Global Change Biology (2007) **13**, 1295–1307, doi: 10.1111/j.1365-2486.2007.01367.x

Multidecadal to millennial-scale shifts in drought conditions on the Canadian prairies over the past six millennia: implications for future drought assessment

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Abstract

Three high-resolution climatic reconstructions, based on diatom analyses from lake sediment cores from the Canadian prairies, show that shifts in drought conditions have prevailed on centennial to millennial time scales for at least the past six millennia. These shifts in mean aridity exhibit broad regional synchrony, with particularly pronounced shifts at all sites between ~1700–2000 cal. yr BP and ~3600–3900 cal. yr BP, as well as at ~5400–5500 cal. yr BP for the two sites which extend back to at least 6000 cal. yr BP. The two Saskatchewan lakes exhibited significant coherence in both the timing and direction of these shifts, whereas inferred changes at the westernmost site in Alberta were significantly correlated to the Saskatchewan sites, but opposite in sign, and exhibited more high-frequency variation on the scale of centuries. The mechanisms behind these abrupt shifts in aridity are poorly understood, but may be linked to changes in oceanic–atmospheric interactions that influence the mean position of the jetstream and the associated storm tracks. Natural shifts in mean climatic conditions may accelerate with increasing carbon dioxide levels intensifying the likelihood of extreme droughts in North American prairies.

Keywords: Canada, drought, millennial scale, prairie, rapid climatic change, water availability

Received 6 October 2006; revised version received 19 January 2007 and accepted 25 January 2007

Introduction

Abrupt climatic shifts with widespread environmental effects have occurred throughout the geological record (Alley *et al*., 2003). Evidence for millennial-scale climatic shifts during the Holocene are emerging from paleoclimatic records from many sites in the Northern and Southern Hemispheres (e.g. Mayewski *et al*., 2004). In general, it appears these shifts are because of orbital variations and the consequent variability in solar input amplified through oceanic and atmospheric dynamics (e.g. Bond *et al*., 2001; Mayewski *et al*., 2004).

The degree of variability that can be detected in paleoclimatic records depends on the temporal and spatial analysis of the study (MacDonald & Case, 2000). For example, the initial view that the Holocene was climatically stable (e.g. Dansgaard *et al*., 1993) developed in the context of the much larger magnitude changes associated with glacial cycles. However, abundant evidence now exists to suggest that variation observed during the Holocene has been substantial and that these changes have had large effects on ecological and human systems (e.g. deMenocal, 2001).

Water is in short supply in many regions of the world. The recent multiyear drought from 1998 to 2004 that impacted the Canadian prairies (Schindler & Donahue, 2006), with similar temporal timing in the western US (Cook *et al*., 2004), may be a sign of the future. As in most droughts, the onset, intensity and spatial extent varied within the regions impacted, however, within the Canadian prairies this recent drought is contended to be more severe than the 1930s (Schindler & Donahue, 2006). Even so, numerous studies now indicate that

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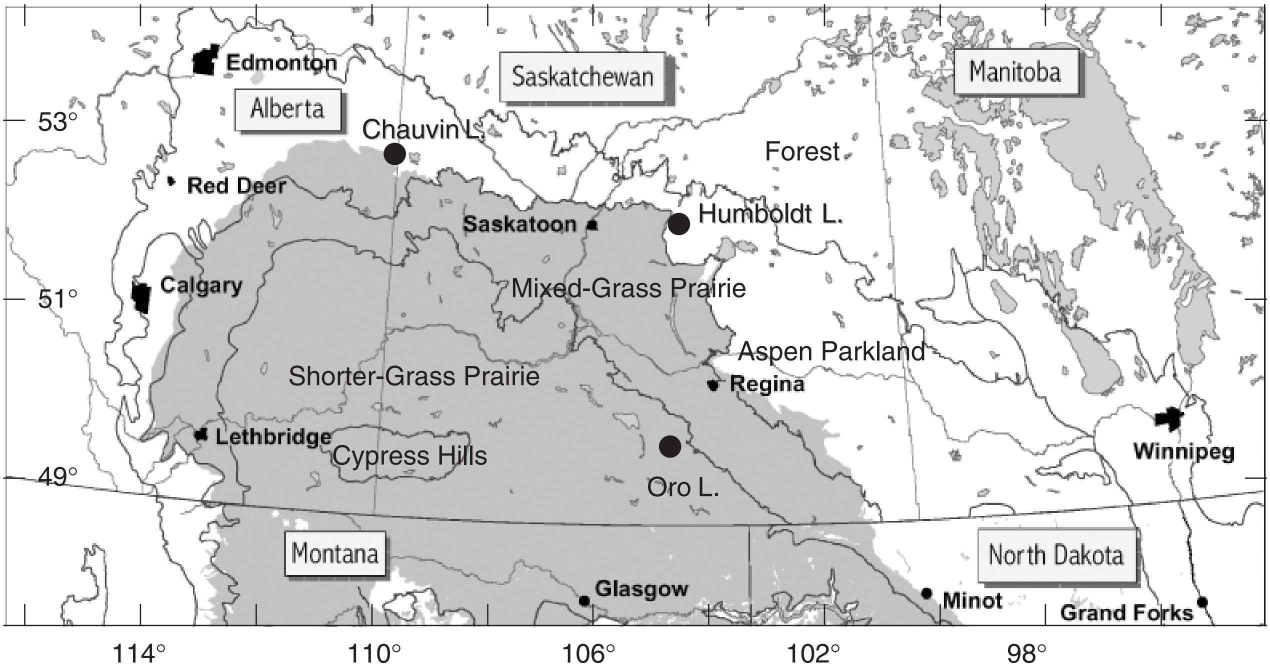

Fig. 1 Map of the Canadian Great Plains showing the location of Chauvin, Humboldt and Oro lakes. The ecozones Cypress Hills, shorter-grass prairie, mixed-grass prairie, Aspen parkland and forest are indicated. The shorter-grass prairie is not true-short grass prairie found further to the south, but rather is phenotypically short due to the generally high aridity of this region (Grimm, 2001). The shaded region represents the Brown Chernozenic Soil zone.

droughts of the 20th century within the northern Great Plains prairie region and western Canada were shorter and less extreme than many that occurred during the past several thousand years (Laird *et al*., 2003; Sauchyn *et al*., 2003; Cook *et al*., 2004; Woodhouse, 2004). Multidecadal megadroughts of the 13th and 16th century are recorded in many paleoclimatic records (e.g. Woodhouse, 2004), while century-long arid periods have also been documented before the 13th century for the northern US prairies and western North America (Laird *et al*., 1996b; Cook *et al*., 2004).

Agriculture is the predominant economic activity throughout much of the Canadian prairie grasslands stretching across the southern portions of Alberta and Saskatchewan (Fig. 1), and is critically dependent on water and soil resources that are directly affected by climate (Lemmen *et al*., 1997; Gan, 2000). A recent study of major rivers within Canada's prairie provinces indicates that climatic warming and human impacts have reduced water availability (Schindler & Donahue, 2006). Furthermore, such human-mediated shortfalls may be intensified by abrupt natural changes (National Research Council, 2002). Consequently, improved knowledge of the modes and possible causes of temporal variability in aridity are essential to ensure sustainable human occupation of dry regions.

A recent synthesis of high-resolution lake sediment records of three sites within the Canadian prairies and three sites in the northern US prairies (Laird *et al*., 2003) showed that abrupt shifts in aridity and mean climatic conditions have been a prevalent feature of the northern Great Plains during the past ~2000 years. These decadal-scale lake records showed regionally coherent changes of the biological communities on a multicentennial scale, suggesting continental-scale changes in climatic conditions (Laird *et al*., 2003). Few high-resolution records exist for this region, whereas many century-scale paleolimnological records of Holocene climatic conditions on the Canadian prairies (e.g. Vance *et al*., 1995) and northern US prairies (e.g. Laird *et al*., 1996a) indicate climatic conditions have been dynamic since the last glacier retreat. Although, the more recent focus on the past two millennia indicates that decadal dynamics can be locally and temporally variable (e.g. Fritz *et al*., 2000), longer multicentennial-scale patterns appear to have regional coherency (Laird *et al*., 2003). A question stemming from this latter research is whether high-resolution records of aridity in the northern Great Plains over a longer time frame would provide evidence for millennial-scale shifts in mean climatic conditions seen in other regions. For example, a sedimentary record from western Canada indicates that shifts in aridity have occurred approximately every 1200 years during the last six millennia (Cumming *et al*., 2002) corresponding broadly with worldwide fluctuations in glaciers (Denton & Karlen, 1973) and ocean dynamics (e.g. Bond *et al*., 2001). To begin to address this question, in this study we examine the millennial-scale dynamics of three sites in the Canadian prairies.

