Spatial Patterns of Preinstrumental Moisture Variability in the
Southern Canadian Cordillera

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ABSTRACT

Extreme wet and dry intervals of the last 350 yr in the Canadian Cordillera and adjacent United States
are examined using a network of 25 tree-ring-based precipitation and Palmer Drought Severity Index
(PDSI) reconstructions. Reconstructed twentieth-century-mapped patterns compare well with patterns
based on the instrumental records at both annual and decadal scales. During the most extreme events, dry
conditions occurred over the entire area. The longest widespread drought in the last 350 yr occurred from
1917 to 1941. Shorter intervals of more severely dry conditions occurred in the early 1720s, 1750s, 1790s,
1860s–70s, and the 1890s. Many of the driest individual years and most extreme dry periods of <7 yr are
reconstructed for the eighteenth century. The longest, wettest periods identified by these reconstructions
occurred in the early twentieth century. In agreement with published studies that explore links between
instrumental precipitation records from the region and conditions in the
Pacific Ocean, the reconstructed
records show that drier (wetter)-than-normal conditions are associated
with El Niño (La Niña) events and
the positive (negative) phase of the Pacific decadal oscillation (PDO).

1. Introduction

The majority of dendroclimatic work conducted in the southern Canadian Cordillera has focused on generating estimates for individual climatic time series: either for a single meteorological station (e.g., Watson and Luckman 2001a) or a regionally representative time series (e.g., Luckman et al. 1997; Wilson and Luckman 2003). Although these studies have greatly expanded our knowledge of climatic variability at sites within the region, they have not systematically explored variability across the region. Climate reconstructions for individual records contain local-, regional- and large-scale signals that cannot be differentiated, or verified, without the broader view and replication that a network of sites affords. The recent development of a gridded network of Palmer Drought Severity Index (PDSI) reconstructions for the contiguous United

States (Cook et al. 1996, 1999) has demonstrated the tremendous potential for tree-ring-based reconstructions to document spatial as well as temporal patterns of preinstrumental climate variability. Reconstruction of such patterns allows us to compare the magnitude and spatial extent of documented extreme events (e.g., the 1920s–1930s drought) with those in the preinstrumental period. This type of information cannot be elicited from individual station reconstructions and is highly significant because of the relatively greater economic and social costs of widespread prolonged drought vis-à-vis shorter, more localized severe events.

Much of the southern Canadian Cordillera and the neighboring prairies lie in the rainshadow of adjacent mountains and consequently have low mean annual precipitation totals (often less than 400 mm). The spatial and temporal variability of precipitation is therefore a significant control of many economic activities and an important conditioner for forest fire activity within the region. The extreme forest fire season of 2003 in the British Columbia interior was preceded by three years of drought and cost the province an estimated 700 million dollars, destroyed over 300 homes,
Few instrumental PDSI records are available for the southern Canadian Cordillera and therefore preference was given to reconstructing precipitation variables (Watson and Luckman 2002).
b. Comparing instrumental and reconstructed precipitation patterns

The individual reconstruction models pass conventional verification tests that evaluate the year-to-year performance and levels of explained variance in the time series over several intervals (Watson and Luckman 2004; Cook et al. 1999; Sauchyn and Beaudoin 1998; Case and MacDonald 1995). However, these tests do not evaluate the collective ability of the reconstructions to reconstruct spatial patterns. The degree of similarity between spatial patterns may be assessed visually and by calculating correlation and congruence coefficients (Richman 1986; Cook et al. 1999). Congruence coefficients provide more information on the similarity of the magnitude of the anomalies in each annual map pair than correlation coefficients that provide a metric of how well the annual map patterns co-vary (Richman 1986; Cook et al. 1999). The mean correlation and congruence coefficients over the interval 1920–94 are 0.60 and 0.67, respectively (Fig. 2). This difference is not unexpected, as congruence coefficients are biased to higher values than the correlation coefficient (Richman 1986; Cook et al. 1999). These values are similar to those identified by Cook et al. (1999) between instrumental and reconstructed patterns of summer PDSI over a much larger region. These results indicate that the reconstructions consistently capture large-scale annual spatial patterns providing a convincing verification of both the signal at individual sites and its spatial representativeness. The ability to replicate the annual patterns is, in and of itself, a verification of the skill of the individual reconstructions.

