Hydroclimate of the northeastern United States is highly sensitive to solar forcing

Jonathan E. Nichols[1,2,3] and Yongsong Huang[1]

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[1] Dramatic hydrological fluctuations strongly impact human society, but the driving mechanisms for these changes are unclear. One suggested driver is solar variability, but supporting paleoclimate evidence is lacking. Therefore, long, continuous, high-resolution records from strategic locations are crucial for resolving the scientific debate regarding sensitivity of climate to solar forcing. We present a 6800–year, decadally-resolved biomarker and multidecadally-resolved hydrogen isotope record of hydroclimate from a coastal Maine peatland, The Great Heath (TGH). Regional moisture balance responds strongly and consistently to solar forcing at centennial to millennial timescales, with solar minima concurrent with wet conditions. We propose that the Arctic/North Atlantic Oscillation (AO/NAO) can amplify small solar fluctuations, producing the reconstructed hydrological variations. The Sun may be entering a weak phase, analogous to the Maunder minimum, which could lead to more frequent flooding in the northeastern US at this multidecadal timescale.

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1. Introduction

[2] The influence of solar variability on climate has been investigated for decades, but numerous questions remain [*Lean*, 2010]. While cosmogenic nuclide production (^{10}Be and ^{14}C) reconstructions have provided detailed records of solar variability during the Holocene [*Solanki et al.*, 2004; *Steinhilber et al.*, 2009], the climate response to these variations are poorly defined. Many paleoclimate records display significant similarities to solar variability during the Little Ice Age (LIA), and Medieval Climate Anomaly (MCA), times of low and high solar irradiance, respectively [*Zhang et al.*, 2008; *Richey et al.*, 2007], but the records do not typically extend beyond the past two millennia [*Ammann et al.*, 2007; *Hodell et al.*, 2001]. Attribution of the LIA in particular to solar variation is also confounded by evidence for volcanic forcing as a driver [*Shindell et al.*, 2003]. Other records have identified significant periodicity similar to that of radionuclide records, but do not always vary consistently with the solar irradiance changes at both century and millennial time scales [*Asmerom et al.*, 2007; *Zhao et al.*, 2010]. The difficulty in obtaining a long term paleo-proxy correlation with total solar variations most likely results from the small amplitude (0.05% to 0.5%, depending on wavelength) of solar irradiance changes, too small to dominate other climate forcings and yield large and readily recognizable climate responses in the absence of strong regional amplification mechanisms [*Lean*, 2010]. One solution to this ambiguity of solar forced climate response is to acquire paleoclimate records from sites where solar forcing is potentially the dominant driver of a particular climate variable over other forcings. Climate response to the solar signal would then be sufficiently strong at both short and long time scales, allowing a more conclusive assessment of solar impact on climate.

[3] Here we present a high-resolution record of paleohydrology from TGH, an ombrotrophic peatland in coastal Maine, northeastern US (Figure S1). Our data record relative droughts and pluvials from the Northeastern US, displaying centennial and millennial-scale variations in solar forcing, as well as prominent solar cyclicity. GCM simulations have suggested that the pole-to-equator pressure gradient is sensitive to solar forcing through an amplification mechanism involving changes in both stratospheric ozone and tropical convection [*Meehl et al.*, 2009; *Emile-Geay et al.*, 2007]. These changes in pressure gradient in the mid- to high latitudes are described using two indices, the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO), which measure the relative strength of the polar vortex and the pressure difference between the Atlantic subtropical high and the subpolar low respectively. Variations in the strength of these atmospheric systems may be a critical conduit for the solar impact on the climate of the northeastern US [*Shindell et al.*, 2001; *Trouet et al.*, 2009]. Unfortunately, paleohydrological records with sufficient temporal resolution or length in our study region to test the effects of solar forcing are sparse. Ombrotrophic peatlands, common in northern New England, are extremely sensitive to changes in regional climate and insensitive to changes in local surface water and groundwater hydrology, and have been used extensively for paleoecological and paleoclimatological reconstructions, especially in Europe [*Blackford*, 2000]. Recent studies have shown that the abundances of leaf waxes of *Sphagnum* and vascular plants, along with their hydrogen isotopic ratios are excellent recorders of hydroclimatic changes in ombrotrophic bogs [*Nichols et al.*, 2006, 2009; *Zhou et al.*, 2005]. Because they are hydrophobic and absent from below-ground plant parts, plant leaf waxes, when deposited in peatlands, cannot migrate vertically post-production and can therefore provide high-resolution records [*Pancost et al.*, 2002].

