A Proxy Record of Drought Severity for the Southwestern Canadian Plains

Written comments on this paper will be accepted until December 2001

David J. Sauchyn[1] and Walter R. Skinner[2]

ABSTRACT

This paper examines the statistical relationships between Palmer Drought Severity Index (PDSI) data from the southwestern Canadian plains and tree–ring index chronologies from nearby sites. Standardized tree–ring widths from white spruce (*Picea glauca*) from the Cypress Hills (Alberta and Saskatchewan) and from lodgepole pine (*Pinus contorta*) from the Bears Paw Mountains (Montana) account for 47% and 39% of the variance in regional July PDSI. The corresponding regressions are the basis for the first reconstructions of PDSI for the Canadian plains. This proxy PDSI record extends from 1597 and demonstrates that, although 1937 was the worst single drought year, the 20th century lacked the prolonged droughts of the 18th and 19th centuries, when decades of July PDSI were consistently below zero. Clusters of drought years in the 1690s, 1720s, 1750s–60s, 1790s–1800s, 1820s, 1850s–60s and 1890s, support the notion of a 20– to 25–year drought cycle for the northern Great Plains. These prolonged droughts lower the resistance of ecosystems and soil landscapes to disturbance from hydroclimatic events, such that thresholds of landscape change are exceeded and the recovery of natural systems can take decades or centuries. These droughts also seriously affect the soil and water resources that support dryland agriculture.

RÉSUMÉ

Le présent article porte sur les liens statistiques entre l'indice Palmer de gravité de sécheresse (IPGS) des Plaines du sud-ouest du Canada et les dendrochronologies de sites à proximité. Les largeurs dendométriques normalisées de l'épinette blanche (*Picea glauca*), des collines du Cyprès (Alberta et Saskatchewan), et du pin de Murray (*Pinus contorta*) des Bears Paw Mountains (dans le Montana) représentent 47 % et 39 % respectivement de la variance dans l'IPGS de juillet régional. Les régressions correspondantes sont la base des premières reconstitutions de l'IPGS

[1] Department of Geography, University of Regina, Regina, SK
[2] Climate Research Branch, Environment Canada, Downsview, ON

pour les grandes plaines de l'Ouest. Ce relevé climatique indirect (IPGS) a été entrepris en 1597 et il révèle que, bien que 1937 a été la pire année de sécheresse, le XXe n'a pas connu les sécheresses prolongées des XVIIIe et XIXe siècles, siècles au cours desquels les décennies de l'IPGS de juillet étaient sous zéro de façon constante. Des grappes d'années de sécheresse dans les années 1690, 1720, 1750–1760, 1790-1800, 1820, 1850–1860 et 1890 confirment la notion d'un cycle de sécheresse de 20 à 25 ans pour la Région des grandes plaines septentrionale. Ces sécheresses prolongées ont pour effet de diminuer la résistance des écosystèmes et des paysages de sol à la perturbation causée par les événements hydroclimatiques, de telle sorte que les seuils de changement du paysage sont dépassés et que les systèmes naturels peuvent mettre des décennies, voire des siècles, à récupérer. De plus, ces sécheresses nuisent gravement au sol et aux ressources en eau sur lesquels repose l'agriculture sur des terres arides (arido-culture).

INTRODUCTION

Monthly and yearly lack of precipitation and soil moisture is a significant ecological and socio–economic condition in subhumid environments, where the natural systems are sensitive to fluctuations in the surface and near–surface water balances (Herrington *et al.*, 1997; Lemmen and Vance, 1999). Drought lowers the resistance of ecosystems and soil landscapes to disturbance from hydroclimatic events, such that thresholds of landscape change are exceeded and the recovery of natural systems can take decades or centuries (Wolfe *et al.*, in press). Drought also seriously affects the soil and water resources that support dryland agriculture (Nemanishen, 1998).

On the western Canadian plains, agricultural land use and management systems are adjusted to historical climatic variability (Hill and Vaisey, 1995; PFRA, 2000), but now must adapt to unprecedented climatic change, which probably will include variability that exceeds the historic experience. The Canadian Centre for Climate Modelling and Analysis' transient climate change simulation suggests that the largest CO_2–induced rise in mean surface temperature in southern Canada will occur in the Interior Plains (Boer *et al.*, 2000). A regional climate model for western Canada forecasts similar trends, but with higher spatial resolution and local variability (Laprise *et al.*, 1998). Instrumental records for the prairie provinces show statistically significant trends in various climate variables (Akinremi *et al.*, 1999; Cutforth *et al.*, 1999; Zhang *et al.*, 2000). A common climate change scenario also suggests more frequent extreme conditions including drought and major hydroclimatic events (Hengeveld, 2000).

Most general circulation models also project increased precipitation in winter, and decreased net soil moisture and water resources in summer. However, predictions of precipitation are less certain than those for temperature (Herrington *et al.*, 1997). This weakness in climate projection is critical for the prairie region, where the variability of precipitation is characteristically large, with profound impacts on natural and human systems. More than anywhere else in Canada, understanding

long–term precipitation variability would contribute to the sustainable management of land and water resources: "During the 1984–1990, the drought years found all three levels of government unprepared. ...Millions of dollars could have been saved and more timely response provided if drought forecasts had been available." (Nemanishen, 1995). The knowledge base for drought forecasting requires data on pre–settlement climatic variability and, in particular, the frequency and intensity of extreme hydroclimatic conditions not yet experienced by the agricultural community.

These climate change scenarios and the consequences of 20th century drought have generated considerable interest in the paleoclimatology of the Canadian plains (Vance and Last, 1994; Lemmen and Vance, 1999). Lake sediment records (Last and Sauchyn, 1993; Wilson and Smol, 1999) span the Holocene, but are relatively coarse and thus tend to show smooth trends and gross chronological subdivisions. Notwithstanding the high–resolution sampling of lacustrine sediments (*e.g.,* Laird *et al.*, 1996), the proxy data of consistently highest resolution are derived from tree rings. Recent climate studies (Briffa, 2000; Cook *et al.*, 1999; Stahle *et al.*, 2000; Mann *et al.*, 1999) have established tree rings as the preferred proxy data for the evaluation of climate variability and for long records of extreme hydroclimatic conditions. These proxy data are a crucial source of climate history where reliable instrumental records are relatively short (the past 100 years) and for documenting climate variability at decade–to–century time scales. Tree–ring data also have been used to investigate and extrapolate historical fluctuations of atmospheric and oceanic teleconnections, such as the ENSO (El Niño Southern Oscillation), NAO (North Atlantic Oscillation) and PDO (Pacific Decadal Oscillation) (Cook et al., 1998; Allan and D'Arrigo, 1999; Gedalof and Smith, 2001). Various climatic parameters reconstructed from tree–ring series also can be used to validate the spatial and temporal trends output from global and regional climate models (Barnett *et al.*, 1996; Jones *et al.,* 1998).

