

# Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia

Kathleen R. Laird\*, Brian F. Cumming\*†, Sybille Wunsam\*§, James A. Rusak\*¶, Robert J. Oglesby||, Sherilyn C. Fritz\*\*, and Peter R. Leavitt‡

\*Paleoecological Environmental Assessment and Research Laboratory, Department of Biology, Queen's University, Kingston, ON, Canada K7L 3N6;

‡Limnology Laboratory, Department of Biology, University of Regina, Regina, SK, Canada S4S 0A2; ¶National Space Science and Technology

Center, Marshall Space Flight Center, National Aeronautics and Space Administration, 320 Sparkman Drive, Huntsville, AL 35805; and

\*\*Department of Geosciences, University of Nebraska, Lincoln, NE 68588

Communicated by H. E. Wright, Jr., University of Minnesota, Minneapolis, MN, January 10, 2003 (received for review May 14, 2002)

Six high-resolution climatic reconstructions, based on diatom analyses from lake sediment cores from the northern prairies of North America, show that shifts in drought conditions on decadal through multicentennial scales have prevailed in this region for at least the last two millennia. The predominant broad-scale pattern seen at all sites is a major shift in moisture regimes from wet to dry, or vice versa (depending on location), that occurred after a period of relative stability. These large-scale shifts at the different sites exhibit spatial coherence at regional scales. The three Canadian sites record this abrupt shift between *anno Domini* 500 and 800, and subsequently conditions become increasingly variable. All three U.S. sites underwent a pronounced change, but the timing of this change is between *anno Domini* 1000 and 1300, thus later than in all of the Canadian sites. The mechanisms behind these patterns are poorly understood, but they are likely related to changes in the shape and location of the jet stream and associated storm tracks. If the patterns seen at these sites are representative of the region, this observed pattern can have huge implications for future water availability in this region.

Drought is a recurring natural feature of climate that has had dramatic environmental, economic, and social impacts on modern (1) and ancient (2) civilizations. Decade- to century-scale episodes of prolonged drought or high rainfall have been recorded from North America in continental archives as diverse as tree rings (3), tree stumps (4), lake sediments (5), and river deposits (6, 7). The prairie region of North America is particularly susceptible to extreme droughts (8). However, few high-resolution proxy records of climate exist from the prairies. Tree-ring records on the prairies typically are spatially limited to wooded areas at the periphery of the prairies (9) and temporally limited to, at best,  $\approx 500$  years (10). Sediments from closed-basin lakes can provide high-temporal-resolution paleoclimatic information from prairie regions for much longer periods.

Here we provide evidence from high-resolution (subdecadal to decadal) sediment core records from six lakes on the Canadian and northern U.S. prairies (Fig. 1). All of the sites indicate that shifts in drought regimes have been a prevalent feature of this region, occurring on decadal through multicentennial scales. Inferred changes in climatic conditions over the past two millennia are based on analysis of diatom assemblages preserved in sediment cores, a commonly used technique for tracking past climatic conditions (11). Our focus here is on long-term dynamics and broad-scale similarities among the lake records. This approach is in part undertaken because of the inherent difficulties of comparing short-term dynamics across records constrained by carbon-dated chronologies.

## Materials and Methods

**Diatom Inferences.** Diatom remains in sediment cores from six lakes were used to reconstruct variables influenced by climatic

conditions. Diatom-inferred salinity estimates were used in five lakes to reconstruct relative changes in effective moisture [ $E/P$ , the balance between precipitation ( $P$ ) and evaporation ( $E$ )], with high salinity implying high  $E/P$  (12). Diatoms are common algae of inland saline and freshwater lakes, and their taxonomic distribution is highly related to lakewater salinity (13, 14). Statistical models developed from the contemporary distribution of diatom taxa in various regions of the world (reviewed in ref. 12) have been used successfully to estimate past lakewater salinity from diatom assemblages preserved in well-dated sediment cores (5, 15, 16). The predictive ability of diatom-based salinity-inference models, as judged from the relationship between inferred and observed salinity in a suite of modern lakes, is strong and highly significant (bootstrapped  $r^2 = 0.8\text{--}0.9$ ,  $P < 0.01$ ; ref. 12). To infer past lakewater salinity in this study, we developed a modern-day calibration set of 287 lakes, consisting of 79 lakes from the prairie region (ref. 14; S.C.F., unpublished data) and 208 lakes from British Columbia (13). The resultant predictive model to infer salinity was as strong as earlier models, but the larger number of lakes (and taxa) on which this model was based allowed an expanded set of appropriate analogs for reconstructing salinity from the diatom assemblages encountered in the cores.

Total phosphorus (TP) was inferred from diatoms in a sediment core from Elk Lake, because changes in phosphorus were the dominant signal in the diatom assemblages. In Elk Lake, TP levels are driven largely by the degree of water-column mixing and stratification as related to general climatic conditions (17). Thus TP estimates at Elk Lake can provide a sensitive proxy for climate. Diatoms are highly influenced by TP levels, which can be reconstructed by using inference models (reviewed in ref. 18).

