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A paleoclimatic context for the drought of 1999–2001 in the northern Great Plains of North America

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The least annual precipitation in the western interior of North America occurs in the northern Great Plains, including an area that encompasses parts of south-eastern Alberta, south-western Saskatchewan and eastern Montana. During 1999–2001, most climate stations in this region had record low precipitation. This paper examines this three-year drought in the context of historical climate records from Medicine Hat, Alberta and Havre, Montana and summer (June–July) and annual (August–July) precipitation reconstructed from standardized tree-ring widths (residual chronologies) from *Pinus contorta* (lodgepole pine) sampled in the Cypress Hills of Alberta and Saskatchewan and the Bears Paw Mountains of north-central Montana. Drought is operationally defined as precipitation in the lower 10th and 20th percentiles. Plots of reconstructed precipitation and cumulative departure from median values indicate a shift in climate variability prior to the twentieth century, when EuroCanadians settled in this region. The eighteenth and nineteenth centuries are characterized by sustained periods of progressively wetter and drier conditions, including prolonged drought. Various archival sources document the significant impacts of these prolonged droughts. While drought was frequent in the twentieth century, it tended to be of short duration and the impacts also were ameliorated by intervening periods of relatively high precipitation. Increasing aridity in response to global warming could expose a larger area of the northern Great Plains to the impacts of drought.

KEY WORDS: Canada, USA, Great Plains, dendroclimatology, tree rings, drought

Introduction

Lack of precipitation and soil moisture for months to years is a significant ecological condition and socio-economic problem in the northern Great Plains of North America. Drought affects the soil and water resources that support dryland agriculture (Nemanishen 1998). It 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.* 2001). The European history of this region has been punctuated by the impacts of drought, with significant costs in terms of social cohesion (1930s) and financial relief (1980s). Whereas native people were mobile and thus, in this respect, less vulnerable, there is evidence of illness related to poor water quality during dry years (Binnema 2001).

The reoccurrence of dry years is reflected in low mean annual precipitation measured over many years. In Figure 1, precipitation from a gridded global database (Legates and Willmott 1990) is mapped for the period 1950–96 for the western interior of North America. The least precipitation (<330 mm) occurs in the northern Great Plains, including a significant area that spans north-central Montana, south-eastern Alberta and south-western Saskatchewan. During 1999–2001, this region was subject to the worst drought conditions in North

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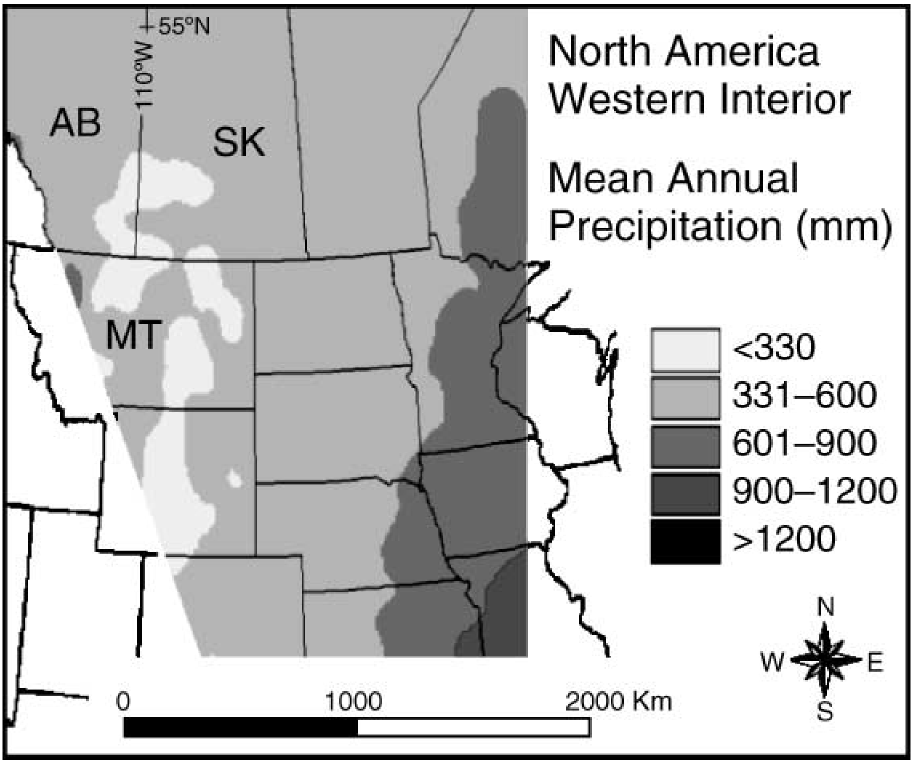