In the Prairie Provinces, dendrochronology has been largely confined to the forested margins of the Prairie Ecozone (Case and MacDonald, 1995; Luckman and Innes, 1991; St. George and Nielsen, 2000; Watson and Luckman, 2001). Trees are lacking in the subhumid northern Great Plains, where proxy precipitation records can contribute to understanding climate variability and the management of water resources. Although the native vegetation is mixed grass prairie, the cooler climate of some uplands supports trees. The first precipitation reconstruction from within the Prairie Ecozone of Canada was based on a 315–year ring–width chronology for white spruce (*Picea glauca*) from the Cypress Hills (Sauchyn and Beaudoin, 1998). The present study is based on this chronology and other unpublished tree–ring data from nearby uplands in north–central Montana.

Instrumental precipitation data are widely available and are commonly used for the calibration of tree–ring parameters and reconstruction of drought. The Palmer Drought Severity Index (PDSI), a direct measure of drought, has been reconstructed throughout the United States (Cook *et al.*, 1997, 1999; Meko, 1992; Meko *et al.*, 1993, 1995; Stockton and Meko, 1975; Cleaveland and Duvick, 1992; Hughes and Brown, 1992). There are no proxy PDSI data for western Canada, because there are

relatively few moisture–sensitive tree–ring chronologies (Case and McDonald, 1995; Sauchyn and Beaudoin, 1998). This paper examines the statistical relationships between PDSI data from the southwestern Canadian plains and standardized tree–ring widths from nearby sites (Figure 1) and applies these relationships to a reconstruction of July PDSI prior to the settlement of the Canadian plains and the collection of instrumental weather data.

STUDY AREA AND DATA SETS

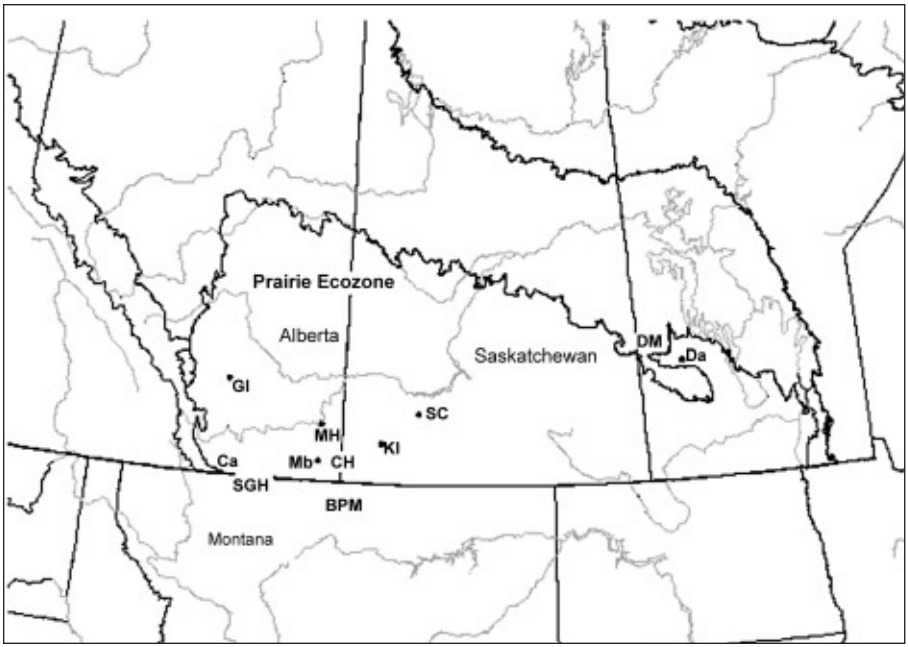

Figure 1. Locations of the Tree–Ring Chronologies: Sweet Grass Hills (SGH), Bears Paw Mountains (BPM), Cypress Hills (CH), Duck Mountains (DM), and of the Climate Stations: Carway (Ca), Gleichen (Gl), Manyberries (Mb), Medicine Hat (MH), Klintonel (Kl), Swift Current (SC), Dauphin (Da). The Heavy Irregular Lines are the Ecozone Boundaries for Western Canada.

The semi–arid to dry–subhumid Prairie Ecozone of western Canada (Figure 1) is commonly referred to as the Palliser Triangle, because Captain John Palliser concluded from his 1857–60 expedition, that this region was "by no means a desirable district for settlement" and that a large area "will forever be comparatively useless" (Palliser, 1859). Motivated or perhaps duped by the prophecies of optimistic speculators and bureaucrats, EuroCanadians settled Palliser's Triangle and converted it to agricultural land use, but not without major and continuous adaptations to climatic variability, especially seasonal shortages of water (Jones, 1987). Conversion

of the mixed grass prairie to farmland occurred mostly in the 20th century. Between 1906 and 1916, the population of census divisions in southeastern Alberta (#1, 3, 5) and southwestern Saskatchewan (#4, 8) rose from 14,418 to 125,934 (Government of Canada, 1938), more than twice the rural population today. Following the 'dust bowl' of the 1930s, soil and water conservation practices and a more favourable climate led to expanding crop production through the 1940s to 1970s, notwithstanding periodic crop failures in individual drought years such as 1961. The drought years of the 1980s, and changes in agricultural policy, have resulted in larger areas of permanent cover and continuous cropping. The vulnerability and adaptation to climatic hazards are central issues in the continuous adjustment of prairie agriculture to economic and environmental factors (Schweger and Hooey, 1991; Wilhite and Wood, 1995; Nemanishen, 1998).