Comparison of the reconstructed and instrumental annual patterns (Fig. 2) indicate that only about 10% (around 8 of 75, depending on the criterion used) of the years are poorly modeled. An examination of the instrumental and reconstructed patterns for these years (Fig. 3) is instructive. The annual contour maps in Fig. 3 show reconstructed and instrumental annual precipitation/PDSI values expressed in standard deviation units based on the period 1920–94. In all cases, the reconstructed patterns include some points that are the incorrect sign (i.e., a reflection of local climatic or non-climatic anomalies) and others that are the correct sign but underestimate (or overestimate) the magnitude of deviation. However, if one were to coarsely summarize the entire region as being either wet or dry (or half wet and half dry), the reconstructions perform well even for these poor years. When the annual maps are composited over longer intervals (Fig. 4), local anomalies are reduced by the averaging process making longer-term patterns more comparable than those for individual years. Mean correlation and congruence coefficients calculated between the pairs of decadal maps (similar to the maps of widespread anomalies presented later in this paper) are higher than for individual years (0.78 and 0.79; Fig. 4).

3. Results

a. Evaluation of the relative severity of prolonged dry and wet periods

The magnitude of prolonged dry and wet intervals can be defined by ranking the mean standardized anomalies for all 25 reconstructions (Tables 1a and 2a) or the 13 records from the southern Canadian Cordillera (Tables 1b and 2b) for equivalent intervals of time. Only 1 (entire area, Table 1a) or 3 (13 site network, Table 1b) of the 10 most extreme dry individual years occur in the twentieth century compared with 5 (Table 2a) or 3 (Table 2b) of the 10 wettest years. These results suggest that the twentieth-century instrumental record does not contain many examples of the most extreme dry years experienced in this region in the last 350 yr.

At the decadal time scale, a dry period originating in the first quarter of the eighteenth century (~1717) is identified as well as a period in the 1790s (Table 1a only, it is identified in shorter intervals in Table 1b) and the early twentieth-century drought. Shorter dry intervals (i.e., <7 yr) are identified for the late 1750s to early 1760s, and the late 1860s through early 1870s (Tables 1a and 1b). The 3-yr mean for the period 1661–63 is identified as dry for the southern cordillera alone (Table 1b). Several of these shorter intervals (those in the early and mid-1700s) are also considerably more severe than equivalent periods during the early twentieth century.

At longer time scales (>10 yr means), the documented drought that occurred in the early twentieth-century dominates (Table 1). The reconstructions indicate that it is clearly the longest, most severe dry spell to have affected the region in the past 350 yr. Within this drought, the 3-yr interval 1929–31 was particularly dry (Tables 1a and 1b). The next most severe 20-yr periods in the entire region in the past 350 yr are 1717–36 (mean −0.25, ranked 14th), 1781–1800 (mean −0.18, ranked 21st), and 1840–59 (mean −0.15, ranked 29th; not shown in Table 1a).

The strongest, most prolonged wet interval appears to have occurred in the early part of the twentieth century (~1897–1916: Tables 2a and 2b). There are some differences in the order of severity of other prolonged wet intervals between the entire region (Table 2a) and the southern Canadian Cordillera (Table 2b). In the
Fig. 2. Measures of agreement between the reconstructed and instrumental annual maps. (a) The number of stations available in each pair of annual maps. (b) Correlations between the instrumental and reconstructed maps in each year. Years with nonsignificant correlation coefficients are labeled prior to 1980, after which correlations become a less reliable measure because of the decreased number of observations. Note that the significance levels displayed do not account for any spatial autocorrelation that may exist in the dataset. They are only a guide to identify poorly modeled years. (c) Congruence coefficients for the same data. There is no theoretical sampling distribution for testing the significance of congruence coefficients (Richman 1986).
series for the entire region (Table 2a), anomalous wet periods occurred in the first quarter of the twentieth century, 1900–19 and in the late seventeenth century (1666–85). In the series for the southern Canadian Cordillera, the second, third, and fourth wettest 20-yr periods include the mid-twentieth century (1947–66), the period 1801–20, and the late seventeenth century (as seen in the regional series). At shorter intervals, the latter part of the 1870s to the mid-1880s is also reconstructed as being particularly wet.

