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Hydroclimatic Change in Southern Manitoba Since A.D. 1409 Inferred from Tree Rings

Scott St. George[1]

Geological Survey of Canada, 360-1395 Ellice Avenue, Winnipeg, Manitoba, R3G 3P2

and

Erik Nielsen

Manitoba Geological Survey, 360-1395 Ellice Avenue, Winnipeg, Manitoba, R3G 3P2

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A record of estimated annual (prior August to current July) precipitation derived from a regional bur oak (*Quercus macrocarpa* Michx.) tree-ring chronology indicates that southern Manitoba's hydroclimate has been relatively stable over the last 200 yr. Although this stability was interrupted briefly by pronounced wet intervals in the late A.D. 1820s and 1850s, hydroclimatic conditions since permanent Euro-Canadian settlement were much less variable and persistent than those prior to A.D. 1790. The reconstruction indicates that the Red River basin experienced extremely dry conditions between A.D. 1670 and 1775, with below-normal precipitation occurring approximately 2 years out of 3. Annual precipitation was estimated at more than two standard deviations below the mean during A.D. 1477, 1485, 1556, 1595, 1612, 1644, 1661, 1743, 1900, and 1980. Comparisons with limnological records from North Dakota and Minnesota suggest that multidecadal fluctuations in regional hydroclimate have been remarkably coherent across the northeastern Great Plains during the last 600 yr. However, individual dry years in the Red River basin were usually associated with larger scale drought across much of the North American interior.

Key Words: **Canadian Prairies; dendrochronology; Manitoba; palaeoclimate; palaeohydrology; precipitation; *Quercus macrocarpa;* tree rings.**

INTRODUCTION

The 1997 Red River flood and the recent, unrelenting rise of Devils Lake in North Dakota (Wiche *et al.*, 2000) have provided stark illustrations of the importance of understanding climatic variability in the northeastern Great Plains. Studies across North America have demonstrated that long proxy climate records may be recovered from climatically sensitive trees growing at forest–prairie ecotones (e.g., Case and MacDonald, 1995; Woodhouse and Brown, 2000). Dendroclimatic reconstructions in Canada have largely been restricted to alpine sites in western Alberta and British Columbia (Case and MacDonald, 1995; Luckman *et al.*, 1997; St. George and Luckman, 2001; Watson and Luckman, 2001). Although tree-ring climate reconstructions have been developed recently for Saskatchewan and Manitoba (Sauchyn and Beaudoin, 1998; Case, 2000), long high-resolution palaeoclimatic records from the Canadian Prairies are still relatively rare. While the scarcity of long-lived trees within this predominantly grassland region has been a significant obstacle to developing lengthy dendrochronological records, the recovery of well-preserved subfossil trees from the alluvium of prairie rivers holds great promise for developing moisture-sensitive tree-ring chronologies that span the last several centuries. In this study, we use a ringwidth chronology developed from living, historical and subfossil bur oak (*Quercus macrocarpa* (Michx.)) in the Red River basin (Fig. 1; Table 1) to reconstruct annual precipitation in southern Manitoba since A.D. 1409. This record has been used previously to develop proxy flood series from anatomical signatures in riparian trees (St. George and Nielsen, 2000; St. George and Nielsen, submitted).

METHODS

Red River Basin Tree-Ring Network

Samples from living trees were collected at 16 sites inside a 100-km-long corridor following the Red River. The dominant ecosystems in southern Manitoba are tall- and mixed-grass prairie, with trees found most commonly in narrow (100–200-m-wide) forest belts along rivers and streams. We sampled *Q. macrocarpa* due to its abundance in southern Manitoba, long life span (up to 300 yr; K. Wolfe, personal communication, 1999) and excellent preservation in riverbank alluvium. The oldest living specimen was located in Kildonan Park and attained an inner ring age of 279 yr before its death in A.D. 1999. Timbers were recovered from nearly a dozen historical buildings and

[1] To whom correspondence should be addressed. Fax: (204) 945-1406. E-mail: sstgeorg@nrcan.gc.ca.

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Euro-Canadian archaeological sites, the majority of which were located inside present-day Winnipeg. Most subfossil logs were recovered from alluvial sections (between Emerson and Morris on the Red River and between Portage la Prairie and Winnipeg on the Assiniboine River) that were exposed during low water stages (Fig. 1). Tree-ring samples were prepared, measured, and cross-dated following standard techniques (Stokes and Smiley, 1968; Grissino-Mayer *et al.*, 1996). The combined *Q. macrocarpa* record for the Red River basin includes 398 cross-dated trees and extends from A.D. 1286 to 1999.

To preserve as much low-frequency climate information as possible in the ringwidth series, age-related growth trends were removed using regional curve standardization (RCS; Briffa *et al.*, 1992; Cook *et al.*, 2000). RCS detrending aligns ringwidth measurements by biological age to estimate a mean growth curve that reflects the expected trend in radial tree growth during the lifetime of any individual tree (Cook *et al.*, 2000). The RCS method allows the final composite record or chronology to retain low-frequency variance greater than the length of its component segments (Briffa *et al.*, 1992).