The study area map (Figure 1) shows the locations of the climate stations and tree–ring chronologies referred to in this paper. In Figure 2, mean annual and summer precipitation for the period 1950–96 are mapped for the North American interior (Legates and Willmott, 1990). These maps show the strong gradient east of the Rocky Mountains and the decreasing precipitation from south to north with increasing continentality. The map of annual precipitation shows a dry belt centered on the junction of Alberta, Saskatchewan and Montana and extending across the Great Sand Hills of southwestern Saskatchewan, the largest area of sand dunes in southern Canada. This region of low precipitation encompasses most of our study sites. Villmov (1956) examined the synoptic climatology of this Canadian 'Dry Belt', describing it as "a vast feeding area of subsidence and divergence". He suggested that,

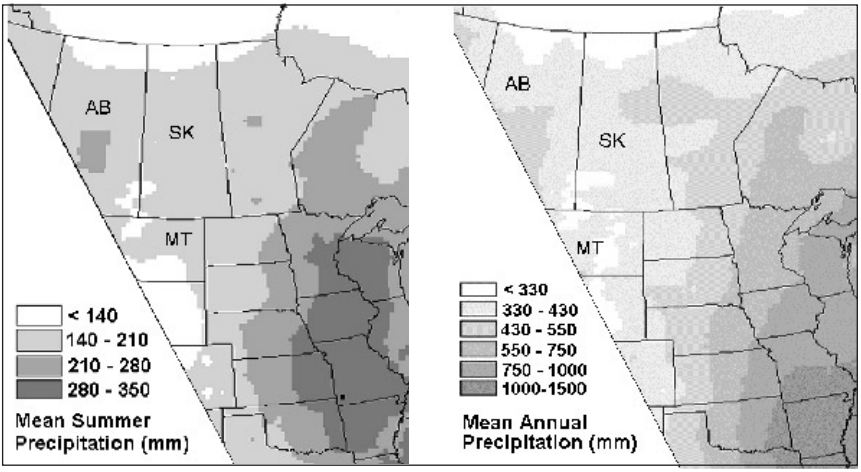

Figure 2. Mean Summer and Mean Annual Precipitation for the Interior of North America. These Maps Illustrate the Relatively Large Area of Low Precipitation in Southwestern Saskatchewan, Southeastern Alberta and an Adjacent Part of Montana.

unlike the debate over Palliser's conclusions, "opinion based upon climatological observations has been unanimous in its indictment of the area".

TREE–RING CHRONOLOGIES

The tree–ring data consist of the widths of annual growth rings derived from four tree species at four sites (Figure 1): *Picea glauca* (white spruce) from the Cypress Hills (CH–Pg), *Pinus contorta* (lodgepole pine) from the Bears Paw Mountains (BPM–Pc), *Pinus albicaulis* (whitebark pine) from the Sweet Grass Hills (SGH–Pa), and *Picea mariana* (black spruce) from the Duck Mountains (DM–Pm). Although the distribution of trees is severely limited in subhumid environments, where they exist at higher elevations and in sheltered coulees, they record a strong signal of annual and seasonal moisture. The tree–ring chronology from the Cypress Hills was the basis for a reconstruction of annual (August to July) precipitation for the period 1682–1994 (Sauchyn and Beaudoin, 1998). This chronology was more than doubled in length by cross–dating the annual rings of dead wood collected from log buildings and those from living trees with a maximum age of about 150 years. In the Sweetgrass Hills and Bears Paw Mountains, there are *Pinus contorta* and *Pinus albicaulus* with more than 400 growth rings, so the chronologies from these sites are based entirely on living trees. The chronology from the Duck Mountains of west–central Manitoba is short (180 years) for a tree–ring record, but it enables an analysis of growth response to drought on the eastern margin on the Prairie Ecozone.

All wood samples were processed in the Tree–Ring Laboratory at the University of Regina following standard procedures (Stokes and Smiley, 1968; Ferguson, 1970; Grissino–Mayer *et al*., 1996; Schweingruber, 1988). Ring widths were measured to within .001 mm using a 40× stereomicroscope, a Velmex UniSlide digitally–encoded traversing table, and the ring–width measuring software MEDIR. Cross–dating of all tree–ring series enabled the detection of anomalous series and missing or false rings, and ensured that the correct calendar year was assigned to each tree ring. The raw ring–width data were converted to index chronologies (averaged standardized ring widths) using the program ARSTAN (Grissino–Mayer *et al*., 1996). The raw data were detrended to remove low frequency variation which usually reflects tree age and forest stand dynamics. The remaining high frequency variation generally represents growth response to annual and seasonal climate. The raw ring widths were divided by estimates from the best–fit curve, and a biweight robust estimate of the mean ring–width index for each year was computed. These values comprise the tree–ring index chronology for a specific site.

CANADIAN PALMER DROUGHT SEVERITY INDEX

The PDSI has been computed for approximately 140 Canadian stations from the rehabilitated historical air temperature and precipitation database having co–located monthly mean air temperature and monthly total precipitation records during the

20th century (Skinner *et al.*, In preparation). A database of homogenized and long–term temperature time series of monthly maximum, minimum and mean temperatures has been specifically designed for climate change analyses in Canada (Vincent, 1998; Vincent and Gullett, 1999). Missing values were estimated using highly correlated neighbouring stations. It was necessary in some cases to join short–term station segments to create long–term series and test for 'relative homogeneity' with respect to surrounding stations. The methodology involves the identification of inhomogeneities in the temperature series, which are often non–climatic steps due to station alterations including changes in site exposure, location, instrumentation, observer, observing program, or a combination of the above. Monthly adjustment factors were derived from the regression models, and adjustments were applied to bring each homogeneous segment into agreement with the most recent homogenous part of the series.

Similar to air temperature, long–term and homogenized precipitation datasets have been prepared for climate change analyses in Canada (Mekis and Hogg, 1999). The network density is insufficient to allow widespread use of surrounding station data to identify and adjust inhomogeneities. Instead, the primary goal was to correct daily rain and snow measurements for all known inhomogeneities. Adjustments were applied on the daily level for rain and snow separately. Where necessary, records from neighboring stations were joined employing a technique based on a simple ratio of observations. Overlapping periods were used to minimize possible inhomogeneities. Recent analyses of these data in gridded form have identified distinct temperature and precipitation trends in Canada since 1950 (Zhang *et al.*, 2000).

STATION PALMER DROUGHT SEVERITY INDEX

The PDSI has been a commonly used drought index in North America and was developed to measure intensity, duration, and spatial extent of drought. It is a soil moisture accounting algorithm based on the water balance. The computational procedure is described by Palmer (1965) and Alley (1984). PDSI values are derived from on–going measurements of precipitation, air temperature and soil moisture and are normalized with respect to time and location. This allows comparison of the index in time and space. The PDSI has become the primary tool for describing and monitoring prevailing drought (Louie, 1986). The PDSI model allows measurement of prolonged abnormal dryness or wetness across a region and can be related directly to past weather conditions. Negative PDSI values indicate dry conditions and positive values indicate wet conditions. PDSI values generally fall between −6 and +6 (Table 1).

Table 1. Severity classes of PDSI (Alley, 1984).