Correspondence analysis, which indicates the main direction of variation in multivariate data, such as diatom assemblages in a core, was undertaken for each of the six sites to ensure that our inferences tracked the major changes in the diatom assemblages. Correspondence analysis axis-one scores for four of the lakes were strongly correlated with inferred log-salinity estimates ( $r = 0.67\text{--}0.94$ ,  $P < 0.01$ ), and for Elk Lake, with log TP ( $r = 0.90$ ,  $P < 0.01$ ). For Nora Lake, inferred salinity was strongly related to axis-two scores ( $r = 0.87$ ,  $P < 0.01$ ). These strong correlations confirm that our diatom-based salinity or TP inferences are a good summary and simplification of the changes in the diatom assemblages from the cores.

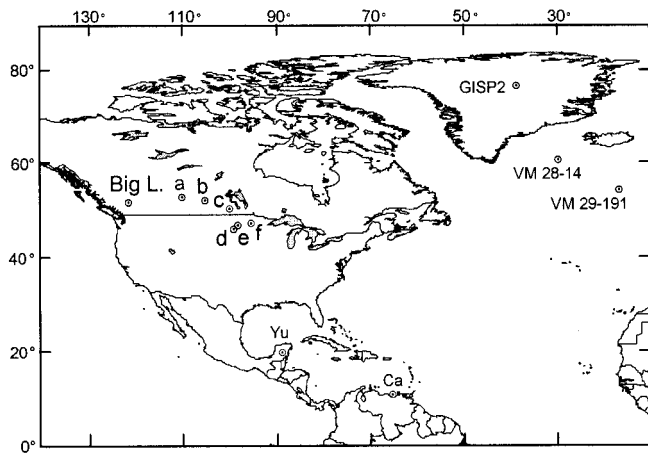
To provide an estimate of the major stratigraphic changes in

Abbreviations: TP, total phosphorus; *ca.*, circa; A.D., *anno Domini*.

†To whom correspondence should be addressed. E-mail: cummingb@biology.queensu.ca.

§Present address: 11437 76 Avenue, Edmonton, AB, Canada T6G 0K5.

¶Present address: Center for Limnology, University of Wisconsin, Madison, WI 54512.

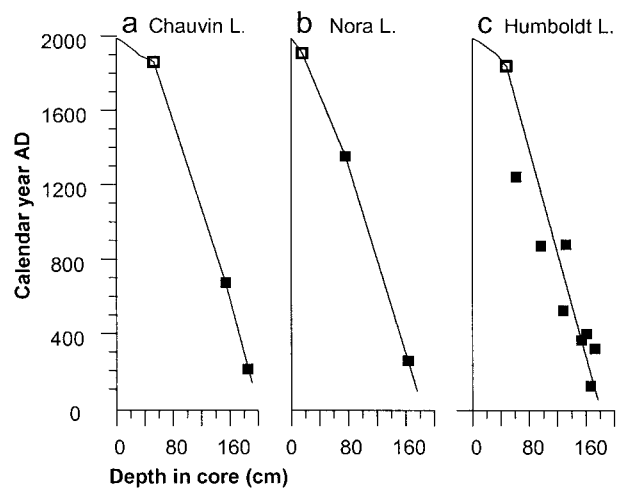


**Fig. 1.** Location of the North American prairie sites (lakes: a, Chauvin; b, Humboldt; c, Nora; d, Coldwater; e, Moon; and f, Elk) and other key sites (Big L., Big Lake, British Columbia; Yu, Lake Chichancanab, Yucatan Peninsula; Ca, Cariaco Basin; GISP2, Greenland Ice Sheet Project 2, Summit Greenland ice core; and VM 28-14 and VM 29-191, North Atlantic marine cores) cited in the text.

diatom assemblages in the cores from each site, we performed a constrained cluster analysis on the diatom assemblages, with a chord distance as the measure of dissimilarity, using the program *TILIA v. 1.16* (19). The significance and robustness of the major zones produced by the constrained cluster analysis (19) was examined by comparison with both binary and optimal splitting zonation methods (20) by using *PSIMPOLL v. 4.10*. In all records, the primary splits were virtually identical to those from the constrained cluster analyses. However, here we use the preferred method of defining the zones based on the technique of optimal splitting by information content (20), using the highest variance reduction as a percent of the total variance to define the major zones. This approach was taken to focus on long-term dynamics (centennial and millennial), as opposed to the highly variable (both spatially and temporally) shorter-term decadal dynamics. In all cases this resulted in two zones, with the exception of Chauvin and Humboldt lakes, which produced three zones. In the case of the Humboldt Lake record, the most recent diatom assemblage [circa (*ca.*) *anno Domini* (A.D.) 1950] was the most distinct; however, this assemblage is caused by recent eutrophication from urban inputs (P.R.L., unpublished data) and thus is not discussed further here.

