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Widespread drought episodes in the western Great Lakes region during the past 2000 years: Geographic extent and potential mechanisms

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We dedicate this paper to the memory of Dr. Barbara J. Madsen (1954–2005), who suggested Minden Bog to us as a study site, and who led the fight to preserve this unique ecological and geological treasure

Abstract

We compared high-resolution reconstructions of peatland water-table depth at two raised bogs in the western Great Lakes region separated by ~1000 km. The sites included Minden Bog in southeastern Michigan and Hole-in-the-Bog in north-central Minnesota. Our objectives were to 1) determine whether large, decadal to multidecadal droughts of the past 2000 yrs were spatially and temporally coherent across the region, and 2) assess the underlying mechanisms of widespread droughts in the region. We found a strong correlation between bog-inferred records of moisture variability in the two regions ($r=0.53$). Between 2100 and 600 BP, extreme drought events centered on 1850, 1800, 1650, 1000, 800, and 700 BP are recorded in both regions. Many of these drought events were contemporaneous with large droughts already documented at sites far to the west in the Great Plains and Rocky Mountains. To identify potential modern climate analogues, we used empirical orthogonal function (EOF) analysis to reveal spatial modes of variability in drought and precipitation records of North America for the past century. The first EOFs of annual precipitation and Palmer Drought Severity Index (PDSI) were similar to each other, and consistent with a pattern of widespread continental drought. Correlations between these EOFs and annual sea surface temperatures (SSTs) indicate strong relationships to SSTs in both the Atlantic and Pacific basins. We hypothesize that widespread droughts between 1000 and 700 BP were related to amplification of a spatial mode of moisture variability associated with an anomalously warm North Atlantic, a warm mid-latitude North Pacific, and an anomalously cold Tropical Pacific. A more extensive network of hydroclimate records, developed using a consistent set of methods and proxies, could be used in conjunction with high-resolution records of past SSTs to test this hypothesis.
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1. Introduction

Most information on late Holocene drought variability in North America derives from tree-ring based

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reconstructions, which tend to be concentrated in semi-arid regions west of about 100°W [1–3]. Paleohydrological records from lake sediments in the northern Great Plains have attempted to extend high-resolution records of late Holocene drought variability into the mid-continent [4]. However, climatic interpretation of these records has been problematic, and they have not clearly shown spatiotemporal coherence [4,5]. In fact, many of these records suggest a high degree of spatial and temporal heterogeneity in drought events [4], and it is difficult to assess whether this heterogeneity represents a genuine pattern of climate variability or the strong influence of non-climatic factors (e.g., local groundwater dynamics). There is a clear need for additional hydroclimate records to determine whether late Holocene drought events were coherent at continental to regional spatial scales and to assess potential mechanisms and dynamics. Records from the mid-continent and eastern North America are particularly needed to assess the relative importance of Atlantic and Pacific Ocean influences on North American drought [2,6,7].

Peatlands are common in the western Great Lakes region immediately east of the Great Plains, and peatland sediments can provide sensitive records of hydroclimate variability with decadal to multidecadal resolution [8–10]. Proxy-climate records from peatlands in the region show substantial decadal to millennial-scale hydroclimatic variability during the late Holocene, indicating the region is susceptible to large, ecologically significant droughts, despite being relatively humid [9,11,12]. Several large multiyear drought events of the past century (e.g., 1930s) extended from the Great Plains into the region [13–15]. Peatland records of late Holocene moisture variability from the western Great Lakes region can be compared to tree-ring and other records from further west to assess the spatial extent, temporal coherence, and climate dynamics of past drought events. For example, large droughts in the western United States during the Medieval Warm Period (MWP), a warm interval lasting several centuries [16], may have been associated with an anomalously cool eastern tropical Pacific [3]. However, if these droughts also affected the Great Lakes region, changes in the Atlantic were likely also involved.

Recent studies in Europe and North America clearly demonstrate that ombrotrophic peatlands contain robust, sensitive, and high-resolution hydroclimate records [24–26,9,11,12]. Ombrotrophic peatlands receive all moisture from atmospheric sources, with no groundwater influence at the peatland surface [17]. The direct relationship between surface-moisture and atmospheric conditions results in high sensitivity to hydroclimate variability [17,18] and makes these systems less susceptible to the hydrologic idiosyncrasies of groundwater-dominated systems such as lakes [5]. A wide range of biological and physical proxies have been developed, refined, and applied towards reconstructing past peat surface-moisture conditions, including testate amoebae [19–21], plant macrofossils [22–24], and peat humification [25,26]. Application of these methods has resulted in hydroclimate records with decadal to centennial-scale resolution, and different proxies show a high degree of temporal correspondence [9,27–29]. Temporal patterns of moisture variability within and among peatlands also show good correspondence and a high degree of replicability [11,20,23,28,29] and are similar to reconstructions obtained from other proxy-climate archives [9,11,12,30]. Correlations with instrumental climate data for the last couple of centuries are also strong ($r = 0.46$ to 0.72) [8,10].

In this study, we compare peat-based records of moisture variability from two ombrotrophic peatlands in the western Great Lakes region that are separated by approximately 1000 km. Our primary objective is to test the hypothesis that extreme hydroclimate fluctuations during the past 2000 yrs were spatially widespread in the region. We also compare these records to tree-ring and other proxy-climate records from the western United States, to assess whether these large drought events affected much of the mid-continent. We then investigate spatial modes of variability in the instrumental records of precipitation and drought for the past century, and use the observed patterns to develop hypotheses regarding the potential causes of widespread mid-continental droughts.

