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Possible linkages of late-Holocene drought in the North American midcontinent to Pacific Decadal Oscillation and solar activity

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[1] Paleorecords are key for evaluating the long-term patterns and controls of drought. We analyzed calcite in annually laminated sediments from a Minnesota lake for oxygen-isotopic composition ($\delta^{18}O$). The $\delta^{18}O$ record of the past ~3100 years reveals that droughts of greater severity and duration than during the 20th century occurred repeatedly, especially prior to 300 AD. Drought variability was anomalously low during the 20th century; ~90% of the variability values during the last 3100 years were greater than the 20th-century average. $\delta^{18}O$ is strongly correlated with the index of the Pacific Decadal Oscillation (PDO) during the past 100 years, and periodicities of the late-Holocene $\delta^{18}O$ record are similar to those of the PDO. Furthermore, time series of $\delta^{18}O$ and atmospheric $\Delta^{14}C$ are generally coherent after 700 AD. Both the Pacific climate and solar irradiance probably played a role in drought occurrence, but their effects were non-stationary through the late Holocene. **Citation:** Tian, J., D. M. Nelson, and F. S. Hu (2006), Possible linkages of late-Holocene drought in the North American midcontinent to Pacific Decadal Oscillation and solar activity, *Geophys. Res. Lett.*, *33*, L23702, doi:10.1029/2006GL028169.

1. Introduction

[2] The detrimental societal, economic, and environmental repercussions of 20th-century drought episodes are evident in the North American midcontinent [e.g., *Kunkel et al.*, 1999]. However, the intensity, duration, and frequency of 20th-century drought are dwarfed by those inferred from paleoclimatic records in some areas [e.g., *Laird et al.*, 1996; *Woodhouse and Overpeck*, 1998]. The causal mechanisms of these "megadroughts" in paleorecords remain elusive, although factors such as solar irradiance and modes of atmosphere-ocean teleconnection may have played an important role. Understanding the spatio-temporal variability of natural drought occurrence and the controlling mechanisms is important because such variability may modify the trajectory of climatic change and exacerbate the effects of anthropogenic changes. In many regions, this understanding is hampered by the scarcity of high-quality paleoclimatic records.

[3] Here we present a high-resolution record of calcite $\delta^{18}O$ from Steel Lake (46°58′N, 94°41′W, 415 m asl), north-central Minnesota. The lake is located in the confluence of the Caribbean, Arctic, and Pacific air masses, making it sensitive to changes in atmospheric circulation patterns (Figure 1a) [*Bryson and Hare*, 1974]. Its late-Holocene sediments are annually laminated (varved); varve counts and nine AMS ^{14}C dates together afford an exceptionally strong chronology [*Tian et al.*, 2005]. Sediment samples were analyzed for $\delta^{18}O$ and a number of other proxies [*Tian*, 2005]. In this paper, we focus on the $\delta^{18}O$ record and use it to infer past aridity. To guide paleoclimatic interpretation, we compared $\delta^{18}O$ data of the 20th century with instrumental climate data and climate modes thought to influence the regional moisture regime. We then evaluated the patterns and controls of drought occurrence for the past ~3100 years.

2. Site Description and Methods

[4] Steel Lake is a small (0.23 km^2) and deep (21 m) kettle basin (Figure 1b), with a watershed area of 1.08 km^2 and a small stream running through it today. The lake is located within the Itasca moraine in north-central Minnesota. Modern vegetation around the lake is second-growth, mixed deciduous-coniferous forest [*Wright et al.*, 2004]. At Walker Ah Gwah Ching, Minnesota, ~15 km northeast of Steel Lake, the mean annual temperature and precipitation are 4.4°C and 649 mm, respectively. In July 2001, the lake was thermally stratified with an anoxic hypolimnion (below ~8 m) (Figure 1c).

[5] The great depth and anoxic hypolimnion of Steel Lake facilitate varve formation and preservation. Each late-Holocene varve couplet consists of a light and a dark layer [*Tian et al.*, 2005]. The light layer is primarily low-magnesium calcite of small crystal sizes (~1 μm) on the basis of mineral identification using X-ray diffraction and crystal examination using an environmental scanning electron microscope equipped with energy dispersive X-ray spectroscopy. The calcite crystals likely formed as a result of algal photosynthesis during the growing season when lake waters were supersaturated with calcite. The dark layer consists of organic-rich material deposited during the remainder of the year.