The data set was separated into two groups prior to RCS standardization to correct for anthropogenically induced disturbances. As early as the mid-A.D. 1850s, observers stated

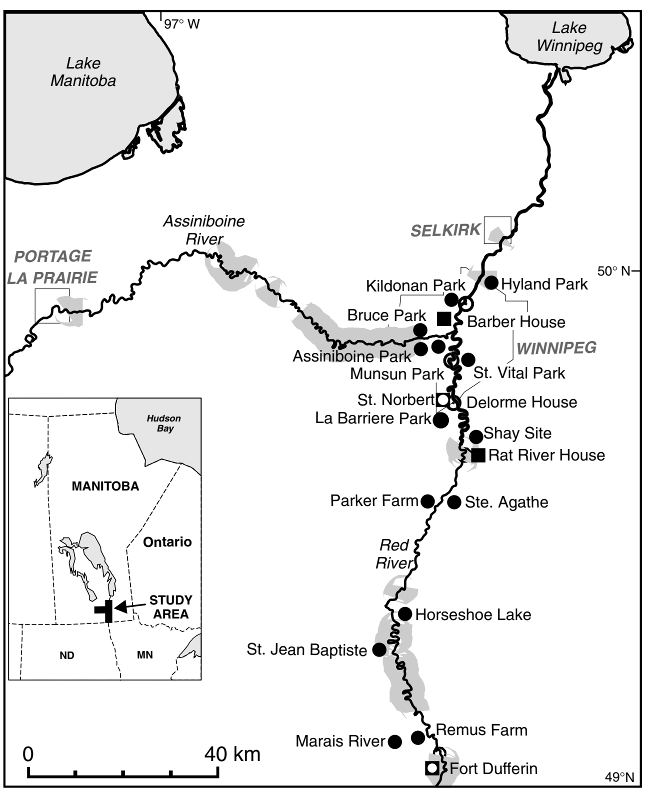

FIG. 1. The Assiniboine and Red River basins in southern Manitoba and the *Q. macrocarpa* sampling network. Circles represent living-tree sites. Squares indicate selected historical buildings and archaeological sites. Shaded corridors along the rivers represent reaches where alluvial subfossil logs were collected. From St. George and Nielsen (submitted).

TABLE 1
Locations of *Q. macrocarpa* Sampling Sites in the Red River Basin

Site	Lat. (°N)	Long. (°W)	Type	No. of trees	Span
Hyland Park	49°59′05″	97°02′55″	Living	17	1823–1999
Kildonan Park	49°56′30″	97°06′00″	Living	38	1720–1999
Winnipeg	Various locations		Living	15	1822–1994
			Historical	22	1644–1865
Barber House	49°54′20″	97°07′15″	Historical	38	1648–1864
Munsen Park	49°52′30″	97°09′40″	Living	9	1860–1999
Bruce Park	49°52′30″	97°13′30″	Living	15	1855–1999
St. Vital Park	49°49′45″	97°08′05″	Living	17	1830–1998
St. Norbert	49°45′25″	97°08′50″	Living	10	1855–1998
LaBarriere Park	49°43′10″	97°10′30″	Living	11	1892–1998
Delorme House	49°33′40″	97°11′05″	Historical	3	1696–1853
Shay	49°38′45″	97°06′45″	Living	14	1907–1999
Rat River House	49°35′15″	97°08′15″	Historical	6	1659–1859
Ste. Agathe	49°32′45″	97°12′10″	Living	11	1856–1998
Parker Farm	49°31′50″	97°13′00″	Living	24	1877–1998
Horseshoe Lake	49°20′25″	97°19′30″	Living	15	1907–1999
St. Jean Baptiste	49°16′35″	97°19′50″	Living	10	1883–1997
Remus Farm	49°04′20″	97°12′30″	Living	10	1875–1998
Marais River	49°03′50″	97°18′35″	Living	13	1850–1998
Fort Dufferin	49°01′50″	97°12′10″	Living	12	1866–1999
			Historical	3	1723–1872
Assiniboine alluvium	Various locations		Subfossil	34	1286–1968
Red River alluvium	Various locations		Subfossil	43	1448–1997

that the Red River settlement (present-day Winnipeg) had been completely deforested by timber cutting (Ross, 1856). Effects of reduced competition caused mean ringwidth in the late 19th and early 20th centuries to be greater than at any time since the early A.D. 1400s (Fig. 2). Mean ringwidth increased nearly 200% between A.D. 1840 and 1900. Deriving a mean RCS growth curve by aligning measurements from all trees would result in a biased composite chronology, as living trees that experienced this anthropogenically induced growth release make up more than 60% of the Red River database. Since trees that grew prior to the mid-19th century lack the extreme growth release present in later trees, detrending using a biased RCS curve would inflate tree-ring indices past A.D. 1850 and underestimate regional tree growth prior to A.D. 1800.

Two RCS curves were used to standardize the Red River record, with samples divided into groups for trees established before and after A.D. 1800 to remove this disturbance event from the composite record. The mean ringwidth series for trees established prior to A.D. 1800 is reasonably simple (Fig. 3B), with ringwidth declining nearly linearly with tree age.[2] In contrast,

[2] Due to the limited number of older trees, the variance of the pre-A.D. 1800 RCS curve increases dramatically after 200 years. Since the present data set cannot provide a good estimate of regional tree growth for this age range, the ringwidth records for 11 trees in the pre-A.D. 1800 group were truncated at 196 yr before being incorporated into composite and site chronologies.

