Persistent millennial-scale shifts in moisture regimes in western Canada during the past six millennia

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Inferences of past climatic conditions from a sedimentary record from Big Lake, British Columbia, Canada, over the past 5,500 years show strong millennial-scale patterns, which oscillate between periods of wet and drier climatic conditions. Higher frequency decadal- to centennial-scale fluctuations also occur within the dominant millennial-scale patterns. These changes in climatic conditions are based on estimates of changes in lake depth and salinity inferred from diatom assemblages in a well dated sediment core. After periods of relative stability, abrupt shifts in diatom assemblages and inferred climatic conditions occur approximately every 1,220 years. The correspondence of these shifts to millennial-scale variations in records of glacial expansion/recession and ice-rafting events in the Atlantic suggest that abrupt millennial-scale shifts are important to understanding climatic variability in North America during the mid- to late Holocene. Unfortunately, the spatial patterns and mechanisms behind these large and abrupt swings are poorly understood. Similar abrupt and prolonged changes in climatic conditions today could pose major societal challenges for many regions.

Evidence of millennial-scale fluctuations of climate during the Holocene are well documented in the Greenland ice core (1) and in marine cores from the North (2, 3) and Mid Atlantic (4). The correspondence of temperature inferences from marine cores off the coast of West Africa and ice-rafted debris (IRD) from the North Atlantic suggests that such patterns may be global in nature (4). This recent evidence corroborates Denton and Karlen's (5) controversial suggestion of predictable millennial-scale climate pacing based on worldwide fluctuations in glaciers during the Holocene. This view was not widely accepted initially because many climate proxy records, particularly prominent records from the Greenland ice cores (6), suggested that the Holocene was climatically stable. However, this view of stability was in comparison to the much larger changes observed over glacial–interglacial cycles.

Evidence for millennial-scale shifts during the Holocene outside of the Atlantic region is extremely limited (7). Further, most of this evidence is based on discontinuous records analyzed at a relatively coarse temporal resolution. For example, syntheses of flood records from the U.S. Southwest (8, 9) and the Upper Mississippi Valley (10) suggest that major changes in precipitation regimes have occurred on a millennial scale for at least the past 7,000 years. Millennial-scale fluctuations during the Holocene have been inferred in the Jura and French subalpine regions (11, 12) based on composite records of changes in lake level; however, these records are dominated by large variations at the centennial to multicentennial scales rather than at the millennial. Similarly, the few higher-resolution records from western North America exhibit predominantly decadal to multicentennial variations (13).

Recent focus on the Holocene (1–3) has now shown dramatic shifts in climate that may have global ramifications, especially if they result in changes in water availability on the continents. Abrupt and prolonged changes in climatic conditions are difficult for societies to cope with, particularly if they result in changes in water quality and quantity. Modern civilizations that base water management plans on historical and instrumental data are likely to be in for a surprise. Reliance on such short-term records is now known to be unrepresentative of the natural variations in water availability. This study was undertaken to investigate further the importance of decadal- to millennial-scale variability in climatic conditions during the middle to late Holocene in western Canada.

Here, we present a continuous decadal-scale record of lake depth and salinity from Big Lake, British Columbia, Canada, for the past 5,500 years, a period that has been described as representing modern, stable climatic conditions (14). In contrast to these earlier studies, we find strong evidence for a millennial-scale pacing of change in water availability. Water levels in Big Lake reflect prevailing climatic conditions. In recent times, Big Lake experienced declines in lake level and increases in salinity coincident with the drought of the late 1980s and early 1990s. Patterns of diatom assemblages in a ^{210}Pb-dated sediment core suggest that this lake was sensitive to changes in climate over the period of measured meteorological observations (15).