Here, we present the spatial and temporal patterns of hydroclimatic change during the last 6000 years as inferred from fossil diatoms in sediments of three closed-basin lakes on the Canadian Prairies that have been shown to be sensitive to recent climatic changes (Stuart, 1999; Laird *et al*., 2003). The remains of diatoms in lake sediments have been used in paleolimnological studies to estimate past lake water salinity and climate (e.g. Fritz *et al*., 1999). This study was undertaken to investigate the persistence and coherence of long-term climatic shifts (100–1000 year) and the implications for future water availability on the Canadian Great Plains.

Materials and methods

Study sites

The response of lakes to climatic influences can be complex and depends on the morphology of the lake and its geological and hydrological setting. Although the hydrological budget of prairie lakes is dominated by precipitation and evaporation, groundwater interactions can influence lake chemistry (Winter & Woo, 1990). Furthermore, even though the majority of annual precipitation occurs between May and September, changes in snow pack can influence the hydrological budget. Because of these complexities, careful site selection is of utmost importance in establishing an interpretable record of past climatic changes (e.g. Fritz, 1996). Consequently, we selected three closed-basin lakes on the Canadian Great Plains (Fig. 1) with evidence of strong linkages between lake chemistry and the historical climate (Stuart, 1999; Sauchyn *et al*., 2002; Laird *et al*., 2003). In addition, aerial photographs of all three lakes exhibited substantial reductions in surface areas (SA) during historical dry periods.

The most western site, Chauvin Lake (52°41.2′N, 110°06.2′W), is located in east-central Alberta within the prairie zone and at the edge of the mixed-grass region, a region that is sensitive to the variations in the position of the summertime ridge of high pressure that regulates the position of the jet stream and associated storm tracks. In 2003, the water of Chauvin Lake was alkaline and subsaline (salinity = $2.1\,\mathrm{g\,L^{-1}}$) with a maximum depth of 10 m. The SA is ~0.9 $\mathrm{km^2}$, with a watershed area (WA) of ~10 $\mathrm{km^2}$ and a WA/SA ratio of ~11. Humboldt Lake (52°08.4′N, 105°06.3′W) in central Saskatchewan, also at the edge of the mixed-grass prairie (Fig. 1), is presently alkaline and subsaline (salinity = $1.4\,\mathrm{g\,L^{-1}}$), and has a maximum depth of 6.3 m. The SA is ~6.4 $\mathrm{km^2}$, with a WA of ~94 $\mathrm{km^2}$ and a WA/SA ratio of ~15. Finally, Oro Lake (49°47.0′N, 105°20.0′W) is located in south-central Saskatchewan, a short-grass region encompassing one of the driest parts of the Canadian prairies and one of the most climatically sensitive regions of the country (Lemmen & Vance, 1999). Oro Lake is presently alkaline, meromictic, and hyposaline (salinity = $19\,\mathrm{g\,L^{-1}}$), with a maximum depth of 7 m. The SA is ~0.5 $\mathrm{km^2}$, with a WA of ~8.0 $\mathrm{km^2}$ and a WA/SA ratio of ~16.

At present, all three lakes are surrounded by agricultural land use. Before European settlement, the natural vegetation was either mixed-grass Prairie (Chauvin and Humboldt lakes) or short-grass Prairie (Oro Lake). The climate on the Canadian Great Plains is continental and subject to changing influences of three major air masses; warm and dry air flow from the Pacific, cold and dry arctic air, and moist tropical air from the Gulf of Mexico (Bryson & Hare, 1974). Mean daily temperature during January is −13 °C for the regions around Chauvin and Oro lakes, and −17 °C for Humboldt Lake, while July averages are ~19 °C for all three sites (Canadian Climate Normals, 1971–2000). The region receives ~340–380 mm of precipitation per year, while the annual evapotransporation is ~600 mm for Chauvin and Humboldt lakes and ~900 mm for Oro Lake (Canadian National Committee for the International Hydrologic Decade, 1978). Such strong annual moisture deficit is one of the most distinguishing climatic characteristics of the prairie region.

Coring and sediment methods

All lakes were cored with a 1 m Livingstone square-rod piston corer (Glew *et al*., 2001). An 8.24 m core consisting of nine sections was collected from Oro Lake in June 2001. This core spanned ~10 000 years (Fig. 2). In July 2003, two piston cores were collected from the deepest part of Chauvin (Core 1 = 10.2 m, Core 2 = 12.6 m) and Humboldt lakes (Core 1 = 3.5 m, Core 2 = 4.2 m). The Chauvin Lake record included the past ~12 000 years, whereas that from Humboldt Lake spanned only the last ~ 5000 years (Fig. 2). Cores were stored at 4 °C in the dark.

All cores were split, described using Munsell Soil Color Charts, and photographed. One half of each core was archived, while the other half was sectioned at 0.5 cm intervals. Subsamples for diatoms analysis from Core 2 were taken every 2 cm for both Chauvin and Humboldt lakes, each representing a temporal resolution of ~13 years. In contrast, samples were collected every 2 cm for the top ~6 m of the Oro Lake core and achieved a temporal resolution of ~23 years.

The two cores from each of Chauvin and Humboldt lakes were correlated using visible lithostratigraphic

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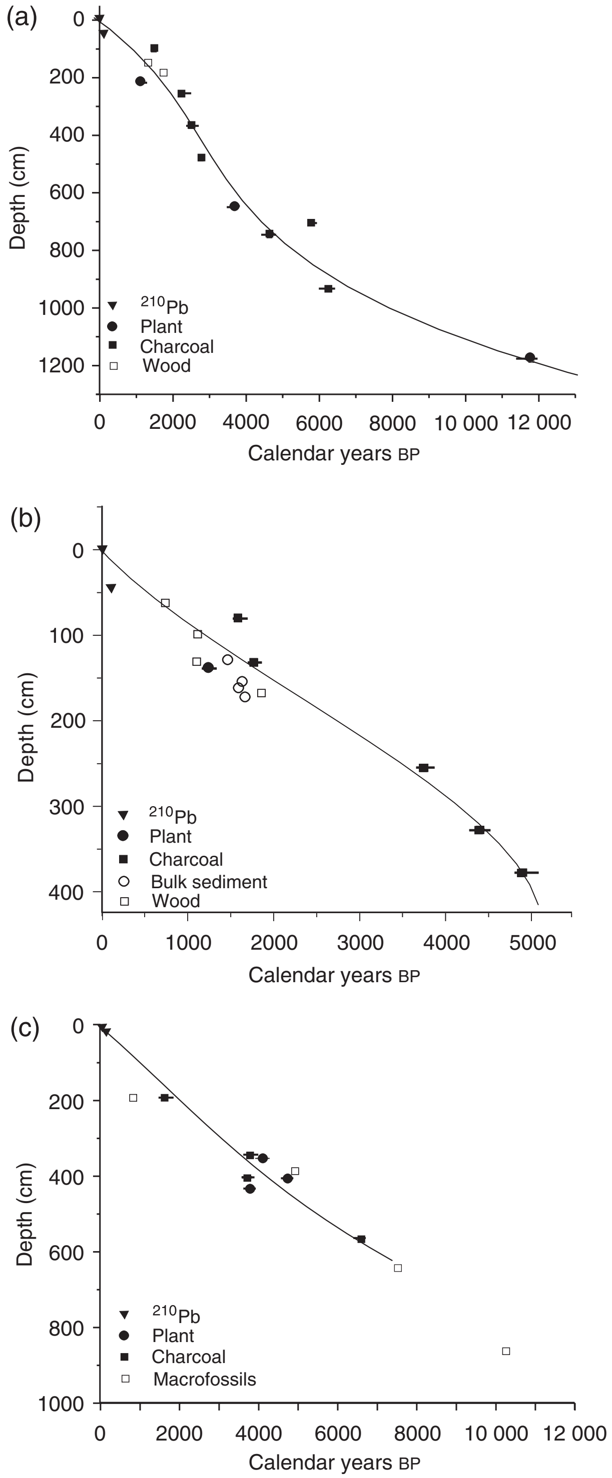

Fig. 2 Age-depth models (solid lines) for (a) Chauvin, (b) Humboldt, and (c) Oro lakes. BP = 1950. Radiocarbon dated intervals are represented by filled squares, whereas ^{210}Pb-derived dates are represented by filled triangles. Error bars are $\pm 2\sigma$ ranges. Open symbols represent dates from previous cores (Stuart, 1999; Laird *et al.*, 2003) and were not used in developing the age-depth models.

features (laminated and banded units), X-ray analysis, and diatom profiles. In rare cases where there were gaps between any two consecutive core sections they were completed by enumerating diatoms in the equivalent section of the second core. This procedure resulted in 8.7 m of analysed sediments for Chauvin Lake and 4.0 m for Humboldt Lake.