2. Study sites

Both study sites are ombrotrophic peatlands, one located in north-central Minnesota and the other in southeastern Michigan. Hole-in-the-bog peatland (47°18′00″, 94°14′57″) (hereafter “Hole Bog”) is a basin-filled raised bog located in Cass County, Minnesota (Fig. 1). *Sphagnum* mosses are the dominant vegetation, and the bog crest is forested with *Picea mariana* and *Larix laricina*. Other common plants include ericaceous shrubs (e.g., *Chamaedaphne calyculata*, *Kalmia polifolia*, *Andromeda glaucophylla*, *Ledum groenlandicum*) and sedges (e.g., *Carex oligosperma*, *Carex trisperma*, *Eriophorum spissum*). Additional details of vegetation and water chemistry of Hole Bog are listed in Glaser [31]. Minden Bog (46°36′38″, 82°50′05″) is a raised bog located in Sanilac County,

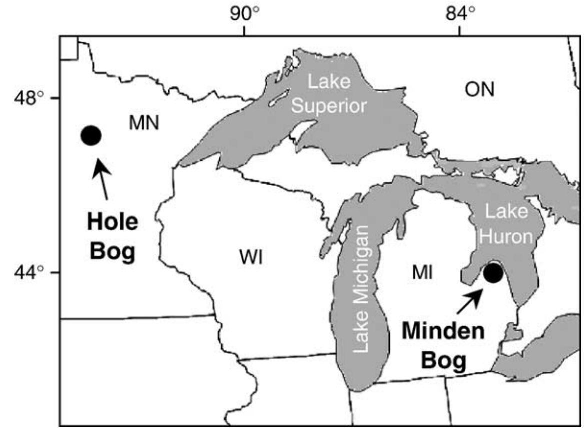

Fig. 1. Map showing the locations of Minden Bog and Hole Bog in the western Great Lakes region.

Michigan. Vegetation is dominated by *Sphagnum* mosses, shrubs (e.g., *K. polifolia*, *C. calyculata*), and widely scattered trees (e.g., *L. laricina*). Site characteristics are detailed in Booth and Jackson [9] and Booth [32].

3. Methods

3.1. Paleohydrological methods

Sediment cores were collected from the two sites using a modified Livingstone piston-corer (10.2-cm diameter) [33]. Peat samples (2 cm^3) were collected from every centimeter along the entire length of the cores for testate amoeba analysis. Sample processing followed standard sieving procedures [34], and the size fraction between 355 and 15 μm was analyzed. We attempted to identify and count 150 testate amoebae from each sample, although in a portion of the Hole Bog core this count total could not be achieved and thus reconstructions were not made. Taxonomy follows Charman et al. [35], except as noted by Booth [32].

We used the calibration dataset of Booth [32], along with ninety-seven additional modern testate amoeba assemblages collected from nine peatlands in northern Wisconsin, to reconstruct the hydrologic history of the two peatlands. Transfer functions were developed from this modern dataset using several standard models, and validated using jack-knifing techniques [36]. All models performed well in cross-validation and produced similar water-table depth reconstructions, so we only report the results of the transfer function based on weighted averaging [36] (Fig. 2). Water-table depth reconstructions are given in centimeters below the peat surface, so larger values indicate drier conditions. Error estimates on reconstructions were made using bootstrapping techniques ($n = 1000$) and the software program C2 [37].

Age models were developed using accelerator mass spectrometry (AMS) radiocarbon dates in conjunction with the position of the rise in *Ambrosia* pollen associated with the timing of European land clearance (Fig. 3). All radiocarbon dates were obtained on *Sphagnum* moss or terrestrial plant material, and each sample spanned one cm of peat (Table 1). Radiocarbon ages were calibrated using CALIB 5.0 [38,39].

3.2. Analysis of the instrumental precipitation and drought records of North America

Instrumental records of drought and precipitation were used to explore recent spatial modes of drought and precipitation, and to compare the instrumental record of drought in southeastern Michigan and north-central Minnesota. Annual precipitation data for global land areas on a 2.5°×3.75° grid was obtained for 1900–1998 from CRU (Climatic Research Unit) [40–42]. Annual Palmer Drought Severity Index (PDSI) was computed for the same period over North America on a 2.5°×2.5° grid, using Dai PDSI data [43] from the NOAA-CIRES Climate Diagnostics Center. Unrotated EOF (empirical orthogonal function) analysis was performed on normalized annual precipitation and PDSI datasets for North America [44,45]. Prior to computing EOFs, both datasets were low-pass filtered twice, using weights of 0.25, 0.50, and 0.25. The effect

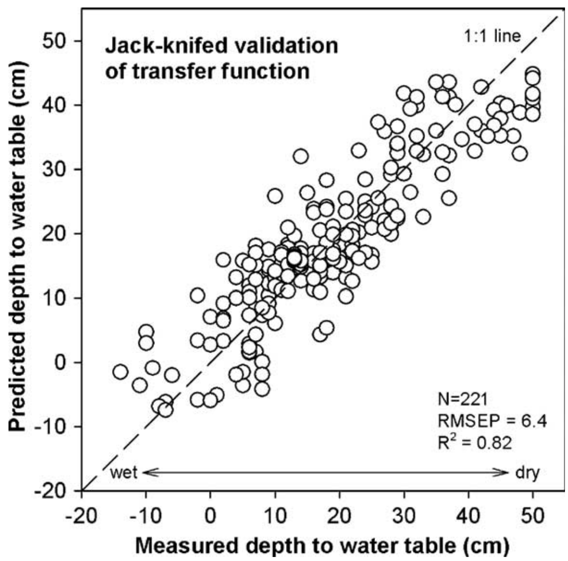

Fig. 2. Jackknifed validation of the transfer function used to infer water-table depth from testate amoeba assemblages, including the root mean square error of prediction (RMSEP) and correlation coefficient.