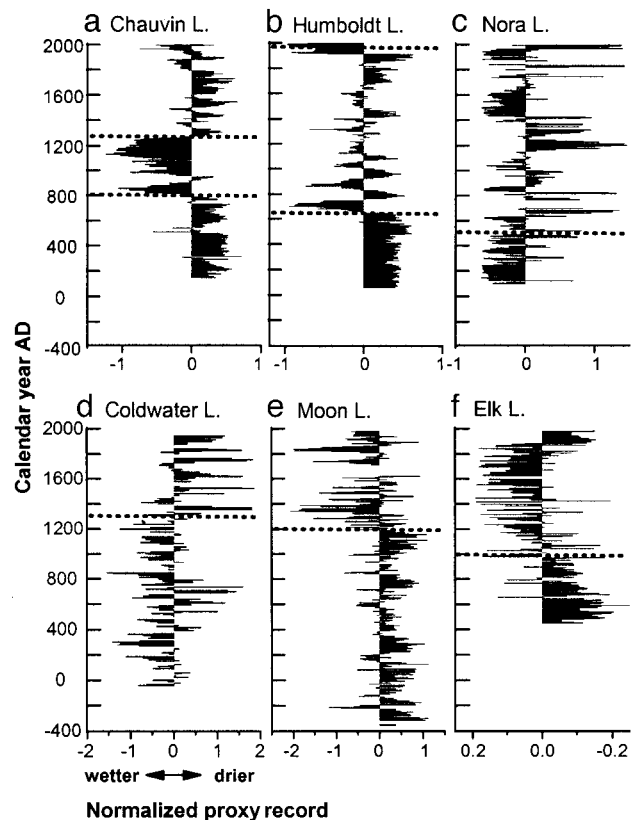
**Lake Sensitivity to Climate.** Climatic influences on lakes can be complex, with a lake's response, both in magnitude and timing, depending on the morphology of the lake and its geological and hydrological setting (11, 12). The hydrological budget of prairie lakes is dominated by precipitation and evaporation; however, groundwater interactions can significantly influence lake chemistry (21) and thus the biota of the lake. Because of these complexities, careful site selection is of utmost importance in establishing an interpretable record of past climatic change (11, 22).

All six prairie sites presented here were selected carefully because of evidence of strong linkages between lake chemistry and the historical climate record. The three Canadian lakes are located at the edge of the short-grass prairie, a region sensitive to climatic change near the northern edge of the summertime ridge of high pressure that influences the position of the jet stream and associated storm tracks. The sensitivity of all of the Canadian prairie lakes to climatic changes has been demonstrated through examination of instrumental records, aerial photographs, and data on agricultural production (P.R.L., un-

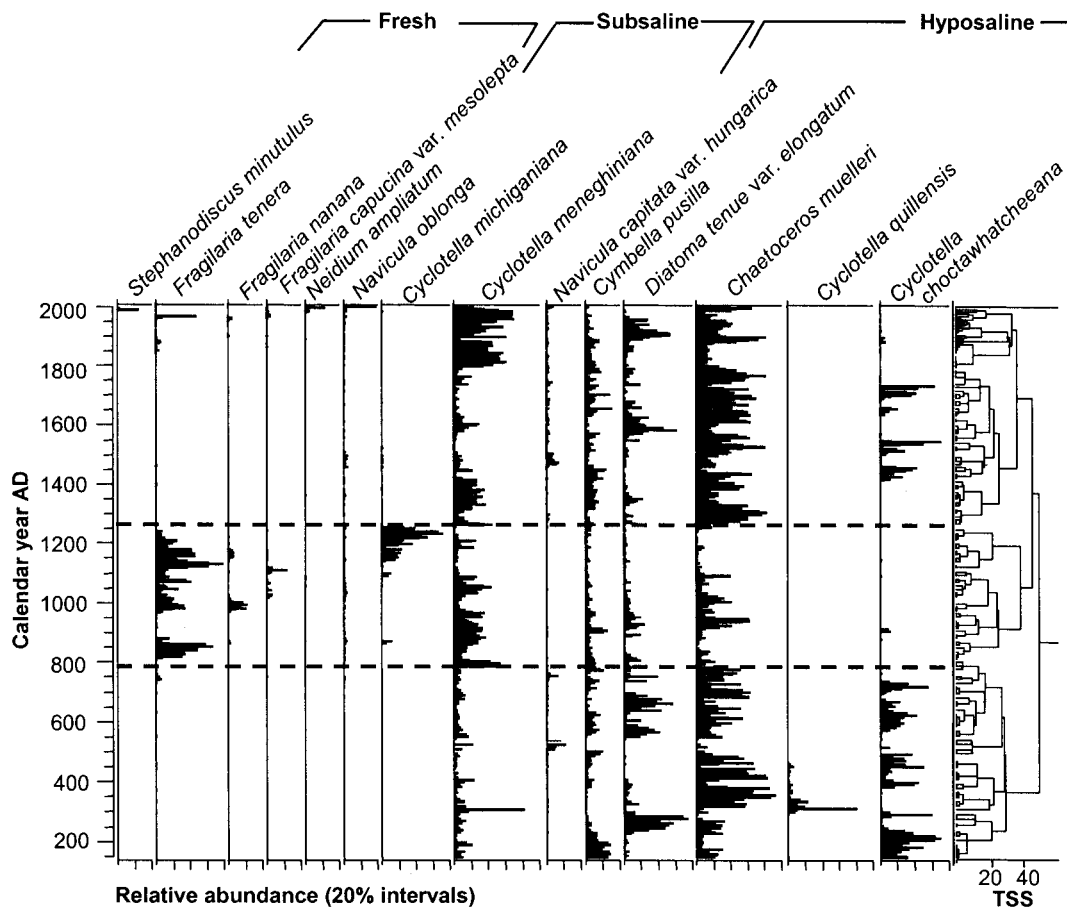


**Fig. 2.** Age models (solid lines) for Chauvin (a), Nora (b) and Humboldt lakes (c). ■, Radiocarbon-dated levels; □, Dates from the bottom of  $^{210}\text{Pb}$  profiles. Chronologies for Moon, Coldwater, and Elk lakes can be found in refs. 15, 25, and 26, respectively.