[6] Stratigraphically overlapping sediment cores were collected with a freeze corer and a modified Livingstone piston corer. The annual nature of the sediment laminations was verified by examination of lamina characteristics in thin section as well as by ^{137}Cs and ^{14}C ages [*Tian et al.*, 2005]. The varve chronology of the last 3100 years in comparison with nine AMS ^{14}C dates was discussed in detail by *Tian et al.* [2005]. We sampled the sediments contiguously at 3-year

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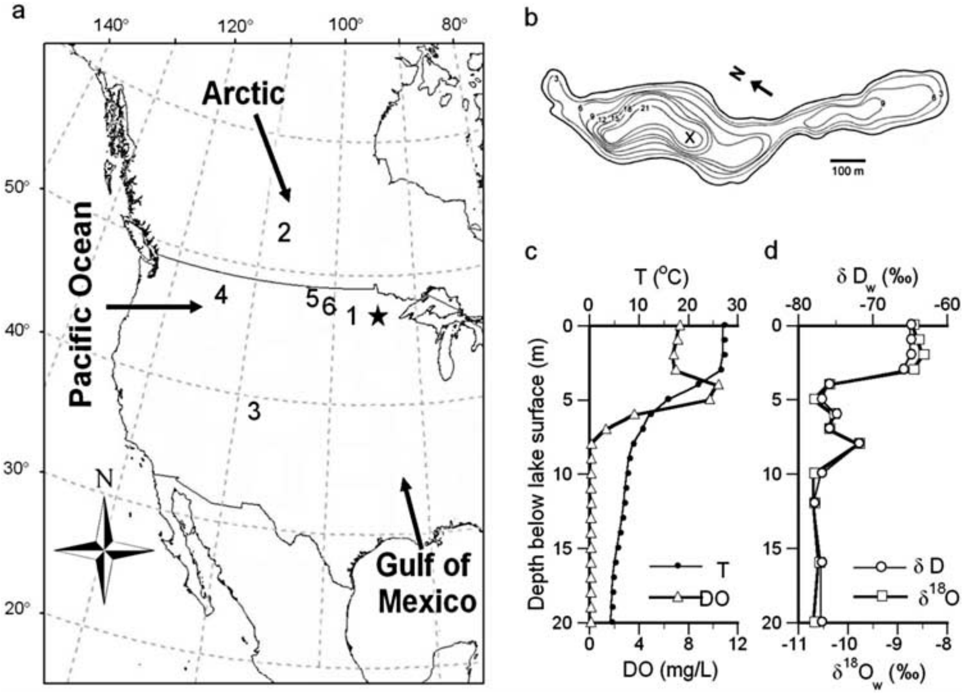

Figure 1. (a) Locations of Steel Lake (star) and other sites (numbers) mentioned in the text. (b) Bathymetric map of Steel Lake (meters). X = coring location. Depth profiles of (c) temperature and dissolved oxygen (DO) and (d) water δD and δ^{18}O in July 2001.

intervals for the past 250 years and at 5-year intervals for the remainder of the past 3100 years. Calcite δ^{18}O was measured with a Finnigan MAT 252 isotope-ratio mass spectrometer (IRMS) interfaced with an automated Kiel device. The precision of δ^{18}O analysis was 0.1‰ on the basis of laboratory standards. To examine the periodicity of the δ^{18}O record, we performed spectral analysis with the computer program REDFIT [*Schulz and Mudelsee*, 2002] and wavelet analysis with the computer program Interactive Wavelets [*Torrence and Compo*, 1998]. The wavelet power spectrum was scaled to the global wavelet spectrum.

[7] For comparison with our δ^{18}O data, we obtained several datasets from various sources. Temperature and precipitation records of 1893–1999 AD from weather stations within 15 km of Steel Lake were downloaded at http://climate.umn.edu/doc/historical.htm (Minnesota Climatology Working Group). Effective moisture was estimated as the difference between precipitation and actual evapotranspiration (P-AET), where AET was calculated using the Thornthwaite method with the computer program EVAP [*Sellinger*, 1996]. Time series of the indices of several climatic modes, including Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), Pacific North American (PNA) index, and the El Niño Southern Oscillation (ENSO), were obtained from http://www.cdc.noaa.gov/ClimateIndices/ (NOAA Climate Diagnostics Center). The atmospheric Δ^{14}C record came from http://depts.washington.edu/qil/datasets/ (University of Washington Quaternary Isotope Lab).