b. Evaluation of mapped patterns

In the previous section, reconstructed dry and wet events were ranked according to their severity across the region for a number of time scales. This approach excludes information on their spatial extent and less severe but more extensive droughts may not be identified. It is also difficult to define the most appropriate length of period to identify dry and wet events as they overlap at a number of time scales (Tables 1 and 2). In
the following sections, we present maps of dry and wet events (defined according to their spatial extent) at three time scales: annual events, 5–10-yr periods and intervals >10 yr in length.

1) Annual Maps

Patterns of precipitation anomalies may be mapped over the network for each year from about 1640 to 1996. Prior to 1640, there are <10 records available and the contoured patterns are unduly influenced by the distribution of the records. Between 1640 and 1996, the number of records varies between 9 and 25 because of the different lengths of the individual reconstructions.

Figures 5b and 5c show less extreme sequences of consecutive years that are highly significant in the history of settlement of the Canadian west. The Palliser Triangle is a semiarid, drought-prone region of the Canadian Prairies located in southeast Alberta and south-

Fig. 4. A comparison of patterns of instrumental and reconstructed precipitation/PDSI anomalies by decade from 1920 to 1989. Here, \( r \) and \( cc \) refer to the correlation and congruence coefficients between each pair of decadal maps. Data are expressed as standard deviations from the 1920–94 mean.

Conditions during two of the most extreme dry and wet years reconstructed (Fig. 5a; Tables 1a and 2a) display large areas where precipitation/PDSI is more than one standard deviation from the mean and roughly one quarter of the values are more than two standard deviations from the mean. These diagrams indicate that for individual years strong anomalies of the same sign can occur across the entire region.

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FIG. 4. A comparison of patterns of instrumental and reconstructed precipitation/PDSI anomalies by decade from 1920 to 1989. Here, \( r \) and \( cc \) refer to the correlation and congruence coefficients between each pair of decadal maps. Data are expressed as standard deviations from the 1920–94 mean.
west Saskatchewan. It is named after the British explorer Captain John Palliser who visited the region in the late 1850s and said that it was too dry to be suitable for agricultural settlement (Fig. 5b; Koshida 1992; Palliser 1859). In a later expedition during the 1870s, the botanist John Macoun found the region to be suitable for agriculture based on the comparatively wet conditions that prevailed during that interval (Fig. 5c; Nemani 1998; Koshida 1992). His findings encouraged settlement of the area that we now know receives an average of <350 mm of precipitation per year but produces 75% of Canadian wheat (Koshida 1992). Agreement between these documentary sources and the tree-ring-based reconstructions provides mutual verification while demonstrating the important context that these longer records provide for evaluating more recent instrumental climate records.

Although it is important to examine the magnitude of departures in widespread patterns that occur in particular years (e.g., for water resource planning), it is perhaps more important to study widespread patterns that persisted for several years. The examples presented in Fig. 5 are not isolated extreme years but occur within sequences where the pattern of departures may persist for several years and thereby have a more pronounced impact than single year extreme events. In the rest of this paper we present a series of maps that explore longer-term, widespread dry and wet anomalies across the region.

