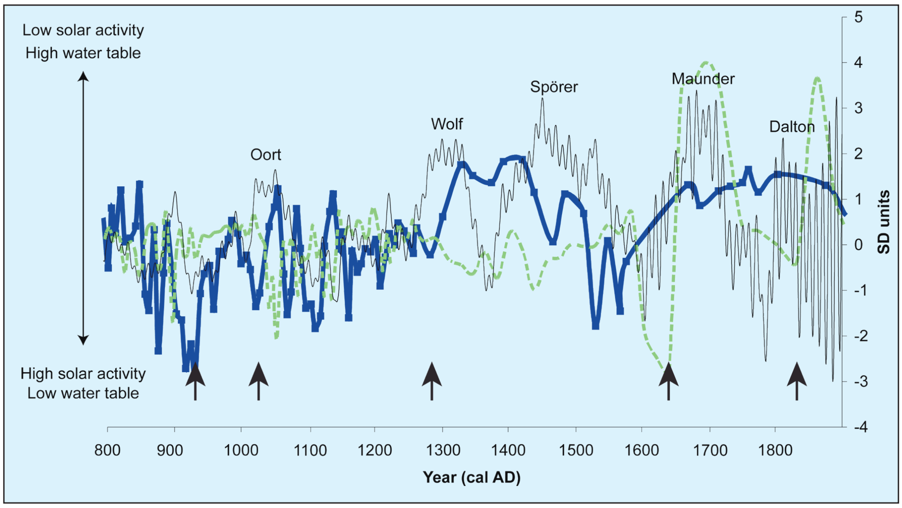

*Figure 2: Focus Interval III (cal a AD 800–1800) of the ACCROTELM project, showing proxy-climate data from the Danish bog site: **Blue line** = normalized testate amoebae water table reconstruction (inverted); **Green dashed line** = plant macrofossil Dupont wetness index; **Gray line** = normalized ^{14}C relative production rate (q). Arrows indicate start of significant rises in water table. Historical solar minima are indicated. Figure adapted from Mauquoy et al., 2008. For further discussion of solar-climate relationships in peat records, see van Geel and Mauquoy, this issue.*

organic and elemental content (de Jong et al., 2006; De Vleeschouwer et al., 2009), and research continues to extract a separate temperature signal from biomarkers.

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Using peatland archives to test paleoclimate hypotheses

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A network of peatland surface-moisture reconstructions is providing a richly detailed, synoptic-scale perspective on past hydroclimate variability in many regions, well suited to investigate the spatial structure and dynamics of past hydroclimate changes.

Synoptic networks of proxy records of hydroclimate variation provide an important means for identifying long-term relationships between oceanic forcing and continental-scale patterns of decadal- to centennial-scale drought variability, and for assessing responses of the coupled ocean-atmosphere system to changes in external forcing. Tree-ring records provide the gold standard in this context, because of their demonstrated hydroclimatic sensitivity, temporal precision and accuracy, robustness of proxy inferences, and widespread distributions in space. However, tree-ring records are limited in temporal depth and spatial coverage, and inferences can be confounded by other factors, particularly in humid regions. Alternative archives are desirable to extend temporal depth, corroborate tree-ring inferences, and add complementary information and sensitivity at different time and spatial scales. Among the alternative archives are ombrotrophic peatlands, which are sensitive to hydroclimatic variation at decadal timescales, capable of sub-centennial chronological precision and accuracy, contain multiple paleohydrological and paleoclimatic proxies (Fig. 1a), and are widely distributed at mid- to high latitudes in the northern and southern hemispheres. Comparison of peatland proxies with instrumental records