Figure 1 Mean annual precipitation for the western interior of North America from gridded global climate data for the period 1950–96 (Legates and Willmott 1990). This map illustrates that the region of least precipitation (<330 mm) includes our study areas in north-central Montana, south-eastern Alberta and south-western Saskatchewan (Figure 2). MT, Montana; AB, Alberta; SK, Saskatchewan

America according to the Canadian Drought Watch (http://www.agr.gc.ca/pfra/drought.htm) and the US Drought Monitor (http://www.drought.unl.edu/dm/index.html). This paper examines the severity of this drought relative to instrumental and proxy climate data. Precipitation records from Medicine Hat, Alberta and Havre, Montana (Figure 2) are used to rank the recent droughts and to calibrate tree-ring chronologies from lodgepole pine (*Pinus contorta*) from the Cypress Hills (CH) of Alberta and Saskatchewan and the Bears Paw Mountains (BPM) of north-central Montana (Figure 2).

A paleoclimatic perspective is necessary for planning adaptation to drought, because the non-aboriginal inhabitants of the northern Great Plains have had limited experience with the climatic variability of this region. The paleosalinity of prairie lakes suggests drought cycles on decadal through multicentennial scales over the past two millennia (Laird *et al.* 1996 2003). Although most tree-ring records from this region are limited to the last 500 years, tree rings provide annual resolution and thus are the preferred proxy for the evaluation of climate variability (e.g. Briffa 2000; Cook *et al.* 1999; Stahle *et al.* 2000). The dendroclimatic data presented here coincide with the period of exploration of the west and the fur trade and thus written weather observations. Both the natural and cultural proxies are crucial sources 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.

Methods and analysis

Monthly precipitation data for Medicine Hat, Alberta and Havre, Montana (Table 1) were applied to an historical analysis of drought severity and for the calibration and verification of the tree-ring modelling of drought. These instrumental records are amongst the longest from the western part of the northern Great Plains (the high plains) and are in close proximity to the sources of the tree-ring chronologies. The tree-ring data consist of the