2) WIDESPREAD DRY AND WET INTERVALS

Major widespread dry and wet periods reconstructed for the southern Canadian Cordillera over the past ~350 yr are presented in Figs. 6 and 7. These periods are defined as intervals longer than 4 yr when >50% (>60% before 1700 when n < 8) of the 13 annual precipitation reconstructions developed for British Columbia and Alberta are below (dry) or above (wet) their 1831–1978 average (the period common to all 25 reconstructions). In some cases, single years within the interval fall below this 50% criterion. These intervals

<table>
<thead>
<tr>
<th>Year</th>
<th>1 Year</th>
<th>3 Year</th>
<th>5 Year</th>
<th>10 Year</th>
<th>20 Year</th>
</tr>
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<td>1717–1736</td>
<td>0.25</td>
<td>0.39</td>
<td>0.53</td>
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* Identifies the two most highly ranked nonoverlapping 20-yr periods.
are defined using the method outlined in Watson and Luckman (2004).

The aggregate maps produced reduce the localized anomalies created by poor estimates for individual years in specific reconstructions. The standardized anomalies on these maps are defined by the standard deviations of the annual series over the 1831–1978 common period. However, averaging reduces the absolute magnitude of these anomalies that display a reduced range of departures from those seen in the annual maps (e.g., Figure 5; Table 1). For this reason, the absolute magnitudes of the anomalies in the annual (Figs. 3 and 5) and composite maps (Figs. 4 and 6–8) are not directly comparable as they express anomalies averaged over different time intervals. The absolute values are compared for specific intervals in Tables 1 and 2.

The maps of the extended dry and wet intervals include data from precipitation and PDSI reconstructions in adjacent areas that were not used in defining these events. The coincident occurrence of pronounced moisture anomalies in reconstructions from adjacent areas verifies the significance of the periods identified using the smaller 13-reconstruction dataset. If the spatial scale was broadened and all 25 reconstructions were used to define extreme periods, fewer intervals would be identified because it is less common to find droughts that affect the entire region. Smaller-scale dry/wet events unique to the southern Canadian Cordillera would not be as readily identified. Therefore these additional data are included to provide more information about the spatial scale of the reconstructed anomalies. Maps of the dry and wet periods are arranged according to their length to enable direct comparison of periods of similar length. The patterns or the spatial scale of dry/wet events of different lengths should be more directly comparable than the actual magnitude of departures.

(i) **Dry periods <10 yr in length**

The majority of the spatially extensive dry periods identified are less than 10 yr in length (Fig. 6). The most severe are in the mid-1750s, which coincides with dry conditions over much of the western United States, and the 1790s. On average ~60% of the 24 reconstructions that extend back to the 1790s drought have values more than half a standard deviation below their mean with particularly dry conditions reconstructed in the Rockies and the foothills. A streamflow reconstruction for the North Saskatchewan River, which flows eastward from this region, reconstructs very low flows during the 1790s (Case and MacDonald 2003).

Wolfe et al. (2001) document a widespread period of dune activity in the Great Sand Hills region of the Palliser Triangle in Saskatchewan during the early 1800s. They attribute this activity to the dry conditions that prevailed throughout much of the 1700s and the extremely dry conditions of the 1790s [as based on precipitation reconstructions in Case and MacDonald (1995) and Sauchyn and Beaudoin (1998), also used in

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**Table 2. The 10 highest mean standardized anomalies ranked over different intervals. For explanation see Table 1.**

<table>
<thead>
<tr>
<th>(a)</th>
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<th>3 Year</th>
<th>5 Year</th>
<th>10 Year</th>
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<tr>
<td>7</td>
<td>1913</td>
<td>1.16</td>
<td>1992–1994</td>
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</tr>
<tr>
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<td>1899–1902</td>
<td>0.68</td>
<td>1749–1753</td>
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<td>1.15</td>
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<td>0.68</td>
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</table>

