 ring is more than one standard deviation below the mean in 50 of the 52 chronologies (Watson and Luckman, 2001a). Case and MacDonald (1995) identify 1869 as one of the driest 25 years in their 487-year long reconstruction of annual precipitation for the Rocky Mountain Foothills and 1868 is one of the driest years identified in July PDSI reconstructions developed for southeastern Alberta and southwestern Saskatchewan by Sauchyn and Skinner (2001). This evidence suggests that 1868/1869 was an extremely dry year at low-elevation sites within interior B.C., the Rocky Mountain foothills and the prairies. Crop failure and grasshopper plagues occurred on the Canadian Prairies in 1868 (Phillips, 1990) and recent fire-scar evidence* suggests that 1869 was an extensive fire year in the Cariboo region of southern British Columbia (Gray et al., 2002).

Dry conditions occurred in >60% of the reconstructions during the interval 1793–1800 (Figure 6a). This dry period also appears to have been widespread (Figures 5 and 7) and is identified in reconstructions from the Canadian Prairies (Sauchyn and Beaudoin, 1998; Sauchyn and Skinner, 2001), Rocky Mountain Foothills (Case and MacDonald, 1995) and the northwestern United States (Cook et al., 1999). Over half of the reconstructions are drier than normal during the years

Figure 7 (facing page). Decadal maps (1700–1989) of standardised moisture-related anomalies from tree-ring based reconstructions across western Canada and the northwestern United States. Data points represent the reconstructions developed in this paper plus those shown in Figure 5 (except Winnipeg) and some additional grid points from the Cook et al. (1999) dataset. Values for the three regional reconstructions (Waterton Lakes, North Thompson and the Foothills record) are plotted for a central location. The standardised values are calculated for each reconstruction using their mean and standard deviation computed either (i) from 1700 or (ii) over the entire reconstruction. The value plotted is the mean annual standard deviation averaged over the decade. Approximately 25% of these decadal averages have anomalies $> \pm 0.5$ and therefore represent the most extreme dry and wet decades.

* Studies have demonstrated links between regional-scale fire occurrence (i.e., presence of fire-scars in trees from across a wide area) and drought years (Swetnam, 2002).

Table VI

Periods of widespread dry and wet conditions in the southern Canadian Cordillera

Dry period	Length	Wet period	Length
1985–1989	5 [a]	1990–1994	5
1968–1979	12 [a]	1980–1984	5
1917–1941	25 [a]	1942–1960	19 [a]
1889–1897	9 [a]	1898–1916	19 [a]
1868–1875	8	1879–1888	10 [a]
1839–1859	21 [a]	1801–1814	14 [a]
1793–1800	8	1819–1830	12 [a]
1768–1772	5	1778–1782	5
1756–1761	6	1749–1755	7
1717–1732	16	1689–1700	12 [a]
1701–1708	8	1664–1668	5
1641–1653	13	1597–1614	18 [a]
1626–1630	5	1544–1549	5
1581–1586	6		

The dry (wet) intervals are defined as periods when >50% of the reconstructions (60% before 1700) show below (above) average precipitation for >4 consecutive years.
[a] Indicates that single years within the interval fall below the 50% criterion.

1768–1772 as are the reconstructions from the Prairies, Winnipeg and the Rocky Mountain Foothills (Figure 5). The six year interval 1756–1761 is dry in over half of the reconstructions that date back to this period (the years 1759 and 1760 are among the most spatially extensive dry years reconstructed; Figure 6b) and is also identified as dry in the PDSI reconstructions from the U.S. (Figure 5). The most prolonged spatially extensive period of drought in the 18th century is reconstructed from 1717–1732 (Table VI, Figures 4, 5 and 6a). During all but five of these years >60% of the 10 available reconstructions estimated drier than normal conditions. The 1740s were also fairly dry (Figures 6a and 7) suggesting that, though conditions were somewhat variable, the first half of the eighteenth century was dry across the region.

Four reconstructions cover the entire 17th century and indicate common dry spells occurred between ca. 1626–1630 and 1641–1653 (the latter is seen in six reconstructions, Figure 4). Somewhat drier conditions are also present in the Foothills reconstruction (Case and MacDonald, 1995) during the period 1641–1653.

Tree-ring reconstructions of precipitation/PDSI from southern Canada, the continental U.S. and northwestern Mexico exhibit a period of severe and prolonged drought in the mid-late 16th century (Stahle et al., 2000b). Dry conditions are present in the Banff reconstruction from 1555–1585 and the Lytton reconstruction shows a shorter dry period from about 1575–1585 (Figure 4). The Williams Lake (1570–1590) and Big Creek (1580–1590) reconstructions also show dry conditions in the late 16th century (Figure 4). Although the early sections of the latter two chronologies have very limited replication ($SSS < 0.85$, Figure 4) they suggest that this drought also occurred west of the Rocky Mountains in southern Canada. The Foothills record shows relatively dry conditions during the period ~1560–1580 but the estimated annual values do not drop below the long term mean (Figure 5). The Banff, Lytton and Winnipeg reconstructions show drier conditions in the latter half of the 15th century (Figure 5).