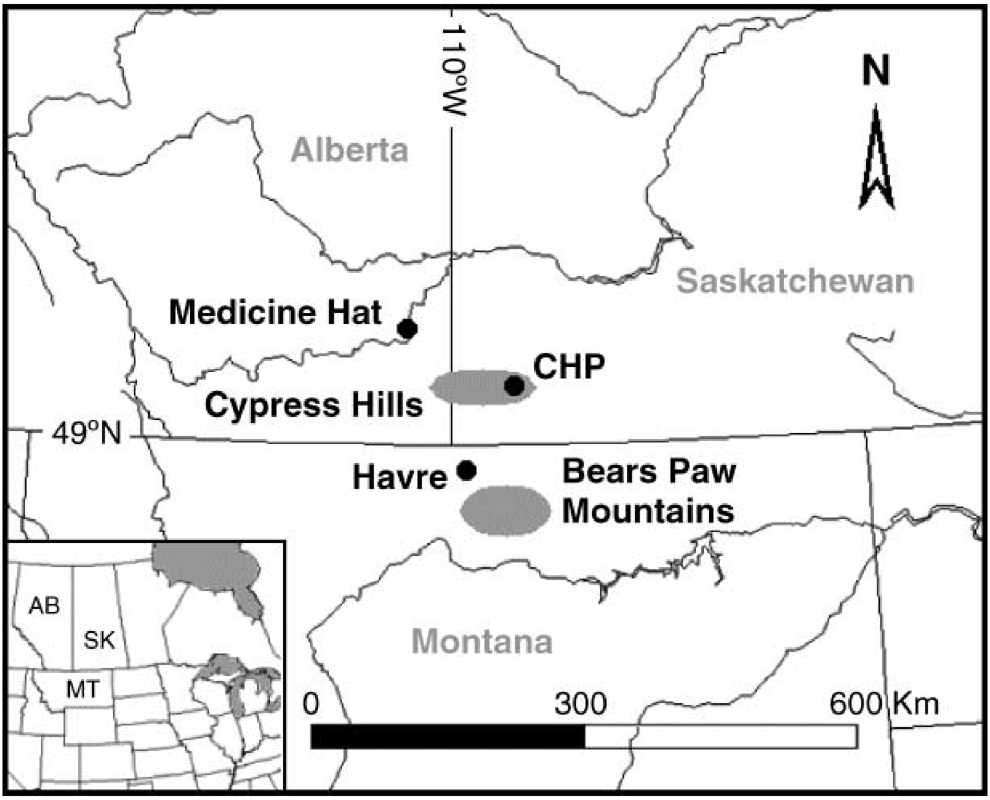

Figure 2 Location of the source of the tree-ring chronologies, the Bears Paw Mountains and Cypress Hills, and instrumental climate data: Havre, Medicine Hat and Cypress Hills Park (CHP). The location of the provinces of Alberta and Saskatchewan and the state of Montana are shown on the inset map of the interior of North America. MT, Montana; AB, Alberta; SK, Saskatchewan

Table 1 Monthly precipitation records used for the historical analysis of precipitation and to calibrate and validate the tree-ring models

Station	Medicine Hat, AB	Havre, MT
Station ID	3034480	243996
Source	Meteorological Service of Canada	US National Climate Data Center
Latitude (°N)	50.02	48.55
Longitude (°W)	110.72	109.77
Period of record	1884–2001	1901–1996
Missing data		1911

widths of annual growth rings from lodgepole pine from the Bears Paw Mountains of north-central Montana and the Cypress Hills that span the Alberta–Saskatchewan boundary (Figure 2).

All tree cores and disks were processed in the Tree-Ring Lab at the University of Regina, following standard procedures (Cook and Kairiukstis 1990). Cross dating of the 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

Table 2 Characteristics of the lodgepole pine (PICO) tree-ring chronologies from the Cypress Hills (CH) and Bears Paw Mountains (BPM)

	CH_PICO	BPM_PICO
Latitude (°N)	49.5	48.25
Longitude (°W)	110.0	109.5
Number of series	53	58
Length of the master dating series	1708–2001	1595–1998
Series length for SSS > 0.85	1754–2001	1727–1998
Series intercorrelation	0.481	0.528
Average mean sensitivity	0.231	0.296

Note: SSS, sub-sample signal strength

detrended to remove low-frequency variation, related mostly to tree age, by applying the best fit negative exponential curve or spline with a 50% cutoff at 100 years. The standardized series were filtered to remove first-order autocorrelation ($r = 0.732$ for the Bears Paw Mountains and 0.854 for the Cypress Hills). A biweight robust estimate of the mean ring-width index for each year comprised the residual index chronologies.

The chronology statistics in Table 2 indicate that the Bears Paw Mountains chronology has higher intra-site correlation and mean sensitivity, although there is also relatively good cross-dating and ring width variability with the Cypress Hills chronology. In the Bears Paw Mountains, there are lodgepole pines with more than 400 growth rings, so the chronologies from this site are based entirely on living trees. In the Cypress Hills, the age of the oldest lodgepole pines is about 150 years, so a 294-year chronology was achieved by cross-dating the annual rings of dead wood collected from log buildings and those from living trees. The Cypress Hills are the only source of logs over a very large area. Local residents verified the local source of the building materials from family histories. The wood was identified from thin sections as either white spruce or lodgepole pine. Family histories from farmers and ranchers were informal and collected over many months. Key information included who cut the logs used in construction and when they were cut. These details were cross referenced, where possible, with descriptions of logging and cabin construction in the area (Merry Battlers Ladies Club 1993; Saville 1982).

Statistical models for the reconstruction of precipitation were derived for each chronology from the simple linear regression of precipitation data against residual ring widths. We used a split sample approach to validating the reconstructions. Two regression models per chronology were calibrated using different halves of the instrumental record and then validated using the other half of the record.

An operational definition of the concept of drought (a protracted period of deficient precipitation; Byun and Wilhite 1999) is required in order to derive a drought history from proxy precipitation. Among the various sources of paleoclimatic data, moisture-sensitive tree-ring chronologies are a relatively direct proxy of agricultural and hydrological drought, since trees respond to the soil water balance. For the purpose of this study, we expressed drought as periods of precipitation in the lowest 10th and 20th percentiles. This approach facilitates comparison of the instrumental and proxy records and conforms to the methods of drought monitoring and mapping used for the Canadian Drought Watch and US Drought Monitor mentioned above.