For all sites, sediment chronologies are based on ^{210}Pb dating for the recent sediments (Stuart, 1999; Laird *et al.*, 2003) and on radiocarbon dates determined by accelerator mass spectrometry (AMS) of terrestrial charcoal and plant macrofossils (Table 1). Each dated charcoal sample consisted of $\sim$0.1 g of charcoal isolated by hand using a stereomicroscope from an interval of 2–10 cm of adjacent sediment following preconcentration onto a 150 μm seive (Table 1). A 2σ calibration of the ^{14}C ages was performed with OXCAL version 3.3 (Table 1) (Stuiver *et al.*, 1998). A third-order polynomial equation was used to interpolate sedimentation rates and infer chronology between dated sediment depths (Fig. 2).

Sediment samples for diatom analyses were processed according to Wilson *et al.* (1996), except that the HCl step was omitted, and the diatoms were mounted in Naphrax® (refractive index = 1.74). Diatoms were counted along transects under oil immersion using a Leica DMRB microscope fitted with a × 100 fluotar objective ($NA = 1.3$) and using differential-interference-contrast optics. A minimum of 300 valves, identified to species, were counted whenever possible. A minimum count of 100 valves was required to be included in the analyses. The main taxonomic references were Krammer & Lange-Bertalot (1986, 1988, 1991a,b) and Cumming *et al.* (1995).

Statistical analyses

Major stratigraphic zones were identified from fossil diatom assemblages using a constrained cluster analysis (CONISS), a squared-chord distance to estimate dissimilarity, and were performed with the program TILIA v. 2.02 (Grimm, 1987). The significance and robustness of the zones was evaluated by comparison with both binary and optimal splitting zonation methods using PSIMPOLL v. 4.10. (Bennett, 1996). In all records, both methods produced identical major zones. However, we used the optimal splitting technique and maximal variance reduction to define the points of transition among zones. This approach was taken to focus on dynamics expressed at century and millennial scales rather than high frequency variability (interdecadal 'noise'). Additional subzones were defined based on high-total sum of square (TSS) splits in CONISS. All of these subzones were significant based on PSIMPOLL analysis.

Table 1 AMS radiocarbon dates for CH, H and O lakes

Depth (cm)	Material dated	^{14}C age	Calender years BP ($\pm 2\sigma$ range)	Age used in depth model	Lab. number
CH 97–106	Charcoal	1601 ± 38	1398–1565	1475	1533A/1423 CH110
CH 218–218.5	Leaves	1215 ± 54	1051–1277	1125	AA63898
CH 250–260	Charcoal	2337 ± 47	2309–2492	2231	1516A/1411 CH289
CH 365–371	Charcoal	2465 ± 36	2363–2710	2497	1517A/1412 CH407
CH 475–485	Charcoal	2656 ± 37	2740–2845	2760	1535A/1426 CH537
CH 647–647.5	Twig	3442 ± 43	3611–3832	3700	AA63899
CH 700–711.5	Charcoal	5112 ± 44	5742–5936	5800	1521A/1431 CH777
CH 745–751.5	Charcoal	4083 ± 63	4428–4820	4640	1532A/1425 CH819
CH 930–940	Charcoal	5470 ± 100	5996–6446	6250	1530A/1419 CH1012
CH 1180–1180.5	Wood	10 109 ± 63	11 394–11 992	11 800	1520A/1417 CH2513
H 78–82	Charcoal	1675 ± 35	1518–1695	1583	1515A/1409 H75
H 130–134	Charcoal	1812 ± 36	1689–1827	1770	1522A/1418 H132
H 139–139.5	Plant	1292 ± 41	1167–1298	1230	LRC 1507B
H 251–259	Charcoal	3484 ± 38	3681–3852	3750	1523A/1432 H269
H 325.5–329.5	Charcoal	3956 ± 41	4288–4523	4400	1524A/1414 H354
H 373.5–381.5	Charcoal	4399 ± 47	4854–5068	4900	1518A/1413 H402
O 190.5–194.5	Charcoal	1728 ± 83	1480–1830	1620	1525A/1420 O191
O 338.5–346.5	Charcoal	3568 ± 42	3722–3978	3830	1534A/1422 O347
O 350–350.5	Plant	3776 ± 57	3979–4299	4150	1531A/1421 O410
O 399–407	Charcoal	3465 ± 38	3639–3834	3750	AA63901
O 404–404.5	Thorn	4222 ± 45	4615–4861	4770	1526A/1424 O578
O 433–433.5	Twigs	3571 ± 44	3721–3981	3830	AA63902
O 561.5–570.5	Charcoal	5782 ± 42	6471–6674	6600	AA63903

Depth represents the cumulative depth in the core.
CH, Chauvin; H, Humboldt; O, Oro.

Estimates of past lake water salinity were inferred from diatom inference models (e.g. Fritz *et al*., 1999). As shown elsewhere, changes in the balance between precipitation and evaporation (effective moisture) influences the salt concentrations of prairie lakes (Fritz, 1996) and in turn the contemporary distribution of diatom taxa in climatically sensitive regions worldwide (e.g. Fritz *et al*., 1999). Following Laird *et al*. (2003), a weighted-averaging regression and calibration model based on 208 western Canadian lakes (Wilson *et al*., 1996) and 79 lakes from the prairie region (S. C. Fritz, 1996 unpublished data) was used to infer the log salinity from the three lakes with the computer program C2 (Juggins, 2003).

Correspondence analysis, which indicates the main direction of variation unconstrained to any variables in multivariate data, was undertaken for each of the three sites to ensure that our salinity inferences tracked the major changes in the diatom assemblages. In addition, for purposes of correlation among the sites, the log salinity data were smoothed using a five-point fast fourier transform filter using MICROCAL ORIGIN version 6.0 (Microcal™, 1999) to produce salinity time series of similar temporal resolution for each lake.

Results

Dating and zonation

A third-order polynomial equation provided a reliable chronological model for all sites ($r^2_{\text{Chauvin}} = 0.96$, $r^2_{\text{Humboldt}} = 0.97$, $r^2_{\text{Oro}} = 0.97$). Furthermore, good correspondence of our dates with independently dated samples from other cores from the three lakes (Stuart, 1999; Laird *et al*., 2003), suggest the age-depth model based on ^{210}Pb and the ^{14}C dates is highly reproducible (Fig. 2). All ages are in calendar years before present (cal. yr BP; BP = 1950).

Cluster and zonation analyses indicated three major diatom assemblage zones could be identified in each lake, A–C (Fig. 3). The first split in all three lakes occurred at ~2000 cal. yr BP, while the second splits were recorded at ~4600 cal. yr BP for Chauvin Lake, ~3900 cal. yr BP for Humboldt Lake and ~5500 cal. yr BP for Oro Lake. These major zones were divided further into significant multicentennial periods of relative stability in the diatom assemblage (e.g. A1, A2) in order to provide a common framework to discuss changes in climatic and limnological conditions. The