<table>
<thead>
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<th>(b)</th>
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<th>5 Year</th>
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<td>1696–1698</td>
<td>1.33</td>
<td>1694–1698</td>
</tr>
<tr>
<td>2</td>
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<td>1.67</td>
<td>1693–1697</td>
<td>1.22</td>
<td>1693–1701</td>
</tr>
<tr>
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<td>1752</td>
<td>1.46</td>
<td>1697–1699</td>
<td>1.07</td>
<td>1696–1701</td>
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<tr>
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<td>1996</td>
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<td>1900–1902</td>
<td>1.00</td>
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</tr>
<tr>
<td>5</td>
<td>1900</td>
<td>1.39</td>
<td>1879–1881</td>
<td>0.96</td>
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<tr>
<td>6</td>
<td>1789</td>
<td>1.34</td>
<td>1670–1672</td>
<td>0.93</td>
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<tr>
<td>7</td>
<td>1819</td>
<td>1.24</td>
<td>1750–1752</td>
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<td>1670</td>
<td>1.23</td>
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<td>9</td>
<td>1879</td>
<td>1.21</td>
<td>1804–1806</td>
<td>0.85</td>
<td>1899–1903</td>
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<td>10</td>
<td>1981</td>
<td>1.20</td>
<td>1752–1754</td>
<td>0.84</td>
<td>1672–1676</td>
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</table>
Fig. 5. Annual maps showing reconstructed moisture conditions over a number of intervals. (a) Two of the driest and wettest years reconstructed (see Tables 1 and 2); n is the number of reconstructions used to produce the map. The percentage of records that are more than 0.5 standard deviations (sd) from their 1831–1978 mean are listed. (b), (c) Selected years during the nineteenth century (refer to text for discussion). The maps show reconstructed conditions for each record expressed in standard deviation units from the mean of the period common to all 25 reconstructions (1831–1978).
Fig. 6. Widespread dry periods in the southern Canadian Cordillera after 1650. The dry intervals are defined as periods when >50% (>60% before 1700) of the 13 reconstructions developed by Watson and Luckman (2004; Fig. 1) show below average precipitation for >4 consecutive years. Single years within some intervals fall below the 50% criterion. The z scores are derived using the mean and standard deviation calculated over the common period of all reconstructions (1831–1978). (a), (b) Dry intervals < and >10 yr are plotted sequentially, and (c) subdivisions of the 1917–41 period are shown. The number of years in each period is given in brackets.
Fig. 7. Widespread wet periods in the southern Canadian Cordillera after ~1650. For explanation see Fig. 6.
The results presented here support this interpretation as the greatest concentration of dry periods identified in the past 350 yr occurs during the 1700s. In addition to the 1750s and 1790s, dry intervals are identified from 1701–08 and 1768–72. During both of these periods, most of the PDSI records from the United States show wetter than normal conditions.

The 1868–75 drought is not particularly striking in terms of the magnitude of the standardized anomalies or its duration, but it appears to have had a strong impact on the landscape. In particular, the year 1869 was very dry (80% of the 25 reconstructions have values more than one standard deviation below the mean). The widespread dry conditions estimated for 1869 coincide with fire-scar evidence of an extreme fire year in the Cariboo Forest region of southern British Columbia (Daniels and Watson 2003; Gray et al. 2002) and with documented crop failure and grasshopper plagues on the Canadian Prairies in 1868 (Phillips 1990).

The period 1889–97 was also very dry across the region with the driest conditions estimated for the eastern reconstructions. Major forest fires burned approximately 9% and 20% of Banff and Jasper National Parks in the Canadian Rockies in 1889 (Luckman 1998). Phillips (1990) reports that 9 yr of drought during the 1890s led to farm abandonment on the Canadian Prairies and severe drought also occurred in the U.S. Great Plains during the 1890s (Woodhouse and Overpeck 1998). The 1750s, 1790s, 1860s, and 1890s droughts are recorded in a tree-ring-based reconstruction of July PDSI developed for the Canadian Prairies by Sauchyn and Skinner (2001).

The most recent short (i.e., <10 yr), dry interval identified for the region occurred in the 1980s (1985–89). This drought had severe impact on agriculture in western Canada and an estimated 10% of farmers and farm workers left the agricultural sector in 1988 (Phillips 1990). The year 1985 was one of the worst fire years on record in British Columbia and cost roughly 300 million dollars in timber losses and fire-fighting expenses (Phillips 1990).