Results

Table 3 lists the ten single years and five three-year periods with the least precipitation in the historical climate records from Medicine Hat, Alberta and Havre, Montana. At Medicine Hat, 2001 had the least precipitation on record, less than 150 mm, the threshold for an arid climate. With the year 2000 ranking tenth, total precipitation for 1999–2001 was the least on record for a three-year period, less than the driest three years of the 1930s or 1980s. At Havre, 1999–2001 was also the driest three-year period on record; and 2000 and 2001 were the third and sixth driest years altogether. This simple analysis establishes the current drought as the most severe, in terms of prolonged intensity, since settlement of this region, although the instrumental record provides a short perspective on the variable climate of the northern Great Plains. Our tree-ring records nearly triple the length of this historical context.

Precipitation and ring-width data from the Cypress Hills (Figure 3) illustrate the moisture sensitivity of the sampled lodgepole pine. The correlation drops when precipitation data are used from Medicine Hat, about 50 km northwest of the Cypress Hills but about 700 m lower than the stands of lodgepole pine; however, the additional 98 years of climate data enable the calibration and validation of a tree-ring model. Over the period 1884–2001, the correlation of residual ring-width index with precipitation is 0.506 for June–July and 0.451 for the plant year (August of the previous year to July of the current year). For data from Havre and the Bears Paw Mountains, the higher correlation is for plant year precipitation (0.550 versus 0.392 for June–July). While all the correlations are statistically significant ($p < 0.001$), they indicate that ring

Table 3 The ten single years and five three-year periods with the least precipitation (mm) in the historical climate records from Medicine Hat, Alberta and Havre, Montana. Data for 1999–2001 are in bold type

Medicine Hat				Havre			
Single years		Three-year droughts		Single years		Three-year droughts	
2001	**147.3**	**1999–2001**	**662.6**	1990	126.7	**1999–2001**	**667.0**
1907	173.1	1907–09	681.6	1988	162.1	1934–36	693.7
1943	182.2	1918–20	716.4	**2001**	**176.3**	1988–90	699.8
1928	194.1	1905–07	721.5	1984	177.5	1935–37	715.5
1919	195.6	1928–30	724.9	1952	186.4	1929–31	716.7
1997	197.3			1961	188.7		
1929	207.0			**2000**	**195.8**		
1924	207.6			1971	204.5		
1961	207.7			1976	208.8		
2000	**214.3**			1966	209.0		

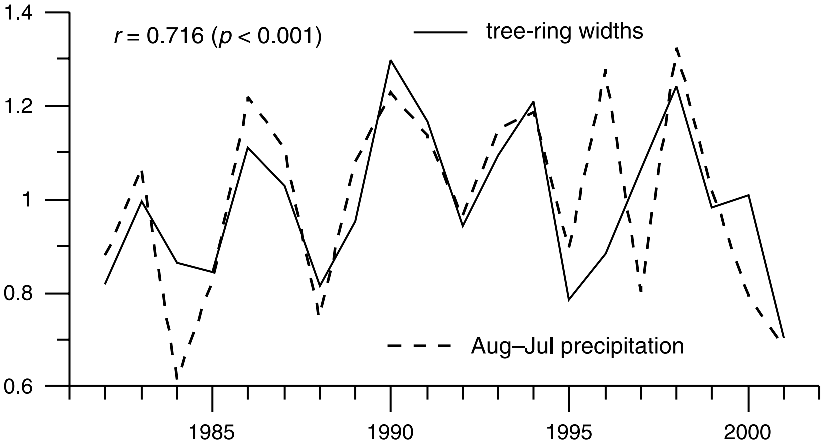

Figure 3 A plot of standardized tree-ring widths and August–July precipitation at a similar elevation in the Cypress Hills

width accounts for only about 25–30% of the variance in precipitation. Tree-ring widths underestimate extreme precipitation, especially unusually wet conditions, because soil properties and tree physiology limit the response of tree growth to precipitation. Our interest, however, is in the dry conditions. Tree rings are a particularly good proxy of the timing and duration of drought (Cook *et al.* 1999; Meko *et al.* 1995; Stahle *et al.* 1998).