Previous study on Big Lake inferred changes in postglacial climatic conditions based on diatoms, pollen, phototrophic pigments, biogenic silica, and changes in organic/inorganic carbon (15). Inferred climatic conditions corroborated the broad trends inferred from palynological syntheses from this region, including a xerothermic early Holocene followed by a mesothermic early to middle Holocene. However, in contrast to the palynological syntheses, there were large changes during the late Holocene, suggesting that climate history was much more complex than previously assumed (15). The rationale for this current study was based on the climatic sensitivity and the excellent chronology of the Big Lake record. In contrast to the 200- to 300-year resolution of the entire Holocene analysis (15), this study is based on changes in diatom assemblages at decadal to bidecadal resolution (consecutive 1-cm samples for the uppermost ≈3.7 m, with ≈15 years in each 1-cm interval).

Study Site

Big Lake (51°40.1′N, 121°27′W) is located in a closed basin at an elevation of 1,030 m on the Cariboo Plateau of British Columbia (Fig. 1). It is situated in the interior Douglas fir biogeoclimatic zone, a region consisting of Douglas fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and scattered grasslands (16). Average annual precipitation of the immediate area surrounding Big Lake is ≈400 mm/year (17). Big Lake has a mean depth of 3.2 m, a maximum depth of ≈8 m, and a surface area of 110 hectares (15). The water of this lake is fresh (August 1993 salinity = 370 mg/liter) and consists of an ionic composition dominated by magnesium carbonate.

Methods

A core representing the complete postglacial sedimentary record of Big Lake was removed from a depth of ≈7.5 m in

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Abbreviations: IRD, ice-rafted debris; cal. yrs. BP, calendar years before present; CA, correspondence analysis.

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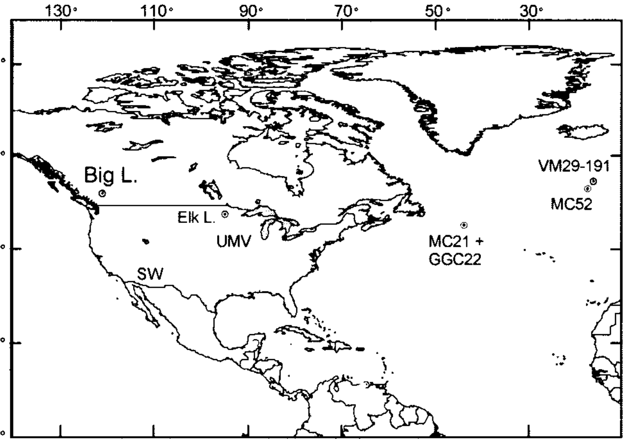

Fig. 1. Location of Big Lake (British Columbia, Canada) and other sites cited in the text. SW, Southwest (8, 9); UMV, Upper Mississippi Valley (10); Elk L., Elk Lake, MN (30); MC52, V29191, MC21, and GGC22, North Atlantic marine cores (2, 3).

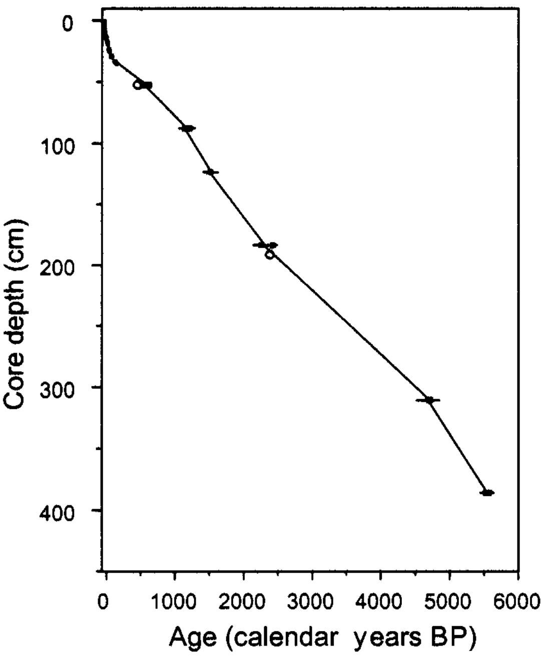

Fig. 2. Age model used for the chronology of Big Lake. Radiocarbon-dated intervals are represented by large filled squares, whereas ^{210}Pb-derived dates are represented by the small filled squares in the first ≈40 cm of the core. Error bars shown on the radiocarbon-dated intervals represent 2δ range of the calibrated dates (20). The open circle at ≈45 cm represents an age estimate based on extrapolating the rate of sedimentation (g dry weight per cm^2) from ^{210}Pb analysis to the level of the first radiocarbon-dated interval; the open circle at ≈200 cm represents the age of the Bridge River tephra (19). Details on the radiocarbon samples can be found in ref. 15.