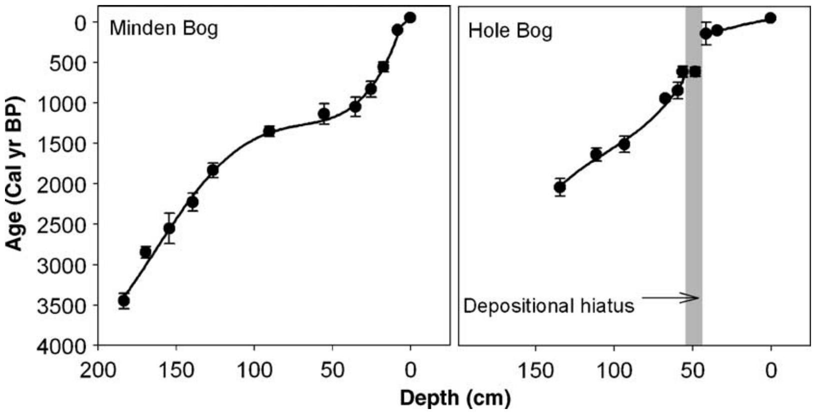

Fig. 3. Age-depth models for the Minden Bog and Hole Bog sediment cores. Note the existence of a sediment hiatus at Hole Bog, which is also supported by poorly preserved testate amoebae and abundant macroscopic charcoal and charred plant remains. Age models were developed by fitting a polynomial to the midpoints of the calibrated age ranges, except above the hiatus at Hole Bog where linear interpolation was used.

of this two-pass filtering was to reduce sub-decadal variability by approximately 65% while retaining the decadal variability and facilitating comparison with the lower frequency bog-inferred hydroclimate records. Correlations between leading EOFs and annual sea surface temperatures (SSTs) were explored using the Hadley SST dataset for the same time period [46]. For comparison of drought records from southeastern Michigan and north-central Minnesota, climate division data were also obtained from the NOAA-CIRES Climate Diagnostics Center. Climate division data are monthly averages of instrumental data from regions within states that are assumed to be climatically uniform. We used Minnesota division 2 and Michigan division 7 for our analyses.

4. Results and discussion

4.1. Temporal resolution, testate amoebae, and paleohydrology

Radiocarbon evidence indicates a sediment hiatus at Hole Bog sometime after 600 BP (Fig. 3). Testate amoebae are poorly preserved and charcoal and charred plant remains are abundant between 55 and 32 cm depth (Fig. 4), suggesting a time interval of frequent fires and little peat accumulation. Because we cannot date the resumption of sediment accumulation with any precision, we focus our comparison of paleohydrological variability on the time interval where the two records overlap with good temporal resolution (i.e., 2100 to 600 BP).

Average deposition times within the Minden and Hole Bog sediment cores between 2100 and 600 BP are 13 and 16 yrs/cm respectively. Both records show high temporal variability in composition of testate amoeba assemblages, and reconstructed water-table depths inferred from these assemblages are correspondingly variable (Figs. 4 and 5). At Hole Bog, inferred drier time periods (i.e., deeper water-table depths) are characterized by assemblages dominated by xerophytic taxa like *Trigonopyxis arcula*, *Hyalosphenia subflava*, and *Centropyxsis arcelloides* type (Fig. 4). Wetter time periods are characterized by relatively mesophytic taxa like *Amphitrema flavum* and *Heleopera sphagni* (Fig. 4). Similar patterns characterize the Minden Bog core (Fig. 5), and are described in more detail elsewhere [9].

4.2. Comparison between sites and to other regions

The hydroclimatic records from Minden Bog and Hole bog show high temporal correspondence ($r = 0.53$), particularly in view of their physical separation of approximately 1000 km (Fig. 6). The highest-magnitude moisture fluctuations in both regions occurred during an interval roughly overlapping with the Medieval Warm Period (MWP), with individual drought events centered on 1000 BP, 800 BP, and 700 BP. These drought events were associated with major ecological changes in southeastern Michigan, including abrupt changes in vegetation and fire regime, and similar ecological changes are recorded to the east in southern Ontario [9].

A running correlation (500-yr window) between the two records from 2100 to 600 BP, after interpolating each record to 15-yr intervals, reveals that the strong overall correlation is primarily due to the high-magnitude moisture fluctuations and centennial-scale trends that occurred between about 1000 and 700 BP, as well as during an earlier interval from 1900 to 1600 BP. During the intervening time period of lower variability

Table 1
AMS radiocarbon dates obtained from the Hole Bog (H) and Minden Bog (M) sediment cores

Depth (cm)	Material dated	Lab number	^{14}C yr BP	Calibrated yr BP [a]
(H) 41–42	*Sphagnum* moss	GX-30210	90±50	140±140
(H) 48–49	*Sphagnum* moss	GX-30208	640±40	612±55
(H) 56–57	*Sphagnum* moss	GX-30206	660±50	611±65
(H) 59–60	*Sphagnum* moss	UGA-10731	950±40	846±103
(H) 67–68	*Sphagnum* moss	GX-30209	1030±30	943±30
(H) 93–94	*Sphagnum* moss	GX-30207	1610±40	1507±98
(H) 111–112	*Sphagnum* moss	GX-30211	1740±30	1635±79
(H) 135–136	*Sphagnum* moss	UGA-10732	2080±40	2041±108
(M) 17–18	*Sphagnum* moss	GX-28721	490±40	557±61
(M) 25–26	*Sphagnum* moss	GX-28472	920±40	831±98
(M) 35–36	*Sphagnum* moss	GX-27974	1110±40	1050±117
(M) 55–56	*Sphagnum* moss	GX-27642	1220±40	1137±126
(M) 90–91	*Sphagnum* moss	GX-28473	1470±40	1355±62
(M) 126–127	*Sphagnum* moss	GX-27222	1910±30	1834±90
(M) 139–140	*Sphagnum* moss	GX-28474	2210±40	2228±110
(M) 154–155	*Sphagnum* moss	GX-27975	2510±30	2553±189
(M) 169–170	*Sphagnum* moss	GX-28475	2750±30	2849±73
(M) 183–184	*Picea* needles	GX-27641	3200±40	3449±95

[a] Mean and 95% probability interval are shown (38).