published data). During the 20th century, measured climatic variables explained large and statistically significant variation in the fossil diatom assemblages in dated sediment cores



**Fig. 3.** Normalized records of climatic change over time, as deviation from the mean log salinity (mean TP for f), for the six diatom-based climate-proxy records. Records are plotted from west to east, with the Canadian sites (a–c) on top and the U.S. sites (d–f) below. Sites are labeled as in Fig. 1 (sites a–f). All records are plotted on calendar year A.D. chronology. The dashed line(s) across each record represents the main zonation(s) of the diatom assemblages in each site as defined from optimal zonation. See *Materials and Methods* for details.



**Fig. 4.** Dominant diatom taxa (>20%) for Chauvin Lake, Alberta, ordered according to increasing salinity optima. Groupings are based on the following optima: Fresh (<0.5 g/liter), Subsaline (0.5–3 g/liter), and Hyposaline (3–20 g/liter). Results of the depth-constrained cluster analysis are shown on the far right. The primary zones defined by optimal zonation are indicated by the dashed lines, which separate the more saline taxa from the less saline taxa. The split ca. A.D. 800 is the primary split, whereas the split ca. A.D. 1300 is the secondary split. See *Materials and Methods* for details. TSS, total sum of squares.

(P.R.L., unpublished data). For Moon Lake, the sensitivity was assessed through high-resolution diatom analyses of recent sediments, which were compared with an instrumentally based drought index ( $r = 0.49$ ,  $P < 0.01$ ; ref. 15). Ice-out data, sediment-trap data, and corresponding diatom data from Elk Lake suggest that the sediment record tracks climatic changes (23). The sensitivity of Coldwater Lake is documented by aerial photographs spanning wet versus dry periods in the 20th century and by instrumental measurements of lake chemistry (24).

**Coring and Chronology.** Sediment cores from the three Canadian prairie lakes were collected during the summers of 1998 and 1999 by using a gravity corer for near surface sediments and a piston corer to collect an overlapping continuous 2-m section. These cores were sectioned into 0.25-cm intervals. Details of coring and chronology for Moon, Coldwater, and Elk lakes can be found in refs. 15, 25, and 26, respectively.

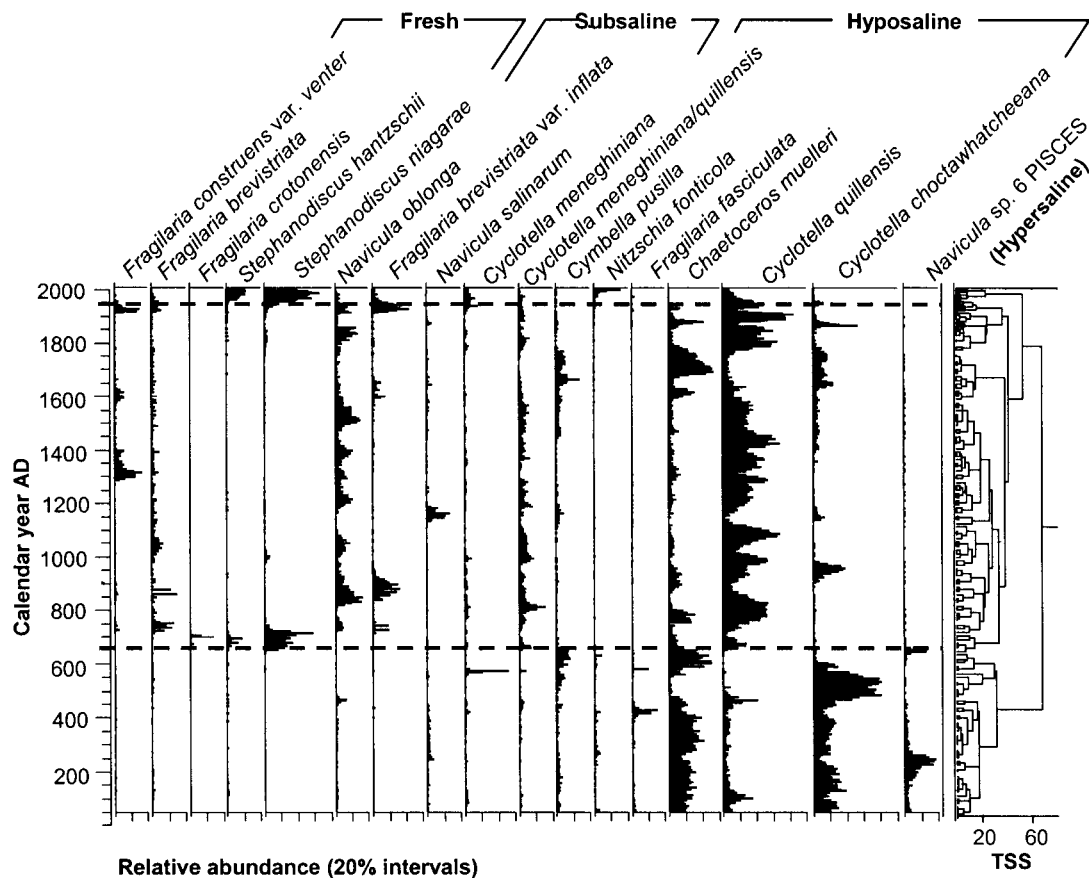
For all sites, sediment chronologies are based on  $^{210}\text{Pb}$  dating for the recent sediments and on linear interpolation or, at one site, linear regression between accelerator mass spectrometry radiocarbon dates for older sediments, except at Elk Lake, where annual (varved) layers were used (26). The average temporal resolution of diatom analyses ranged from 5 to 6 years, except for Coldwater Lake (25), which has an average resolution of 10 years. Radiocarbon ages were calibrated to calendar years A.D. with the programs CALIB 3.0 (27) for Moon and Coldwater lakes and CALIB 4.0 (28) for the three Canadian sites. For all of the