3. Results and Discussion

[8] The δ^{18}O of endogenic calcite in lake sediments primarily reflects the temperature and δ^{18}O of the lake water. Lake-water δ^{18}O is, in turn, influenced by a number of factors, including moisture source, atmospheric temperature, and evaporative ^{18}O enrichment. Disentangling these factors is often difficult in paleolimnological studies. However, two lines of evidence indicate that at Steel Lake, evaporative ^{18}O enrichment related to aridity was the dominant control. First, the δ^{18}O values of water samples from the epilimnion and hypolimnion of Steel Lake were -8.7 and -10.7‰, respectively, in July 2001 (Figure 1d). The elevated δ^{18}O value of the epilimnetic water resulted from evaporative ^{18}O enrichment, suggesting that Steel Lake is sensitive to evaporation. Second, calcite δ^{18}O and P-AET show good correspondence during the 20th century (Figure 2). In particular, the most severe historic drought events in north-central Minnesota, the 1988 drought [*Trenberth et al.*, 1988] and 1930s Dust Bowl [*Worster*, 1979], are recorded by the heaviest δ^{18}O values at Steel Lake (Figures 2a and 3a). However, the correspondence is imperfect between δ^{18}O and P-AET. Some mismatches are expected given the fact that P-AET is only an approximate indicator of aridity. For example, the 1960s aridity peak indicated by P-AET is not nearly as pronounced in the Palmer Drought Severity Index (PDSI), another metric of aridity. In addition, calcite δ^{18}O is influenced by factors (e.g., temperature and watershed "damping effect" [*Tian*, 2005]) other than aridity. For these reasons, we do not attempt to pinpoint the timing and magnitude of each individual drought episode using our late-Holocene δ^{18}O record.

[9] The calcite δ^{18}O record from Steel Lake showed marked fluctuations over the past 3100 years, ranging from -11.2 to -8.1‰ (Figure 3a). A striking feature of the record is the mean-state shift around 300 AD; drought was prevalent and long-lasting before 300 AD, as suggested by the sustained high values of δ^{18}O. The ^{18}O enrichment

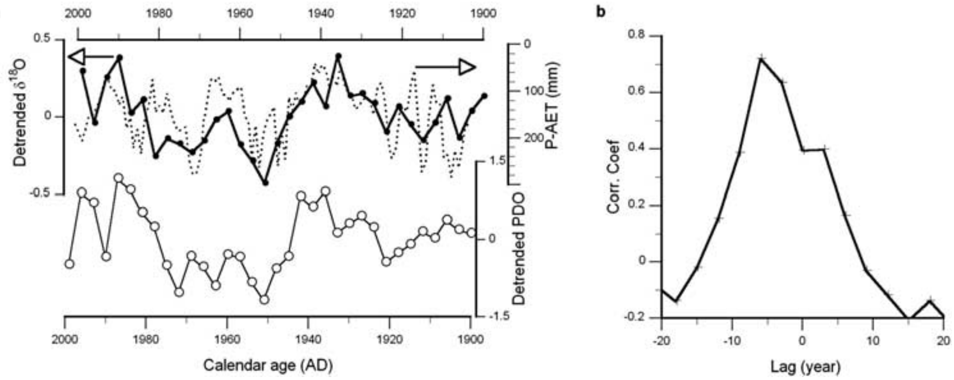

Figure 2. (a) Detrended (100-year window) δ^{18}O record from Steel Lake, P-AET, and detrended PDO index of the 20th century. The δ^{18}O record was shifted backward by 3 years (sample resolution). (b) Cross-correlation between δ^{18}O and the PDO. The correlation improves from r = 0.39 to r = 0.63 (n = 32, p < 0.001) with the 3-year shift in δ^{18}O. The 3-year lag likely reflects groundwater influence on δ^{18}O.