PDSI	Class
≥ 4.00	Extremely wet
3.00 to 3.99	Very wet
2.00 to 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
−0.49 to 0.49	Near normal
−0.50 to −0.99	Incipient drought
−1.00 to −1.99	Mild drought
−2.00 to −2.99	Moderate drought
−3.00 to −3.99	Severe drought
≤ −4.00	Extreme drought

The PDSI reflects long–term moisture, runoff, evapotranspiration, recharge and deep percolation. It is useful for drought analysis over periods of months or seasons. Also, it has proven useful for drought reconstruction prior to the instrumental record from climate proxy data in the conterminous U.S.A. (Cook *et al.*, 1999). Canadian station monthly PDSI records vary in length from as early as 1895 to as late as 1998. For climate response function analysis and PDSI reconstruction, seven monthly PDSI records were selected for stations in close proximity to the tree–ring chronologies (Table 2).

Table 2. Monthly instrumental PDSI records used for PDSI reconstruction.

Station ID	Station	Latitude (°N)	Longitude (°W)	Years
3031400	Carway, AB	49.00	113.37	1915–1998
3032800	Gleichen, AB	50.88	113.05	1914–1998
3034480	Medicine Hat, AB	50.02	110.72	1896–1998
3044200	Manyberries CDA, AB	49.12	110.47	1929–1993
4028040	Swift Current A, SK	50.28	107.68	1895–1994
4024080	Klintonel, SK	49.68	108.92	1912–1998
5040680	Dauphin A, MB	51.10	100.05	1911–1995

RESULTS

The reconstruction of climate from trees rings requires a statistical relationship between tree–ring and meteorological variables, representing a growth response to climate variability (Fritts, 1976). Table 3 lists significant ($p < 0.05$) product moment correlations among the tree–ring index chronologies and monthly PDSI data for the 'normal' climate period, 1961–90. The highest correlations are mostly in July. This conforms to previous tree–ring studies of PDSI for the United States (Cook, *et al*., 1997, 1999; Meko, 1992; Meko *et al*., 1993, 1995; Stockton and Meko, 1975; Cleaveland and Duvick, 1992; Hughes and Brown, 1992), where high July correlations are characteristic of sites from the northern United States. The highest correlations in Table 3 are between the tree–ring widths from the Cypress Hills (CH–Pg) and PDSI data from nearby Medicine Hat and Manyberries, the two climate stations within the region of lowest precipitation shown in Figure 2. Correlation coefficients decline toward the margins of the subhumid plains. For example, there are no significant correlations in Table 3 for Carway, Alberta and Dauphin, Manitoba.

The correlation of PDSI and tree–ring widths beyond the growing season reflects the strong serial autocorrelation that is inherent in the algorithm for the calculation of PDSI. There are negative correlations between *Pinus albicaulis* ring widths from the Sweetgrass Hills and PDSI data from Gleichen, Alberta, because this index chronology contains both moisture and temperature signals. The Sweetgrass Hills rise above the northern Great Plains to 2130 m, near the elevation of timberline in the Rocky Mountains to the west. At this elevation, tree growth is enhanced by summer heat which is associated with drought on the surrounding plains.

July PDSI and the tree–ring widths from the Cypress Hills and Bears Paw Mountains are positively correlated for all five stations listed in Table 3, suggesting a consistent regional drought signal for the driest sector of the Prairie Ecozone. When July PDSI is averaged for Medicine Hat, Gleichen, Manyberries, Swift Current and Klintonel, the correlation with the BPM–Pc index chronology (0.560) is stronger than any of the coefficients listed in Table 3 for this chronology. The correlation between the regional July PDSI and the CH–Pg index chronology (0.634) is lower than the correlation (0.715) with Medicine Hat PDSI, but it exceeds the coefficients for the other four climate stations.

Serial autocorrelation is common in tree–ring records because soil moisture and tree growth in one year can influence growth response to climate in subsequent years. When the previous year's ring width is held constant, the partial correlation coefficients are only marginally higher than the coefficients reported in Table 3 (0.678 versus 0.634 for regional July PDSI and CH–Pg). This minor improvement suggests that nearly all annual growth is in response to net soil moisture for the current year. It also supports a simple growth response model with a single predictor, standardized ring width for the current year, at least as a first approximation of proxy PDSI.

Regional July PDSI for southeastern Alberta and southwestern Saskatchewan and the tree–ring index chronologies from the Cypress Hills and Bears Paw Mountains are plotted in Figure 3 for the years 1896–1998, the complete span of the

Table 3. Significant ($p < 0.05$) product moment correlations among standardized tree–ring widths and the mean monthly Palmer Drought Severity Index for five stations in southeastern Alberta and southwestern Saskatchewan.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Swift Current												
BPM–Pc	0.406					0.370	0.520					
CH–Pg			0.376	0.361	0.377	0.432	0.363	0.399	0.439	0.368		
Klintonel												
BPM–Pc							0.378					
CH–Pg	0.451						0.383					
Medicine Hat												
BPM–Pc							0.555	0.445				
CH–Pg		0.384	0.369	0.450	0.468	0.583	0.715	0.647	0.498	0.485	0.437	
Manyberries												
BPM–Pc						0.396	0.381					
CH–Pg	0.381					0.533	0.588	0.504	0.405			
Gleichen												
SGH–Pa	−0.377	−0.377	−0.516	−0.419		−0.395	−0.472		−0.389	−0.368		−0.473
BPM–Pc							0.397					
CH–Pg						0.379	0.431	0.451	0.445			

BPM: Bears Paw Mountains
CH: Cypress Hills
SGH: Sweet Grass Hills

Pg: *Picea glauca* (white spruce)
Pc: *Pinus contorta* (lodgepole pine)
Pa: *Pinus albicaulis* (white bark pine)

instrumental climate records. While the positive correlation among these records is apparent, there are years or groups of years (the late 1940s), where discrepancies among the curves imply differences in July weather among the climate stations or between the stations on the plains and those on the uplands supporting the trees.