Canadian sites, the midpoints of the 95.5% confidence interval of the calendar dates were used as anchors in the development of the age/depth models. The age models for Chauvin and Nora lakes are based on linear interpolation between bottom  $^{210}\text{Pb}$  dates and two radiocarbon dates (Fig. 2 *a* and *b*). In Humboldt Lake, a linear regression through eight radiocarbon dates, anchored to the bottom  $^{210}\text{Pb}$  date at A.D. 1850, was used to construct an age model (Fig. 2*c*).

## Results

The dominant broad-scale pattern over the past two millennia at all sites is a large and abrupt change in inferred climatic conditions, between A.D. 500 and 800 at the Canadian sites (Fig. 3 *a–c*) and between A.D. 1000 and 1300 at the U.S. sites (Fig. 3 *d–f*). This major shift was from wet to dry conditions, or vice versa, and occurred after a period of inferred stable climatic conditions. As outlined in *Materials and Methods*, these large shifts were defined based on individual cluster and zonation analyses of the diatom assemblages in each core (shown for the Canadian sites in Figs. 4–6). Higher frequency changes also are present in the lake records, which may be the result of high climatic variability or more local catchment factors, such as groundwater interactions and terrestrial processes.

All Canadian sites exhibit relatively stable diatom assemblages (Figs. 4, 5, and 6) and inferred climatic stability (Fig. 3 *a–c*) for 400 to 500 years before approximately A.D. 500–800. Consistent with modern meteorological patterns, the two western prairie