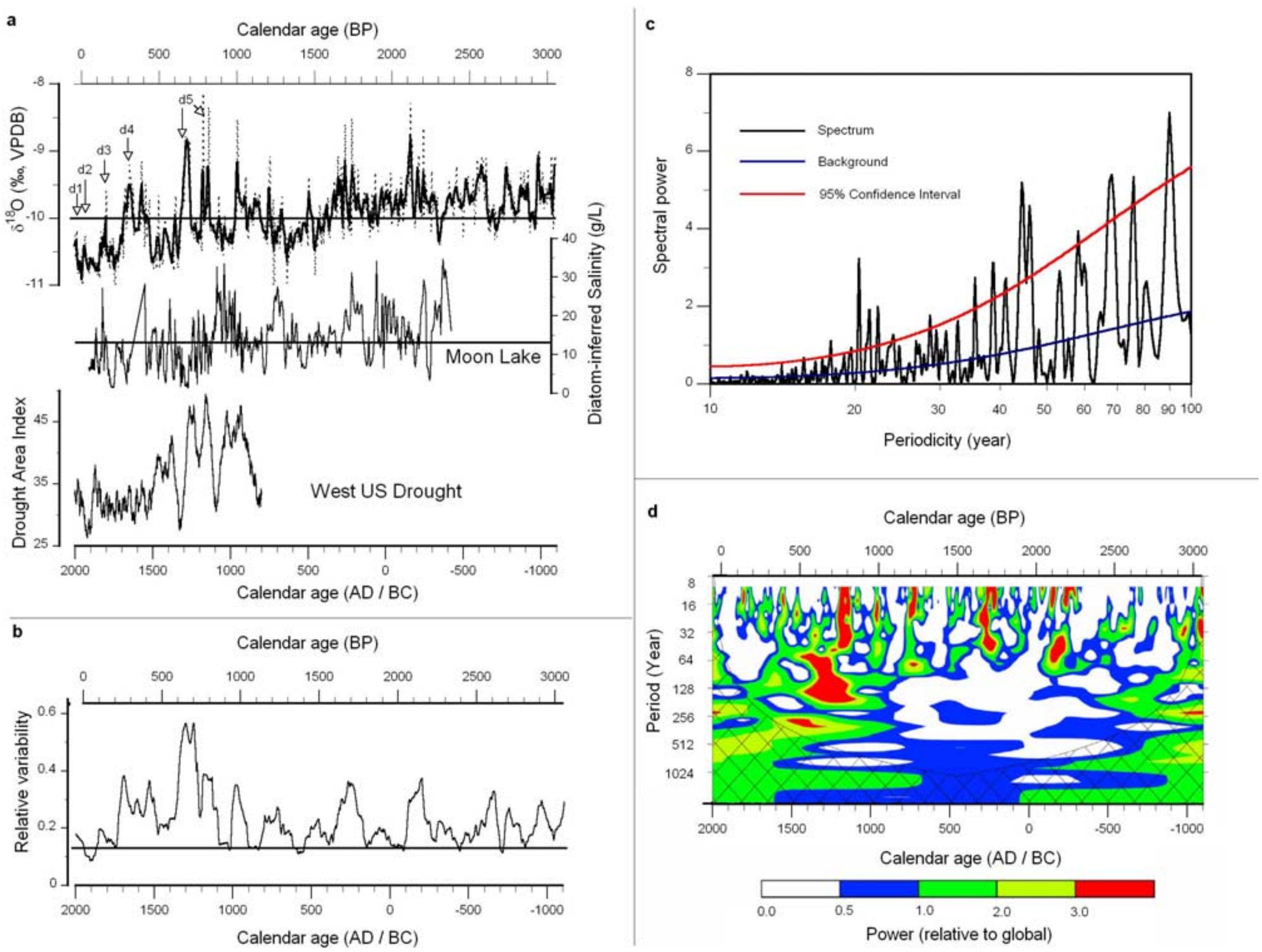

Figure 3. (a) Time series of calcite δ^{18}O from Steel Lake (dotted line = raw data; thick line = 3-point moving average) in comparison with drought records from Moon Lake, ND [*Laird et al.*, 1996] and from western United States [*Cook et al.*, 2004]. The horizontal lines represent the mean values of δ^{18}O at Steel Lake (past 3100 years) and diatom-inferred salinity at Moon Lake (past 2300 years). Previously documented droughts are labeled d1–d5, as in text. (b) Relative variability of the detrended (100-year window) δ^{18}O data. The horizontal line represents the mean value of 20th-century variability. (c) Spectral patterns of the detrended δ^{18}O data from Steele Lake. (d) Wavelet power spectrum of the δ^{18}O data from Steele Lake.