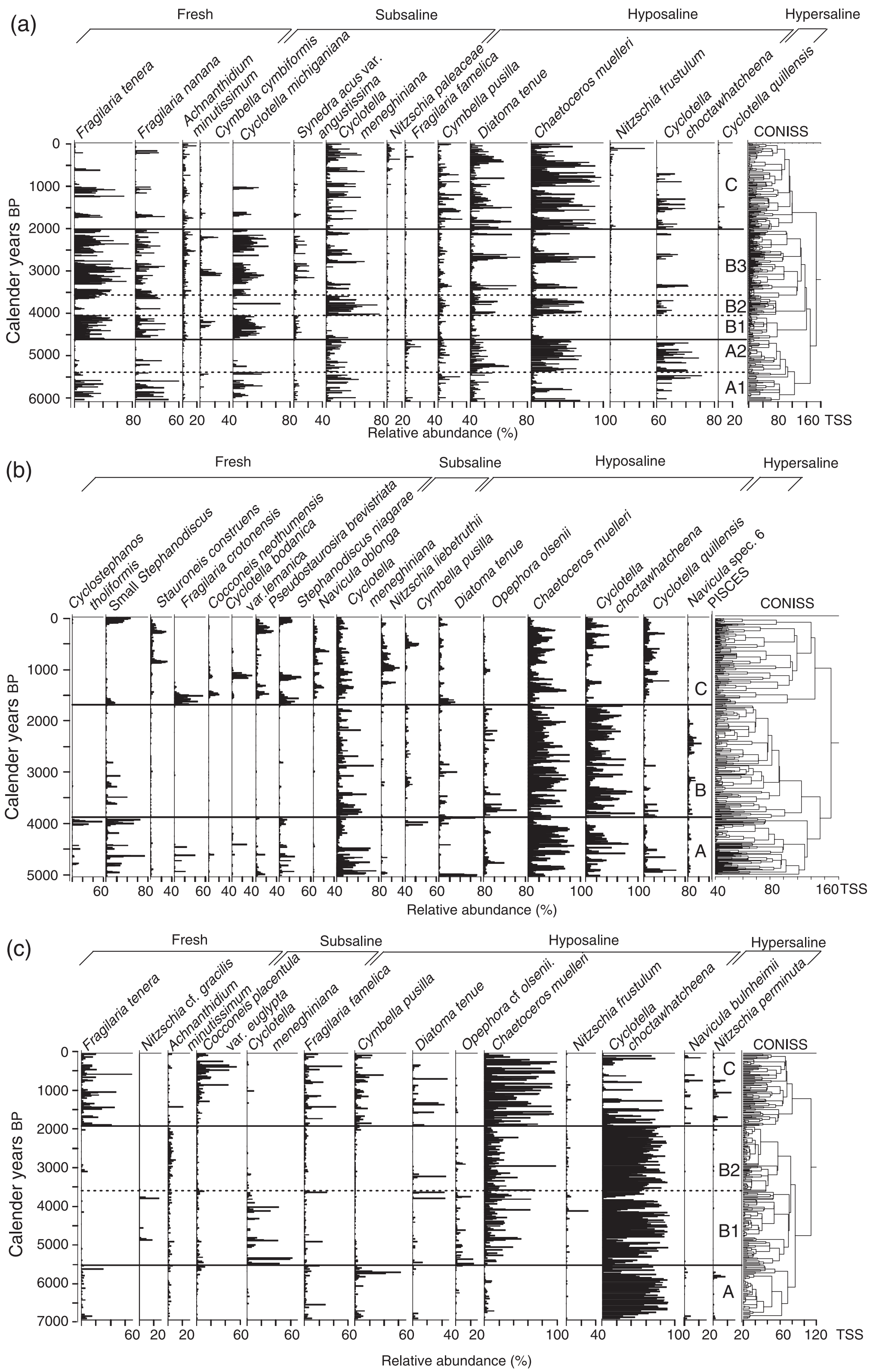

Fig. 3 Dominant diatom taxa (>20%) from (a) Chauvin, (b) Humboldt, and (c) Oro lakes. Taxa are arranged according to estimates of their optima to salinity. Salinity categories are: fresh ($<0.5\,\mathrm{g\,L^{-1}}$), subsaline (0.5–$3.0\,\mathrm{g\,L^{-1}}$), hyposaline (3–$20\,\mathrm{g\,L^{-1}}$) and hypersaline ($>20\,\mathrm{g\,L^{-1}}$). Results of the constrained cluster analysis are shown on the right. TSS, total sum of squares. Zones are based on CONISS and PSIMPOLL analyses, see 'Materials and methods' for details.

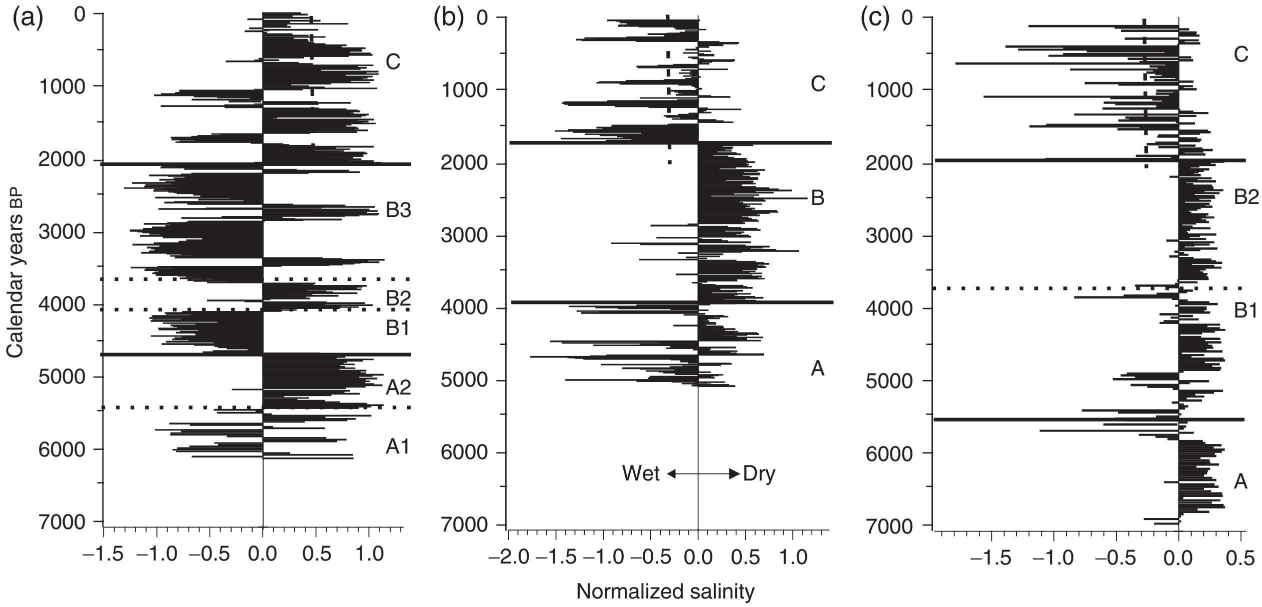

Fig. 4 Deviation from mean log salinity over the past 5000–7000 years from the diatom-inferred mean log salinity from (a) Chauvin, (b) Humboldt, and (c) Oro lakes sediment cores. Records are plotted from west to east. Dashed horizontal lines across each record represents the main zonation of the diatom assemblages in each site as defined from cluster and zonation analyses. Dashed vertical line across each record represents the mean log salinity over the past 2000 years. BP = 1950.

duration of each zone ranged from 400 to 2200 years with a mean of ~1400 years.

Alberta site

Six different periods of comparatively stable diatom composition were identified for the core from Chauvin Lake, the westernmost site (Fig. 3a). Zone A lasted from ~6100 to 4600 cal. yr BP and was split into two subzones. Subzone A1, ~6100–5400 cal. yr BP, was characterized by variations in the relative proportions of freshwater taxa [*Fragilaria tenera* (W.Sm.) Lange-Bertalot, *Fragilaria nanana* Lange-Bertalot], subsaline species (*Cyclotella michiganiana* Skvortzow, *Cyclotella meneghiniana* Kützing) and hyposaline diatoms (*Chaetoceros muelleri* Lemmermann) indicating frequent fluctuations between a dry and wet climate (Fig. 4a). Zone A2, ~5400–4600 cal. yr BP, was composed mainly of hyposaline taxa (*C. muelleri*, *Cyclotella choctawhatcheena* Prasad), indicating an arid climate. In contrast, Zone B, ~4600–2000 cal. yr BP, was characterized primarily by freshwater taxa (*F. tenera*, *F. nanana*) and subsaline species (*C. michiganiana*), suggesting a generally wetter climate. However, Zone B was also composed of three subzones, including an extended arid period from ~4100 to 3700 cal. yr BP (Zone B2) during which freshwater taxa were abruptly replaced by subsaline (*C. meneghiniana*) and hyposaline species (*C. muelleri*, *C. choctawhatcheena*). Zone B3 extended from ~3700 to 2000 cal. yr BP and was marked by the return of freshwater *Fragilaria* species and subsaline *C. michiganiana* with the exception of two short arid periods, ~3400–3300 cal. yr BP and ~2800–2600 cal. yr BP. Notably these shifts occurred over the course of only a few decades. Finally, Zone C encompassed the past ~2000 years, characterized primarily by hyposaline species consistent with a return to arid conditions (Fig. 4a). During this last interval, freshwater taxa were abundant for only short periods between ~1700–1600 cal. yr BP and ~1150–1050 cal. yr BP (Fig. 3a).