March 1993. The uppermost 52 cm was retrieved by using a modified Kajak-Brinkhurst (K-B) gravity corer (17) and was sectioned into 1-cm intervals on site. A 10.4-m sediment core was recovered in 1-m intervals with a Livingstone piston corer (internal diameter of 2.5 cm). Because of the absence of macrofossils of sufficient size, core chronology for the complete lake record is based on 18 accelerator MS (AMS) radiocarbon dates on bulk sediment samples (eight replicates; see table 1 in ref. 15), which show excellent agreement with two independently dated volcanic tephras (Fig. 2). These tephras were identified as Mazama [≈7,545 calendar years before present (cal. yrs. BP; ref. 18)] and Bridge River (≈2,360 cal. yrs. BP; ref. 19). The overlap between the gravity core and piston core was based on extrapolation of sedimentation rates based on ^{210}Pb analyses and matches between organic and inorganic matter in the cores. Chronology for the older sediments is based on linear interpolation between AMS radiocarbon dates (Fig. 2). Radiocarbon ages were calibrated to cal. yrs. BP with the CALIB 3.0 computer program (20).

Estimates of changes in climatically sensitive limnological variables (salinity and lake depth) were inferred from transfer functions based on the modern distributions of diatom assemblages in 219 lakes from western Canada (21), a demonstrated tool for tracking past limnological and climatic conditions (22, 23). Estimates of changes in lake depth and salinity were used to represent relative changes in effective moisture [the balance between precipitation (P) and evaporation (E), or E/P], with high salinity and low lake levels implying high E/P (22), whereas low salinity and high lake levels represent low E/P conditions. The predictive ability of our diatom-based salinity and depth inference model, as judged from the strong relationship between inferred and observed salinity in a suite of modern lakes, is strong and highly significant (r^2 = 0.9 for salinity and ≈0.6 for depth; ref. 21). Unlike many calibration data sets, the apparent predictive abilities are extremely similar to both jackknifed or bootstrapped models, likely because of the uncharacteristically large number of lakes used in the development of these models (21, 22).

Correspondence analysis (CA) was used to determine whether the inferred limnological variables were strongly related to the main directions of variation in the diatom assemblages in the core (i.e., the site scores on the first CA axis). A strong correlation between the CA site scores and the inferred limnological variable allows us to use these estimates as a simplification of the changes in the diatom assemblages. Further, these inferences can give insights into the direction of change in climatic conditions (e.g., inferred increases in salinity and lower lake levels would imply drier climatic conditions).

To provide an estimate of the major zones of diatom assemblages in the core, we used a constrained cluster analysis on the diatom assemblages, with a chord distance as the measure of dissimilarity, using the program TILIA V.1.16 (24).

Results

The strong linear relationship between the 10 radiocarbon-dated intervals (four replicates) with core depth over the past 5,500 years and the excellent correspondence with two independently dated horizons suggest that the age–depth model based on ^{210}Pb and interpolation between radiocarbon-dated intervals is accurate and reliable (Fig. 2).

The cluster analysis indicated that the diatom assemblages in the core could be divided into five major zones over the past 5,500 years, which have been labeled Zones A through E (Fig. 3*c*) to provide a common framework to discuss shifts in climatic and limnological conditions.

The diatom assemblage within each zone is distinct and relatively stable, in comparison to those between zones (Fig. 3*a*). The length of each zone ranges from 1,140 to 1,400 years, with a mean of 1,220 years (Fig. 3). The transitions between the zones are abrupt, in many cases occurring in less than a few decades. These transitions occur 4,960, 3,770, 2,300, and 1,140 cal. yrs. BP (Fig. 3*c*).

