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Abrupt cooling repeatedly punctuated early-Holocene climate in eastern North America

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Abstract

Climate proxy records and general circulation models suggest that Atlantic Meridional Overturning Circulation (AMOC) plays a key role for global climate changes. Paleoceanographic data document multiple episodes of prominent AMOC weakening during the early Holocene. However, proxy records at adjacent continents have not been demonstrated to fully capture the climate responses to multiple AMOC variation due to temporal resolution and/or the proxy sensitivity. Here we present decadal- to multidecadal-resolution hydrogen isotopic records of aquatic biomarkers from Blood Pond, Massachusetts during the early Holocene. Our data reveal a full series of prominent and abrupt cooling events centered on 10.6, 10.2, 9.5, 9.2, 8.8 and 8.4 ka. These abrupt climatic reversals coincide with key intervals of weakened AMOC, suggesting an apparent relationship between AMOC oscillations and the abrupt continental climate changes in northeastern North America. The noticeable connection implies that the AMOC variation did play an important role in the abrupt climate changes during the early Holocene. Our data also suggest that northeastern North America may experience significant climatic variations should the predicted major disturbance of AMOC occur in the coming century as a result of anthropogenic greenhouse gas emissions.

Keywords

abrupt climate event, AMOC, compound-specific D/H ratios, early Holocene, northeastern North America

Introduction

Abrupt climate changes exert significant impacts on natural ecosystems and human societies (Overpeck and Cole, 2006). One widely proposed mechanism for abrupt climate changes is perturbation of the Atlantic Meridional Overturning Circulation (AMOC) (Clark et al., 2002; Overpeck and Cole, 2006), which occurred numerous times from the Late Pleistocene to the early Holocene as a result of freshwater outbursts from proglacial lakes which originated from the melting Laurentide ice sheet (LIS) (Clark et al., 2001; Stouffer et al., 2006). The Younger Dryas (YD) and the 8.2 ka events are two of the well-known abrupt climate events attributed to slowdown in AMOC (Alley and Agustsdottir, 2005; Clark et al., 2001, 2002; Clarke et al., 2009; LeGrande et al., 2006). However, carbon isotopic ratios of benthic foraminifera and glacial landform mapping record multiple episodes of freshwater outbursts and AMOC changes from the Late Pleistocene to the early Holocene (Clark et al., 2001; Teller and Leverington, 2004). A few terrestrial and marine records suggest the influence of the AMOC on the decadal- to centennial-scale climate change in the North Atlantic and neighboring regions (Bamberg et al., 2010; Daley et al., 2009). Of particular significance is the absence of records of abrupt climate changes in a critical region – northeastern North America, which climate models indicate is highly sensitive to AMOC. The inconsistency between the proposed climate driver (AMOC) and climate records may result from (1) the fact that the existing climate records from northeastern North America cannot fully capture the relatively short scale (decadal to multidecadal) climate variability, either because of insufficient temporal resolution or inadequate proxy sensitivity; (2) regional climate sensitivity to AMOC differs under different climatic boundary conditions, with sensitivity being particularly high at the YD and 8.2 events. General circulation model simulations predict substantial reductions in the strength of AMOC with the ongoing rapid rise in anthropogenic greenhouse gases (Schmidt et al., 2005), but inconsistency in the paleoclimate records of the North Atlantic and North America raises important questions about the climatic sensitivity to changes in AMOC. This inconsistency has fueled significant debates over the role of AMOC on abrupt climate variability, with some arguing a pivotal role (Rhines et al., 2008), whereas others a negligible one (Seager and Battisti, 2007).

Here, we present decadal-scale compound-specific hydrogen isotope records from Blood Pond, south-central Massachusetts, USA (Figures 1 and 2). The D/H ratios of behenic acid (δD_{BA}), mainly produced by aquatic macrophytes at Blood Pond (Hou et al., 2006), record lake water isotope composition and hence precipitation isotopic ratios in a cool and wet region such as New England (Hou et al., 2007). We have previously demonstrated that the centennial- to millennial-scale δD_{BA} records from Blood Pond