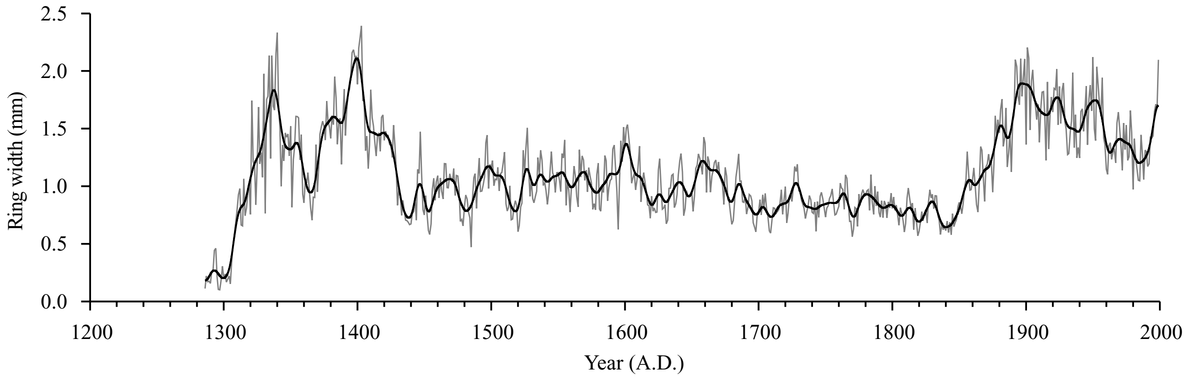

FIG. 2. Mean (unstandardized) ringwidth, Red River *Q. macrocarpa* network. Solid line represents the 15-yr weighted mean.

the post-A.D. 1800 group grew faster than the pre-A.D. 1800 trees and also exhibits a juvenile increase during the first 30 yr. The post-A.D. 1800 RCS curve (Fig. 3A) stabilizes between 30 and 40 years of age, then declines in a nearly linear fashion afterward. Since both RCS curves contain noise unrelated to age–growth trends, smoothed curves were used to detrend and standardize the individual ringwidth series for each establishment group. The post-A.D. 1800 chronology was detrended with a 40% spline to further remove the late-19th-century growth increase caused by logging. The pre- and post-A.D. 1800 chronologies extend from A.D. 1286 to 1883 and A.D. 1822 to 1999, respectively, and were combined (using an average weighted by the number of trees in each chronology) to produce a single composite record that extends from A.D. 1286 to 1999 (Fig. 4A).

The strength of the common signal in the RCS chronology can be assessed using running series of average correlation (Rbar) and expressed population signal (EPS; Wigley *et al.*, 1984), calculated over 50-yr moving windows with 1-yr overlaps. Over most of the last 600 yr, the Rbar (Fig. 4B) is relatively consistent, ranging between 0.2 and 0.4. The running EPS value (Fig. 4C) expresses the degree to which the composite chronology portrays the hypothetically perfect chronology (Briffa and Jones, 1990). The chronology maintains an EPS greater than 0.9 back

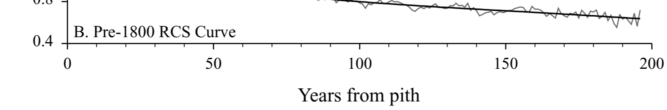

FIG. 3. Regional curve standardization (RCS) used in standardization for trees established (A) following and (B) prior to A.D. 1800. Ring width is plotted against the number of annual rings from the pith (the center of the tree stem).

until A.D. 1563, where declining sample depth causes it to fall briefly below 0.85. The chronology's EPS value then recovers and stays above 0.85 until the early 15th century. The apparent gap in Rbar and EPS values between the two age groups circa A.D. 1840 is an end effect created by the use of the 50-yr window. Based on these measures of signal strength, we determined that the chronology was suitable for dendroclimatic reconstruction back to A.D. 1409. Noise associated with decreasing sample depth during the earliest period in the tree-ring record reduces the reliability of the composite record and precludes palaeoclimatic reconstruction.

RESULTS

Climate Reconstruction

Possible climatic signals in the Red River *Q. macrocarpa* network were identified by correlating the detrended ringwidth chronologies from the 16 living-tree sites against local climate records. The Meteorological Service of Canada (MSC) has produced a database of Canadian meteorological records that have been corrected for inhomogeneities and missing data (Mekis and Hogg, 1999; Vincent and Gullett, 1999). This data set includes two stations in the Red River valley, with corrected monthly temperature and precipitation records in Winnipeg running from A.D. 1895 to 1999, and a shorter precipitation series at Emerson extending from A.D. 1943 to mid-1997. While other long climate records (greater than 50 yr) in the Red River valley are available from Morris and Ste. Agathe, these data have not been corrected by the MSC and were not used in this study.