2. Methods

[4] Twenty-five radiocarbon age measurements provide a well-constrained, 6800-year chronology of our 5-meter core

[1]Department of Geological Sciences, Brown University, Providence, Rhode Island, USA.
[2]Goddard Institute for Space Studies, New York, New York, USA.
[3]Lamont-Doherty Earth Observatory, Earth Institute at Columbia University, Palisades, New York, USA.

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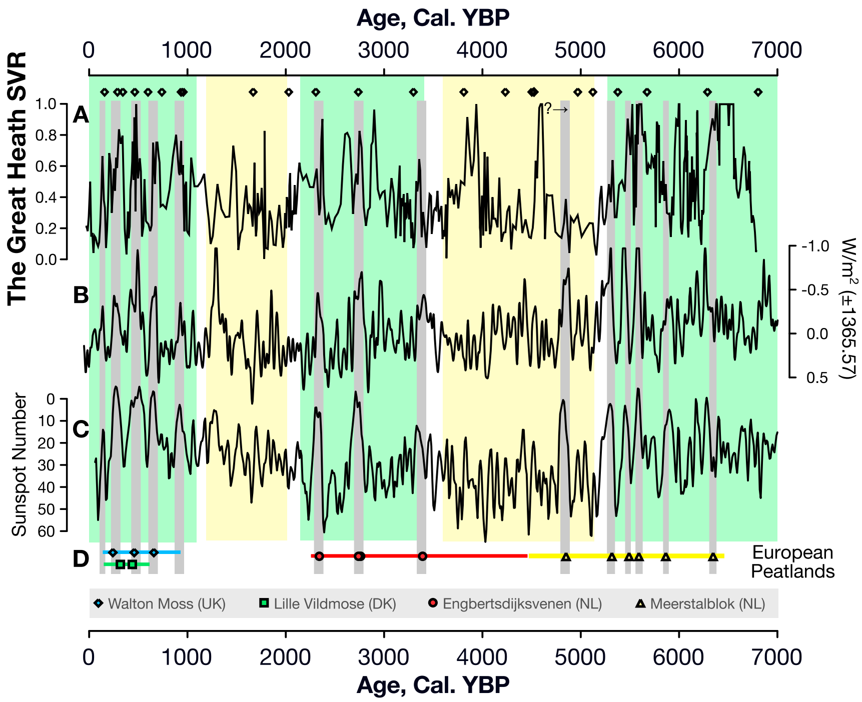

Figure 1. (a) The *Sphagnum*/Vascular Ratio (SVR) from The Great Heath (TGH). Black diamonds indicate radiocarbon age determinations (Table S1). Gray bars are drawn at multidecadal/centennial scale wet conditions concurrent with solar minima as indicated by the records of (b) total solar irradiance change and (c) reconstructed sunspot number. (d) A composite of northwestern European peatland-based hydrological records. Horizontal lines indicate the time covered by each peat record, while markers indicate wet shifts reconstructed using assemblages of plant macrofossils. Color bands, green for pluvial and yellow for drought, indicate millennial scale hydrological periods based on the paleolimnological information displayed in Figure 3.

(see auxiliary material for details on age-depth modeling).[1] We measured relative abundances and stable hydrogen isotope ratios of leaf wax compounds (see auxiliary material for detailed methods), and computed *Sphagnum*/Vascular Ratio (SVR) at one centimeter (~decadal) resolution. SVR is a rescaling of a ratio of biomarker *n*-alkanes and is indicative of the relative productivity of wet-loving *Sphagnum* (represented by C_{23} *n*-alkane) and dry-tolerant vascular plants (represented by C_{29} *n*-alkane) [*Nichols et al.*, 2006]. We also reconstructed the δD of precipitation using the δD of the vascular plant biomarker, C_{29} *n*-alkane at lower resolution. Peatland water represents the annual average precipitation which is influenced by seasonal rainfall distribution as well as temperature [*Nichols et al.*, 2009].