Zone A is primarily dominated by the eutrophic freshwater taxa *Stephanodiscus hantzschii* Grunow and *Stephanodiscus parvus* Stoermer & Håkansson (Fig. 3*a*). Zone B is distinguished from Zone A by the abrupt appearance of several planktonic

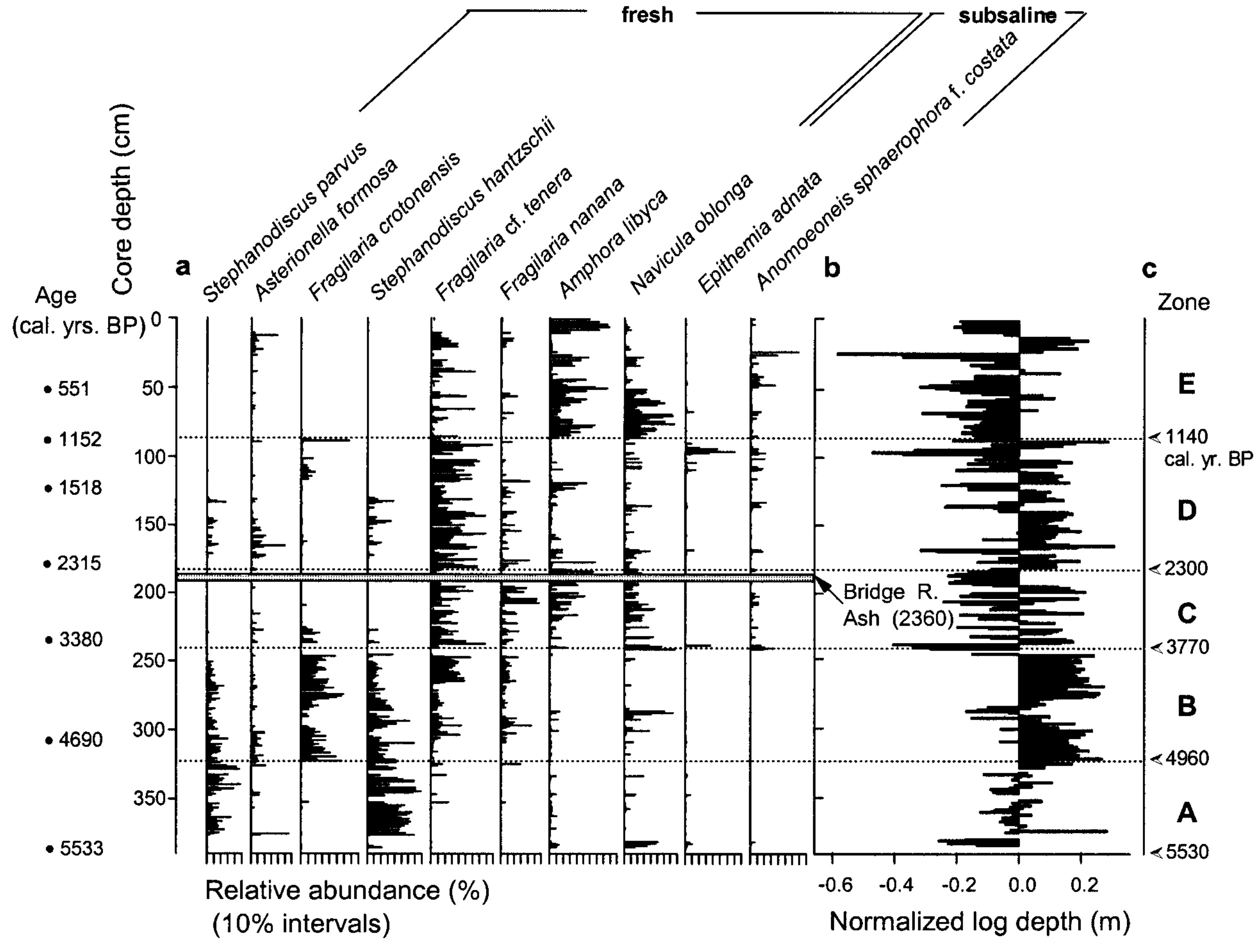

Fig. 3. (*a*) Dominant diatom taxa (>20%) from the Big Lake sediment core, British Columbia. The taxa are ordered according to estimates of their optima to salinity (21). Groupings are based on the following optima: fresh (<0.5 g/liter) and subsaline (0.5–3 g/liter). (*b*) The normalized log depth represents the deviation from the mean inferred log depth over the period of this record, which was based on the optima of taxa to log depth in a modern data set of 219 lakes (21). (*c*) The five major transitions in the cores (zones) are based on a depth-constrained cluster analysis (24).

Fragilaria species [e.g., *Fragilaria crotonensis* Kitton, *Fragilaria* cf. *tenera* (W. Smith) Lange-Bertalot, and *Fragilaria nanana* Lange-Bertalot]. Zone C is characterized by the disappearance of freshwater planktonic taxa (e.g., *S. parvus*, *S. hantzschii*, and *F. crotonensis*) and the appearance or increased occurrences of benthic taxa, such as *Amphora libyca* Ehrenberg, *Navicula oblonga* (Kützing) Kützing, and *Anomoeoneis sphaerophora* f. *costata* (Kützing) Schmid, the latter of which thrives under subsaline conditions (21). Zone D marks the return of several freshwater planktonic taxa (e.g., *S. parvus*, *S. hantzschii*, *Asterionella formosa* Hassall, and *F. crotonensis*) and decreases in the benthic taxon *A. libyca*. Zone E is primarily characterized by the reestablishment of many benthic taxa (e.g., *A. libyca* and *N. oblonga*) and large decreases in *F.* cf. *tenera*.