Several researchers have found that ringwidth correlates most strongly with annualized data that includes contributions from the previous year (e.g., Duvick and Blasing, 1981; Case and MacDonald, 1995; Watson and Luckman, 2001). Therefore, correlations were run between the living-tree chronologies and monthly, seasonal, and annual combinations of temperature and precipitation. The average correlations were highest for all 16 sites with August–July precipitation at Winnipeg; all sites had a significant correlation ($p = 0.01$) with this variable. Correlations with annual temperature were usually negative but

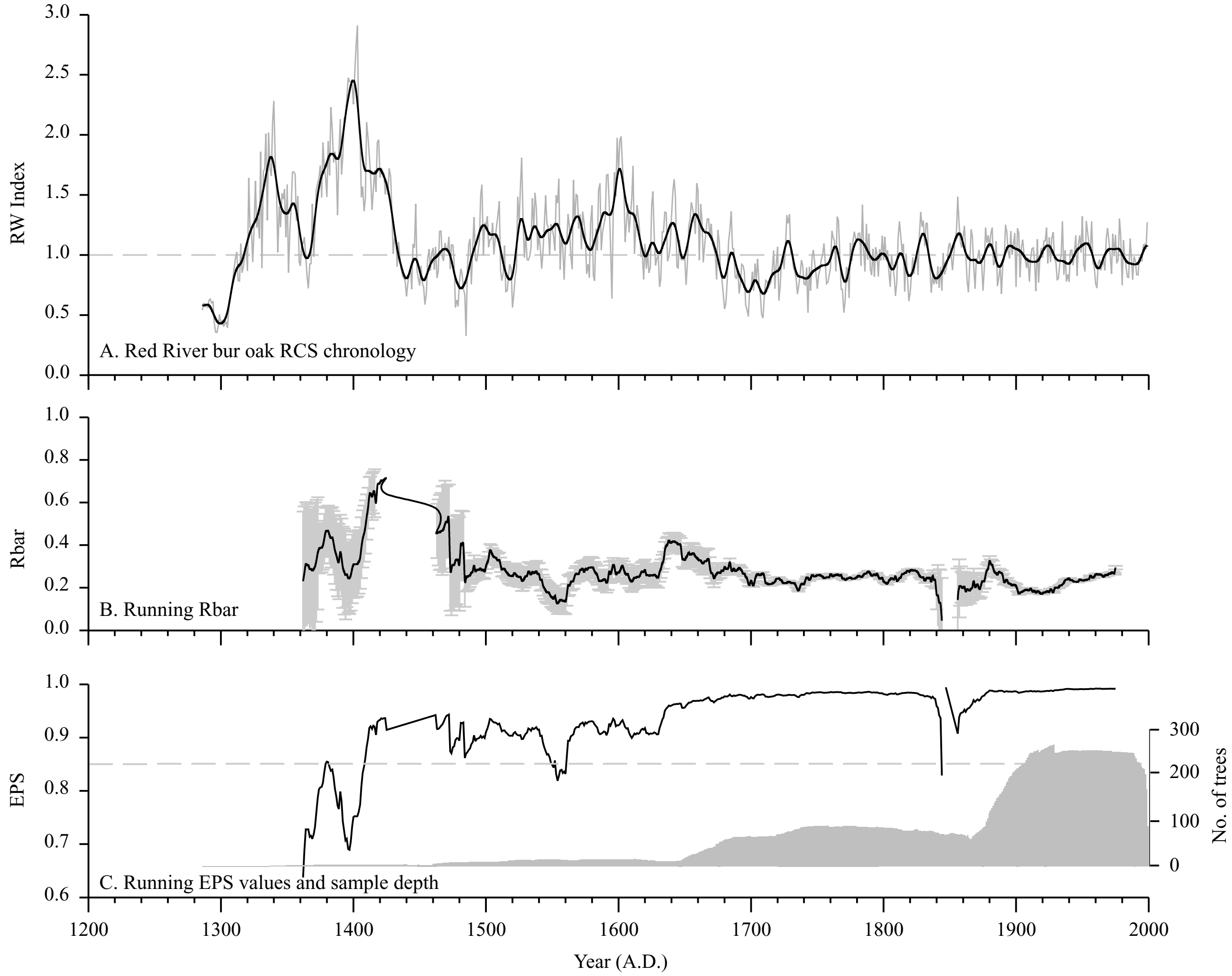

FIG. 4. The Red River *Q. macrocarpa* regional curve standardization (RCS) chronology (A) and its running series of average correlation (Rbar) (B) and expressed population signal (EPS) (C) statistics. The Rbar and EPS values were computed using a 50-yr moving window with 1-yr overlaps. The grey bars on the Rbar plot are two standard errors. Standard errors cannot be calculated between A.D. 1416 and 1463, as only two trees cover this interval.

rarely significant. These results suggested that *Q. macrocarpa* ringwidth was strongly influenced by the amount of precipitation received between July of the growth year and prior August and that this variable was the best candidate for dendroclimatic reconstruction.