Reconstructions of annual (August–July) precipitation for Havre and June–July precipitation for Medicine Hat were derived from the regression models described in Table 4. Whereas the full chronologies are 404 and 294 years in length, respectively, the sub-sample signal strength (SSS; Wigley *et al.* 1984) is less than 0.85 until 1727 for the Bears Paw Mountains lodgepole pine and 1754 for the Cypress Hills lodgepole pine. The plots in Figure 4 are truncated accordingly. The results of split-sample cross validation of these reconstructions (Table 4) indicate that the model errors and accuracy are within acceptable limits. In each case, the standard error of the calibrated model (SE_e) and the validation root mean square error ($RMSE_v$) are of similar magnitude. A positive value for the reduction of error (RE) statistic suggests that the tree-ring models have some predictive capacity. Higher RE and model R^2 apply to the reconstructions using instrumental data from Havre, which is in closer proximity to the Bears Paw Mountains than Medicine Hat to the Cypress Hills. Plots of observed versus predicted precipitation (Figure 5)

Table 4 Regression model and validation statistics

Predictand	June–July precipitation, Medicine Hat	August–July precipitation, Havre
Predictor	CH_PICO	BPM_PICO
Full calibration		
Calibration period	1884–2001	1901–1996
Adjusted R^2	0.249	0.296
F	39.83	40.45
p-value	<0.0001	<–0.0001
SE_e	40.93	69.66
Split-sample cross validation		
Calibration period	1884–1942	1901–1948
Validation period	1943–2001	1949–1996
Adjusted R_2	0.369	0.223
F	34.95	14.22
p-value	<0.0001	<0.0005
SE_e	37.71	73.10
$RMSE_v$	45.26	69.09
RE	0.076	0.353
Calibration period	1943–2001	1949–1996
Validation period	1884–1942	1901–1948
Adjusted R^2	0.157	0.360
F	11.77	27.44
p-value	0.0011	<0.0001
SE_e	43.44	64.86
$RMSE_v$	39.29	76.45
RE	0.309	0.238

Notes: SE_e, standard error of estimate; $RMSE_v$, root mean squared error of validation; RE, reduction of error: a measure of the predictive skill of the regression model

show that the reconstructions capture the lower frequency (decadal) variation and the timing, if not magnitude, of anomalous wet and dry years. A few droughts appear more severe in the tree ring data than in the precipitation records, because excessive heat can result in moisture stress and narrow tree rings even though the precipitation is not indicative of drought.

Discussion

The proxy precipitation records presented here suggest that the frequency of drought years has been relatively consistent for the past three centuries, but sustained drought occurred only prior to the Euro-Canadian settlement of this region. These results have implications for our understanding and perception of the climate of the northern Great Plains, and strategies for the management of natural resources, based on the interpretation and analysis of instrumental records. Our conclusions are constrained, however, by the limited spatial extent of this study and the variance unexplained by the tree rings. A larger network of tree-ring chronologies would increase the geographic coverage and probably the explained variance. Unfortunately trees grow at very few sites on the northern Great Plains. Ironically, the best conventional sources of paleoclimate data (trees and lakes) tend to be lacking in extreme and variable climates, where proxy data are required to capture the full range of climatic variability.

Natural and human systems generally have the capacity to withstand one or two years of drought, irrespective of the severity, and recover largely unaffected in the long term. Prolonged or persistent drought, on the other hand, has more serious consequences and thus has been the subject of recent investigations (Meko *et al.* 1995; Pelletier and Turcotte 1997; Stahle *et al.* 1998; Wolfe *et al.* 2001). If the below average precipitation of 1999–2001 were to persist for another few years, the first decade of the twenty-first century may be analogous to the prolonged droughts of the eighteenth and nineteenth centuries. The occurrence and impacts of these pre-settlement droughts are documented in the journals and accounts of fur traders and explorers (e.g. Johnson 1967; Binnema 2001).

Following several years on the southern Canadian plains, John Palliser drew his famous conclusion:

> This large belt of country embraces districts, some of which are valuable for the purposes of the agriculturalist, while others will forever be comparatively useless. . . . The least valuable portion of the prairie country has an extent of about 80,000 square miles, and is that lying along the southern branch of the Saskatchewan, and southward from thence to the boundary line . . .
>
> Palliser 1859, 21–2

Even though our tree-ring records clearly indicate drought during the mid-nineteenth century, there are few references to unusually dry conditions or impacts of drought in the journals of Palliser or the contemporaneous Hind expedition. The plots in Figure 6 of cumulative departures from median precipitation reveal that 50 years (Medicine Hat) to almost a century (Havre) of mostly positive departures preceded the anomalously low precipitation of the mid-1850s to mid-1860s. In sharp contrast, the droughts of the 1750s–60s and 1790s were the culmination of decades of negative departures from median precipitation. Thus, despite just a few dry years in the 1790s, there are many references to severe water deficits at this time:

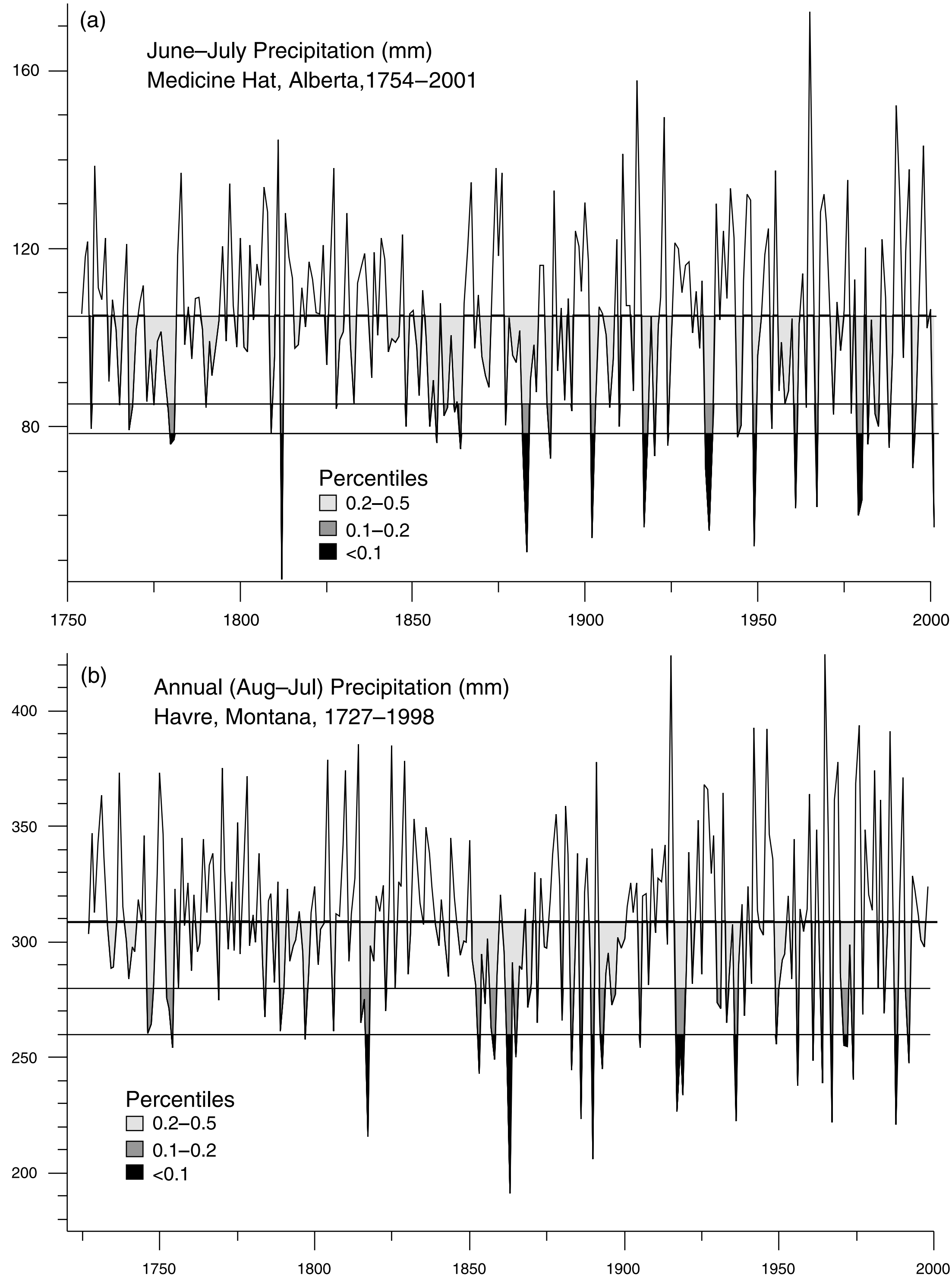

Figure 4 (a) June–July precipitation for Medicine Hat, Alberta as reconstructed from the residual index chronology from the Cypress Hills using the model described in Table 4. (b) Annual (August–July) precipitation for Havre, Montana as reconstructed from the residual index chronology from the Bears Paw Mountains using the model described in Table 4