(ii) Dry periods >10 yr in length

The mapped patterns in Fig. 6 show five discrete dry periods greater than 10 yr in length during the past 350 yr. The earliest reported here is 1641–53 during which time 8 of the 10 available records show below-normal conditions with the driest records located in British Columbia. Mean moisture conditions are reconstructed as below normal for all records during the 15-yr interval 1717–31. During the driest portion of this interval, 1717–21, reconstructed values are on average more than one standard deviation below the common period mean. Evidence for this drought is also indicated by below-normal streamflow estimates for the North Saskatchewan, South Saskatchewan, and Saskatchewan Rivers (Case and MacDonald 2003), and negative summer PDSI estimates on the Canadian Prairies for this interval (Sauchyn and Skinner 2001).

Prolonged dry conditions are estimated for much of the study area over the years 1839–59. This drought corresponds with low streamflow estimates for the South Saskatchewan and Saskatchewan Rivers (Case and MacDonald 2003) and a drought in the western Great Plains of the United States from 1845 to 1856 that may be linked with the decline in the bison population of the area (Woodhouse et al. 2002). Fye et al. (2003) document drought over large areas of the western United States for much of this interval. Dry conditions are also reconstructed for the Canadian Prairies during the 1850s and 1860s (Sauchyn and Skinner 2001).

The longest severe drought identified in the reconstructions occurred during the period 1917–41. All reconstructions show drier-than-normal conditions during this well-known dry interval. Analysis of the annual maps (not shown) reveals that the region of greatest dryness differs between the first and second half of the drought. During the 1920s, the most extreme dry conditions are seen for southern interior British Columbia whereas, during the 1930s, the driest conditions are seen in the southern part of the study region (Fig. 6c). However, the comparison of the instrumental and reconstructed decadal maps for the 1920s (Fig. 4) indicates that the severely dry area in the 1920s extended further south. Over the twentieth century, 7 of the 10 driest years in the instrumental records and 8 of those in the reconstructed records occur during this drought.

(iii) Wet periods

Eleven regionally extensive wet periods dating from the late seventeenth century onward are displayed in Fig. 7. This diagram demonstrates that it is not uncommon to have wet periods that span the entire study.

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2 The reconstructed 1869 year is July 1868–June 1869.
3 The PDSI reconstructions are not included in this map because they terminate in 1978.
4 Calculated as the mean standard deviation from the 1920–94 mean for the set of 25 instrumental records and the set of 25 reconstructed records.
region. Sample depth is limited (n = 10) during the earliest of these intervals (1664–68). All 23 reconstructions covering the 1749–55 interval show above-normal values averaging 0.58 standard deviations above the mean, with the greatest anomalies in the western part of the study region. Wetter-than-normal conditions are reconstructed for almost all of the records during the interval 1778–82. The final two short wet periods occur in the late twentieth century: 1980–84 and the more widespread wet period in 1990–94. Both of these periods are also seen in the instrumental records from the region.

Six wet periods greater than 10 yr in length are identified in the reconstructions. The 12-yr period 1689–1700 is wet across much of the region with the exception of a few records in the southern interior of British Columbia and the most easterly sites. The next four wet periods span parts of the nineteenth century. Notable among these is the period 1819–30, which coincides with the largest flood reconstructed for the Red River in Manitoba in 1826 (St. George and Nielsen 2003). Although the Red River drainage basin is east of the study region, these wet conditions could have extended across the prairies as wet conditions are reconstructed across much of the western United States and the U.S. Great Plains for part of this interval (Fye et al. 2003). The final two wet periods (1898–1916 and 1942–60) bracket the 1920s–1930s drought. The wet period in the early 1900s, which appears to have been more severe in the eastern part of the study region, coincides with high flows on the North Saskatchewan, South Saskatchewan, and Saskatchewan Rivers (Case and MacDonald 2003) and is also seen in PDSI records (both instrumental and reconstructed) from the western United States (Fye et al. 2003).