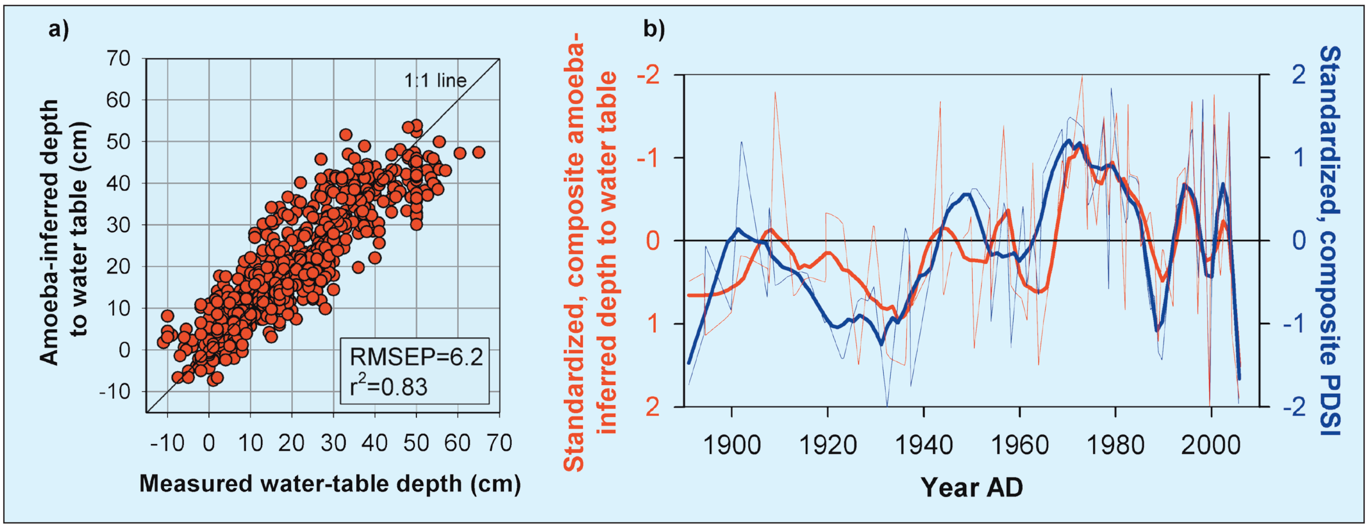

*Figure 1: Validation of the hydrologic and climatic sensitivity of peatland surface-moisture reconstructions. **a)** Cross-validation of testate amoeba transfer function for mean annual water-table depth, based on over 650 samples from North American peatlands (modified from Booth, 2008). **b)** Comparison of a composite testate amoebae-inferred paleohydrological reconstruction (depth to water table) derived from three ^{210}Pb-dated peatland records (red lines) and instrumental records of Palmer Drought Severity Index (PDSI; blue lines) (data from Booth, 2010). Thick, solid lines show approximately decadal-scale smoothing of the composite datasets (thin lines).*

confirms the robustness and temporal precision of paleoclimatic inferences (Fig. 1b).

Over the past few years, significant advances have been made in our understanding of the response of peatland systems to climate changes, facilitating the climatic interpretation of peatland paleoenvironmental records. Peatland surface-moisture reconstructions generally reflect the length and severity of the summer moisture deficit, which in ombrotrophic peatlands is primarily controlled by summer precipitation (Charman, 2007; Charman et al., 2009). Temperature effects are secondary, manifested through evapotranspiration (Charman, 2007; Charman et al., 2009). Not surprisingly, good relationships exist between surface-moisture reconstructions and integrative hydroclimate indices such as the Palmer Drought Severity Index (PDSI) (Booth, 2010). However, because peatlands may undergo long-term developmental changes unrelated to climate (Charman et al., 2006), and are adaptive systems with internal processes that confer some degree of self-regulation (Dise, 2009), paleoclimate responses may not be recorded equally strongly at all temporal frequencies. For example, millennial and multi-millennial changes in surface moisture vary greatly among nearby sites in the United Kingdom (Charman et al., 2006), although shorter-term perturbations are generally coherent there and elsewhere in Europe and North America (Booth et al., 2006). Therefore, the hydroclimatic signal in peatland records may be most robust at multi-decadal to sub-millennial timescales.