By removing one year (1974), from the 1961–90 calibration period, the R^2 values rise from 40% to 47% for the CH–Pg chronology and 31% to 39% for the BPM–Pc chronology. From 1973 to 1974, the average July PDSI rose from less than –2 (moderate drought) to .93, mostly as the result of a wet July in southwestern Saskatchewan. Swift Current's PDSI of –3.25 (severe drought) in 1973 changed to 2.68 (moderately wet) in 1974. In both tree–ring chronologies, however, the ring–

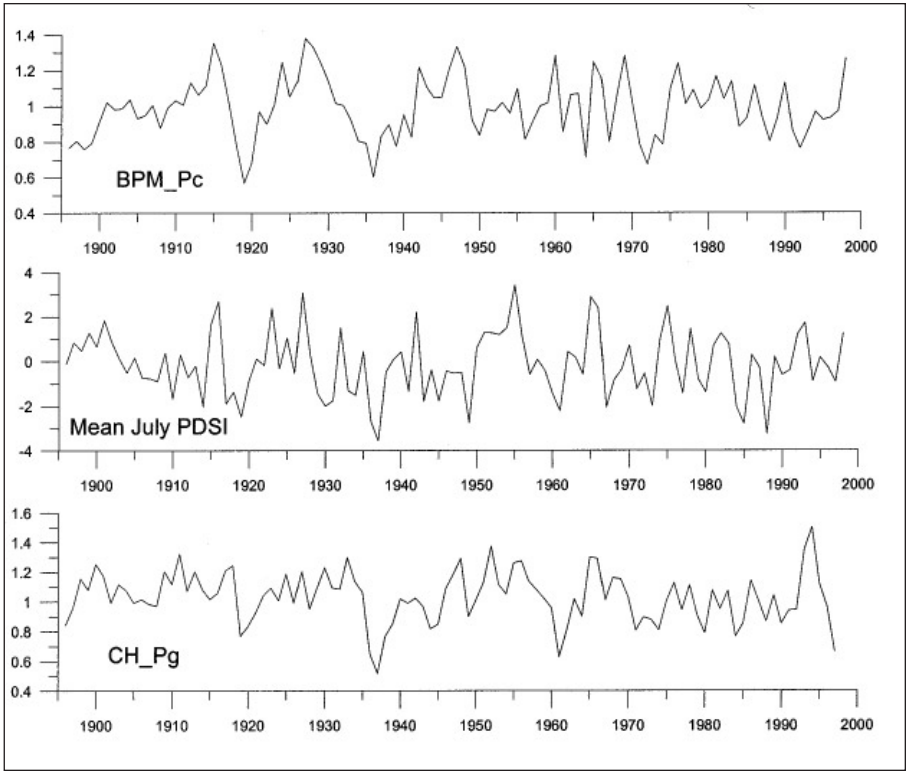

Figure 3. Mean July PDSI for Southeastern Alberta and Southwestern Saskatchewan and the Tree–Ring Index Chronologies from the Bear Paw Mountains (BPM–Pc) and Cypress Hills (CH–Pg).

width index decreased from 1973 to 1974. Severe drought can limit tree growth in a following wetter year. This type of serial autocorrelation is common in tree–ring series. Also the July 1974 weather in the Bears Paw Mountains and western Cypress Hills may have been similar to the weather in southern Alberta (incipient drought to slightly wet) according to the PDSI values. The July weather of 1974 highlights the spatial variability of precipitation in the interior plains, and shows how this constrains the extrapolation of tree–ring records and the reconstruction of a regional drought history.

Our reconstruction of PDSI is therefore based on the calibration of the ring widths using climate data for 1961–90 excluding 1974. Using standardized tree–ring width as the single predictor of mean July PDSI produces the regressions equations in Table 4 and the proxy PDSI records plotted in Figure 4. Whereas the CH–Pg chronology accounts for a larger proportion of the variance in July PDSI, the BPM–Pc chronology provides an extra 85 years of proxy climate data. The use of two chronologies from distinct species and forests provides two different perspectives on regional paleoclimate and drought history.

Table 4. Regression equations for the reconstruction of July PDSI from standardized tree–ring widths. The period of calibration is 1961–90, excluding 1974.

	R^2	adjusted R^2	prob F
July PDSI = 6.70*CH_Pg – 6.86	46.8%	44.8%	0.42×10^{-4}
July PDSI = 6.01*BPM_Pc – 6.33	38.8%	36.6%	3.05×10^{-4}

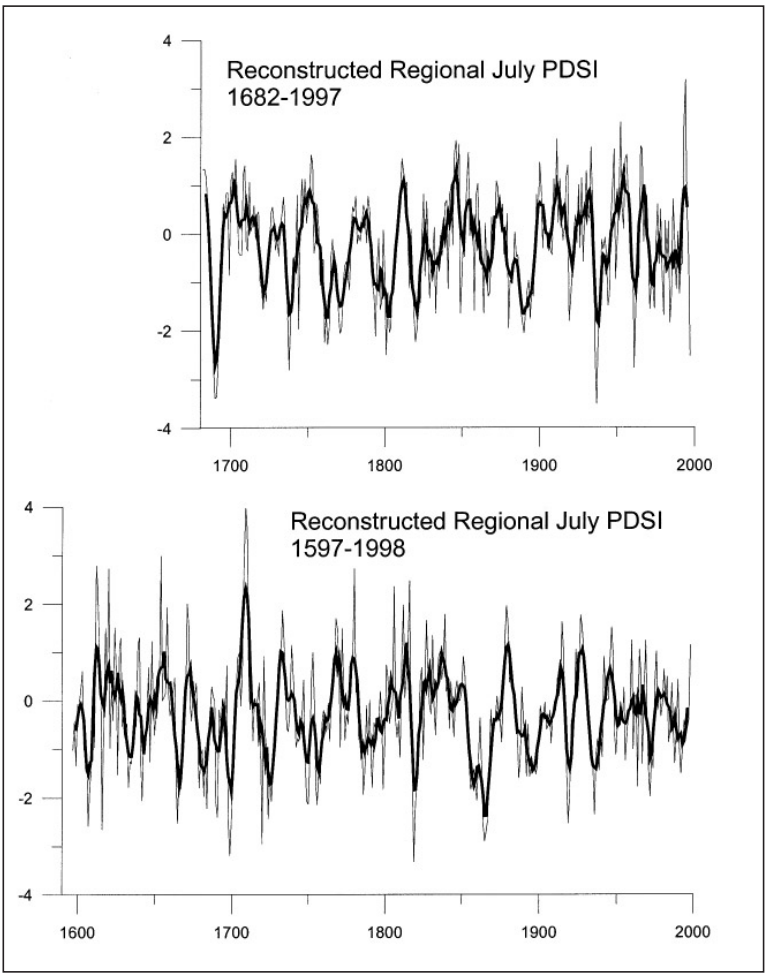

Figure 4. Regional July PDSI for Southeastern Alberta and Southwestern Saskatchewan Reconstructed from Standardized Tree–Ring Widths from *Picea Glauca* from the Cypress Hills (1682–1997) and from *Pinus Contorta* from the Bears Paw Mountains (1597–1998). The Bold Lines represent 5–Year Running Means.