4. Links with Pacific forcing

Precipitation variability in western Canada and the U.S. Pacific Northwest has been linked with known circulation changes in the Pacific Ocean, particularly the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO; Mantua et al. 1997; Gershunov and Barnett 1998; McCabe and Dettinger 1999; Shabbar and Skinner 2004; Bonsal et al. 1993). The influence of these patterns can be seen in the composite maps of moisture anomalies in the instrumental records during the twentieth century (Fig. 8). These composites show that El Niño and positive PDO years are generally drier, whereas La Niña and negative PDO years are generally wetter across the region. More of the records have negative mean anomalies when ENSO and PDO are in phase but the opposite pattern (La Niña, negative PDO) is not as strong. Sample depth is limited for situations where the two patterns are out of phase, but generally the patterns are more mixed. Composite maps produced using the reconstructed records for the same groupings are very similar (Fig. 8), again demonstrating the skill of the reconstructions. Unfortunately, it is not possible to extend this analysis back over the past 350 yr, as no definitive PDO reconstructions are presently available.5

Drought conditions across much of the United States (particularly the southwest and extending into the Great Plains) have been linked to La Niña conditions in the Pacific Ocean (Cole and Cook 1998; Cole et al. 2002). As mentioned above, La Niña events typically produce wetter-than-normal conditions in the study region (Fig. 8). Cole et al. (2002) provide a list of persistent droughts that affect the continental United States and the ENSO-sensitive southwest. In the discussion that follows, the timing of these droughts is compared with conditions in the southern Canadian Cordillera to determine whether widespread anomalies of the same sign occur across western North America and if such anomalies coincide with documented La Niña events.

As one would expect (based on the ENSO response of the two regions described above), there are instances when conditions in the two regions are opposite (e.g., during the persistent U.S. droughts of the early 1750s, 1780s, 1820s, and the 1950s; see Figs. 4 and 7). There are other periods when persistent drought in the United States coincides with near-normal conditions in the southern Canadian Cordillera (e.g., 1855–65). This is not unexpected as the ENSO teleconnection weakens northward; there is great variability in characteristics of different ENSO events, and ENSO teleconnections to surface climate can be unstable as demonstrated by Cole and Cook (1998) for the continental United States. Sometimes, however, persistent drought affects much of the United States and the southern Canadian Cordillera concurrently (e.g., the 1840s, 1890s, and 1930s; Fig. 6). While it is beyond the scope of this paper to explore the causes of such widespread drought, it is interesting to note that the droughts of the 1840s and 1930s are not particularly strong in the ENSO-sensitive region (i.e., the U.S. Southwest) and the concurrent drought of the 1890s does not correspond with La Niña conditions (Cole et al. 2002). These comparisons indicate that widespread droughts (i.e., droughts that affect

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5 Several tree-ring-based reconstructions of the PDO have been developed (e.g., Gedalof and Smith 2001; D’Arrigo et al. 2001; Biondi et al. 2001), but they often disagree with one another prior to the twentieth century.
the western United States and the southern Canadian Cordillera) appear to occur in the absence of La Niña events that are typical of the twentieth century (i.e., something other than La Niña appears to have forced these very large-scale droughts). It is possible that their synchronous occurrence is a coincidence. However, the persistence and scale of these droughts may be related to positive feedbacks that enhance initial land surface anomalies or to more complex interactions with long-term modes of atmospheric/oceanic variability [e.g., the Atlantic multidecadal oscillation (AMO); Enfield et al. 2001; Gray et al. 2003].

\[ \text{Composite maps produced for the different phases of the AMO show weak but generally consistent anomalies across the southern Cordillera (with the positive AMO and dry with the negative AMO), which is consistent with recent work that shows nonsignificant but generally positive correlations between the AMO and summer moisture availability over the region (Shabbar and Skinner 2004).} \]
5. Summary and conclusions

This paper has demonstrated (through comparisons of instrumental and reconstructed precipitation anomaly patterns) that a newly developed set of annual precipitation reconstructions (Watson and Luckman 2004) can be combined with data from adjacent areas to explore spatial patterns of preinstrumental moisture conditions in the southern Canadian Cordillera. This is the first time this type of information has been available for the area. Maps of the most spatially extensive dry events reveal that it is not uncommon for anomalies of the same sign to affect the entire study region.