Stepwise multiple linear regression was used to obtain a statistical expression relating the composite ringwidth chronology (RW) to annual (August–July) precipitation at Winnipeg. To account for lagged and autocorrelated growth effects in the chronologies, forward (RW_{+1}, RW_{+2}, and RW_{+3}) and backward (RW_{-1}, RW_{-2}, and RW_{-3}) lagged ringwidth chronologies were included as potential predictors in the regression analysis. Four variables were retained as predictors of August–July precipitation (Table 2): RW, RW_{-1}, RW_{-2}, and RW_{+1}. The multiple regression model explains approximately 40% of the variance (ar^2, adjusted for degrees of freedom) in the instrumental precipitation record.

Model Verification

The stability of the regression model was evaluated using several parametric and nonparametric techniques, with an independent set of precipitation estimates obtained using the iterative “leave-one-out” procedure (Gordon, 1982). The regression model attained either significant or positive results for all verification tests, including the sign and product means tests and the reduction of error (Table 2C). Residual analysis also revealed no significant first-order autocorrelation during the calibration period. These results indicate that the model adequately represented the ringwidth–climate relationship and was suitable to hindcast precipitation back to A.D. 1409.

August–July Precipitation, A.D. 1409 to 1998

The reconstruction of August to July precipitation (Fig. 5) suggests that climatic conditions following the establishment of

TABLE 2
Annual (August–July) Precipitation Regression Model

(A) Regression results

Calibration period	n	r	r^2	Adjusted r^2	[a]SE of estimate
1896–1996	101	0.653*	0.426*	0.403*	75.1

(B) Regression coefficients

Predictor	Beta	SE of beta	B	SE of B	[b]p level
Intercept			472.3	92.6	0.000002
RW	0.612	0.08	399.0	50.6	0.00000000001
RW_{-1}	−0.196	0.08	−127.9	50.7	0.01
RW_{-2}	−0.153	0.08	−100.3	51.3	0.05
RW_{+1}	−0.081	0.08	−53.0	51.6	0.31

(C) Verification results

Sign test (agree/disagree)	r	[c]PM test	[d]RE	Durbin-Watson
69/34*	0.61*	4.73*	+0.58	2.03[e]

[a] The standard error of estimated August–July precipitation.

[b] p level is the statistical significance of the independent variable's t value.

[c] A significant value for the product means (PM) test indicates that both the signs and the magnitudes of estimated and observed August–July precipitation exhibit a real relationship (Fritts, 1976).

[d] A positive reduction of error (RE) value demonstrates that the regression model is a better estimator of annual precipitation than the mean of the calibration period (Fritts, 1976).

[e] No significant first-order autocorrelation in the residuals.

* Significant at the $p = 0.01$ level. SE = standard error; RW = ringwidth chronology.

the first Euro-Canadian settlement in Manitoba (the A.D. 1811 Red River settlement) does not represent the full range of natural variability. During the last 200 yr, the hydroclimate of southern Manitoba has experienced relatively little long-term change, with mean annual precipitation for the period A.D. 1775–1998 (590 mm) only slightly lower than during the A.D. 1961–1990 reference period (598 mm). However, precipitation trends during the 19th century were highlighted by two wet periods centered around A.D. 1829 and the late A.D. 1850s, when annual precipitation was above average for 7 and 9 consecutive years, respectively. The tree-ring record indicates that these two periods were the most prolonged wet intervals during the last 330 yr. These intervals also coincided with the two largest floods experienced in the lower Red River valley since at least A.D. 1648 (A.D. 1826 and 1852; Rannie, 1998; S. St. George and E. Nielsen, unpublished data, 2002).

Prior to A.D. 1790, precipitation in the Red River basin appears to have been more persistent and variable. The most prolonged extreme dry period identified in the reconstruction occurred circa A.D. 1670–1775. Although this interval was interrupted briefly by short periods of slightly wetter conditions (at approximately A.D. 1685, 1730, and 1760), persistent dry conditions dominated southern Manitoba for over a century. Between A.D. 1670 and 1775, precipitation was below normal for 69 yr and above normal for only 37. Annual precipitation was below normal for 8 consecutive years from A.D. 1730 to 1737. Although reduced annual precipitation is not necessarily accompanied by low rainfall and high temperatures in summer,