Saskatchewan sites

The two Saskatchewan sites, Humboldt and Oro lakes, exhibited similar changes in fossil community compositions and, hence, inferred climatic conditions (Figs 3b and c, 4b and c). Zone A of the Humboldt Lake record (Fig. 3b), ~5000–3900 cal. yr BP, was composed primarily of hyposaline taxa (*C. choctawhatcheena*, *C. muelleri*), and subsaline species (*C. meneghiniana*), with short-lived peaks of freshwater species (small *Stephanodiscus*) and the hypersaline diatom *Cyclotella quillensis* Bailey, suggesting an interval of variable climatic conditions (Fig. 4b). Zone B (~3900–1700 cal. yr BP) was characterized by the sharp decline in freshwater species, consistently high abundances of hyposaline taxa (*C. choctawhatcheena*, *C. muelleri*) and increased occurrence of the hypersaline taxon *Navicula* sp. 6

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PISCES, patterns which together infer arid conditions. Zone C, encompassing the past ~1700 years marked the return of freshwater taxa (*Fragilaria crotonensis* Kitton, *Stephanodiscus niagarae* Ehrenberg, small *Stephanodiscus*) and a decline in hyposaline species (*C. muelleri*, *C. choctawhatcheena*) indicating wetter conditions. Short intervals of arid conditions during Zone C were indicated by the occurrence of the hypersaline diatom *C. quillensis* and short-lived increases in hyposaline taxa (*C. muelleri*, *C. choctawhatcheena*).

Zone A in the Oro Lake record (Fig. 3c), lasted until ~5500 cal. yr BP, and was composed primarily by the hyposaline taxon *C. choctawhatcheena*, indicating predominantly arid conditions (Fig. 4c). Zone B, ~5500–1900 cal. yr BP, was characterized by the increased abundance of *C. muelleri* and the continuing high proportion of *C. choctawhatcheena*. Zone B has two subzones based on the occurrence of lower salinity taxa (e.g. *C. meneghiniana*, *Opephora* cf. *olsenii* Möller) in subzone B1, which extended from ~5500 to 3600 cal. yr BP. Subzone B1 was characterized initially by variable climatic conditions, similar to and corresponding to Zone A of Humboldt Lake. Similarly, the arid subzone B2 (~3600–1900 cal. yr BP) corresponded well to the arid Zone B of Humboldt Lake. Over the last two millennia, (Zone C) the freshwater diatom (*F. tenera*) and hyposaline taxa (*Cocconeis placentula* var. *euglypta* (Ehrenberg) Grunow, *Fragilaria famelica* (Kützing) Lange-Bertalot, *Cymbella pusilla* Grunow ex. A. Schmidt, *C. muelleri*) increased abruptly in Oro Lake sediments, while *C. choctawhatcheena* declined in a similar pattern recorded in Zone C of Humboldt Lake.

Synchrony of diatom community change

Comparison among all three sites during the past six millennia indicated major coherent climatic shifts operating at both multicentennial and millennial scales (Fig. 4). The most pronounced synchronous shift occurred at ~2000 cal. yr BP, when normalized salinity and diatom community composition shifted dramatically at all sites (mean normalized salinity for the past ~2000 years is shown as a vertical line in Fig. 4). Strong and significant correlations between axis-one scores of the correspondence analysis and inferred log-salinity estimates ($r_{\text{Chauvin}} = 0.97$, $r_{\text{Humboldt}} = 0.72$, $r_{\text{Oro}} = 0.80$) confirmed that the diatom-based salinity inferences accurately summarize and simplify the major variations in the diatom community within the cores. In addition, the two Saskatchewan sites (Humboldt and Oro lakes) exhibited significant coherence in both the timing and direction of shifts in mean climatic conditions during the past 5000 years ($r_{\text{Humboldt/Oro}} = 0.47$, $P < 0.01$, $n = 227$). In contrast, inferred climatic conditions at Chauvin Lake were significantly correlated to the Saskatchewan sites but opposite in sign ($r_{\text{Chauvin/Oro}} = -0.40$, $P < 0.01$, $n = 265$; $r_{\text{Humboldt/Chauvin}} = -0.32$, $P < 0.01$, $n = 385$), and exhibited more high frequency variation on a centennial scale.

Discussion

Coherence among study sites

Millennial-scale variations between wet and arid mean climatic conditions were evident from an analysis of fossil diatom assemblages in each of three Canadian prairie lakes over the past 6000 years (Fig. 4). The most pronounced and coherent shift occurred between ~1700 and 2000 cal. yr BP, with a second coherent shift at ~3600 to 3900 cal. yr BP. A third shift occurred between ~5400 and 5500 cal. yr BP and was evident in records which extended back to at least 6000 cal. yr BP.

The onset of modern lake and climatic conditions occurred ~1700–2000 cal. yr BP based on cluster analysis of fossil diatom assemblages. This most recent period is characterized by a substantially different mean normalized salinity as compared with that recorded during the past 5–7 millennia (Fig. 4). In addition, high-resolution changes during the last ~2000 years appear to be consistent with those previously identified at Chauvin and Humboldt lakes (Laird *et al*., 2003), although this study suggests that the shift in mean climatic conditions identified at ~1200 and 1500 cal. yr BP was small in comparison with that which occurred ~2000 years ago, when put into the context of the ecological changes seen over the past ~6000 years.

In the context of the past ~6000 years, Humboldt and Oro lakes exhibited synchronous ecosystem change characteristic of increased humidity during the past ~2000 years. In contrast, analyses at the westernmost site, Chauvin Lake, suggest a transition to drier conditions during that time. Because Humboldt Lake is located due north of Oro Lake, we suggest that the difference between Chauvin and the other sites may be primarily due to a strong east–west gradient in moisture availability. Although this east–west gradient is not apparent in the modern climate records, this is likely related to their shorter temporal scale. However, differences between the western and eastern sites are consistent with changes in the general positioning of the summertime high-pressure ridge, the main control of the jet stream position and associated storm tracks in this region (Dey, 1982; Oglesby & Erickson, 1989). Another possibility is changes in the main precipitation source for the sites, with the western site potentially

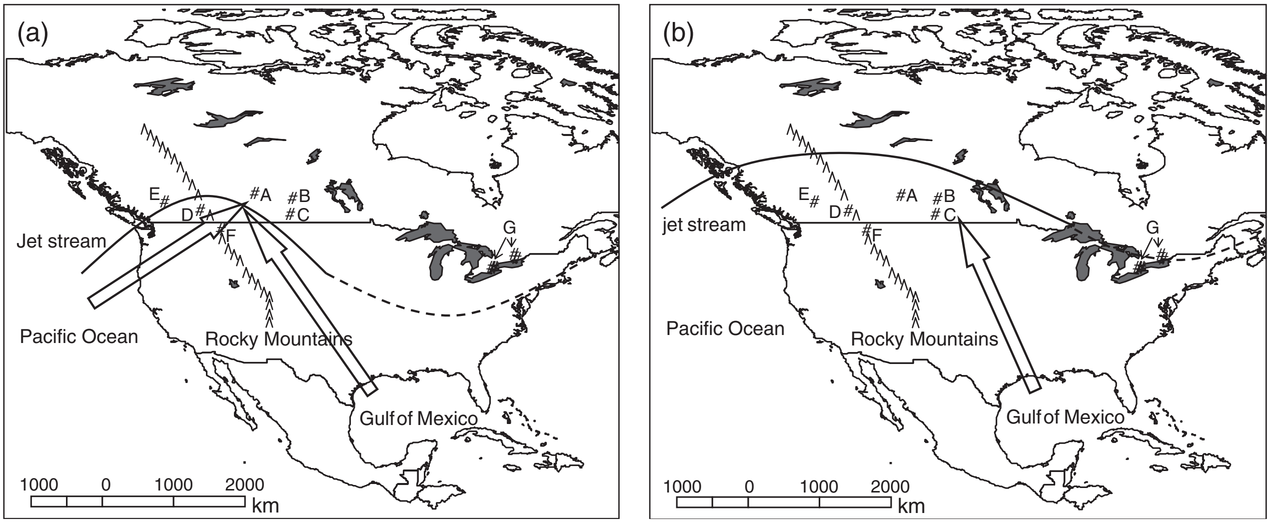

Fig. 5 Mapping of potential moisture sources indicated by the large arrows. Capital letters denote sites in this study and those cited in the text: A, Chauvin Lake (this study); B, Humboldt Lake (this study); C, Oro Lake (this study); D, Dog Lake (Hallett & Hill, 2006); E, Big Lake (Cumming *et al*., 2002); F, Foy Lake (Stone & Fritz, 2006); Ontario sites (Edwards *et al*., 1996; Yu *et al*., 1997). (Scenario a) the jet stream is located in southern British Columbia (BC). Cyclonic storms from the Pacific Ocean tap into moisture from the Gulf of Mexico. This stratiform precipitation pattern could be a winter or summer signal. (Scenario b) the jet stream is located further north in BC. Chauvin is located too far north and west to receive moisture from the Gulf of Mexico, while the eastern sites receive convective precipitation from the Gulf of Mexico. This precipitation pattern would be a summer signal.