(1600–1100 BP) the correlation between the two sites weakens, and even becomes slightly negative (Fig. 6).

The pattern of higher correlation between the sites during time periods of high-magnitude fluctuations is also observed in instrumental drought records from the two regions (Fig. 7). For example, although the annual correlation between PDSI records of the two regions for the last century is modest (r=0.40), during periods of decadal-scale, high-magnitude moisture fluctuations (e.g., 1930–1950), the two regions have been more strongly correlated (Fig. 7). During time periods of lower variability, the annual correlations have weakened considerably (Fig. 7). After applying the low-pass filtering to the two series to decrease interannual variability, the correlation also improves (r=0.49). The consistent pattern in the temporal correlation of the two sites at two very different timescales (past 100 and past 2000 yr), characterized by higher correlations during times of high-magnitude variability, suggests that extreme decadal to centennial-scale moisture fluctuations tend to be geographically coherent.

The large moisture fluctuations documented in the hydroclimate records of both Minden and Hole Bog probably also affected a large portion of the mid-continent. The widespread geographic extent is especially clear for the series of droughts that occurred between 1000 and 700 BP. A variety of proxy-climate records indicate that these droughts affected much of the western United States and Great Plains [3,47–50] (Fig. 6). For example, widespread activation of the Nebraska Sand Hills occurred between 1000 and 700 BP [49,50], and extensive dune activity is also recorded at other sites on the Great Plains [48]. Diatom-inferred salinity records from the northern Great Plains also suggest brief periods of low lake level between 900 and 600 BP [4], as do ostracode–Mg/Ca ratios in lake sediments [51,52]. Increased influx of aeolian-derived materials is evident in sediments of Elk Lake in north-central Minnesota at 800 BP [53] (Fig. 6).

Droughts between 1000 and 700 BP also extended across much of the western United States, where tree-ring records have clearly documented four multi-decadal drought events [3]. Three of these events correspond in time to the three events identified in the Minden and Hole Bog records (Fig. 6). The eastward extent of these drought events is not clear because there are few drought-sensitive records from eastern North America with multidecadal resolution. Reconstructions of spring precipitation from 30-yr smoothed tree ring series in the southeastern United States do show the highest magnitude and most spatially coherent fluctuations of the last 1000 yrs during the period 1000 to 700 BP [54,55]. However, the inverse correlation between spring and summer precipitation in this region makes interpretation difficult [54,55]. Paleoclimate records from sediments in the Chesapeake Bay also suggest a major drought event centered on 1000 BP [56,57]. Clearly the droughts between 1000 and 700 BP were widespread in the western United States and mid-continent, and they may have extended well into eastern North America.

The droughts between ca. 1900 and 1600 BP in the Minden Bog and Hole Bog records have not been as widely documented as the later droughts because few high-resolution records date to this earlier time period. The temporal coherence between the bog records may