3. Results and Discussion

[5] Our results show that moisture balance is highly variable at the Great Heath over the past 6,800 years and displays close correspondence between variations of eastern US hydroclimate and solar irradiance changes. Centennial-scale periods of wetter conditions are concurrent with solar minima (Figure 1), established by cosmogenic nuclide proxies [*Solanki et al.*, 2004; *Steinhilber et al.*, 2009]. Further, we find the well-established 205-year solar de Vries cycle present in our record of SVR (Figure 2). SVR is correlated with both cosmogenic nuclide proxies at the 205 and

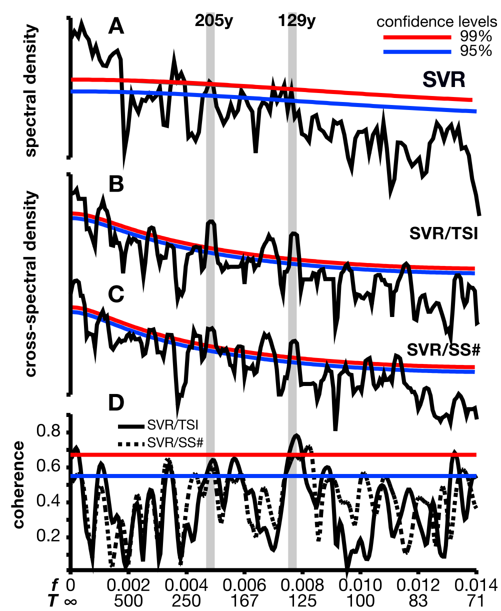

Figure 2. (a) Spectral analysis of SVR from The Great Heath (TGH) and cross-spectrum of SVR with (b) Total Solar Irradiance (TSI), and (c) Sunspot Number (SS#), all performed by the multitaper method. (d) SVR is coherent with both TSI and SS# at the 205 and 129 year cycles. Blue and red lines indicate red-noise 95% and 99% confidence levels respectively. The 88 year cycle, present in the nuclide records, is absent from TGH, likely a result of the uncertainty in the radiocarbon chronology (see supplement).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL050720.

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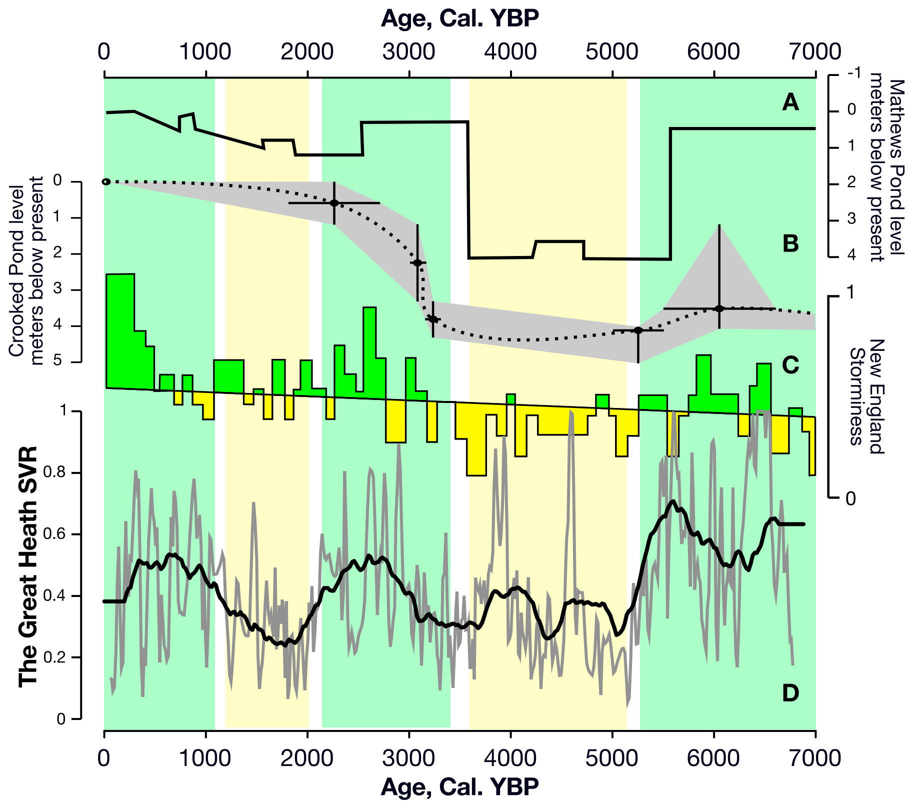