having more influence from the Northern Pacific vs. Gulf of Mexico. Another potential complexity is varying groundwater sources at the three sites (e.g. Fritz *et al*., 2000), however, it is unlikely that varying groundwater sources would be a driver at millennial scales.

The climate of the Great Plains is influenced by different air masses; dry westerly flow of air from the Pacific Ocean, cold and dry arctic air masses from the north, and warm and moist tropical air masses from the south (Bryson & Hare, 1974). The northern Rockies are influenced by mid-latitude cyclonic storms coming in from the North Pacific. Consequently, when the jet stream is located over the northern Rockies, these cyclonic storms ride up and over the high-pressure ridge and tap into moist air from the Gulf of Mexico, leading to increased precipitation at western locations (i.e. Chauvin Lake) and dry conditions to the east (Fig. 5a). Conversely when the jet stream positions cyclonic storms further to the north, the western region tends to be drier, while the eastern sites receive moisture from the Gulf of Mexico (Fig. 5b). Thus, the interplay between the shape and position of the jet-stream and resultant moisture source and storm tracks can result in the spatial heterogeneity seen at these sites.

Synchronous, but out of phase, shifts in fossil diatom assemblages and inferred climate were also evident before ~2000 cal. yr BP. For example, predominantly wet conditions were inferred at Chauvin Lake between ~2000 and 3700 cal. yr BP, whereas the records from both Humboldt and Oro lakes revealed mainly arid conditions during this period. The apparent dipole between the western and eastern sites is most evident at the broad temporal scale of the past ~6000 years providing evidence that at the multimillennial scale the overlying climatic influences are different, whereas higher-frequency temporal changes are more difficult to precisely correlate because of chronological control and potential local hydrological influences.

The timing of the second shift between ~3600 and 3900 cal. yr BP corresponds approximately to previous estimates of the onset of modern climatic conditions in the northern Great Plains, although there remains much debate concerning the precise timing of this transition and the spatial extent over which the transition occurred (see section below).

Onset of modern climatic conditions

Our high-resolution analyses of three sites in the Canadian prairies suggest that modern climatic conditions were established between ~1700 and 2000 cal. yr BP. This estimate is consistent with sites further to the east in Ontario, which also demonstrates a cooler temperate climate commencing around 2000 years ago (Edwards *et al*., 1996; Yu *et al*., 1997). However, at present, there are a wide range of estimates concerning the timing of modern cooler and moister conditions in central North America with estimates ranging from ~5000 to 2000 cal. yr BP for the northern Great Plains (Ritchie & Harrison, 1993; Laird *et al*., 1996a; Lemmen *et al*., 1997; MacDonald & Case, 2000). In addition, some studies propose there is a west–east transgression of dates with an earlier onset at western sites (~7000–6000 cal. yr BP) than at the eastern locations (~5000–3000 cal. yr BP) (Vance *et al*., 1995). Furthermore, many of these studies suggest that the transition to cooler, moister climate occurred over a protracted period that began ~5000–6000 cal. yr BP, but which may have not been completed until ~2000–3000 cal. yr BP. Similarly, syntheses of broad-scale studies for western Canada (Ritchie & Harrison, 1993) and eastern North America (Thompson *et al*., 1993) suggest that modern thermal and lake level conditions were established by ~3000 cal. yr BP having commenced earlier on. Such variability in the timing of modern conditions likely reflects both the temporal resolution and accuracy of fossil reconstructions, as well as the geographic variance in timing of climatic change at specific locations (e.g. Fritz, 1996; Donovan *et al*., 2002).

Mid-Holocene climatic conditions

The broad-scale pattern of mid-Holocene aridity (~9000–4000 cal. yr BP) is well documented for the northern Great Plains by paleoclimatological analyses (e.g. Vance *et al*., 1995; Laird *et al*., 1996a). In the Canadian interior, grassland and parkland boundaries were north of their present-day limits (Vance *et al*., 1995), lake-levels were low (Ritchie & Harrison, 1993), and many shallow lake basins were completely dry (Vance *et al*., 1995). Furthermore, recent evidence from parkland regions indicates that sand dune activity was elevated in central Saskatchewan from ~7500 to 5000 years ago (Wolfe *et al*., 2006), corresponding to similar periods of dune activity within the US Great Plains (Dean *et al*., 1996; Forman *et al*., 2001). The eastward expansion of the US prairies into present-day forested areas during the mid-Holocene is also well documented (e.g. Bradbury *et al*., 1993; Baker *et al*., 2002; Wright *et al*., 2004). The prairie expansion exhibited strong spatial organization, with western-most sites experiencing prairie expansion from ~9000 to 5000 cal. yr BP, while the transition to grassland occurred at eastern sites during ~6500–3000 cal. yr BP (Baker *et al*., 2002). However, broad geographical and temporal-scale patterns may differ from those observed at smaller spatial scales and at higher temporal resolution (e.g. Bradbury *et al*., 1993; MacDonald & Case, 2000). For example, at Chauvin Lake the longest arid period of the mid-Holocene occurred between ~5500 and 4600 cal. yr, after which extended wet periods between ~4600 and 2000 cal. yr BP, with short arid episodes occurred. In contrast, the two central sites exhibited long periods of aridity until ~2000 cal. yr BP, with some extended periods of wetter conditions between ~5500 and 4000 cal. yr BP. Thus, our records suggest that the mid and late Holocene were spatially and temporally complex with rapid oscillations between arid and wet conditions.

Coherence of prairie and continental regions

High-frequency climatic variability during the mid- to late-Holocene evident in the prairie ecozone has also been recorded in other regions of Canada and northern US. For example, analysis of a highly resolved sediment record from western Canada (Cumming *et al*., 2002) demonstrates that major shifts in drought regimes occurred every ~1200 years in central British Columbia (BC), with sharp transitions at ~1100, 2300, 3800 and 4900 cal. yr BP. These shifts correspond broadly with the major climatic shifts observed at our prairie sites, particularly at Chauvin Lake where inferred dry climatic conditions correspond closely with periods of lower lake level at Big Lake, BC. Similarly, a recent analysis of fire history and lake level changes at Dog Lake, BC also identified millennial-scale shifts in climatic conditions that were broadly coherent with those observed at Big Lake (Hallett & Hill, 2006). Finally, analysis of fossil diatoms from a northern US Rocky Mountain lake identified a major change in the climate system at around 4500 cal. yr BP (Stone & Fritz, 2006), as well as several millennial-scale changes in climatic conditions (~2100, 3500, 4500 cal. yr BP), which correspond approximately to the timing observed at our prairie sites, particularly Chauvin Lake.

Global linkages

A recent review of Holocene climatic variability indicates widespread rapid climatic change occurred globally between ~6000 and 5000 cal. yr BP (Mayewski *et al*., 2004). This timing corresponds to the oldest shift recorded here at Chauvin and Oro lakes (~5500–5400 cal. yr BP). Although less spatially consistent, paleoclimatic records from several continents indicate a major change in the climate system at ~4200–3800 cal. yr BP, patterns which again seem to correspond to transitions recorded at our sites (~3900–3600 cal. yr BP). Unexpectedly, the predominant change in lake conditions observed in the Canadian prairies (~1700–2000 cal. yr BP) does not appear to coincide with any known major change in global climate and instead falls between two periods of rapid change (~3500–2500 and

~1200–1000 cal. yr BP). However, because the prairie transition was also observed at adjacent sites in British Columbia (Cumming *et al*., 2002) and Ontario (Edwards *et al*., 1996; Yu *et al*., 1997), we propose that the 1700–2000 cal. yr BP event corresponds to a more regional shift in climatic conditions possibly associated with variability in oceanic–atmospheric interactions. Previous studies have suggested a linkage between Pacific sea surface temperatures (SST) anomalies and dry spells in the Canadian Prairies (Bonsal *et al*., 1993), which may be related to El-Nino Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) influencing moisture availability in Canada (Shabbar & Skinner, 2004).