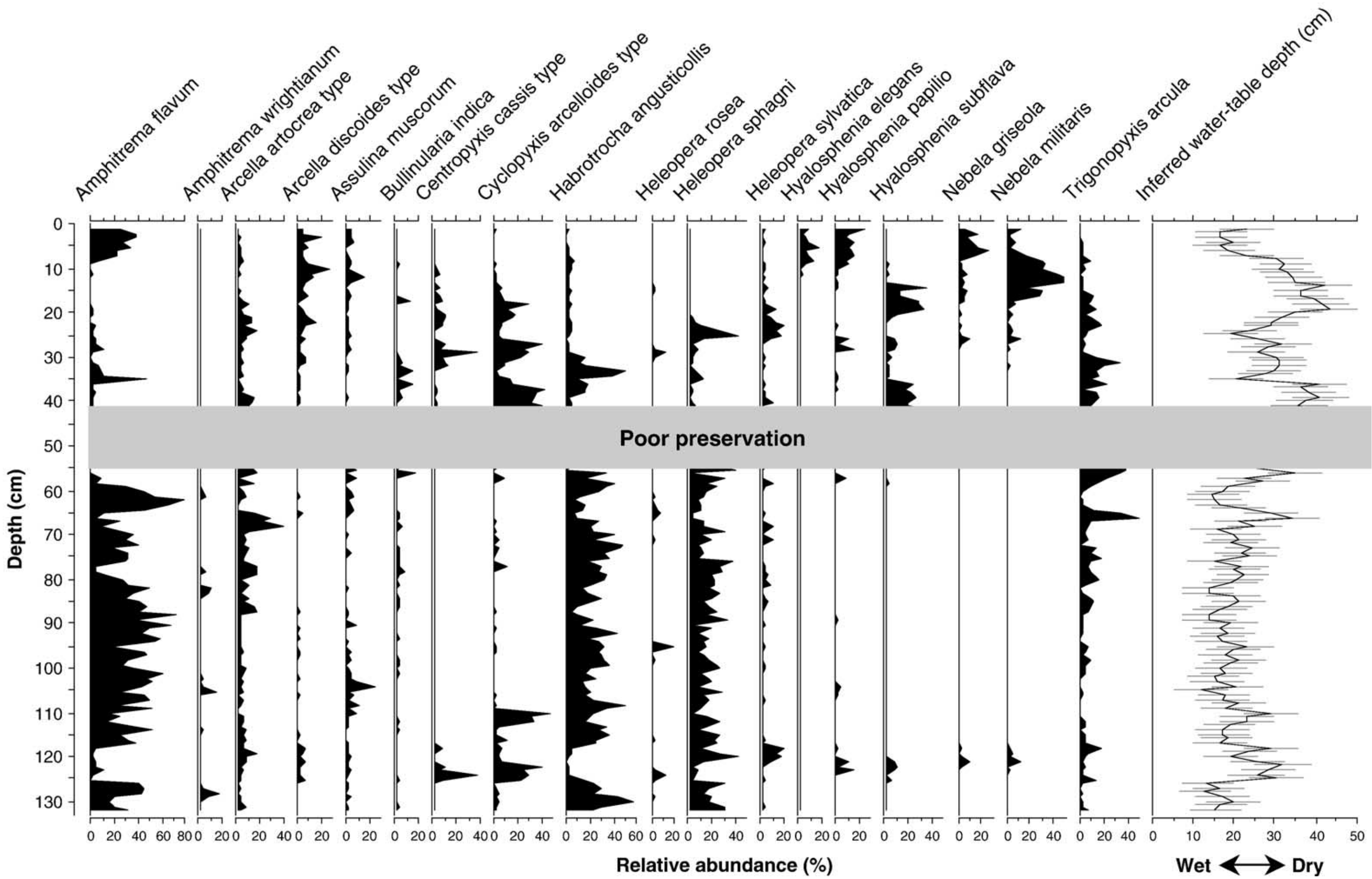

Fig. 4. Relative abundance of dominant testate amoeba taxa (>15%) and inferred changes in water-table depth plotted against depth in the Hole Bog sediment core.

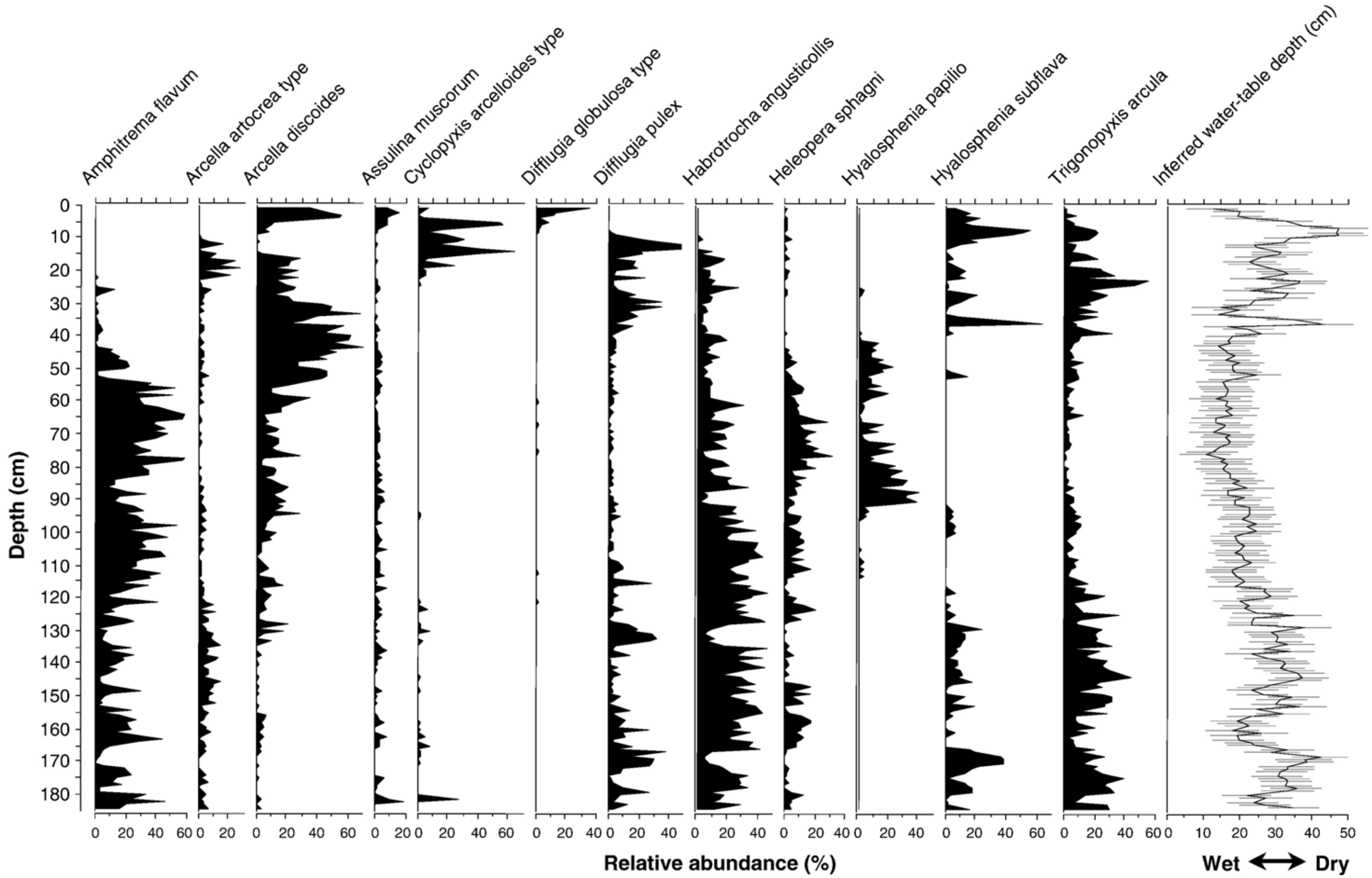

Fig. 5. Relative abundance of dominant testate amoeba taxa (>15%) and inferred changes in water-table depth plotted against depth in the Minden Bog sediment core.