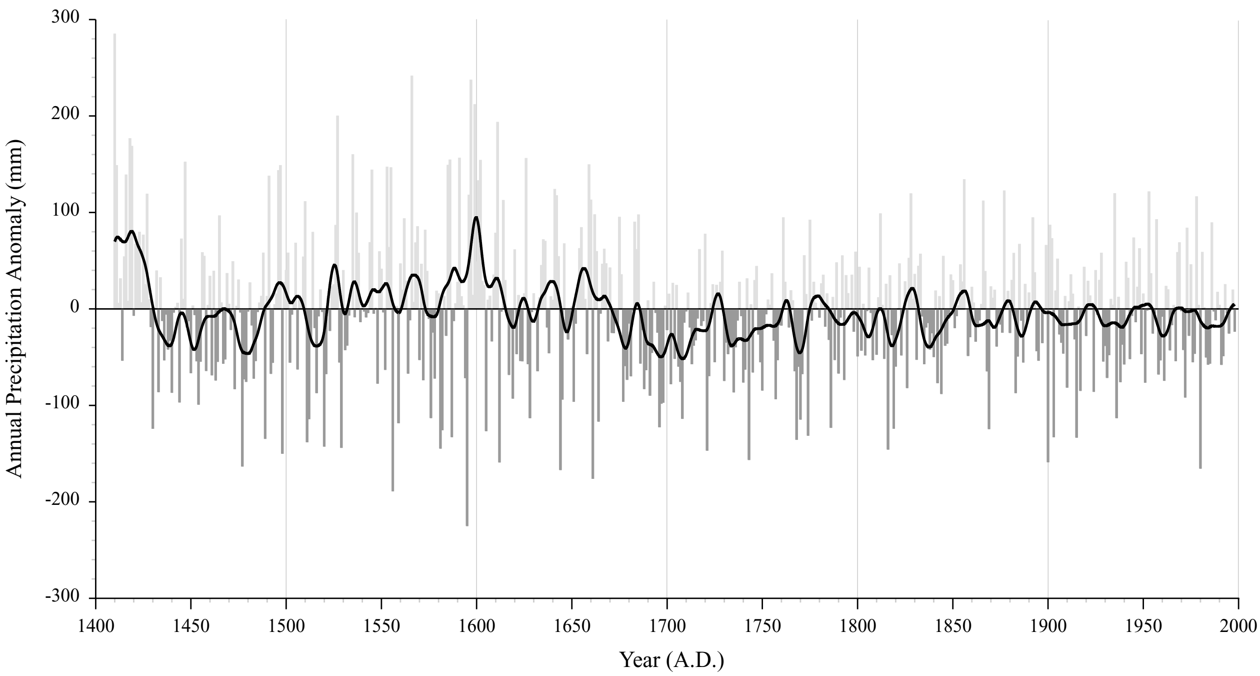

FIG. 5. Reconstructed annual (August–July) precipitation at Winnipeg from A.D. 1409 to 1998. Units are mean annual precipitation deviations from 1961 to 1990. Black line represents 15-yr weighted running mean.

it seems likely that the Red River basin experienced an increased frequency of summer droughts between A.D. 1670–1775. This arid period was preceded by a major wet interval between A.D. 1520 and 1670, with 15-yr mean precipitation reaching its highest value in the record circa A.D. 1600.

Most extreme annual precipitation values fall within the earliest half of the reconstruction (Table 3). All years with reconstructed annual precipitation values greater than two standard deviations above the A.D. 1961–1990 mean occur prior to A.D. 1800. Extremely dry years are less frequent than wet years but are more evenly distributed through time. The 16th century appears to have been particularly extreme, as this century contains 5 of the 6 wettest years and 2 of the 3 driest years in the 591-yr record. Two years in the 20th century (A.D. 1980 and 1900) represent the sixth and eighth driest years in the Red River basin during the last six centuries.

TABLE 3
Extreme Years in the Reconstructed Precipitation Series

Wettest years		Driest years	
Year	Deviation[a]	Year	Deviation[a]
2 SD above or below the mean			
1410	3.77	1595	−2.91
1566	3.20	1485	−2.60
1597	3.15	1556	−2.44
1599	2.81	1661	−2.27
1524	2.70	1644	−2.15
1527	2.66	1980	−2.13
1611	2.57	1477	−2.10
1418	2.35	1900	−2.04
1419	2.25	1612	−2.04
1535	2.13	1743	−2.01
1591	2.09		
1626	2.07		
1586	2.06		
1602	2.06		
1447	2.03		
1625	2.01		
1580	2.01		
1784	2.01		
1659	2.00		
1.5–2 SD above or below the mean			
1585	1.99	1498	−1.92
1497	1.99	1721	−1.89
1411	1.99	1816	−1.87
1553	1.96	1581	−1.86
1555	1.96	1529	−1.85
1496	1.92	1520	−1.83
1545	1.91	1511	−1.77
1416	1.86	1768	−1.74
1491	1.84	1489	−1.72
1856	1.79	1915	−1.71
1601	1.78	1587	−1.70
1641	1.66	1903	−1.69
1877	1.64	1774	−1.68
1953	1.62	1605	−1.62
1583	1.62	1582	−1.61
1592	1.62	1869	−1.59
1935	1.61	1819	−1.59
1828	1.60	1430	−1.59
1427	1.60	1786	−1.57
1596	1.58	1696	−1.57
1642	1.58	1559	−1.51
1978	1.56		
1660	1.52		
1614	1.51		

[a] Units are deviations from mean annual precipitation from A.D. 1409–1998.

DISCUSSION

Comparison with Archival Climate Records

Rannie (1998) used written records from the Hudson's Bay Company archives to develop runoff estimates for the Red River valley from A.D. 1793 to 1870 and argued that hydroclimatic conditions in the Red River valley were relatively wet during the 19th century, featuring higher annual runoff and more frequent flooding. The archival and tree-ring records generally follow the same interannual trends; excluding those years when runoff was classified as "normal," a sign test yielded 26 agreements and 8 disagreements between the two proxies. Both records suggest that relatively wet conditions prevailed circa A.D. 1810, the late A.D. 1820s, and circa A.D. 1850. Dry intervals during the late A.D. 1810s, mid A.D. 1830s, and circa A.D. 1860 are present in both records.