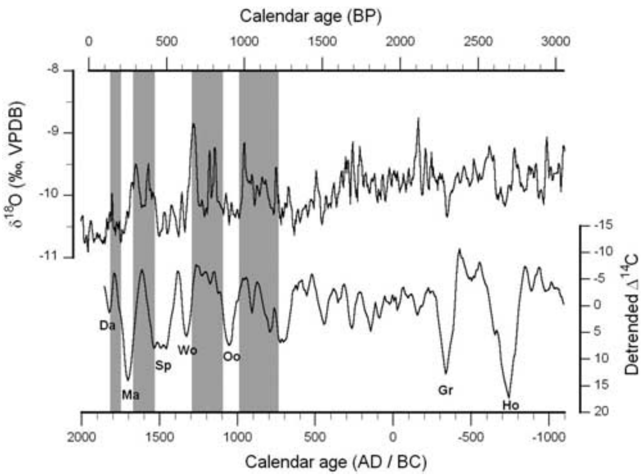

Figure 4. Comparison of δ^{18}O and detrended atmospheric Δ^{14}C data for the last 3100 years. Grey bars highlight intervals with high δ^{18}O and low Δ^{14}C values. Note that the Δ^{14}C scale is reversed. Well-known solar minima (Δ^{14}C maxima) are labeled: Da – Dalton, Ma – Maunder, Sp – Spörer, Wo – Wolf, Oo – Oort, Gr – Greek, and Ho – Homeric.

during the 1988 drought (Figure 3a, d1) and 1930s Dust Bowl (Figure 3a, d2) was minor compared to that during many other time intervals both before and after 300 AD. Thus drought events of greater magnitude than the aridity extremes of the 20th century were not uncommon during the late Holocene.

[10] In addition to the broad patterns, our δ^{18}O record suggests that the region was relatively dry during the Medieval Climate Anomaly (MCA; ~1400–1100 AD) and relatively wet during the Little Ice Age (LIA; ~1850–1500 AD), but that the moisture regime varied greatly within each of these two periods. Severe drought occurred during the MCA, as suggested by the high average values and distinct peaks in δ^{18}O (Figure 3a, d5). However, a prolonged wet period (~1180–1250 AD) also occurred within the MCA. The lower average values of δ^{18}O between ~1850 and 1500 AD suggest that the LIA was generally wetter. However, the LIA was punctuated by drought episodes, as evidenced by several pronounced δ^{18}O peaks (Figure 3a, d3 and d4).

[11] Some of the drought patterns inferred from the Steel Lake δ^{18}O record agree with data from other sites in the North American midcontinent. For example, the occurrence of severe drought during the MCA has been documented in paleoclimatic records from the Great Plains [*Laird et al.*, 1996] (Figure 1a, site 1 and Figure 3a), western [*Cook et al.*, 2004] (Figure 3a), and midwestern [*Booth et al.*, 2006] United States. Furthermore, tree-ring records indicate severe drought episodes around 1800 AD in the central Canadian prairie region [*Case and MacDonald*, 1995] (Figure 1a, site 2) and during the 16th century in the southern Rocky Mountains [*Gray et al.*, 2003] (Figure 1a, site 3). Thus some of these drought events might have been widespread across the North American midcontinent.

[12] The timing of a mean-state shift in a paleoclimatic record depends, in part, on the length of the record. Because of the scarcity of high-resolution climatic reconstructions that extend beyond the past 2000 years from the region, it is difficult to assess the spatial extent of the mean-state hydroclimatic shift around 300 AD, as inferred from the Steel Lake record. A high-resolution diatom record of the past 2300 years from Moon lake in eastern North Dakota [*Laird et al.*, 1996] also shows that the regional climate was generally dry before 300 AD but a mean-state shift appeared to have occurred at 1200 AD (Figure 3a). A mean-state shift at 300 AD did not occur in areas farther to the west on the basis of paleoclimatic records from Foy Lake in northwestern Montana [*Stevens et al.*, 2006] (Figure 1a, site 4) and Kettle Lake in northwestern North Dakota [*Brown et al.*, 2005] (Figure 1a, site 5). Discrepancies in the timing and/or direction of late-Holocene hydroclimatic change have been reported previously [*Fritz et al.*, 2000; *Laird et al.*, 2003], although regional coherency in terms of the timing of major shifts has also been documented among certain sites [*Laird et al.*, 2003]. These discrepancies may reflect proxy sensitivity differences, spatial heterogeneity of climatic change, and/or chronological uncertainties.