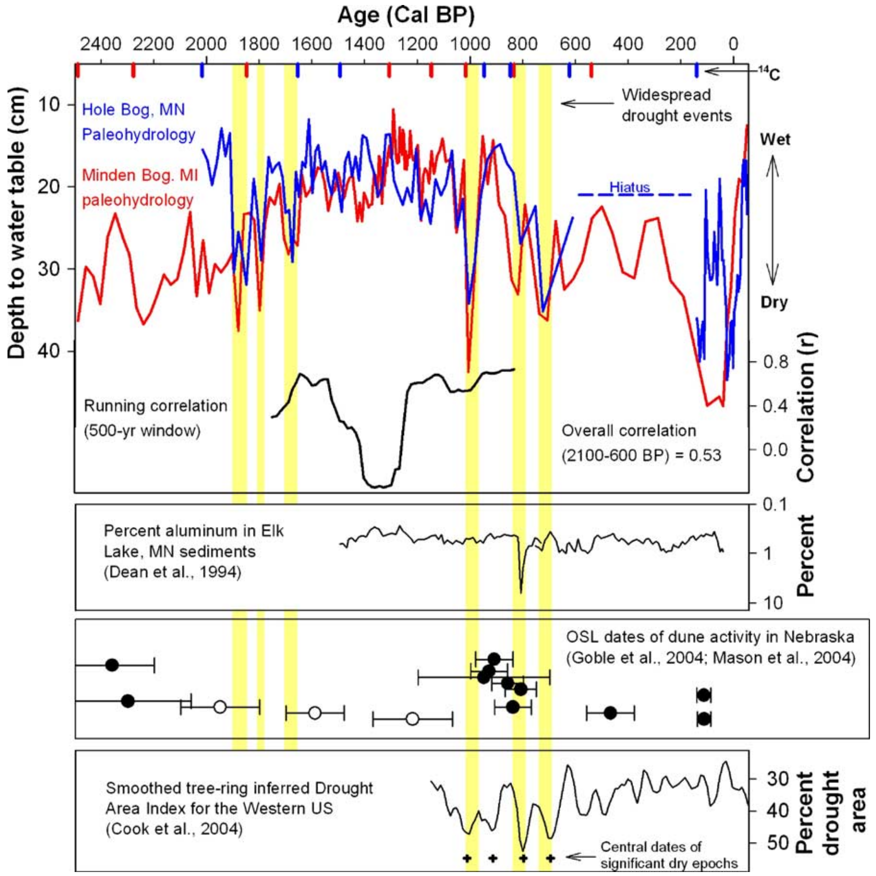

Fig. 6. Upper panel shows a comparison of hydroclimate histories reconstructed from Hole Bog, MN (Blue) and Minden Bog, MI (red) for the past 2500 yrs. Correlation between the two records ($r = 0.53$) was calculated after interpolating to 15-yr intervals ($n = 93$). A running correlation of the two records (500-yr window) reveals that the strong overall correlation from 2100 to 600 BP is primarily the result of extreme and spatially extensive moisture fluctuations between 1900–1600 and 1100–600 BP. Lower panels show comparison of the drought events at Hole and Minden Bog to other selected other records of drought, with records arranged in the same direction with respect to moisture changes (dry = down, wet = up). For the records of dune activity in the Nebraska sand hills, open circles indicate times where the original authors interpreted the dates as corresponding to minor or localized dune activity, and bars indicate 1 sigma range.

imply a pattern of widespread drought similar to the droughts between 1000 and 700 BP, but droughts between ca. 1900 and 1600 BP may not have affected areas outside of the western Great Lakes region, if different underlying controls were operating. More high-sensitivity, high-precision, and unequivocal records of hydroclimate are needed for this time period in the Great Plains and Rocky Mountains.

4.3. Potential causes of widespread drought events in the mid-continent

Many widespread droughts during the last century have been linked to internal dynamics of the coupled ocean–atmosphere system, particularly variability in SSTs and the associated downstream changes in atmospheric circulation [7,13–15,58]. By assuming that past mechanisms of drought were similar to those of the past century, we can use the instrumental record of climate to develop hypotheses regarding the internal dynamical mechanisms of earlier droughts. We used EOF analysis to identify dominant modes of multiyear to decadal drought variability in North America during the past century to determine if any specific patterns of widespread drought have characterized the climate system during this time.