Changes in the floristic composition of diatoms over the past 5,500 years may be interpreted as being primarily climatically driven because the main direction of variation in the diatom assemblages (CA axis-1 site scores) is highly correlated with both diatom-inferred log salinity ($r = 0.84$, $P < 0.01$) and log depth ($r = -0.66$, $P < 0.01$), which are themselves highly correlated ($r = -0.83$, $P < 0.01$), a finding that is consistent with a strong climatic linkage with effective moisture. Because Big Lake is a relatively large lake with a low mean depth, large changes in depth cause large changes in surface area without causing changes of the same magnitude in salinity. Consequently, we present reconstructions of lake depth as a simplification of the floristic changes in the diatom assemblages that have occurred in this lake (Fig. 3*b*).

We interpret the diatom zones as representing distinct changes in both depth and salinity (Fig. 3*b* and data not shown). Diatom-inferred depth over the past 5,500 years has varied between $\approx$2 and 14 m, with mean depths in each of the zones ranging from 5 to 9 m. Mean depth has fluctuated back and forth on a millennial scale, with Zones A, C, and E representing relatively low stands (mean zone depths = 5.2–6.4 m), whereas Zones B and D represent relatively high stands (mean zone depths = 9.2 and 7.1 m, respectively). Within each of these zones, distinct decadal to multicentennial fluctuations occur, with some zones characterized more by greater decadal- to multidecadal-scale variability (i.e., Zones A, C, and D) in comparison with other zones (i.e., Zones B and E). A major increase in salinity occurs at the boundary of zones B and C (from 200 to 300 mg/liter), represented by the disappearance of fresher taxa, such as *S. parvus*, *S. hantzschii*, and *F. crotonensis*, and increases in benthic taxa with higher salinity optima, such as *A. libyca* and *N. oblonga*, along with sustained increases in the subsaline benthic taxon *A. sphaerophora* f. *costata*. Smaller inferred fluctuations in salinity occur between the other zones, whereas larger changes occur in depth.