[13] To assess the relative variability of drought occurrence at the centennial time scale (Figure 3b), we first resampled the δ^{18}O data at 5-year resolution for the past 250 years to match the resolution for the remainder of the record and then detrended the δ^{18}O time series with a 100- year time window. Relative variability was calculated as: $\frac{1}{n}\sum|x - \bar{x}|$, where x is the δ^{18}O value of each sample, and $\bar{x}$ the mean δ^{18}O value and n the number of data points within the moving window. This measure of variability does not differentiate the frequency and magnitude of drought based on δ^{18}O. In addition, because our sample resolution at every 5 years masks the inter-annual variation in the drought regime, the relative variability, as defined here, is at best an approximation of the real variability in the moisture regime.

[14] Results indicate much greater variability before 1900 AD than after, with particularly pronounced variation during certain time intervals (e.g. 1100–1700 AD). Some of these periods of high variability were probably widespread. For example, drought variability at Moon Lake [*Laird et al.*, 1996] was high in several time intervals when variability was also high at Steel Lake (e.g., around 1600 AD, 750 AD, 200 AD, and 200 BC; data not shown). Periods with variability similar to that of the 20th century at Steel Lake spanned a maximum of one to two centuries, and they were intermittent among multi-centennial intervals of greater variability (Figure 3b). In all, ~90% of the variability values during the last 3100 years were greater than the average of the 20th century. Thus drought variability was anomalously low during the 20th century. This low variability was atypical of the last 3100 years, and it probably should not be expected as the prevailing state of variability for the future.

[15] To help elucidate the factors controlling drought occurrence, we compared the 20th-century δ^{18}O data from Steel Lake with several indices of climatic modes (e.g., PDO, AMO, PNA, and ENSO) that are known to influence atmospheric circulation and the moisture regime of the North American midcontinent today [e.g., *McCabe et al.*, 2004]. δ^{18}O is not significantly correlated with the indices of these climatic modes except the PDO, a long-lived El Niño-like pattern of sea surface temperature (SST) variabil-

ity in the North Pacific. As illustrated in Figure 2, a highly significant, positive correlation (r = 0.63, n = 32, p < 0.0001) exists between δ^{18}O and the PDO. This pattern can be explained by the negative correlation of the PDO with measured winter (r = −0.44, n = 103, p < 0.001) and summer (r = −0.35, n = 103, p < 0.001) precipitation near Steel Lake. Dry winters likely decrease the proportion of ^{18}O-depleted winter precipitation entering the lake, and dry summers enhance evaporative ^{18}O-enrichment of lake water.

[16] Although the underlying mechanisms of the Pacific climatic variability remain unclear, several recent studies provided an understanding on the linkages between the Pacific climate and the moisture regime of the midwestern United States. Warm SSTs in the eastern North Pacific (positive PDO) cause a strengthening and eastward shift in the position of the Pacific air mass during the winter [e.g., *Budikova*, 2005] and summer [e.g., *Ting and Wang*, 1997]. These changes prevent moisture from the Gulf of Mexico from reaching the upper midwestern United States, leading to a reduction in precipitation.

[17] Because of the brevity of the instrumental PDO record, it is difficult to rigorously test whether the strong δ^{18}O-PDO correlation of the 20th century existed throughout the past 3100 years. Nonetheless, several spectral periods in our δ^{18}O data fall into the ranges associated with PDO (Figure 3c, 15–25 and 50–70 years) [*Mantua and Hare*, 2002; *Minobe*, 1999]. These periods were discontinuous during the late Holocene, as indicated by wavelet analysis of the same δ^{18}O record (Figure 3d). Thus SST variability of the North Pacific probably has intermittently exerted a major influence on moisture transport to the Steel Lake region during the late Holocene.