Investigating drought climatology

An emerging network of peatland records in North America is providing new perspectives on moisture variability in humid regions, complementing and extending the tree-ring record from semi-arid regions, as well as hydroclimate histories derived from other natural archives. These efforts are motivated by the revelation that characteristic spatial modes of drought and precipitation variability, often with important centers of action in humid regions, have been driven in part by oscillations in sea-surface temperature (SST) anomalies sometimes spanning decades or more (Dai et al., 2004; McCabe et al., 2004, 2008; McCabe and Palecki, 2006; Seager et al., 2008; Woodhouse et al., 2009) (Fig. 2). Modeling efforts underscore the importance of these teleconnections, and are beginning to reveal potential underlying mechanisms (Sutton and Hodson, 2005, 2007; Seager et al., 2007). However, our knowledge of SST variability and associated teleconnections is primarily derived from a mere century of instrumental records, and rising global temperatures are expected to alter the oceanic forcing of drought patterns in the coming decades (Jansen et al., 2007). In addition, the relative importance of oceanic forcings (i.e., Atlantic vs Pacific influences) on North American hydroclimate is still unclear (Sutton and Hodson, 2005; McCabe and Palecki, 2006; Cook et al., 2007; Goodrich, 2007; Graham et al., 2007; Seager et al., 2007; Feng et al., 2008; McCabe et al., 2008), as are relationships to synoptic modes of atmospheric circulation (Trouet et al., 2009; Helama et al., 2009) and external forcing (i.e., solar variability and volcanism). Delineation of past spatial modes of moisture variability, when interpreted in conjunction with the growing body of proxy SST records and estimates of changes in external forcing, provides a means to assess long-term dynamics of the coupled ocean-atmosphere system.

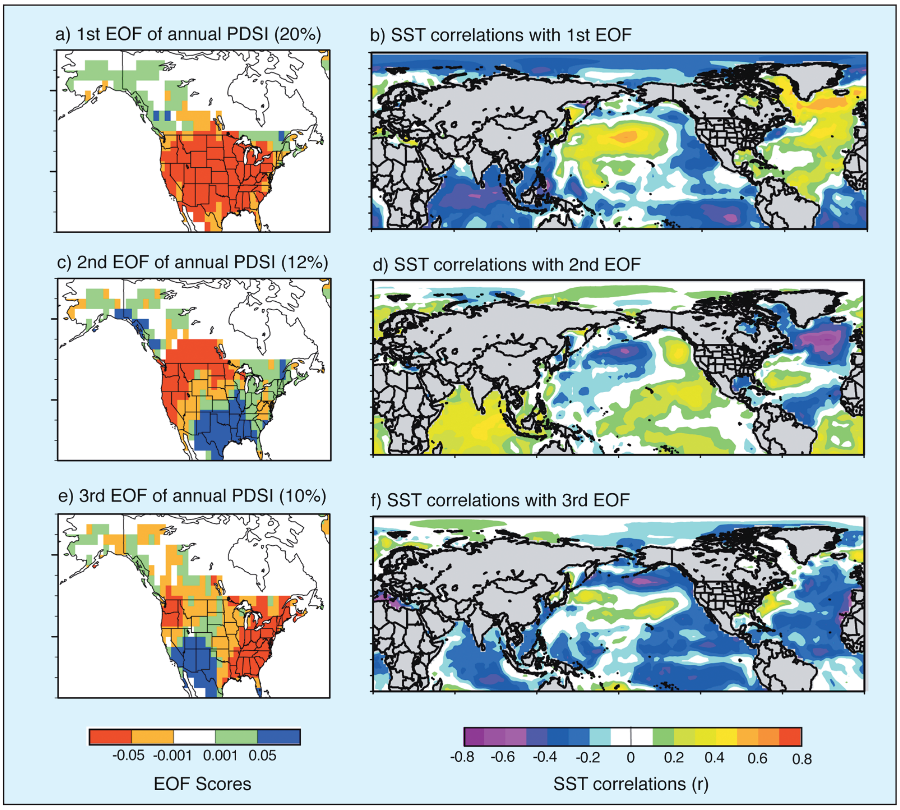

*Figure 2: Natural modes of variability in low-pass filtered Palmer Drought Severity Index (PDSI) data from North America over the last century (1900-1998) as indicated by Empirical Orthogonal Function (EOF) analysis (**a, c, e**) (methods detailed in Booth et al., 2006). Percent variance explained by each EOF is indicated. Correlations between sea surface temperatures (SSTs) and the three dominant EOFs indicate SST patterns associated with dominant modes of hydroclimate variability (**b, d, f**). A network of peatland records has been designed to test the hypothesis that similar modes of drought variability have affected North American hydroclimate during the past several thousand years, with ongoing work in the Great Lakes region, the Pacific Northwest, and northeastern North America.*