Previous studies and instrumental records have documented the severity and duration of the droughts that affected much of southwestern Canada and the United States during the 1920s and 1930s. An examination of preinstrumental dry events in the region suggests that this drought is of unmatched length and severity over the past 350 yr. Shorter intervals of more severely dry conditions include the early 1720s, 1750s, 1790s, late 1860s through early 1870s, and the 1890s. Many of the driest individual years and short dry periods (i.e., <7 yr) are reconstructed for the eighteenth century. The longest, wettest period identified in the reconstructions occurred in the early twentieth century (~1898–1917). Most of the dry and wet periods identified are corroborated by the occurrence of synchronous events in independent records from western North America. The results suggest that the most severe extended dry (1917–36) and wet (1897–1916) intervals of the past 350 yr occurred during the twentieth century, thus indicating that the instrumental record provides a broad range of conditions that is well-suited for the calibration of tree-ring-climate relationships.

It is difficult to compare the spatial patterns of the anomalies without also considering their severity (which is not directly comparable—see previous discussion). However, the dry events of the 1720s, 1750s, 1790s, and early twentieth century appear to have been the most extensive, showing strong anomalies throughout the southern cordillera and the adjacent United States. Extensive negative anomalies also prevailed during the 1890s but appear to have been more intense in the more easterly sites. These results indicate that although there appear to be analogs to the twentieth-century drought in terms of pattern and severity in the study region, none of the earlier events were as prolonged as that event. The dry periods in the early 1700s and late 1760s–early 1770s are similar in that the dry conditions are concentrated in the interior Canadian sites, whereas the U.S. PDSI grid points actually show wetter conditions. The dry period identified from 1968–79 is unusual in that many of the more northern and coastal PDSI grid points indicate wetter-than-normal conditions.

Overall, the wet periods that have been identified are more regionally coherent than the dry intervals. The extensive wet periods identified for 1778–82, 1879–88, 1898–1916, and 1990–94 are similar in that they show very strong anomalies in eastern portions of the study region and generally weaker anomalies in the United States and interior British Columbia (particularly the first two intervals). In contrast, the strongest anomalies during the 1749–55 and 1980–84 wet intervals are found west of the Rocky Mountains. The three intervals 1689–1700, 1801–14, and 1819–30 have a number of features in common; they show strong anomalies in both southwestern British Columbia and southwestern Alberta and weak negative anomalies in south-central British Columbia and the southeast corner of the study region. Based on these results, the twentieth-century wet periods do not appear to be unprecedented in this region.

A comparison of the occurrence of widespread drought (i.e., drought that is coincident in the study region and the western United States) suggests that these widespread events are not related to La Niña events (a strong control of drought in the southwestern United States). Although this observation is based on only three common drought events, it suggests that caution is warranted when evaluating widespread preinstrumental periods of drought solely in terms of ENSO events [e.g., the sixteenth-century megadrought (Stahle et al. 2000) identified in tree-ring reconstructions from Mexico to western Canada]. The coincident events in the two regions may not be related to a common forcing. However, much more work is needed to evaluate the complex causes and persistence of drought in western North America. In particular, a very limited amount of research has been conducted into relationships between atmospheric and oceanic circulation patterns (and their interactions) and summertime precipitation anomalies (i.e., the period most important to tree growth) in western Canada. Most of the available studies focus on the agriculturally important Canadian Prairies or concentrate on winter conditions. Until a clearer picture is available of the interaction between circulation patterns and moisture anomalies in the southern Canadian Cordillera over the instrumental record, causes of variability in reconstructions of summer precipitation will remain difficult to interpret.

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