Table 5 gives significant ($p < 0.05$) product moment correlations between reconstructed and measured regional July PDSI for various 30–year periods other than the 1961–90 calibration period. Reconstructed and measured PDSI fail to correlate before 1921 in the Cypress Hills record and during the 1940s for the Bears Paw Mountains as evident in Figure 3. Otherwise the data in Table 5 provide verification of our reconstructions of regional July PDSI, particularly when the data for 1935 are removed from the BPM chronology for the same reasons discussed above for excluding 1974 from the calibration period. During 1932–37, there was declining tree–ring width despite wetter conditions in July 1935.

Table 5. Verification of PDSI reconstructions: significant ($p < 0.05$) product moment correlations between reconstructed and measured mean July PDSI for various 30–year (normal) periods other than the calibration period of 1961–90.

	CH–Pg	BPM–Pc (excluding 1935)
1931–60	.563	
1921–50	.405	(.386)
1911–40		.498 (.527)

DISCUSSION

The proxy PDSI records presented here reinforce the results of previous reconstructions of annual precipitation (Sauchyn and Beaudoin, 1998; Case and MacDonald, 1995), but with greater statistical significance, and using a parameter that more closely represents agricultural drought. Previous dendroclimatic studies identified years of low precipitation as more frequent prior to the 20th century and highlighted an especially severe drought of the 1790s (Wolfe *et al.*, 2001). Our proxy PDSI record also demonstrates that while 1937 was the worst single drought year, the 20th century lacked the prolonged droughts of the 18th and 19th centuries, when there were decades with July PDSI consistently below zero. Because PDSI is based on a soil water balance, and thus accounts for water loss by evapotranspiration, it identifies drought resulting from high temperatures and moderate precipitation. Also, the scaling of the PDSI enables the classification of degrees of drought and moisture excess (Table 2), as opposed to simple statistical definitions of drought such as one standard deviation below the mean precipitation for a specified period (30–year normal, 20th century, or entire record).

Table 6 identifies clusters of drought years for the two proxy records. The bold numbers are years of moderate July drought ($-2 < \text{PDSI} < 2.99$). Years of severe July drought ($\text{PDSI} < -3$) are also underscored. There are 73 mild July droughts ($-1.0 < \text{PDSI} < -2.0$) in the BPM–Pc record and 60 in the CH–Pg record. These droughts are identified only if they occurred during a period of sustained drought or coincide

Table 6. Clusters of drought years in the proxy PDSI records reconstructed from the tree–ring chronologies from the Cypress Hills (CH–Pg) and Bears Paw Mountains (BPM–Pc).

CH–Pg	BPM–Pc
	1606, **1607,** 1608–09
	1664, **1665,** 1666–68
1688[1], **1689**[2], **1690–91**[3], **1692**	**1690–91**, **1699**
1719–23	**1720**, 1723, **1724**, 1725, **1726**, 1727
1761, 1762, **1763**, 1764	1748, **1749–50**, 1751…1755, **1756**, 1757–1758
1792–93, **1794**, 1797–98, **1801**, 1802, **1803**, 1804	1786–87, 1789, 1791–92
1819, **1820**, 1821, 1823	1818, **1819**,**1820**, 1821
1858, 1864, 1867–68	1855–1859, **1860**, 1861, 1863, **1864–67**, 1868
1887–89, **1890**, 1891–92, 1894–96	1892, 1894–99
1919, 1920	1918, **1919**, 1920
1937, 1938–39	1934, **1936**, 1937, 1939
1961	1962
1984–85, 1988	1988

[1]mild drought, [2]moderate drought, [3]severe drought.

with moderate to severe droughts in the other proxy record. The mild droughts of the 1980s are included for context, since they are recent and familiar.

A lack of synchroneity between the two proxy records prevents the synthesis of a single regional drought history. On the other hand, the two sites within 250 km provide distinct perspectives on drought, given the difference in tree species, and contrasting geological settings (and therefore substrates, topography and topoclimate). The BPM record contains more moderately wet and moderately dry Julys. Lodgepole pine grows on drier sites than white spruce and therefore is generally more sensitive to fluctuations in soil moisture. Nearly all of the severe and moderate droughts in one record correspond to periods of at least mild drought at the other tree–ring site. Thus the apparent difference between the two records is more in the severity of drought than the timing. This difference in severity may reflect the site differences described above, but also the well–documented spatial heterogeneity of drought (Cook *et al.*, 1999).

Whereas values < −4.0 are common in the instrumental database, there are no extreme droughts in the proxy record, because the standardized tree–ring widths account for less than 50% of the variance in July PDSI. Also, tree rings tend to be a conservative signal of climatic severity. This underestimation is mostly of excessive moisture, since gravity water that exceeds the field capacity of the soil does not contribute to tree growth. Both records indicate severe drought in the 1690s. Otherwise severe July drought is limited to the years 1819 and 1937. Natural and human systems have the capacity to withstand short–duration drought, irrespective

of severity, and recover largely unaffected in the long–term. On the other hand, prolonged or persistent drought has more serious consequences (Wolfe *et al.*, 2001) and thus has been the subject of recent investigations (Allan and D'Arrigo, 1999; Meko *et al.*, 1995; Pelletier and Turcotte, 1997; Stahle *et al.*, 1998). In Table 6, the clusters of drought years in the 1690s, 1720s, 1750s–60s, 1790s–1800s, 1820s, 1850s–60s, and 1890s occur at intervals or multiples of 20–25 years.

An apparent 20–25 years drought cycle has been described in various studies of proxy and instrumental climate data from the Great Plains (Cook *et al.*, 1997; Meko, 1992; Stockton and Meko, 1975) and in less systematic investigations. In response to the devastating impacts of the weather of the 1930s, the government of Canada created the Prairie Farm Rehabilitation Administration and commissioned a report in April 1938, by E.W. Stapleford (1939), who concluded that "There will be groups of years within a period of 50 years that will be extremely dry, constituting a serious drought". Exactly 50 years after Stapleford penned his prediction in 1938, drought occurred in 1988 with devastating impacts. Between 1985 and 1991, mostly as the result of the drought of 1988, the Canadian government dispensed $22 billion to prairie grain farmers in total direct payments (Statistics Canada, 1989–91) .

ACKNOWLEDGEMENTS

The Climate Research Branch of Environment Canada and the Saskatchewan–Canada Agri–Food Innovation Fund supported this research. We thank Jennifer Stroich, Antoine Beriault, Lowell Strauss and Jason Tuchelt for capable assistance in the field and laboratory and Ed Cook and Emma Watson for their comments on the original manuscript.