[18] In addition to the Pacific climate, solar irradiance may have also played a role in the drought regime of the North American mid-continent, as suggested by several recent studies [e.g., *Brown et al.*, 2005; *Yu and Ito*, 1999; *Laird et al.*, 1996]. At Steel Lake, the δ^{18}O spectral peaks around 20–25, 45, 90 (Figure 3c), ∼155, and ∼350 years (not shown) coincide with possible solar cycles identified from the atmospheric Δ^{14}C record [*Haigh*, 1996]. Furthermore, δ^{18}O variation at Steel Lake appears coherent with that of atmospheric Δ^{14}C after 700 AD. In particular, several time intervals of wet conditions (e.g., 1750–1670 AD, 1500–1350 AD, 1130–980 AD), as inferred from low δ^{18}O values, coincide with well-known sunspot minima (Δ^{14}C maxima) (Figure 4) [*Beer et al.*, 2000]. Climatic cooling associated with reduced solar output might have reduced evaporative ^{18}O enrichment of lake water and led to low calcite δ^{18}O values during sunspot minima. These results support recent studies revealing possible Sun-climate connections [e.g., *Hu et al.*, 2003; *Laird et al.*, 1996; *Brown et al.*, 2005].

[19] The interpretation of solar influences on the drought regime of the Steel Lake region remains speculative, and the data supporting such an interpretation are not straightforward. For example, δ^{18}O at Steel Lake and atmospheric Δ^{14}C do not show strong correspondence before 700 AD (Figure 4). In addition, discrepancies exist among available paleoclimatic reconstructions. For example, centennial-scale periodicities occurred mainly after 900 AD and before 400 BC at Steel Lake (Figure 3d), but they appear to be significant for extended periods in other records [*Brown et al.*, 2005]. Furthermore, in contrast to our results, drier conditions co-occurred with reduced solar irradiance over the last 2100 years at Rice Lake in North Dakota (Figure 1a, site 6) [*Yu and Ito*, 1999]. Opposite relationships of drought and solar output between these sites could be caused by factors such as chronological inaccuracy and/or spatial variation in the effects of solar cycles on drought. Additional high-quality paleoclimatic records from the midcontinent are needed to resolve such discrepancies.

[20] It remains uncertain how North Pacific SST variability and solar output affected the hydroclimatic variation of the North American midcontinent during the late Holocene. These factors may interact with each other and with other controls to result in climatic change. For example, recent studies [*Franks*, 2002; *Shen et al.*, 2006] suggest that the PDO may be related to solar variation. However, it is unclear whether the positive/warm phase of the PDO corresponds with sunspot minima (Δ^{14}C maxima) [*Shen et al.*, 2006] or maxima (Δ^{14}C minima) [*Franks*, 2002]. Furthermore, the underlying mechanisms of drought occurrence were non-stationary through the late Holocene, as evidenced by the discontinuous influences of both the PDO and solar irradiance on the drought regime of the Steel Lake region. These factors, along with the spatial heterogeneity of drought manifestation, make paleo-drought detection and attribution a major challenge.

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References

Beer, J., W. Mende, and R. Stellmacher (2000), The role of the sun in climate forcing, *Quat. Sci. Rev.*, *19*, 403–415.

Booth, R. K., M. Notaro, S. T. Jackson, and J. E. Kutzbach (2006), Widespread drought episodes in the western Great Lakes region during the past 2000 years: Geographic extent and potential mechanisms, *Earth Planet. Sci. Lett.*, *242*, 415–427.

Brown, K. J., J. S. Clark, E. C. Grimm, J. J. Donovan, P. G. Mueller, B. C. S.Hansen, and I. Stefanova (2005), Fire cycles in North American interior grasslands and their relation to prairie drought, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 8865–8870.

Bryson, R. A., and F. K. Hare (1974), *Climates of North America*, Elsevier, New York.

Budikova, D. (2005), Impact of the Pacific Decadal Oscillation on relationships between temperature and the Arctic Oscillation in the USA in winter, *Clim. Res.*, *29*, 199–208.

Case, R. A., and G. M. Macdonald (1995), A dendroclimatic reconstruction of annual precipitation on the western Canadian prairies since AD 1505 from *Pinus flexilis* James, *Quat. Res.*, *44*, 267–275.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle (2004), Long-term aridity changes in the western United States, *Science*, *306*, 1015–1018.

Franks, S. W. (2002), Assessing hydrological change: Deterministic general circulation models or spurious solar correlation?, *Hydrol. Processes*, *16*, 559–564.