However, inconsistencies exist for estimates of both decadal trends and for individual years. The archival record suggests that hydroclimatic conditions during the A.D. 1840s and early A.D. 1830s were close to normal, while the tree-ring record indicates most years had below-average annual precipitation. Rannie noted that, although agriculture in the Red River valley appears to have had sufficient moisture to satisfy agricultural requirements circa A.D. 1840, wet areas in southern Minnesota had experienced marked drying from "a few years since" (cited in Rannie, 1998, p. 187). It seems possible that while moisture supply near the Red River settlement was not unusual during the A.D. 1830s and A.D. 1840s, aridity was greater in the southern portion of the valley. While archival and historical accounts suggest that A.D. 1826 and A.D. 1852 were among the wettest experienced in the Red River valley during the 19th century, the tree-ring record estimates annual precipitation for both years as below normal. These discrepancies are due to extreme Red River flooding in both years, which interfered with normal tree growth along the river (St. George and Nielsen, 2000). As inundation during spring flooding causes *Q. macrocarpa* to develop anatomical anomalies and, in some cases, stunted growth, ring-width does not provide a good estimate of annual precipitation for either A.D. 1826 or A.D. 1852.

Multiproxy Evidence for Regional Hydroclimatic Change

To determine whether the hydroclimatic record for the Red River basin reflects regional or local climatic conditions, we compared our reconstruction to other high-resolution palaeoclimatic records in the northern Great Plains (Fig. 6). The varve

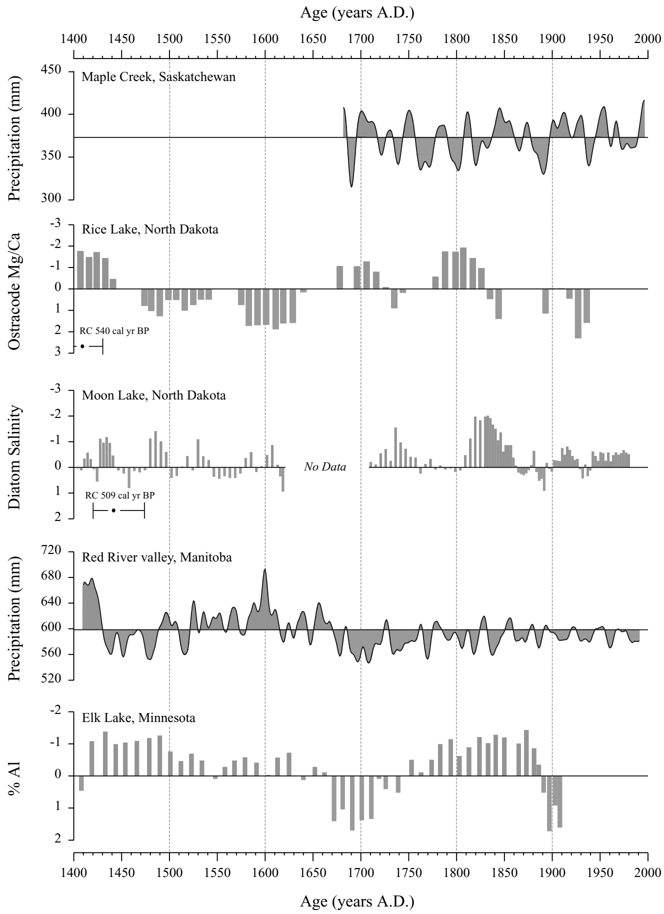

FIG. 6. Proxy records of hydroclimatic change in the northern Great Plains since A.D. 1400, arranged from west to east. The tree-ring reconstructions for the Red River valley and Maple Creek, Saskatchewan, (Sauchyn and Beaudoin, 1998) are smoothed with a 15-yr weighted average. Rice Lake (Yu and Ito, 1999) and Moon Lake (Laird *et al.*, 1996) data are smoothed with a 3-point and 6-point running average, respectively. The uppermost radiocarbon dates (with ±1 SE) are plotted for the Rice and Moon Lake records. The timescale is based on calendar dates (tree-ring records), calendar year equivalents (the varved Elk Lake record) and cal yr (Rice Lake and Moon Lake cores).

record from Elk Lake, Minnesota,documents fluctuations in aluminum concentration in lake sediments, which reflects changes in eolian activity and moisture supply (Dean, 1997). The agreement between the Red River precipitation record and the Elk Lake record is startling. The Elk Lake evidence suggests that aridity and eolian activity over the last 1500 yr peaked between approximately A.D. 1670 and 1750 (Dean, 1997), which coincides almost exactly with the A.D. 1670–1775 arid interval present in the Red River tree-ring record. The 19th century is estimated as being relatively moist, as is the interval between A.D. 1400 and 1650. Inferred salinity records from lakes in North Dakota contain similar patterns in hydroclimatic variation but exhibit slightly different timing. Both Rice Lake (Yu and Ito, 1999) and Moon Lake (Laird *et al.*, 1996) contain a wet interval centered in the early A.D. 1800s. The dry interval in the Rice Lake record between A.D. 1460 and 1630 is not matched by Moon Lake. However, the Moon Lake core was desiccated around A.D. 1600 and data are unavailable for this period. It is possible that the wet and dry intervals in the North Dakota records correspond with those identified in the Red River and Elk Lake series. The chronologies for the Moon and Rice Lake records were derived using linear interpolation from 3-4 accelerator mass spectrometry radiocarbon dates per core, which each have a standard error of at least ±50 yr (Fritz *et al.*, 2000). Although the dating of the Moon Lake record has been supplemented with ^{210}Pb and pollen evidence (Fritz *et al.*, 2000), neither record can match the temporal resolution and dating accuracy of the varve and tree-ring records. Although we cannot match events between records unambiguously, low-salinity intervals in the Rice and Moon Lake cores might be associated with the 19th-century wet period, and the salinity peak in the Rice Lake record dated circa A.D. 1600 could correspond with drier conditions in the late 17th and early 18th centuries.