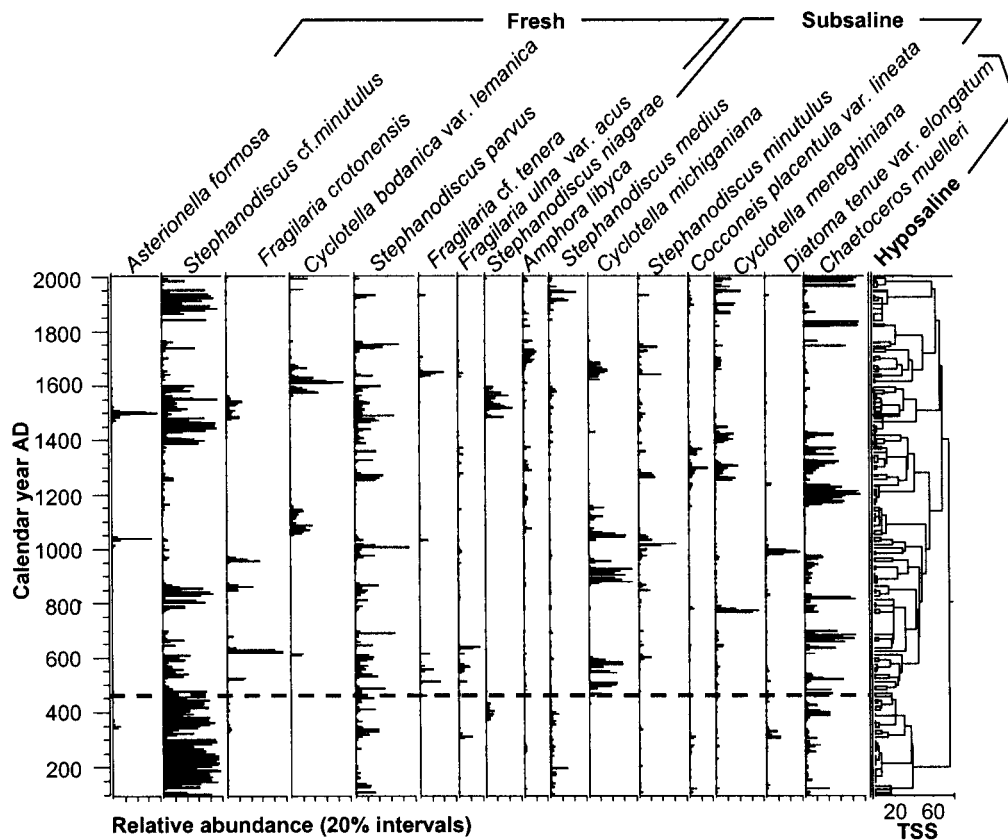


**Fig. 5.** Dominant diatom taxa (>20%) for Humboldt Lake, Saskatchewan, ordered according to increasing salinity optima. Groupings are based on the following optima: Fresh (<math><0.5\text{ g/liter}</math>), Subsaline (<math>0.5\text{--}3\text{ g/liter}</math>), Hyposaline (<math>3\text{--}20\text{ g/liter}</math>), and Hypersaline (><math>50\text{ g/liter}</math>). Results of the depth-constrained cluster analysis are shown on the far right. The recent anthropogenic eutrophication is indicated by the dashed line at A.D. 1950. The primary zones defined by optimal zonation are shown by the dashed line at A.D. 670, which separates the more saline taxa (below line) from the less saline taxa (above line). See *Materials and Methods* for details. TSS, total sum of squares.

sites (Fig. 1, sites a and b) were predominantly arid before approximately A.D. 700–800 (Fig. 3 a and b), whereas the easternmost Canadian site (Fig. 1, site c) was humid (Fig. 3c). Before approximately A.D. 700–800, the diatom floras in the two western prairie sites were dominated by hypo- to hypersaline taxa such as *Cyclotella choctawhatcheeana* Prasad, *Chaetoceros muelleri* Lemmermann, and other saline taxa that were unique to this period (Figs. 4 and 5). After A.D. 700–800, pronounced changes in many subsaline and freshwater diatom taxa suggest that limnological conditions became distinctly different (Figs. 4 and 5). Freshwater taxa appear or increase dramatically in abundance, and some saline taxa disappear (e.g., *Cyclotella quillensis* Bailey in Chauvin Lake and *Navicula* sp. 6 PISCES in Humboldt Lake) or become less dominant and persistent (e.g., *C. choctawhatcheeana* in both lakes). The diatom flora (Fig. 6) of the easternmost Canadian site before approximately A.D. 500 had a sustained predominance of the freshwater taxon *Stephanodiscus* cf. *minutus*. After approximately A.D. 500, many subsaline and hyposaline taxa increase in abundance, including the hyposaline taxon *C. muelleri*.

After A.D. 500–800, the inferred climatic conditions seem much more complex and variable among the Canadian sites (Fig. 3 a–c). The westernmost site (Fig. 3a) exhibits a distinct multi-centennial pattern (note the three zones), with predominantly wetter conditions from A.D. 800–1200 and relatively drier conditions after A.D. 1200. The other Canadian sites (Fig. 3 b and c) exhibit more high-frequency variability between wet and dry conditions after the switch at A.D. 500–700.

All northern U.S. sites (Fig. 3 d–f) show clear shifts in limnological state ca. A.D. 1000–1300. Moon Lake (Fig. 3e; refs. 5 and 15) and Elk Lake (Fig. 3f; ref. 17) records suggest that this change is from drier to wetter conditions. In Moon Lake, the distinct salinity shift is indicated by both the appearance and dramatic increase of several freshwater taxa (15). At Elk Lake, a shift to higher TP levels is indicated by a prolonged increase in the dominance of the eutrophic planktonic diatom *S. minutulus* ca. A.D. 1000, as well as a decrease in *Cyclotella bodanica* Grun. in Schneider by A.D. 1100, which is more abundant under lower TP conditions (17). Sustained higher levels of phosphorus likely result from vigorous and prolonged water-column mixing during cool, stormy climatic conditions, whereas lower TP values occur under warmer and calmer conditions, which promote lake stratification (17). The shifts ca. A.D. 1200–1300 at the two North Dakota sites (Fig. 3 d and e) are distinct but opposite in sign. The dominance of freshwater diatom taxa in Coldwater Lake (Fig. 1, site d) declines relative to more saline taxa after approximately A.D. 1300 (25). The differences between Moon and Coldwater lakes are potentially caused by markedly different lake morphometries and varying groundwater sources (22). The short periods of high salinity between A.D. 400 and 800 in Coldwater Lake, caused by intermittent dominance of the saline taxon *Chaetoceros elmorei*, suggest some temporal linkages to the Canadian sites. However, this interval in Coldwater Lake is distinguished in the third and fourth zonation, which has a much lower variance reduction associated with it and is not charac-



**Fig. 6.** Dominant diatom taxa (>20%) for Nora Lake, Manitoba, ordered according to increasing salinity optima. Groupings are based on the following optima: Fresh (<math>< 0.5\text{ g/liter}</math>), Subsaline (0.5–3 g/liter), and Hyposaline (3–20 g/liter). Results of the depth-constrained cluster analysis are shown on the far right. The primary zones defined by optimal zonation are indicated by the dashed lines, which separate the less saline taxa (below line) from the more saline taxa (above line). See *Materials and Methods* for details. TSS, total sum of squares.

terized by a sustained dominance of saline taxa, as at the Canadian sites.