Fritz, S. C., E. Ito, Z. C. Yu, K. R. Laird, and D. R. Engstrom (2000), Hydrologic variation in the northern Great Plains during the last two millennia, *Quat. Res.*, *53*, 175–184.

Gray, S. T., J. L. Betancourt, C. L. Fastie, and S. T. Jackson (2003), Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains, *Geophys. Res. Lett.*, *30*(6), 1316, doi:10.1029/2002GL016154.

Haigh, J. D. (1996), The impact of solar variability on climate, *Science*, *272*, 981–984.
Hu, F. S., D. Kaufman, S. Yoneji, D. Nelson, A. Shemesh, Y. Huang, J. Tian, G. Bond, B. Clegg, and T. Brown (2003), Cyclic variation and solar forcing of Holocene climate in the Alaskan subarctic, *Science*, *301*, 1890–1893.
Kunkel, K. E., R. A. Pielke, and S. A. Changnon (1999), Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review, *Bull. Am. Meteorol. Soc.*, *80*, 1077–1098.
Laird, K. R., S. C. Fritz, K. A. Maasch, and B. F. Cumming (1996), Greater drought intensity and frequency before AD 1200 in the northern Great Plains, USA, *Nature*, *384*, 552–554.
Laird, K. R., B. F. Cumming, S. Wunsam, J. A. Rusak, R. J. Oglesby, S. C. Fritz, and P. R. Leavitt (2003), Lake sediments record large-scale shifts in moisture regimes across the northern prairies of North America during the past two millennia, *Proc. Natl. Acad. Sci. U. S. A.*, *100*, 2483–2488.
Mantua, N. J., and S. R. Hare (2002), The Pacific Decadal Oscillation, *J. Oceanogr.*, *58*, 35–44.
McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004), Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, *Proc. Natl. Acad. Sci. U. S. A.*, *101*, 4136–4141.
Minobe, S. (1999), Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: Role in climatic regime shifts, *Geophys. Res. Lett.*, *26*, 855–858.
Schulz, M., and M. Mudelsee (2002), REDFIT: Estimating red-noise spectra directly from unevenly spaced paleoclimatic time series, *Comput. Geosci.*, *28*, 421–426.
Sellinger, C. E. (1996), Computer program for estimating evapotranspiration using the Thornthwaite method, pp.1–9, Great Lakes Environ. Res. Lab., Ann Arbor, Mich.
Shen, C., W.-C. Wang, W. Gong, and Z. Hao (2006), A Pacific Decadal Oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China, *Geophys. Res. Lett.*, *33*, L03702, doi:10.1029/2005GL024804.
Stevens, L. R., J. R. Stone, J. Campbell, and S. C. Fritz (2006), A 2200-yr record of hydrologic variability from Foy Lake, Montana, USA, inferred from diatom and geochemical data, *Quat. Res.*, *65*, 264–274.
Tian, J. (2005), Varve chronology, proxy calibration, and Holocene climate of Minnesota, Ph.D. thesis, Univ. of Ill., Urbana, Ill.
Tian, J., T. A. Brown, and F. S. Hu (2005), Comparison of varve and ^{14}C chronologies from Steel Lake, Minnesota, USA, *Holocene*, *15*, 510–517.
Ting, M. F., and H. Wang (1997), Summertime US precipitation variability and its relation to Pacific sea surface temperature, *J. Clim.*, *10*, 1853–1873.
Torrence, C., and G. P. Compo (1998), A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, *79*, 61–78.
Trenberth, K. E., G. W. Branstator, and P. A. Arkin (1988), Origins of the 1988 North American drought, *Science*, *242*, 1640–1645.
Woodhouse, C. A., and J. T. Overpeck (1998), 2000 years of drought variability in the central United States, *Bull. Am. Meteorol. Soc.*, *79*, 2693–2714.
Worster, D. (1979), *Dust Bowl: The Southern Plains in the 1930s*, 277 pp., Oxford Univ. Press, New York.
Wright, H. E., I. Stefanova, J. Tian, T. A. Brown, and F. S. Hu (2004), A chronological framework for the Holocene vegetational history of central Minnesota: The Steel Lake pollen record, *Quat. Sci. Rev.*, *23*, 611–626.
Yu, Z. C., and E. Ito (1999), Possible solar forcing of century-scale drought frequency in the northern Great Plains, *Geology*, *27*, 263–266.

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