Our EOF analyses revealed a dominant mode of drought variability (the first EOF) characterized by a dipole pattern with opposite signs in high and mid latitudes, and a large region of like-sign change across the 48 states (Fig. 8). Although the first EOFs of PDSI and precipitation differ in minor ways, both EOFs are consistent with widespread drought affecting much of the continental United States. These EOFs explain about

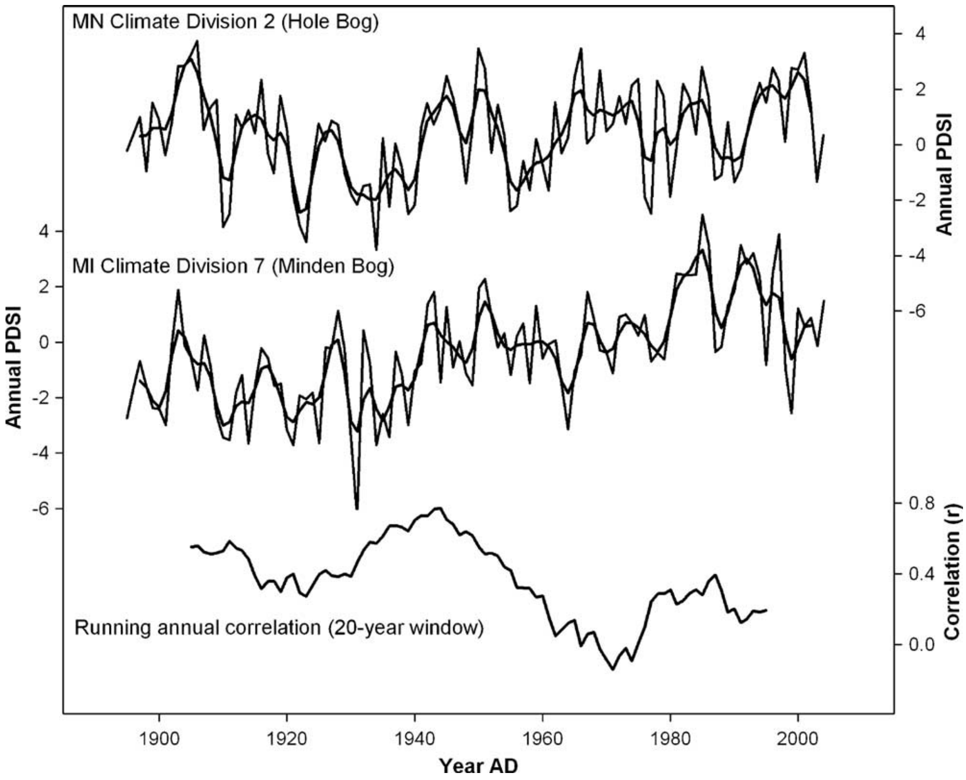

Fig. 7. Comparison of the instrumental record of annual drought (PDSI, Palmer drought severity index) from the climate divisions where Minden and Hole Bogs are located. Annual data and a low-pass filtering (applied twice, see text) are shown. Correlations (r) between the two records are 0.40 and 0.49 for the annual and low-pass filtered series respectively. A running annual correlation of the two records (20-yr window) reveals similar temporal patterns as the running correlation of the paleohydrological records (Fig. 6), with the annual correlation stronger during decadal-scale high-magnitude moisture fluctuations.

20% of the precipitation/drought variability. The spatial patterning of drought between 1000 and 700 BP is consistent with this mode of variability in the mid-latitudes, although more high-resolution records of moisture variability are needed to fully assess the overall similarity, particularly at high latitudes and in eastern North America. Correlations between SSTs and these EOFs suggest strong teleconnections between moisture variability in North America and SSTs in the adjacent oceans (Fig. 8). In particular, both a) low SSTs in the equatorial Pacific and along the southwestern coast of North America and b) warmth in the mid-latitude North Pacific and the North Atlantic are associated with widespread drought. These spatial patterns are similar to the negative phase of the Pacific decadal oscillation (PDO) and the warm phase of the Atlantic multidecadal oscillation (AMO) [6,59]. The correlation between these SST anomalies and the widespread pattern of drought is consistent with other work describing these relationships, where widespread drought has been correlated with anomalously cool tropical Pacific SSTs, warmth in the mid-latitudes of the North Pacific and the negative phase of the PDO, and warmth in the North Atlantic [6,7,13–15,58,59].

Our results are consistent with the suggestion of Cook et al. [3] that the droughts in the western United States during the MWP may have resulted from anomalously cool eastern tropical Pacific sea-surface temperatures and the associated change in moisture transport and precipitation-generating mechanisms in the southwestern United States. A cool tropical Pacific has clearly been linked in the instrumental record to drought in the southwestern United States, and proxy SST records from corals in the east-central tropical Pacific suggest cooler SSTs between 1000 and 700 BP [60]. However, our data indicate that the MWP droughts extended well into the Great Lakes region. Other factors besides tropical Pacific dynamics were therefore probably involved in these widespread moisture deficits.

We hypothesize that SST anomalies in the Tropical Pacific, North Pacific, and North Atlantic had a combined influence on North American climate during the past millennium, leading in at least three occasions (1000, 800, and 700 yr BP) to downstream changes in