When viewed along with the tree-ring record and other natural archives, peatland reconstructions from the Great Lakes region of eastern North America reveal that many high-magnitude fluctuations in water balance during the past 3 ka were spatially extensive, extending from the western United States into eastern North America (Fig. 3; Cook et al., 2004; Mason et al., 2004; Booth et al., 2006; Shuman et al., 2009). Increased multidecadal- to centennial-scale hydroclimate variability also characterized intervals with widespread drought (Fig. 3a). These widespread droughts may represent amplification or persistence of modes of decadal- to multidecadal hydroclimate variability similar to that of the last century (Fig. 2). For example, peatland records clearly indicate that Medieval Climate Anomaly (MCA) droughts, which have been well documented in the western US and Great Plains (central North America) (e.g., Cook et al., 2004; Mason et al., 2004; Daniels and Knox, 2005; Sridhar et al., 2006; Meko et al., 2007; Miao et al., 2007), also extended deep into the Great Lakes region (Booth et al., 2006; Shuman et al., 2009) (Fig. 3a). The widespread pattern of drought is similar to a mode of variability experienced during the 20th century (Fig. 2a), although more records are needed to fully test this hypothesis, particularly from humid regions at mid- to high-latitudes.

Tree-ring based reconstructions of PDSI from the Great Lakes region do not clearly record the MCA droughts (Herweijer et al., 2007); therefore, hypotheses on the mechanisms underlying these events have tended to focus on atmospheric and ocean dynamics that induce drought in western North America only, such as prolonged La Niña-like conditions in the tropical Pacific (Cook et al., 2004, 2007). Although