Figure 3. Lake level records from (a) Mathews Pond in northern Maine and (b) Crooked Pond in southeastern Massachusetts, based on a series of radiocarbon dated paleoshorelines. (c) A record of northeast US storminess, is a composite of grain size changes in the sediments of lakes throughout New England and northern New York State. (d) SVR from The Great Heath smoothed to 20 year (gray) and 500 year (black) resolution. Color bands, yellow for drought and green for pluvial, indicate overall moisture balance in the region.

129 year periods (Figure 2). Because our new hydrologic record shares important cyclicity with the records of solar irradiance and is similar at centennial and millennial timescales over the entire length of the record, we interpret the hydrologic changes reconstructed by the SVR to be closely related to the solar irradiance changes. This record is unique in that it displays all of these important qualities, showing the impact of solar variations on a hydroclimatic parameter, rather than temperature, over the past 6,800 years.

[6] Further, we demonstrate that SVR at TGH is recording regional moisture balance by comparison with other, lower resolution paleohydrologic records from New England. We find that the millennial scale variability in the hydrology of TGH is consistent with the established regional hydroclimate of the mid- to late Holocene. Two representative lake level records, from Mathews Pond in northern Maine [*Dieffenbacher-Krall and Nurse*, 2005] and Crooked Pond in eastern Massachusetts [*Shuman et al.*, 2001], are shown in Figure 3. Millennial-scale New England pluvials (periods centering on 6ka, 3ka, and 0.5ka) are characterized by frequent centennial-scale pluvials at TGH, as well as frequent solar minima, while periods of drought (centering on 4.5ka and 1.5 ka) are quiescent with respect to solar variability. Frequent pluvials result in generally wetter conditions; thus, the centennial-scale variations visible at the resolution of TGH record appear as millennial scale variations in New England lake level reconstructions (Figure 3). Similarly, our SVR record from TGH is consistent with a record of New England storminess based on lake sediment grain size [*Noren et al.*, 2002]. During times where New England experiences more mid-latitude cyclones, increased runoff deposits coarse sediment in small lakes. These times are thought to be associated with diminished westerlies produced by the negative phase of the AO [*Noren et al.*, 2002]. We find that times of increasing coarse sediment input to small New England lakes are concurrent with wet times experienced by TGH and with times of frequent solar minima (Figure 3).

[7] We hypothesize that the exceptional sensitivity of the northeastern US to solar variability is at least partly due to the critical role played by changes in the AO/NAO. Model simulations have shown that the MCA (a time of high solar irradiance) was closely associated with a persistently positive NAO, whereas the LIA closely associated with a negative anomaly of the NAO [*Trouet et al.*, 2009]. Therefore, changes in AO/NAO associated with solar variations may be the important conduit between solar forcing the hydrological response in the northeastern USA. This mechanism for the amplification of solar forcing is also supported by several European peatland records (albeit low sampling resolution relative to our data) [*van Geel et al.*, 1996; *Mauquoy et al.*, 2002; *Blaauw et al.*, 2004; *Charman et al.*, 2006, 2009]. Interestingly, we find that in eastern North America, as in Europe, hydrologic balance shifts toward wetter conditions with decreased solar output. A composite record of these wet shifts is shown in Figure 1.