### Discussion

The synthesis of multiple sites in the prairie region shows that droughts of varying intensity and frequency have been common in this region for at least the last two millennia. Other proxy records from the northern U.S. prairies suggest that century-scale cycles in aridity have been a dominant feature of Late Holocene climate (29, 30) and that drought cyclicality may be related to solar variability (31). Perhaps more importantly, this study shows that large-scale multicentennial shifts in mean climatic conditions seem to exhibit regional coherency. Major shifts in climate occurred between A.D. 500 and 800 in the Canadian prairies and between A.D. 1000 and 1300 in the northern U.S. prairies after centuries of relative stability. These regional differences have not been documented extensively in the literature. Some sites in the Northern Hemisphere show a timed change in climate similar to that of the Canadian prairie sites. For example, diatom inferences from British Columbia (western Canada) show a distinct shift to drier conditions and lower water levels *ca.* A.D. 700 (32). In addition, this shift corresponds closely to a sharp decline in ice-rafting debris in the North Atlantic *ca.* A.D. 600 (VM 28-14 and VM 29-191 Fig. 1; ref. 33), a coincident increase in sea-surface temperature in the Sargasso Sea (34), and a prominent increase in sea-salt Na in the Greenland ice core record (Fig. 1), which was interpreted as an indicator of storminess (35).

Distinct patterns of abrupt change in the Northern Hemisphere are common at or near the termination of the Medieval

Warm Period (*ca.* A.D. 800–1300) and the onset of the Little Ice Age (*ca.* A.D. 1300–1850). Droughts decreased at A.D. 1100 on the Yucatan Peninsula (Fig. 1; ref. 36), and, in the Cariaco Basin (Fig. 1), high but variable precipitation during the Medieval Warm Period changed sharply to decreased precipitation during the Little Ice Age (37). In Greenland, the onset of the Little Ice Age in the Greenland Ice Sheet Project 2 (GISP2) ice core (Fig. 1) is recorded as the most abrupt increase in sea salt and terrestrial dust during the Holocene and is hypothesized to be caused by the expansion of the polar vortex (35). Recent evidence from tree-ring analyses across the Northern Hemisphere indicates a shift to cooler conditions *ca.* A.D. 1200 (38). Together, these patterns suggest that some large-scale climatic shifts may be a common phenomenon, which may reoccur over longer time frames. For example, millennial-scale shifts over at least the past 5,500 years, between sustained periods of wetter and drier conditions, occurring approximately every 1,220 years, have been reported from western Canada (32). The striking correspondence of these shifts to large changes in fire frequencies, inferred from two sites several hundreds of kilometers to the southwest in the mountain hemlock zone of southern British Columbia (39), suggests that these millennial-scale dynamics are linked and operate over wide spatial scales.

The differences in timing of moisture shifts among these prairie sites may relate to fluctuations in the position and shape of the jet stream. All of the prairie sites are in locations that have summertime maxima in precipitation, because thunderstorms tap into moist air from the south (most often from the Gulf of Mexico). A cloudy, rainy summer also would likely have reduced evaporation, further increasing effective precipitation. The cen-

tral U.S. and southern central Canada are predominantly under a high-pressure ridge in summer, which can block precipitation from the south. Consequently, small changes in the shape and location of this ridge can have a profound impact on the spatial patterns of precipitation and drought (40, 41). The Canadian prairie sites fall near the northern edge of this ridge and are therefore susceptible to small fluctuations in its location, as shown by the high variability in the observed yearly and monthly historic rainfall totals. These fluctuations can be north–south or east–west as the center of the ridge shifts position (40), which may explain the differences in timing of the major shift in conditions among the Canadian and U.S. sites. Given the apparent spatial and temporal complexities of drought in the northern prairie region of North America, generalizations based on three sites in each region are difficult to make. As a consequence, further research is necessary to better understand the long-term dynamics of climate in this region. This understanding is particularly important because of the agricultural basis of this region and its susceptibility to extreme droughts. If the patterns seen at these few sites represent long-term dynamics

in prairie climate, they can have huge implications toward future water availability in this region.

## Conclusions

Abrupt changes in climatic conditions from the semiarid prairie region in northern North America indicate that shifts in drought regimes on a multicentennial scale are a common feature of this region. Regardless of the exact timing of these shifts or the direction of these changes, the persistent and abrupt nature of these events represents a scale of variation that is not well understood. Such shifts today would prove a major challenge for society regardless of global warming (42), particularly given that persistent periods of drought have been shown in numerous cases to coincide with societal stress and collapse (2).

We thank O. Olsen for the diatom counting of Humboldt Lake and Mark Brenner and an anonymous reviewer for constructive comments. Radiocarbon analyses were carried out at Lawrence Livermore National Laboratory at the University of California and at Isotracer Laboratory at the University of Toronto. This study was supported by a strategic grant from the Natural Sciences and Engineering Research Council of Canada (to P.R.L.).