The tree-ring precipitation reconstructions available from the Canadian prairies indicate there are considerable east–west differences in hydroclimatic trends. The Maple Creek, Saskatchewan, record (Fig. 6; Sauchyn and Beaudoin, 1998) shares very few of the dry years identified in Table 2, although both records indicate that A.D. 1819 and 1980 were unusually dry. While both records share a mid-19th-century precipitation peak, the Saskatchewan reconstruction contains a much less long-term trend than the Red River record. Although these differences may be attributable in part to differing methods of age and disturbance-effect standardization, it is also possible that they indicate that the eastern Canadian Prairies are more susceptible to multidecadal shifts in regional hydroclimate than those regions further west. Although evidence for severe drought during the A.D. 1790s is present in dendroclimatic records from Maple Creek and the Rocky Mountain foothills of southern Alberta (Case and MacDonald, 1995), annual precipitation in the Red River valley was only slightly below average during this period. While the drought of the A.D. 1790s may have been particularly severe in the western Canadian prairies, it appears to have been more weakly expressed with distance eastward.

Comparisons with the Cook *et al.* (1999) reconstruction of summer Palmer drought severity indices (PDSI) since A.D. 1700 indicate that dry years in the Red River basin coincided with summer drought in the neighboring American states. PDSI maps indicate that severe aridity in southern Manitoba during A.D. 1721, 1743, 1816, 1819, and 1900 was part of extensive summer droughts that spanned much of the continental U.S. Locally dry conditions in A.D. 1869 and 1903 were related to drought in Montana and North Dakota. Although the tree-ring data of Cook *et al.* (1999) do not postdate A.D. 1978, instrumental records for A.D. 1980 show widespread summer drought centered in western North and South Dakota. However, the north-central U.S. was relatively wet during A.D. 1768, 1786, and 1915, which suggests that aridity in these years was restricted to the Red River valley.

There are relatively few high-resolution precipitation records in North America that span the 15th and 16th centuries. The Stahle *et al.* (2000) analysis of a network of long tree-ring hydroclimatic reconstructions ranging from Mexico to Alberta suggested severe drought extended over much of North America during the A.D. 1500s. Conditions were particularly severe during the A.D. 1590s, and overall, droughts during the 16th century appear to have been more extreme, persistent, and widespread than any seen under instrumental observation. However, hydroclimatic proxies from the northeastern Great Plains suggest that this area largely escaped the influence of the 16th-century "megadroughts." The Red River record indicates precipitation was above normal for much of the 16th century, with the period from A.D. 1580 to 1620 being one of the wettest in the last 600 yr. Although this interval includes the driest year in the reconstruction (A.D. 1595), this region may have represented a northeastern limit to overall North American aridity during the A.D. 1500s. None of the reconstructions presented by Stahle *et al.* (2000) show any indication of prolonged dryness circa A.D. 1700.

These results imply that hydroclimatic change in southern Manitoba occurs at two distinct temporal and spatial scales. Over the last 300 yr, most individual dry years were associated with widespread drought across much of the North American interior. However, longer term multidecadal shifts in hydroclimate, such as the A.D. 1700 dry interval, appear to have been restricted to the northeastern Plains. As long-term hydroclimatic change seems to have operated independently of larger scale droughts, it is possible that the mechanisms driving changes in regional aridity depend on the temporal and spatial scales under investigation.

CONCLUSION

Our results indicate that prior to the 20th century, southern Manitoba's climate was more extreme and variable, with prolonged intervals that were wetter and drier than any time following permanent Euro-Canadian settlement. Furthermore, if one assumes that the fluctuations in regional tree-ring and lake records are synchronous, these data suggest that the regional hydroclimate of the northern Great Plains has exhibited remarkable coherence in long-term trends over the last 600 yr. Dendrochronological and limnological records imply that natural variation in this region can generate shifts in precipitation regimes that last for several decades and extend over several thousand square kilometers. As a consequence, it seems likely that climatic case studies in regional drought and flood planning based exclusively on experience during the 20th century may dramatically underestimate true worst-case scenarios. Despite challenges caused by deforestation and disturbances in the 19th century, this study also provides an additional illustration that so-called salvage dendrochronology (Luckman, 1996) can, even for sparsely forested grassland areas, supply palaeoclimatic records that span the last several centuries.

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