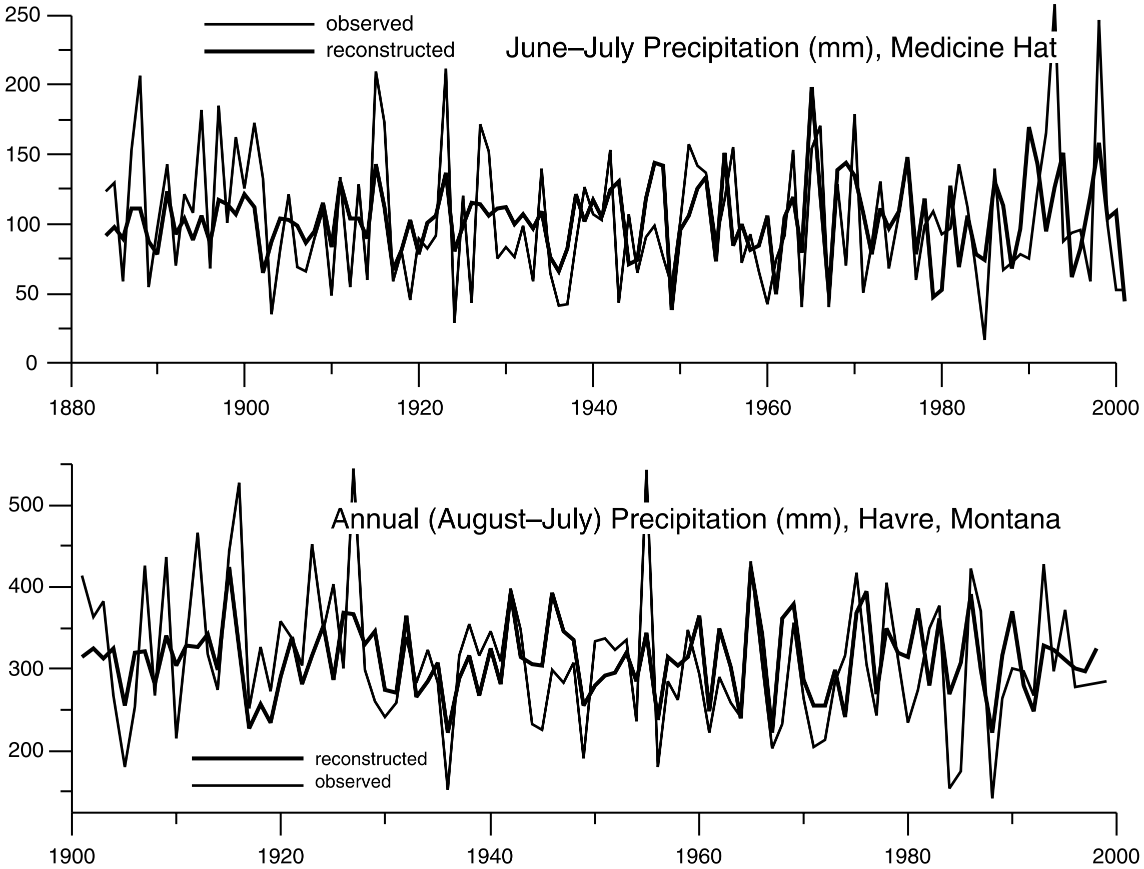

Figure 5 Observed versus reconstructed precipitation for June–July at Medicine Hat, Alberta and August–July at Havre, Montana. These plots illustrate that tree rings underestimate the observed extremes, especially unusually wet seasons and years, but they capture the timing and sequence of droughts

> At Edmonton House, a large fire burned 'all around us' on April 27th (1796) and burned on both sides of the river. On May 7th, light canoes arrived from Buckingham House damaged from the shallow water. Timber intended to be used at Edmonton House could not be sent to the post 'for want of water' in the North Saskatchewan River. On May 2nd, William Tomison wrote to James Swain that furs could not be moved as, 'there being no water in the river'.
>
> Johnson 1967, 33–9, 57

The cumulative precipitation plots (Figure 6) also show that negative departures persist in both proxy records until about 1800. At Edmonton House in April 1800, James Bird attributed poor trade with the Slave and Southern Indians to the 'the amazing warmness of the winter' diminishing the bison hunt and creating a 'want of beaver'. He also reported 'clear weather except for the smoke which almost obscures the sun. The country all round is on fire'. On 15 June, he noted that the 'amazing shallowness of the water' prevented the shipment of considerable goods from York Factory (Johnson 1967, 240–8).

In 1820, Peter Fidler reported that a disease, 'occasioned by the Change in the Air or some other unknown cause' suddenly reduced the beaver to a very few. The pathogen responsible for the epidemic has been identified as *Francisella tularensis*, a zoonotic disease well adapted to stagnant or low water (Martin 1978, 135–40). This drought of the 1820s is most apparent in the tree rings from the Bears Paw Mountains.