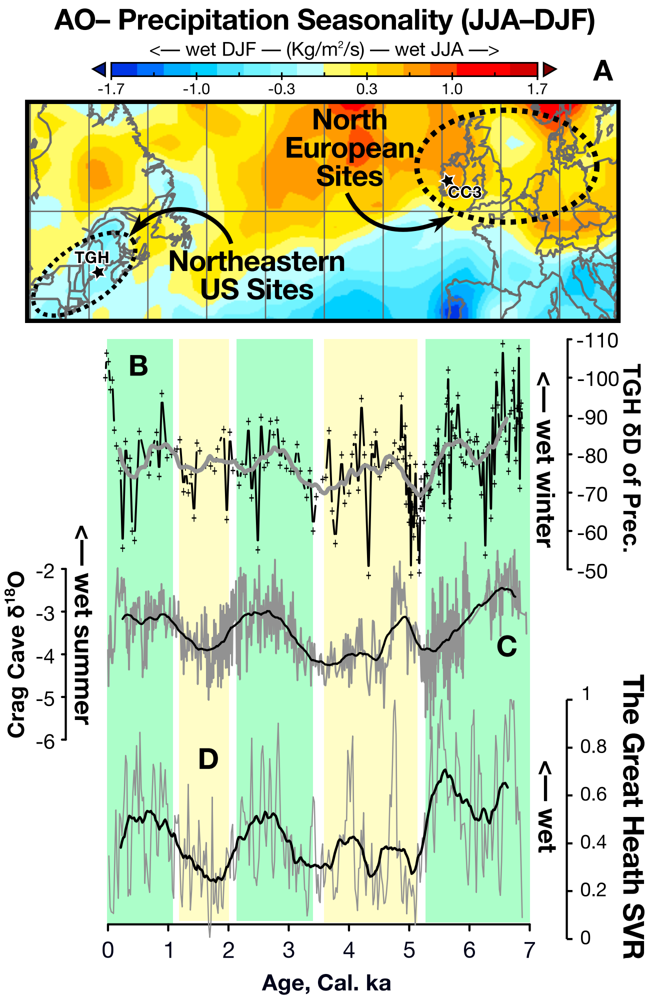

Figure 4. (a) Anomalies in precipitation seasonality during AO– years (composite of NCAR Reanalysis, see supplementary information). This figure is constructed by subtracting the JJA precipitation from the DJF precipitation during years when the AO index during DJF is below −1. (b) δD of precipitation from TGH. (c) δ^{18}O of speleothem calcite from CC3 (30). (d) SVR from TGH. Long-term trends in B, C, and D are indicated with a 500-year running average (heavy lines).

[8] We also compare the record of δD of precipitation from TGH to a record of δ^{18}O of calcite in an Irish Speleothem, Crag Cave 3 (CC3) [*McDermott et al.*, 2001], another site strongly affected by AO/NAO (Figure 4). At millennial timescales, the records are inversely related, supporting a common controlling mechanism. The correlation is clearly imperfect, as many other factors besides NAO also influence the climate and the isotope ratios of precipitation. We interpret the isotope changes as primarily a reflection of shifting precipitation seasonality [*Nichols et al.*, 2009]. During wet times in New England, characterized by frequent solar minima, the annual average δD of precipitation is lower, indicating that the seasonal distribution of precipitation is more heavily weighted towards the winter (Figure 4). In Northern Europe, the opposite effect on precipitation seasonality is apparent. During an AO– year, seasonality shifts in favor of the warm season. This variability of precipitation seasonality, apparent in recent observations (Figure 4), may thus account for the relationship between the hydrogen isotope ratios measured at TGH and the oxygen isotope ratios measured at CC3.

4. Conclusion

[9] Our new reconstruction of hydrologic balance (SVR) and δD of precipitation from TGH arguably provides the strongest evidence for solar impact on the hydrologic cycle in the northeastern US. We propose that the AO/NAO system is critical in amplifying the weak solar signal to force regional hydrological changes at TGH, consistent with model simulations [*Trouet et al.*, 2009] and European records (Figure 1d). Currently, the Sun may be entering another Maunder-like "grand minimum" in activity as has occurred several times during past millennia [*Feulner and Rahmstorf*, 2010]. It is possible that effects of this change in solar irradiance will be felt more strongly in regions particularly sensitive to such amplifying mechanisms, such as the Northeastern US, and may result in increased cool season precipitation, of particular interest in light of recent spring flooding. Transient modeling of hydrological changes in northeastern U.S. as a response to irradiance changes should thus be an important target of further investigation, especially with respect to the interaction between solar forcing with anthropogenic greenhouse gas forcing.

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Y. Huang, Department of Geological Sciences, Brown University, 324 Brook St., Providence, RI 02912, USA.

J. E. Nichols, Lamont-Doherty Earth Observatory, Earth Institute at Columbia University, 61 Rte. 9W, Palisades, NY 10964, USA. (jnichols@ldeo.columbia.edu)

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