REFERENCES

Akinremi, O.O., S.M. McGinn and H.W. Cutforth. 1999. "Precipitation Trends on the Canadian Prairies." *Journal of Climate,* 12(10): 2996–3003.

Allan, R.J. and R.D. D'Arrigo. 1999. "'Persistent' ENSO Sequences: How Unusual was the 1990–1995 El Niño?" *The Holocene,* 9: 101–118.

Alley, W.H. 1984. The Palmer Drought Severity Index: Limitations and Assumptions. *Journal of Climate and Applied Meteorology,* 23: 1100–1109.

Barnett, T.P., B.D. Santer, P.D. Jones, R.S. Bradley and K.R. Briffa. 1996. "Estimates of Low Frequency Natural Variability in Near–Surface Air Temperature." *The Holocene,* 6(3): 255–263.

Boer, G.J., G. Flato and D. Ramsden. 2000. "A Transient Climate Change Simulation with Greenhouse Gas and Aerosol Forcing: Projected Climate for the 21st Century." *Climate Dynamics,* 16: 427–450.

Briffa, K.R. 2000. "Annual Climate Variability in the Holocene: Interpreting the Message of Ancient Trees." *Quaternary Science Reviews,* 19: 87–106.

Case, R.A. and G.M. MacDonald. 1995. "A Dendroclimatic Reconstruction of Annual Precipitation on the Western Canadian Prairies since A.D. 1505 from Pinus Flexilis James." *Quaternary Research,* 44: 267–275.

Cleaveland, M.K. and D.N. Duvick. 1992. "Iowa Climate Reconstructed from Tree Rings, 1640–1982." *Water Resources Research,* 28(10): 2607–2615.

Cook, E.R., D.M. Meko and C.W. Stockton. 1997. "A New Assessment of Possible Solar and Lunar Forcing of the Bidecadal Drought Rhythm in the Western United States." *Journal of Climate,* 10: 1343–1356.

Cook, E.R., R.D. D'Arrigo and K.R. Briffa. 1998. "A Reconstruction of the North Atlantic Oscillation using Tree–Ring Chronologies from North America and Europe." *The Holocene,* 8: 9–17.

Cook, E.R., D.M. Meko, D.W. Stahle and M.K. Cleaveland. 1999. "Drought Reconstructions for the Continental United States." *Journal of Climate,* 12: 1145–1162.

Cutforth, H.W., B.G. McConkey, R.J. Woodvine, D.G. Smith, P.G. Jefferson and O.O. Akinremi. 1999. "Climate Change in the Semiarid Prairie of Southwestern Saskatchewan: Late Winter–Early Spring." *Canadian Journal of Plant Science,* July: 98–137.

Ferguson, C. 1970. "Concepts and Techniques of Dendrochronology." *In Scientific Methods in Medieval Archaeology* (R. Berger). Berkeley: University of California Press.

Fritts, H.C. 1976. *Tree Rings and Climate.* London: Academic Press.

Gedalof, Z. and D.J. Smith. 2001. "Interdecadal Climate Variability and Regime–Scale Shifts in Pacific North America." *Geophysical Research Letters,* 28(8): 1515–1519.

Government of Canada. 1938. *Census of the Prairie Provinces, 1936.* King's Printer, Ottawa.

Grissino–Mayer, H., R. Holmes, and H.C. Fritts. 1996. *International Tree Rings Data Bank Program Library User's Manual.* Laboratory of Tree–Ring Research, University of Arizona, Tucson, AZ.

Hengeveld, H. 2000. *Projections for Canada's Climate Future.* Climate Change Digest 00–01, Environment Canada, Ottawa, ON.

Herrington, R., B.N. Johnson and F.G. Hunter. 1997. *Responding to Global Climate Change in the Prairies:* Volume III of the Canada Country Study: Climate Impacts and Adaptations. Prairie and Northern Region, Environment Canada, Regina, SK.

Hill, H. and J. Vaisey. 1995. "Policies for Sustainable Development." In: D.A. Wilhite, and D.A. Wood (Ed.), *Planning for a Sustainable Future: The Case of the North American Great Plains.* Proceedings of the Symposium, May 8–10, 1995, Lincoln, NE.

Hughes, M.K. and P.M. Brown. 1992. "Drought Frequency in Central California since 101 B.C. Recorded in Giant Sequoia Tree Rings." *Climate Dynamics,* 6: 161–167.

Jones, D.C. 1987. *Empire of Dust: Settling and Abandoning the Prairie Dry Belt Edmonton.* University of Alberta Press, AB.

Jones, P.D., K.R. Briffa, T.P. Barnett and S.F.B. Tett. 1998. "High–Resolution Palaeoclimatic Records for the Last Millennium: Interpretation, Integration and Comparison with General Circulation Model Control–Run Temperatures." *The Holocene,* 8(4): 455–471.

Laird, K.R., S.C. Fritz, K.A. Maasch and B.F. Cumming. 1996. "Greater Drought Intensity and Frequency Before A.D. 1200 in the Northern Great Plains." *USA Nature,* 384: 552–554.

Laprise, R., D. Caya and N.A. McFarlane. 1998. "Climate and Climate Change in Western Canada as Simulated by the Canadian Regional Climate Model." *Atmosphere–Ocean,* 36(2): 119–167

Last, W.M. and D.J. Sauchyn. 1993. "Mineralogy and Lithostratigraphy of Harris Lake, Southwestern Saskatchewan, Canada." *Journal of Paleolimnology* 9: 23–29.

Legates, D.R. and C.J. Willmott. 1990. "Mean Seasonal and Spatial Variability in Gauge–Corrected, Global Precipitation." *International Journal of Climatology,* 10: 111–127.

Lemmen, D.S. and R.E. Vance. 1999. "An Overview of the Palliser Triangle Global Change Project." *In Holocene Climate and Environmental Change in the Palliser Triangle:* A Geoscientific Context for Evaluating the Impacts of Climate Change on the Southern Canadian Prairies (Ed. D.S. Lemmen and R.E. Vance) Geological Survey of Canada Bulletin 534: 7–22.

Louie, P.Y.T. 1986. "An Operational Drought Severity Index Program for Canadian Synoptic Stations." *Proceedings of the Canadian Hydrology Symposium No. 16, Regina, SK,* National Research Council: 101–112.

Luckman, B.H. and T.A. Innes. 1991. "Dendrochronology in Canada." *Dendrochronologia,* 9: 9–33.