The timing and impacts of the drought of the 1790s have implications for the future of the northern Great Plains. The Global Climate Models (GCMs) used by the Canadian Climate Impact Scenarios project (http://www.cics.uvic.ca/scenarios/index.cgi; Canadian [CGM2]; UK Hadley Centre [HadCM2]; German Max Planck Institute [ECHAM4]; Japanese [CCSRNIES];

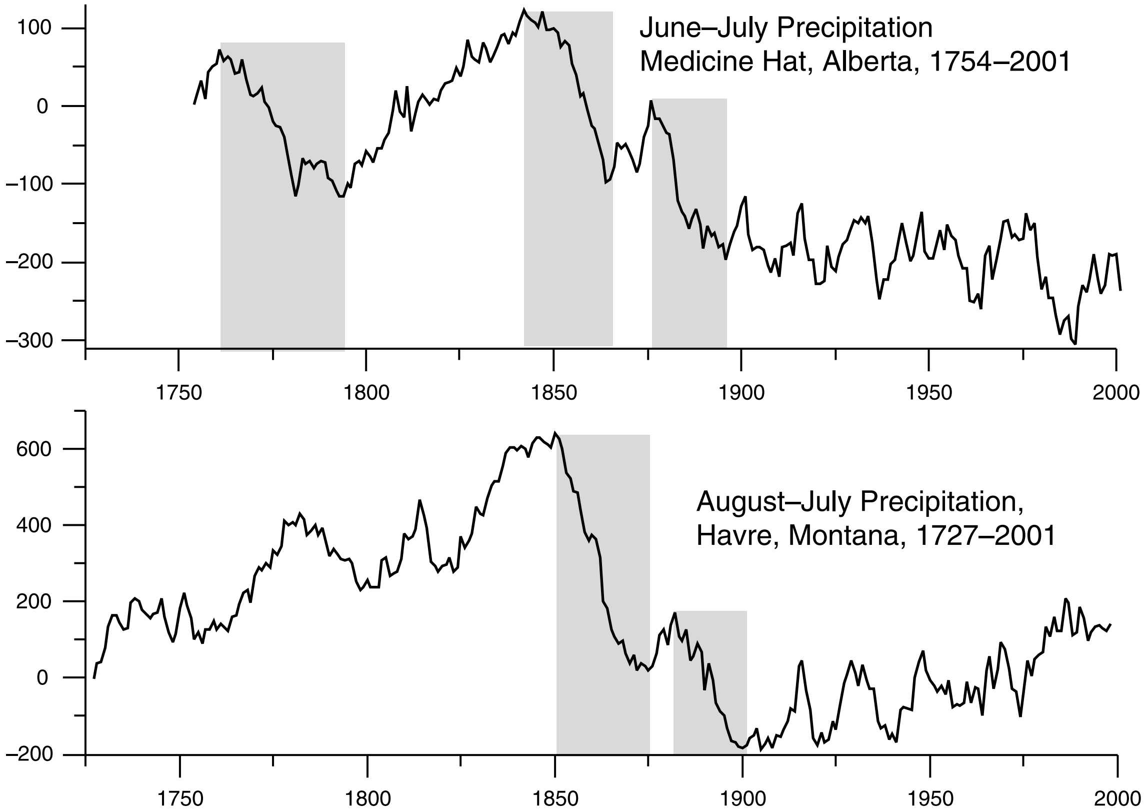

Figure 6 Cumulative departures from median proxy precipitation: June–July at Medicine Hat, Alberta and August–July at Havre, Montana. These plots illustrate the shift in climate variability whereby long periods of consistent drying (highlighted in grey) preceded the twentieth century and thus most of the instrumental weather records

Australian [CSIROMk2b]; and US Geophysical Fluid Dynamics Lab [GFDL-R15]) suggest that the maximum increases in mean surface temperature will occur at high latitudes and in the interiors of the large continents (Herrington *et al.* 1997; Joyce *et al.* 2001; IPCC 2001). Most GCMs also project increased winter precipitation, but with decreased net soil moisture and water resources in summer[1]. If the prolonged drying events of the eighteenth and nineteenth centuries were to reoccur in the twenty-first century they would be superimposed on an increase in regional aridity as forecasted by GCM scenarios for the western interior of North America. That is, future drought could affect a larger region of progressively declining net soil moisture.

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Note

[1] A table of scenarios derived from various experiments and emission scenarios can be found at the Canadian Climate Impacts Scenario Website (http://www.cics.uvic.ca/scenarios/index.cgi).

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