Discussion

Millennial-scale patterns in the floristic composition of diatoms are the dominant feature of the Big Lake record for at least the

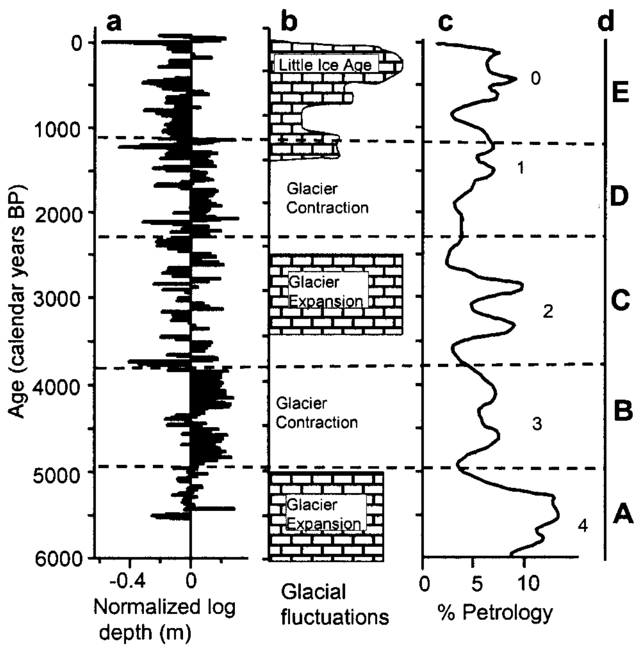

Fig. 4. Representation of the relationship between inferred changes in depth from the Big Lake core (*a*) with a summary of worldwide fluctuations in glaciers (*b*; modified from Fig. 1 and reprinted from *Quat. Res.* **3**, Denton, G. H. & Karlen, W., 155–205, Copyright 1973, with permission from Elsevier Science) and a composite diagram of IRD from a composite of four marine cores (MC52, V29191, MC21, and GGC22; Fig. 1) [*c*; modified from bottom of Fig. 2 and reprinted with permission from Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I. & Bonani, G. (2001) *Science*, Copyright 2001, AAAS]. Numbers 0–4 designate the millennial-scale cycles that are considered part of the North Atlantic's ≈1,500-year cycle (2, 3). (*d*) Major diatom zones from Fig. 3.

past 5,500 years. On the basis of the known ecological preferences of the diatom taxa, alternating millennial-scale periods of high and low moisture availability were inferred, with abrupt transitions in diatom communities (Fig. 3*a*) occurring 4,960, 3,770, 2,300, and 1,140 cal. yrs. BP (Fig. 3*c*). With the exception of the Greenland ice core (1) and marine sediments from the Atlantic (2–4), there is little evidence of millennial-scale climatic fluctuations during the middle to late Holocene, probably because of the discontinuous nature of many proxies analyzed over this time period (e.g., glacial advances), the lack of sensitive climatic proxies, or the lack of continuous well dated records analyzed at a sufficiently high temporal resolution. Below, we briefly compare the millennial-scale dynamics seen in the Big Lake record with discontinuous glacial and flood records, other well dated lake sediment cores, and North Atlantic marine records.

The general coherence of the millennial-scale dynamics of the Big Lake record to such records suggest that large swings in water availability may be a common feature of many regions of North America. The periods of inferred lower lake depth (Zones A, C, and E) correspond closely to the timing of worldwide Holocene glacier expansions (Fig. 4; ref. 5), such as the expansion in the Little Ice Age from A.D. 1300 to 1920 and 3,300 to 2,400 cal. yrs. BP. Glacial advances are also well known in the western U.S. and in the St. Elias Mountains of southern Alaska and the Yukon (5) between 1,250 and 1,050 cal. yrs. BP. The expansion 5,800–4,900 cal. yrs. BP is thought to be less extensive but is not well documented (5). Since Denton and Karlen's (5) synthesis of glacial expansions (contractions), an abundance of excellent work has been undertaken in British Columbia (25–28), which corresponds favorably with this earlier work. The most extensive advance during the Holocene in the Canadian Rockies is that of the Little Ice Age that started *ca.* A.D. 1140 (25, 26). Because many records of glacial advances earlier than the Little Ice Age were overridden, fewer sites record previous advances. However, some evidence exists for earlier and somewhat less extensive advances in the Canadian Rockies *ca.* 2,580–4,000 cal. yrs. BP (27, 28). This advance corresponds to other glacial expansions in British Columbia just west of the Rockies at the Bugaboo Glacier and in the coastal mountains (28). A glacial expansion is also recognized in the coastal mountains of British Columbia 5,800–4,900 cal. yrs. BP (25), but this expansion was limited in comparison to later advances (26).