Many of the reconstructions examined by Stahle et al. (2000b) indicate that the 16th century droughts were the most severe, prolonged and spatially extensive in the western United States and northwestern Mexico in the last 500 years. This does not appear to apply to the five reconstructions discussed above. Stahle et al. (2000b) suggest that the severe drought conditions seen in the reconstructions from the southwestern U.S. and northwestern Mexico during the early half of the 16th century (1540s–1560s) may have been forced by prolonged cool, La Niña-like conditions in the equatorial Pacific. It is interesting to note that extremely wet conditions reconstructed for Banff, Lytton and the Foothills (Figures 4 and 5) coincide with part of this interval. In southwestern Canada, La Niña events are usually associated with wetter than normal conditions as more zonal flow across the Pacific carries storms into the area (Shabbar et al., 1997; Bonsal and Lawford, 1999).

3.3.3. *Wet Intervals*

Most studies of historical precipitation patterns focus on the discussion of droughts because of their profound impact on society, especially when they occur over large areas. However, several synchronous wetter intervals also occur in the southern Cordillera that are as extensive as the dry periods discussed above (Table VI; Figure 4). Examination of the occurrence and timing of these events is also important if linear analyses are subsequently to be used to explore links with larger scale forcing factors.

Three major intervals of above average precipitation are seen in most reconstructions during the 20th century (Table VI). The longest of these, 1942–1960, can be seen in all reconstructions except Westwold (Figure 4) and is also present in the PDSI reconstructions from the northwestern U.S. and the Prairies (Figures 5 and 7). During this 19 year period wet conditions were most widespread for the years 1948–1957 when 60–85% of reconstructions showed above normal precipitation. Several years in the late 20th century were also exceptionally wet (1966, 1981, 1990 and 1996, Figure 6c). On average 65% of the reconstructions also show a wet interval from ca. 1898–1916 (Figures 6c and 7). This wet period is not found in the four most northerly reconstructions (Prince George, Williams Lake, Big Creek and North Thompson; Figure 4) but is present in the reconstructions from the U.S., the Canadian Prairies, Foothills and Lake Athabasca (Figures 5 and 7). The decade 1900–1909 is the wettest reconstructed across the region over the past ~300 years (Figure 7). It is reconstructed as the wettest period of the 20th century in the records from Lytton, Summerland, Oliver, Jasper and Banff (Figure 4) and 1900 appears to be one of the most spatially extensive, extremely wet years post-1700 (Figure 6c; Table IVb).

The late 19th and early 20th centuries show strong decadal shifts in precipitation amounts with the 1868–1875 and 1889–1897 periods being regionally dry and the 1879–1888 and 1898–1916 intervals being exceptionally wet. Above normal precipitation is estimated for most reconstructions in the 1880s (except Cranbrook, Waterton, Prince George and North Thompson), reconstructions from the Canadian Prairies and Rocky Mountain Foothills plus the U.S. reconstructions of PDSI. This accounts for the pronounced ‘double peak’ seen in many of these reconstructions at the turn of the century (Figures 4 and 5). All but seven of the years between 1800 and 1830 are wetter than normal in >50% of the reconstructions (Figures 4 and 6a).

Wet conditions in the 18th century are less spatially coherent than those in the 19th and 20th centuries. The period 1778–1782 is wetter than normal in the four most northern reconstructions (Prince George, Williams Lake, Big Creek and North Thompson) and in the most easterly reconstructions (Jasper, Banff, Cranbrook, Waterton, Foothills and Prairies) but this period is reconstructed as dry in southern B.C. (Lytton, Lillooet, Summerland and Oliver; Figures 4 and 5). The short interval 1749–1755 is estimated as wetter than normal in >60% of the reconstructions and the year 1752 is wet in all 11 reconstructions that include this year (it is the second most spatially extensive extreme year, Figure 6c). Wetter than normal conditions are also found in the Prairies reconstruction during this interval (Figure 5).

Six of the eight new reconstructions available (Figure 4) and the Foothills record (Figure 5) show wetter conditions during the last decade of the 17th century (ca. 1689–1700). Generally wetter conditions from 1664–1668 are particularly pronounced in the Banff and Jasper records (Figure 4). The Williams Lake, Big Creek, Lytton and Banff reconstructions extend back prior to 1629 and show wet conditions around 1600 (Figure 4) as does the reconstruction from Winnipeg (Figure 5). Extremely wet conditions are estimated for Banff over the interval ~1515–1555 but do not match the less-well replicated record from Lytton over this period (Figure 4). The Foothills reconstruction does however show wetter conditions for the years ~1525–1565 (Figure 5).

4. Summary and Conclusions

Precipitation variability is one of the key variables in environmental change and a primary concern for economic analyses of the impacts of future changes. Groisman and Legates (1995) suggest that the impacts of climate change on the hydrological cycle are probably more important to society than increasing global temperatures. However, little is known about pre-20th century precipitation variability in western Canada. This mountainous region is the source area of many important rivers including those draining to the prairies where drought remains a significant problem.