Mann, M.E., R.S. Bradley and M.K. Hughes. 1999 "Northern Hemisphere Temperatures During the Past Millennium; Inferences, Uncertainties and Limitations." *Geophysical Research Letters,* 26: 759–762.

Mekis, Eva and Bill Hogg. 1999. "Rehabilitation and Analysis of Canadian Daily Precipitation Time Series." *Atmosphere–Ocean,* 37(1): 53–85.

Meko, D.M. 1992. "Dendroclimatic Evidence from the Great Plains of the United States." *In Climate Since A.D. 1500* (Ed. R.S. Bradley and P.D. Jones) London: Routledge: 312–330.

Meko, D.M., E.R. Cook, D.W. Stahle, C.W. Stockton and M.K. Hughes. 1993. "Spatial Patterns of Tree–Growth Anomalies in the United States and Southeastern Canada." *Journal of Climate,* 6: 1773–1786.

Meko, D., C.W. Stockton and W.R. Boggess. 1995. "The Tree–Ring Record of Severe Sustained Drought." *Water Resources Bulletin,* 31: 789–801.

Nemanishen, W. 1995. "A Draft Discussion Paper: A PFRA Strategy for Drought Investigations in the Palliser Triangle." PFRA, South Alberta Region.

Nemanishen, W. 1998. *Drought in the Palliser Triangle (A Provisional Primer).* Prairie Farm Rehabilitation Administration.

Palliser, J. 1859. Papers *Relative to the Exploration of that Portion of British North America Which Lies Between the Northern Branch of the River Saskatchewan and the Frontier of the United States; and Between the Red River and the Rocky Mountains.* Greenwood Press, New York.

Palmer, W.C. 1965. *Meteorological Drought. Weather Bureau Research Paper 45,* U.S. Department of Commerce, Washington, DC.

Pelletier, J.D. and D.L. Turcotte. 1997. "Long–Range Persistence in Climatological and Hydrological Time Series: Analysis, Modeling and Application to Drought Hazard Assessment." *Journal of Hydrology,* 203: 198–208.

PFRA. 2000. *Prairie Agricultural Landscapes: A Land Resource Review.* Prairie Farm Rehabilitation, Regina, Saskatchewan. Minister of Public Works and Government Services.

Sauchyn, D.J. and A.B. Beaudoin. 1998. "Recent Environmental Change in the Southwestern Canadian Plains." *The Canadian Geographer,* 42(4): 337–353.

Schweger, C. and C. Hooey. 1991. "Climate Change and the Future of Prairie Agriculture." *In: Alternative Futures for Prairie Agricultural Communities* (Ed. J. Martin) Faculty of Extension, University of Alberta, Edmonton: 1–36.

Schweingruber, F.H. 1988. *Tree Rings: Basics and Applications of Dendrochronology.* Boston: D. Reidel

Skinner, W.R., K. Heinze, L.A. Vincent and E. Mekis. (In preparation). "20th Century North American Summer Moisture Conditions and Associations with Large–Scale Atmospheric Forcings."

St. George, S. and E. Nielsen. 2000. "Signatures of High–Magnitude 19th Century Floods in Quercus Macrocarpa (Michx.) Tree–Rings Along the Red River, Manitoba, Canada." *Geology,* 28: 899–902.

Stahle, D.W., M.K. Cleaveland, D.B. Blanton, M.D. Therrell and D.A. Gay. 1998. "The Lost Colony and Jamestown Droughts." *Science,* 280: 564–567.

Stahle, D.W., E.R. Cook, M.K. Cleaveland, M.D. Therrell, D.M. Meko, H.D. Grissino–Mayer, E. Watson and B.H. Luckman. 2000. Epic 16th Century Drought over North America. *EOS, Transactions of the American Geophysical Union,* 81(12): 121, 125.

Stapleford, E.W. 1939. *Report on Rural Relief due to Drought Conditions and Crop Failures in Western Canada.* Department of Agriculture, Ottawa, ON.

Statistics Canada. 1989–91. *Agriculture Economics Statistics Catalogue #21–603E.* Statistics Canada, Ottawa, ON.

Stockton, C.W. and D.M. Meko. 1975. "A Long Term History of Drought Occurrence in Western United States as Inferred from Tree–Rings." *Weatherwise,* 28(6): 244–249.

Stokes, M.A. and T.L. Smiley. 1968. *An Introduction to Tree–Ring Dating.* University of Chicago Press, Chicago.

Vance, R.E. and W.M. Last. 1994. "Paleolimnology and Global Change on the Canadian Prairies." *Current Research* 1994–B:49–58. Geological Survey of Canada, Ottawa, ON.

Villmov, J.R. 1956. "The Nature and Origin of the Canadian Dry Belt." *Annals of the Association of American Geographers,* 46: 211–232.

Vincent, L.A. 1998. "A Technique for the Identification of Inhomogeneities in Canadian Temperature Series." *Journal of Climate,* 11, 1094–1104.

Vincent, L.A. and D.W. Gullett. 1999. "Canadian Historical and Homogeneous Temperature Datasets for Climate Change Analyses." *International Journal of Climate,* 19(13): 1375–1388.

Watson, E. and B.H. Luckman. 2001. "Dendroclimatic Reconstruction of Precipitation for Sites in the Southern Canadian Rockies." *The Holocene,* 11(2): 203–213.

Wilhite, D.A. and D.A. Wood. 1995. *Planning for a Sustainable Future: The Case of the North American Great Plains.* International Drought Information Center Technical Report Series 95–1. University of Nebraska, Lincoln, NE.

Wilson, S.E. and J.P. Smol. 1999. "Diatom–Based Salinity Reconstructions from Palliser Triangle Lakes: A Summary of Two Saskatchewan Case Studies." *In Holocene Climate and Environmental Change in the Palliser Triangle: A Geoscientific Context for Evaluating the Impacts of Climate Change on the Southern Canadian Prairies* (Ed. D.S. Lemmen and R.E. Vance) Geological Survey of Canada Bulletin 534: 67–80.

Wolfe, S.A., D.J. Huntley, D.J. Sauchyn, P.P. David, J. Ollerhead, and G.M. MacDonald. (In press.) "Geochronologic Evidence for Widespread Dune Activity Induced by Late 18th Century Dryness, Great Sand Hills, Southwestern Saskatchewan." *Canadian Journal of Earth Sciences.*

Zhang, X., L. Vincent, W.D. Hogg and A. Nitsoo. 2000. "Temperature and Precipitation Trends in Canada during the 20th Century." *Atmosphere–Ocean,* 38(3): 395–429.