Comparison of the timing between the millennial-scale shifts at Big Lake and available regional, albeit discontinuous, syntheses of flood records, from the southwest U.S. (i.e., Arizona and Utah; Fig. 1; refs. 8 and 9) and from the Upper Mississippi Valley (i.e., Wisconsin; Fig. 1; ref. 10) suggests only a coarse coherency among these records. Increased flood frequency in the southwest U.S. occurs 5,800–4,200 and 2,400–800 cal. yrs. BP (8, 9), overlapping the periods of high lake level at Big Lake (Zones B and D). No large floods occurred 4,200–2,400 cal. yrs. BP (8, 9), overlapping lower lake levels at Big Lake (Zone C). As observed (10), the flood records from the Upper Mississippi Valley (Fig. 1, UMV) show temporal patterns similar to those of the southwest but were generally out of phase before 600 years ago.

In North America, few high-resolution, well dated records from lake sediments have concentrated on climate dynamics during the last six millennia. However, Elk Lake, a varved lake in Minnesota located on the prairie/forest boundary, has been extensively studied at century scale for the Holocene record (29) and at subdecadal scale for the last 1,500 years (30–32). The dominance of planktonic diatom taxa *F. crotonensis* and *Stephanodiscus minutulus* over the Holocene record suggests a relatively stable limnology (33). These analyses were based on 50 varve year composite samples at a centennial-scale resolution (33). The main pattern in the Holocene analysis from Elk Lake corresponds to the transition of diatom taxa associated with the termination of the prairie period *ca.* 4,000 years ago (33). However, the lack of clear millennial-scale fluctuations may be because of the composite samples and the relatively low sample resolution. For example, the subdecadal analyses of diatom assemblages over the past 1,500 years show that a large and distinct shift in diatom assemblages occurred *ca.* 1,000 cal. yrs. BP (32). Distinct changes in diatom assemblages from two other high-resolution lake sediment records have been documented from North Dakota at approximately the same time (34), but the time frame covered by these later records only spans the last two millennia.

Outside of North America, there is a correspondence between Big Lake and North Atlantic marine records (2). The length of the relatively stable intervals between the abrupt transitions at Big Lake ranges from 1,140 to 1,400 years, with a mean of 1,220 years. This mean interval is similar to the mean Holocene pacing of IRD events estimated at 1,374 years in the North Atlantic (Fig. 1; ref. 2). The midpoints of the Big Lake intervals fall near the peaks in the IRD events (on average, within ≈220 years, Fig. 4). This mismatch in timing may suggest that millennial-scale pacing may exist in different regions without a common causal mechanism.

However, the mechanisms behind these abrupt decadal- to millennial-scale shifts during the Holocene remain poorly understood. Recent evidence from the North Atlantic suggests that the ≈1,400-year cycle in IRD during the Holocene may be driven by solar variability amplified through oceanic and atmospheric dynamics (3). The solar variability hypothesis is not new and is still much debated (35, 36). However, centennial-scale changes in proxy drought records have also been related to solar variability in many regions including the U.S. Great Plains (37) and

Yucatan Peninsula, Mexico (38), as well as in equatorial east Africa (39). In the northern U.S. prairies, proxy variables from lake sediments suggest that periods of aridity are cyclic and are a dominant feature of late Holocene climate (40).

Regardless of the mechanisms behind such abrupt climatic shifts, there is mounting evidence that millennial-scale shifts in climate may be a persistent and widespread phenomena (4, 41, 42). Furthermore, as illustrated in this article and elsewhere, such changes can be abrupt and result in prolonged changes in mean climatic conditions. Further investigations are urgently needed to improve understanding of spatial patterns and mechanisms behind millennial-scale variability in climatic conditions, as well as the implications of these shifts on human societies.

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