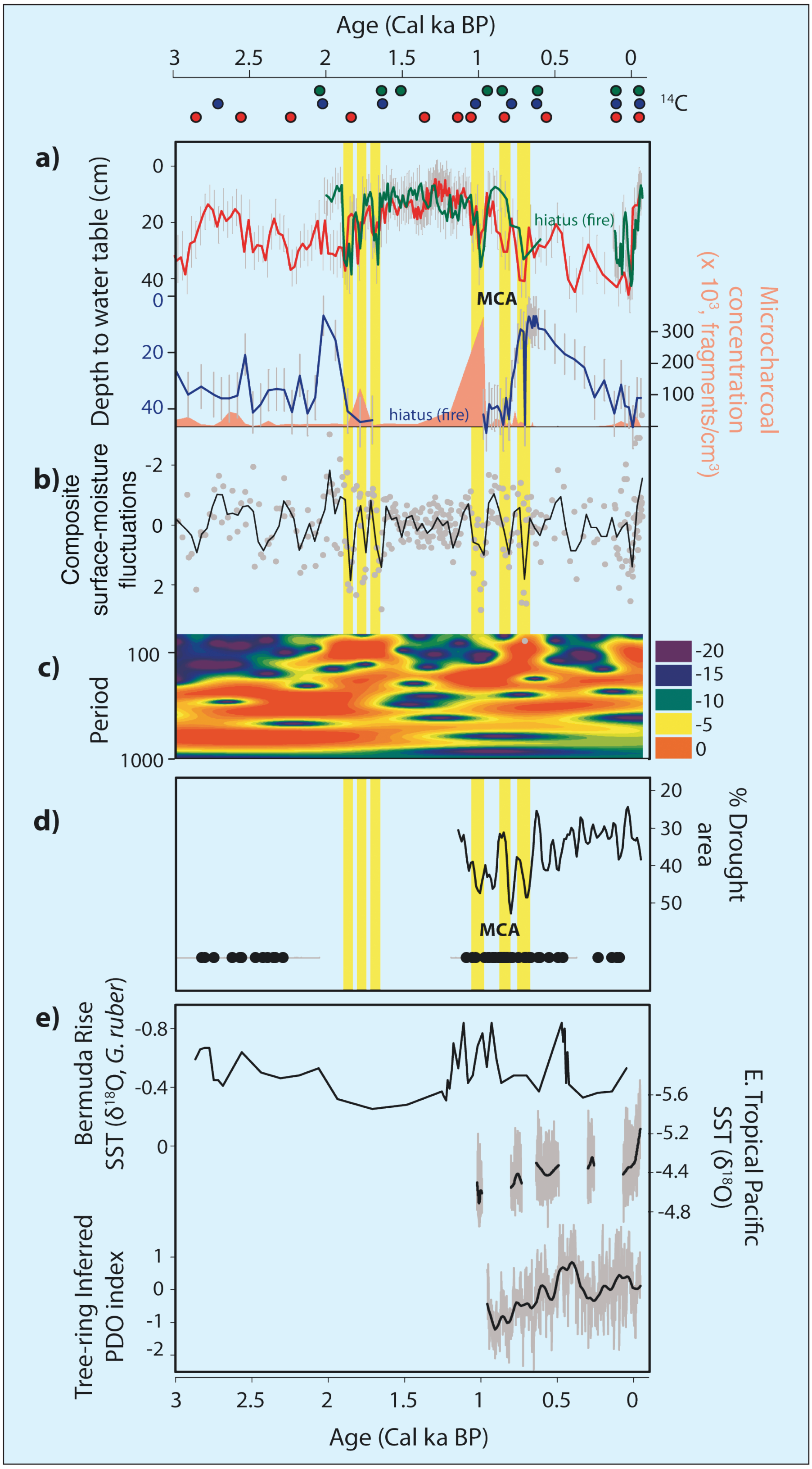

*Figure 3: **a**) Ombrotrophic peatland archives of late Holocene environmental variability in the Great Lakes region (eastern N. America). Green: Hole Bog in north central Minnesota, Blue: Irwin Smith Bog in northeast lower Michigan, Red: Minden Bog in southeast Michigan (Booth et al., 2006, unpublished). Radiocarbon dates indicated at top and color-coded to match sites. All reconstructions based on testate amoebae (see Booth and Jackson, 2003; Booth et al., 2006). Bootstrapped error bars in gray (n=1000). Yellow bars indicate high-magnitude, multidecadal drought events that occurred at all three sites. A peat fire at ~1 ka BP removed lower peat from Irwin Smith Bog, micro-charcoal concentrations are shown in pink. **b**) Composite record from the three sites developed by removing the long-term patterns that may be unrelated to climate (Charman et al., 2006), standardizing the three datasets (gray dots; standardized units), and calculating a 50-year moving average (black line). **c**) Wavelet analysis of composite record highlighting increased centennial and sub-centennial variability during drought intervals. **d**) Tree-ring record of drought in western USA (black line; Cook et al., 2004) and records of dune activity (e.g., aeolian sand movement) on the Great Plains (black dots are activity dates with error bars; Goble et al., 2004; Mason et al., 2004; Miao et al., 2007), highlighting the widespread droughts of the Medieval Climate Anomaly (MCA). **e**) Atlantic (Keigwin, 1996) and Pacific (Cobb et al., 2003; MacDonald and Case, 2005) proxy SST records, from which preliminary patterns suggest that the MCA droughts may have resulted from the combined influence of anomalous Atlantic and Pacific SSTs, perhaps also linked to changes in the North Atlantic Oscillation (Trouet et al., 2009; Helama et al., 2009), as suggested by modeling studies and historical patterns (Fig. 1a, b). PDO = Pacific Decadal Oscillation.*

the eastward and northward extent of the droughts in North America is still unclear, the occurrence of significant droughts in the peatland records from the Great Lakes suggests that additional hypotheses regarding mechanisms and dynamics should be explored, including modulation of Pacific influences by SST variability in the Atlantic source region. Recently, MCA modeling efforts have started to incorporate this idea (Seager et al., 2007; Feng et al., 2008). For example, using a set of modeling experiments, Feng et al. (2008) found that cold eastern Tropical Pacific SST anomalies could explain the intensity of the MCA droughts, a warm North Atlantic could regulate the geographic extent of the droughts, and the combined influence of SST anomalies in both basins was necessary to explain MCA drought severity and persistence. Similar patterns have been associated with widespread mid-continental drought during the past century (Fig. 2a, b) (McCabe et al., 2004, 2008; Booth et al., 2006). Continued development of the peatland network is currently underway in North America and in other circum-boreal regions of the Northern Hemisphere, and coupled with analyses of instrumental data, data-model comparisons, and dynamic modeling experiments will allow critical testing of this and other hypotheses on the mechanisms and dynamics of widespread, prolonged drought.

Acknowledgements

Research supported by grants from the National Science Foundation to Booth (EAR-0902441, ATM-0625298) and Jackson (ATM-0402660).

Data

Minden Bog testate amoeba data available from NOAA Paleoclimatology database (www.ncdc.noaa.gov/paleo/pubs/booth2003/booth2003.html). Other data will be made available via this database and the Neotoma Paleoecology Database (www.neotomadb.org/).

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