Several recent studies have suggested linkages between widespread droughts within central North America and conditions within the Pacific and Atlantic oceans (Hoerling & Kumar, 2003; McCabe *et al*., 2004; Schubert *et al*., 2004). In particular, interactions between the PDO, ENSO, and potentially the Atlantic Multidecadal Oscillation (AMO) may be associated with the intensification of droughts during the 20th century (McCabe *et al*., 2004). Consistent with this view, continental patterns of tree-ring records suggest that a megadrought occurred during medieval times (AD 993–1300, ~650–960 cal. yr BP) in western North America, lasted several centuries and was associated with strongly negative PDO values (MacDonald & Case, 2005). Similarly, ENSO variability has been linked to mid-Holocene droughts in the Southwest US (Menking & Anderson, 2003), while millennial-scale changes in ENSO intensity appear to reflect variations in Earth's orbital position and receipt of solar energy (Moy *et al*., 2002). Together these studies suggest that long-term changes of atmospheric–oceanic linkages are a principle control of the major climatic shifts during the mid to late Holocene. Booth *et al*. (2006) have hypothesized that some of the past widespread droughts in the western Great Lakes region were related to SSTs in the Pacific and Atlantic. Climate models relating specifically to our study site results may help to discern the importance of Pacific and Atlantic conditions at these sites.

Implications for future drought assessment

Our study demonstrates that there have been severe major shifts in prairie climate during the past 5–7 millennia, with some arid periods lasting hundreds to thousands of years. Given that the Canadian prairies are already experiencing large reductions in surface water availability due to climatic warming and human withdrawals (Barnett *et al*., 2005; Schindler & Donahue, 2006), a return to past arid conditions could have devastating impacts on the social, economic, and environmental sustainability of the region. Climate model predictions suggest that the Canadian prairie region is likely to be even more drought-prone under projected global warming (Herrington *et al*., 1997; Sauchyn *et al*., 2002). Further, given that human-induced global warming may increase the probability of rapid shifts in mean climatic conditions (Alley *et al*., 2003), we suggest that adaptation and mitigation strategies must consider the possibility that future climatic change may suddenly shift climatic systems to a sustained era of low water availability.

Acknowledgements

Funding of this project was provided by the Canadian Foundation of Climate Atmospheric Sciences to B. F. C., P. R. L. and T. D. We thank Cortney Ebel and Melissa Moos for assistance in the field work, Isabelle Malcolm and Estaban Estrada-Mora for laboratory assistance and Jackie Cockburn for assistance in the matching of core sections. Additional funding for manuscript preparation was provided by the Canada Research Chair program to P. R. L.

References

Alley RB, Marotzke J, Nordhasu WD *et al*. (2003) Abrupt climate change. *Science*, **299**, 2005–2010.

Baker RG, Bettis EA III, Denniston RF, Gonzalez LA, Strickland LE, Krieg JR (2002) Holocene paleoenvironments in southeastern Minnesota – chasing the prairie-forest ecotone. *Palaeogeography Palaeoclimatology Palaeoecology*, **177**, 103–122.

Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, **438**, 303–309.

Bennett KD (1996) Determination of the number of zones in a biostratigraphical sequence. *New Phytologist*, **132**, 155–170.

Bond G, Kromer B, Beer J *et al*. (2001) Persistent solar influence on north Atlantic climate during the Holocene. *Science*, **294**, 2130–2136.

Bonsal BR, Chakravarti AK, Lawford RG (1993) Teleconnections between North Pacific SST anomalies and growing season extended dry spells on the Canadian Prairies. *International Journal of Climatology*, **13**, 865–878.

Booth RK, Notaro M, Jackson ST, Kutzbach JE (2006) Widespread drought episodes in the western Great Lakes region during the past 2000 years: geographic extent and potential mechanisms. *Earth and Planetary Science Letters*, **242**, 415–427.

Bradbury JP, Dean WE, Anderson RY (1993) Holocene climatic and limnologic history of the north-central United States as recorded in the varved sediments of Elk Lake, Minnesota: a synthesis. In: *Elk Lake, Minnesota: Evidence for Rapid Climate Change in North-Central United States* (eds Bradbury JP, Dean WE), pp. 309–328. Geological Society of America, Boulder, CO, Special paper 276.

Bryson RA, Hare FL (1974) *The Climates of North America Vol. II. World Survey of Climate*. Elsevier, Amsterdam.

Canadian Climate Normals (1971–2000) Environment Canada. http://climate.weatheroffice.ec.gc.ca/climate_normals/

Canadian National Committee for the International Decade (1978) *Hydrologic Atlas of Canada*. Fisheries and Environment Canada, Ottawa.

Cook ER, Woodhouse CA, Eakin CM, Meko DM, Stahle DW (2004) Long-term aridity changes in the western United States. *Science*, **306**, 1015–1018.

Cumming BF, Wilson ES, Hall RI, Smol JP (1995) *Diatoms from British Columbia (Canada) Lakes and Their Relationship to Salinity, Nutrients, and Other Limnological Variables. Bibliotheca Diatomologica Band 3*. Gebrüder Bornträger, Berlin.

Cumming BF, Laird KR, Bennett JR, Smol JP, Salomon AK (2002) Persistent millennial-scale shifts in moisture regimes in western Canada during the past six millennia. *Proceedings National Academy of Science*, **99**, 16117–16121.

Dansgaard W, Johnsen SJ, Clausen HB *et al.* (1993) Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature*, **364**, 218–220.

Dean WE, Ahlbrandt TS, Anderson RY, Bradbury JP (1996) Regional aridity in North America during the middle Holocene. *The Holocene*, **6**, 145–155.

deMenocal P (2001) Cultural Responses to Climate change during the late Holocene. *Science*, **292**, 667–673.

Denton GH, Karlen W (1973) Holocene climatic variations: their pattern and possible cause. *Quaternary Research*, **3**, 155–205.

Dey B (1982) Nature and possible causes of droughts on the Canadian prairies – case studies. *Journal of Climatology*, **2**, 233–249.

Donovan JJ, Smith AJ, Panek VA, Engstrom DR, Ito E (2002) Climate-driven hydrologic transients in lake sediment records: calibration of groundwater conditions using 20th Century drought. *Quaternary Science Reviews*, **21**, 605–624.

Edwards TWD, Wolfe BB, MacDonald GM (1996) Influence of changing atmospheric circulation on precipitation ^{18}O-temperature relations in Canada during the Holocene. *Quaternary Research*, **46**, 211–218.

Forman SL, Oglesby R, Webb RS (2001) Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: megadroughts and climate links. *Global and Planetary Change*, **29**, 1–29.

Fritz SC (1996) Paleolimnological records of climatic change in North America. *Limnology and Oceanography*, **41**, 882–889.

Fritz SC, Cumming BF, Gasse F, Laird KR (1999) Diatoms as indicators of hydrologic and climatic change in saline lakes. In: *The Diatoms: Application for the Environmental and Earth Sciences* (eds Stoermer EF, Smol JP), pp. 41–72. University Press, Cambridge.

Fritz SC, Ito E, Zicheng Y, Laird KR, Engstrom DR (2000) Hydrological variation in the northern Great Plains during the last two millennia. *Quaternary Research*, **53**, 175–184.

Gan TY (2000) Reducing vulnerability of water resources of Canadian Prairies to potential droughts and possible climatic warming. *Water Resources Management*, **14**, 111–135.

Glew JR, Smol JP, Last WM (2001) Sediment core collection and extrusion. In: *Tracking Environmental Change Using Lake Sediments Volume 1: Basin Analysis, Coring, and Chronological Techniques* (eds Last WM, Smol JP), pp. 73–105. Kluwer Academic Publishers, Dordrecht.

Grimm EC (1987) Coniss, a Fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences*, **13**, 13–35.