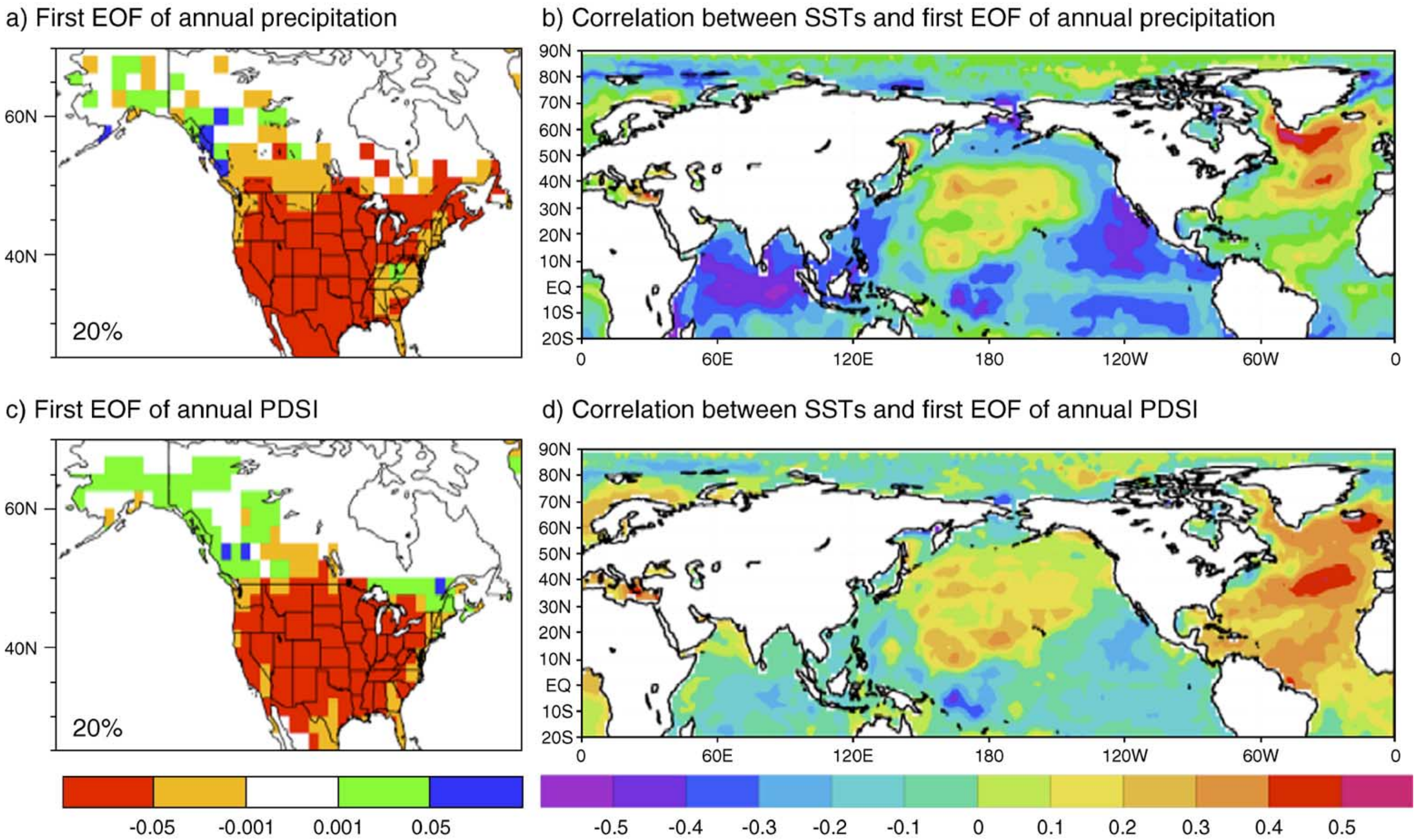

Fig. 8. Dominant modes of variability in the low-pass filtered instrumental record (see text) of a) precipitation and c) drought from 1900 to 1998 AD indicated by EOF analysis. The first EOFs of precipitation and PDSI each explain 20% of the variability in the instrumental record, and both indicate a similar spatial patterning of moisture variability. Correlations (r) between sea surface temperatures (1900–1998 AD) and the first EOFs of b) precipitation and d) PDSI suggest that this pattern of moisture variability is related to dynamics of the coupled ocean–atmosphere system.

atmospheric circulation patterns that promoted widespread drought, perhaps in a spatial pattern similarly widespread as the dominant mode of multiyear to decadal-scale moisture variability during the past century (Fig. 8). SST anomalies in the extratropics of both the Atlantic and Pacific Oceans have been linked to widespread mid-continental drought in the instrumental record [7,58] and some of these changes have been shown to modulate the effects of tropical Pacific variability [6,7]. Similar patterns and dynamics may have occurred during the MWP drought events. Moreover, mid-continent warming can lead to increased evaporation, decreasing soil moisture and enhancing summer dryness [61], and similar feedbacks may have amplified the MWP droughts.

The ultimate causes of the MWP droughts and the eastern equatorial Pacific cooling between 1000 and 700 BP are uncertain and may involve both internal dynamics and external forcing changes. Some evidence exists for increased solar activity or decreased volcanism during the MWP [62], and these changes may have amplified a mode of variability characterized by widespread drought. For example, model-simulated warming in the western and central tropical Pacific forced by increased solar irradiance and reduced volcanism produced enhanced tropical easterlies and increased upwelling, consistent with an observed cooling during the MWP in the eastern tropical Pacific [3,63]. However, other modeling studies suggest that warming in the extratropics, which would also be expected with increased solar irradiance and/or decreased volcanism, might lead to warmer eastern tropical Pacific SSTs [64]. Warming in the North Atlantic region might also promote the warm phase of the AMO, an index based on the SST averaged over of the entire North Atlantic that has been linked to drought in the mid-continent [6,7]. The magnitude of external forcing changes during the past 1000 yrs is still uncertain, and the potential climatic response to changes in both the tropics and extratropics needs to be studied with the full range of available climate models.

Additional high-resolution records of water balance are needed from consistent data sources in continental regions, particularly from high latitudes and in eastern North America, to delineate spatial patterns of moisture variability associated with the widespread droughts between 1000 and 700 BP, as well as other large drought events of the late Holocene. Peatland archives show great promise as sources of information on these past drought events, particularly in humid, continental regions. Once spatiotemporal patterns can be confidently delineated, they could be used in conjunction with the developing network of proxy-SST records, estimates of past external forcing changes, and dynamic modeling studies, to fully assess the causes of widespread North American drought at timescales ranging from decadal to millennial.

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