Thirteen annual (pJuly–June) precipitation reconstructions have been developed for a network of sites across the southern Canadian Cordillera. The reconstructions range in length from 165 to 688 years, verify well against independent data at both high and low frequencies and calibrate 39–64% of the variance in the instrumental climate records. Separate latewood width chronologies enter the regression equation as the most important independent variable in 75% of the reconstructions where they were available indicating that this parameter should be more extensively utilised for precipitation reconstructions in this region.

These reconstructions are the only paleo-precipitation data available in Canada from sites west of the Canadian Rockies. The reconstructions capture both the temporal and spatial patterns seen in the instrumental data and individual reconstructions correlate well with precipitation across much of the southern Cordillera. These data constitute the largest network of precipitation reconstructions in Canada and, in addition to documenting precipitation variability in the southern Canadian Cordillera, extend our knowledge of the spatial extent of historical droughts in western Canada and the western United States (Figure 7).

The reconstructions show local, sub-regional and cordillera-wide patterns of precipitation variability. The synchroneity of a number of pronounced wet and dry intervals reconstructed across the region and significant correlations with previously developed reconstructions from adjacent areas indicate that: (1) the individual reconstruction models are well-developed and (2) that they appear to capture information on both local and regional scale precipitation variability. Historical precipitation patterns can be grouped into geographically distinct northern, southern and eastern sub-regions.

The precipitation reconstructions indicate major periods (>10 years) of regionally dry conditions occurred from ca. 1717–1732, 1839–1859, 1917–1941 and 1968–1979. Shorter dry intervals are identified between 1701–1708, 1756–1761, 1768–1772, 1793–1800, 1868–1875, 1889–1897 and 1985–1989 and there is limited evidence for dry periods between 1581–1586, 1626–1630 and 1641–1653. The driest decades in the majority of reconstructions coincide with the widespread droughts of the 1750s, 1790s and first half of the 20th century (Table IVb). There is no indication of significant changes in the mean precipitation between the 20th century and earlier periods at the majority of sites (Table IVa). The long term context provided by these reconstructions indicates that the severity of the drought of the 1920–1930s is not unprecedented for individual sites. However, this event was the most widespread severe dry period to have affected the southern Cordillera over the past 300 years. Significant intervals of wetter conditions are less well defined but are found in the periods 1689–1700, 1750–1755, 1778–1789, 1800–1830, 1880–1890, 1898–1916 and 1942–1960 in most records and ca. 1595–1615 in the four longest records. In particular, the southern and eastern regions show strong, well-defined shifts between wetter and drier intervals at decadal and longer timescales between ca. 1860–1960. This timing corresponds with the findings of several authors that recognise a reorganisation of patterns of SST variability in the Pacific Ocean after 1850 (see Villalba et al., 2001). The scale and variability of spatial patterns of precipitation within this region and their linkages to larger-scale modes of atmospheric and oceanic variability will be the focus of further research utilising these data.

The occurrence of numerous common wet and dry intervals across this region indicates that, although there is local scale variability, regionally extensive synchronous events can be recognised. Despite the assumed heterogeneity of precipitation patterns in mountain areas, annual precipitation reconstructions from these valley floor sites can produce records that are consistent over relatively large regions and are not primarily governed by local conditions. Such reconstructions can provide the extended database necessary to explore the frequency and variability of precipitation anomalies across mountain areas, allowing the development of preliminary maps of decadal precipitation anomalies for western Canada over the last three centuries.

These reconstructions also provide a source of data which can be included in efforts to reconstruct historical streamflow variations for southern British Columbia and, more significantly, in western Alberta. Precipitation reconstructions developed from sites within the Canadian Rockies (the eastern sub-region) are correlated with sites in the adjacent prairies. The availability of longer chronologies and reconstructions from the mountains can provide a more comprehensive perspective of past precipitation variability in the Prairies to the east where few long annually-resolved paleo-records are available. These precipitation reconstructions also complement the extensive collection of proxy temperature data that exists for this region (e.g., Luckman et al., 1997; Wilson and Luckman, 2003). The combination of such regional datasets from a range of paleoclimate variables should allow the development of more comprehensive reconstructions of the past atmospheric and oceanic circulation patterns that are the primary drivers of climate variability in this region.

Acknowledgements

This research was supported by funds from the Meteorological Service of Canada (MSC), the Natural Sciences and Engineering Research Council of Canada and Waterton Lakes National Park. We thank Walter Skinner (of the MSC) for his help and guidance throughout this project. We are grateful to Don Youngblut, Norma Froelich, Anne Stacey, Nick Neary, Bonnie Robinson, Heather Luckman, Helen Luckman, and Rob Wilson for their assistance in the laboratory and in the field. We also thank Margaret Colenutt for providing the Douglas-fir chronologies she developed from Waterton Lakes National Park. We are grateful to the three anonymous reviewers of the original manuscript for their suggestions.

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(Received 21 March 2003; in revised form 9 September 2003)