Grimm EC (2001) Trends and palaeoecological problems in the vegetation and climate history of the northern Great Plains, USA. *Proceedings of the Royal Irish Academy*, **101B**, 47–64.

Hallett DJ, Hill LV (2006) Holocene vegetation dynamics, fire history, lake level and climate change in the Kootenay Valley, southeastern British Columbia, Canada. *Journal of Paleolimnology*, **35**, 351–371.

Herrington R, Johnson B, Hunter F (1997) *Responding to Global Climate Change in the Prairies. Canada Country Study: Climate Impacts and Adaptation*, Vol. III. Environment Canada, Ottawa.

Hoerling M, Kumar A (2003) The perfect ocean for drought. *Science*, **299**, 691–694.

Juggins S (2003) *C2 Software for Ecological and Palaeoecological Data Analysis and Visualisation User guide Version 13*. University of Newcastle, Newcastle, UK.

Krammer K, Lange-Bertalot H (1986) Bacillariophyceae. 1: teil: Naviculaceae. In: *Süß*wasserflora von Mitteleuropa, Band 2/1 (eds Ettl H, Gärtner G, Gerloff J, Heynig H, Mollenhauer D), Gustav Fischer Verlag, Stuttgart/New York.

Krammer K, Lange-Bertalot H (1988) Bacillariophyceae. 2: teil: Bacillariaceae, Epithmiaceae, Surirellaceae. In: *Süßwasserflora von Mitteleuropa, Band 2/2* (eds Ettl H, Gärtner G, Gerloff J, Heynig H, Mollenhauer D), Gustav Fischer Verlag, Stuttgart.

Krammer K, Lange-Bertalot H (1991a) Bacillariophyceae. 3: teil: Centrales, Fragilariaceae, Eunotiaceae. In: *Süßwasserflora von Mitteleuropa, Band 2/3* (eds Ettl H, Gärtner G, Gerloff J, Heynig H, Mollenhauer D), Gustav Fischer Verlag, Stuttgart.

Krammer K, Lange-Bertalot H (1991b) Bacillariophyceae. 4: teil: Achnanthaceae. In: *Süßwasserflora von Mitteleuropa, Band 2/4* (eds Ettl H, Gärtner G, Gerloff J, Heynig H, Mollenhauer D), Gustav Fischer Verlag, Stuttgart.

Laird KR, Cumming BF, Wunsam S, Rusak JA, Oglesby RJ, Fritz SC (2003) Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia. *Proceedings of the National Academy of Science*, **100**, 2483–2488.

Laird KR, Fritz SC, Grimm EC, Mueller P (1996a) Century-scale paleoclimatic reconstruction from Moon Lake, a closed-basin lake in the northern Great Plains. *Limnology and Oceanography*, **41**, 890–902.

Laird KR, Fritz SC, Maasch KA, Cumming BF (1996b) Greater drought intensity and frequency before AD 1200 in the Northern Great Plains, USA. *Nature*, **384**, 552–554.

Lemmen DS, Vance R (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. Geological Survey of Canada Bulletin 534* (eds Lemmen DS, Vance RE), pp. 7–22. Natural Resources Canada, Ottawa.

Lemmen DS, Vance R, Wolfe SA, Last WM (1997) Impacts of future climate change in the southern Canadian Prairies: a paleoenvironmental perspective. *Geoscience Canada*, **24**, 121–133.

MacDonald GM, Case RA (2000) Biological evidence of multiple temporal and spatial scales of hydrological variation in the western interior of Canada. *Quaternary International*, **67**, 133–142.

MacDonald GM, Case RA (2005) Variations in the Pacific Decadal Oscillation over the past millennium. *Geophysical Research Letters*, **32**, L08703, doi: 10.1029/2005GL022478.

Mayewski PA, Rohling EE, Stager JC *et al*. (2004) Holocene climate variability. *Quaternary Research*, **62**, 243–255.

McCabe GJ, Palecki MA, Betancourt JL (2004) Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States. *Proceedings of the National Academy of Science*, **101**, 4136–4141.

Menking KM, Anderson RY (2003) Contributions of La Niña and El Niño to middle Holocene drought and late Holocene moisture in the American Southwest. *Geology*, **31**, 937–940.

Microcal™ S (1999). *Origin TM User's Manual*, Microcal Software Inc., Northampton, MA.

Moy CM, Seltzer GO, Rodbell DT, Anderson DM (2002) Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, **420**, 162–165.

National Research Council (2002) *Abrupt Climate Change: Inevitable Surprises*. National Academy Press, Washington, DC.

Oglesby RJ, Erickson DJ (1989) Soil-moisture and the persistence of North-American drought. *Journal of Climate*, **2**, 1362–1380.

Ritchie JC, Harrison SP (1993) Vegetation, lake levels and climate in western Canada during the Holocene. In: *Global Climates Since the Last Glacial Maximum* (eds Wright HE Jr, Kutzbach JE, Webb T III, Ruddiman WF, Street-Perrott FA, Bartlein PJ), pp. 401–414. University of Minnesota Press, Minneapolis, MN.

Sauchyn DJ, Barrow EM, Hopkinson RF, Leavitt PR (2002) Aridity on the Canadian Plains: the pre-settlement record of prairie drought and a forecasts of future aridity and what they mean for the management of soil and water resources. *Géographie Physique et Quaternaire*, **56**, 247–259.

Sauchyn DJ, Stroich J, Beriault A (2003) A paleoclimatic context for the drought of 1999–2001 in the northern Great Plains of North America. *The Geographical Journal*, **169**, 158–167.

Schindler DW, Donahue WF (2006) An impending water crisis in Canada's western prairie provinces. *Proceedings of the National Academy of Science*, **103**, 7210–7216.

Schubert SD, Suarez MJ, Pegion PJ, Koster RD, Bacmeister JT (2004) On the cause of the 1930s Dust Bowl. *Science*, **303**, 1855–1859.

Shabbar A, Skinner W (2004) Summer drought patterns in Canada and the relationship to global sea surface temperatures. *Journal of Climate*, **17**, 2866–2880.

Stone JR, Fritz SC (2006) Multidecadal drought and Holocene climate instability in the Rocky mountains. *Geology*, **34**, 409–412.

Stuart CTL (1999) *Diatom-inferred historic and Holocene climatic changes from a closed-basin saline lake in southern Saskatchewan*. MS thesis, Queen's University, Kingston, ON, 107 pp.

Stuiver M, Reimer PJ, Bard E *et al*. (1998) INTCAL98 radiocarbon age calibration 24 000 – 0 cal BP. *Radiocarbon*, **40**, 1041–1083.

Thompson W III, Bartlein PJ, Harrison SP, Anderson KH (1993) Vegetation, lake levels, and climate in eastern North America for the past 18 000 yr B.P. In: *Global Climates Since the Last Glacial Maximum* (eds Wright HE Jr, Kutzbach JE, Webb T III, Ruddiman WF, Street-Perrott FA, Bartlein PJ), pp. 415–467. University of Minnesota Press, Minneapolis, MN.

Vance RE, Beaudoin AB, Luckman BH (1995) The paleoecological record of 6 ka BP climate in the Canadian prairie provinces. *Géographie Physique et Quaternaire*, **49**, 81–98.

Wilson SE, Cumming BF, Smol JP (1996) Assessing the reliability of salinity inference models from diatom assemblages: an examination of a 219-lake data set from western North America. *Canadian Journal of Fisheries and Aquatic Sciences*, **53**, 1580–1594.

Winter TC, Woo M (1990) Hydrology of lakes and wetlands. In: *Surface Water Hydrology* (eds Wolman MG, Riggs HC), pp. 158–188. Geological Society of America, Boulder, CO.

Wolfe SA, Ollerhead J, Huntley DJ, Lian OB (2006) Holocene dune activity and environmental change in the prairie parkland and boreal forest, central Saskatchewan, Canada. *The Holocene*, **16**, 17–29.

Woodhouse CA (2004) A paleo perspective on hydroclimatic variability in the western United States. *Aquatic Sciences*, **66**, 346–356.

Wright HE Jr, Stefanova I, Tian J, Brown TA, Hu FS (2004) A chronological framework for the Holocene vegetational history of central Minnesota: the Steel Lake pollen record. *Quaternary Science Reviews*, **23**, 611–626.

Yu Z, McAndrews JH, Eicher U (1997) Middle Holocene dry climate caused by change in atmospheric circulation patterns: evidence from lake levels and stable isotopes. *Geology*, **25**, 251–254.