1. Wheaton, E. E., Arthur, L. M., Chorney, B., Shewchuk, S., Thorpe, J., Whiting, J. & Wittrock, V. (1992) *Climatol. Bull.* **26**, 188–205.
2. deMenocal, P. B. (2001) *Science* **292**, 667–673.
3. Hughes, M. K. & Brown, M. (1992) *Clim. Dyn.* **6**, 161–167.
4. Stine, S. (1994) *Nature* **369**, 546–549.
5. Laird, K. R., Fritz, S. C., Maasch, K. A. & Cumming, B. F. (1996) *Nature* **384**, 552–554.
6. Ely, L. L., Enzel, Y., Baker, V. R. & Cayan, D. R. (1993) *Science* **262**, 410–412.
7. Knox, J. C. (2000) *Quat. Sci. Rev.* **19**, 439–457.
8. Karl, T. R. (1983) *J. Clim. Appl. Meteorol.* **22**, 1356–1366.
9. Cook, E. R., Meko, D. M., Stahle, D. W. & Cleaveland, M. K. (1999) *J. Clim.* **12**, 1145–1162.
10. Case, R. C. & MacDonald, G. M. (1995) *Quat. Res.* **44**, 267–275.
11. Smol, J. P. & Cumming, B. F. (2000) *J. Phycol.* **36**, 986–1011.
12. Fritz, S. C., Cumming, B. F., Gasse, F. & Laird, K. R. (1999) in *The Diatoms: Applications for the Environmental and Earth Sciences*, eds. Stoermer, E. & Smol, J. P. (Cambridge Univ. Press, Cambridge, U.K.), pp. 41–72.
13. Wilson, S. E., Cumming, B. F. & Smol, J. P. (1996) *Can. J. Fish. Aquat. Sci.* **53**, 1580–1594.
14. Fritz, S. C., Juggins, S. & Battarbee, R. W. (1993) *Can. J. Fish. Aquat. Sci.* **50**, 1844–1856.
15. Laird, K. R., Fritz, S. C. & Cumming, B. F. (1998) *J. Paleolimnol.* **19**, 161–179.
16. Bennett, J. R., Cumming, B. F., Leavitt, P. R., Chiu, M., Smol, J. P. & Szeicz, J. (2001) *Quat. Res.* **55**, 332–343.
17. Bradbury, J. P., Cumming, B. F. & Laird, K. R. (2002) *J. Paleolimnol.* **27**, 321–340.
18. Hall, R. I. & Smol, J. P. (1999) in *The Diatoms: Applications for the Environmental and Earth Sciences*, eds. Stoermer, E. & Smol, J. P. (Cambridge Univ. Press, Cambridge, U.K.), pp. 128–168.
19. Grimm, E. C. (1987) *Comput. Geosci.* **13**, 13–35.
20. Bennett, K. D. (1996) *New Phytol.* **132**, 155–170.
21. Winter, T. C. & Woo, M. (1990) in *The Geology of North America, Surface Water Hydrology*, eds. Wolman, M. G. & Riggs, H. C. (Geol. Soc. Am.), Vol. 0–1, pp. 158–187.
22. Fritz, S. C. (1996) *Limnol. Oceanogr.* **41**, 882–889.
23. Bradbury, J. P. (1988) *J. Paleolimnol.* **1**, 115–131.
24. Jovanelly, T. J. (2001) M. Sc. thesis (Univ. of Nebraska, Lincoln).
25. Fritz, S. C., Ito, E., Yu, Z., Laird, K. R. & Engstrom, D. R. (2000) *Quat. Res.* **53**, 175–184.
26. Dean, W. E., Anderson, R. Y., Bradbury, J. P. & Anderson, D. M. (2002) *J. Paleolimnol.* **27**, 287–299.
27. Stuiver, M. & Reimer, P. (1993) *Radiocarbon* **35**, 215–230.
28. Stuiver, M., Reimer, P., Bard, E., Beck, J. W., Burr, G. S., Hughen, K. A., Kromer, B., McCormac, G., van der Plicht, J. & Spurk, M. (1998) *Radiocarbon* **40**, 1041–1083.
29. Dean, W. E. & Schwab, A. (2000) *Quat. Int.* **67**, 5–20.
30. Yu, Z., Ito, E., Engstrom, D. R. & Fritz, S. C. (2002) *The Holocene* **12**, 605–617.
31. Yu, Z. & Ito, E. (1999) *Geology* **27**, 263–266.
32. Cumming, B. F., Laird, K. R., Bennett, J. R., Smol, J. P. & Salomon, A. K. (2002) *Proc. Natl. Acad. Sci. USA* **99**, 16117–16121.
33. Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I. & Bonani, G. (2001) *Nature* **411**, 2130–2136.
34. Keigwin, L. D. (1996) *Science* **274**, 1504–1508.
35. O'Brien, S. R., Mayewski, P. A., Meeker, L. D., Meese, D. A., Twickler, M. S. & Whitlow, S. I. (1995) *Science* **270**, 1962–1964.
36. Hodell, D. A., Brenner, M., Curtis, J. H. & Guilderson, T. (2001) *Science* **292**, 1367–1370.
37. Haug, G. H., Hughen, K. A., Sigman, D. M., Peterson, L. C. & Röhl, U. (2001) *Science* **293**, 1304–1308.
38. Esper, J., Cook, E. R. & Schweingruber, F. H. (2002) *Science* **295**, 2250–2253.
39. Hallett, D. J., Lepofsky, D. S., Mathewes, R. W. & Lertzman, K. P. (2003) *Can. J. For. Res.* **33**, 292–312.
40. Oglesby, R. J. & Erickson, D. (1989) *J. Clim.* **2**, 1362–1380.
41. Oglesby, R. J., Marshall, S., Roads, J. O. & Robertson, F. R. (2001) *J. Geophys. Res. Atmos.* **106** (D4), 3357–3369.
42. Overpeck, J. & Webb, R. (2000) *Proc. Natl. Acad. Sci. USA* **97**, 1335–1338.