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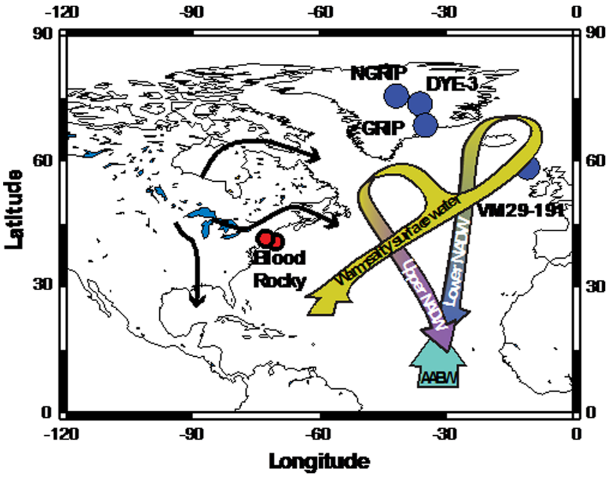

Figure 1. Map showing the location of Blood Pond and other sites discussed in the text. Three routes of freshwater outbursts are indicated: (A) Hudson Bay (8.2 ka event); (B) North Atlantic Ocean; (C) Gulf of Mexico. Key components of the Atlantic Meridional Overturning Circulation (AMOC) relevant to this study are also shown

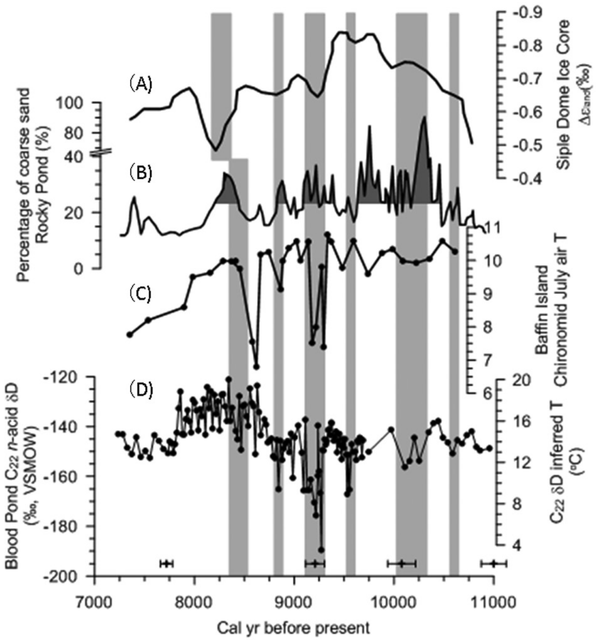

Figure 2. Comparison of hydrogen isotope records from Blood Pond (71.961°W, 42.081°N) with other terrestrial records. (A) Inferred global terrestrial $^{18}O/^{16}O$ fractionation ($\Delta\varepsilon_{LAND}$ ‰) based on $\delta^{18}O$ of oxygen gas from the Siple Dome ice core, Antarctica (Xu and Liu, 2007). (B) Sediment grain size from Rocky Pond, Massachusetts (Kaser et al., 2004). (C) Temperature inferred from chironomid assemblages in Lake CF8, Baffin Island (Haeberli and Gruber, 2009). (D) Stable hydrogen isotope records of C_{22} *n*-alkanoic acid (δD_{BA}) and inferred temperature variability . Chronology of the Blood Pond sediment core is defined by a total of 15 accelerator mass spectrometry radiocarbon dates (5 AMS dates for the study section in this study)

faithfully capture the regional climate history (Hou et al., 2006, 2007). The objectives of this study are: (1) to investigate the relationship between the decadal- to multidecadal-scale hydrogen isotope records during the early Holocene and the reconstructed freshwater outbursts from the LIS as well as the inferred AMOC changes; (2) to further evaluate the effect of AMOC variations on adjacent continental climate changes.

Samples and methods

Blood Pond (42.081°N, 71.961°W, 212.1 m a.s.l.) is a kettle pond located in Massachusetts (Figure 1). The lake is mainly recharged by groundwater and precipitation, with a southerly overflow outlet. The sediment core was collected in 2001, and samples for isotope analyses were selected at 2 cm intervals. Chronology for the core is provided by AMS-^{14}C dating of bulk organic matter which were converted to calendar years before present (cal. yr BP) using OxCal 3.9 (Hou et al., 2006). The sedimentation rate of the early Holocene (11–7 ka) at Blood Pond is ~1.3 cm/10 yr, allowing for the evaluation of decadal- to centennial-scale climate variation.

The preparation of the samples and the measurement of hydrogen isotopes have been described previously (Hou et al., 2006). Briefly, lipids were extracted from freeze-dried sediment using an Accelerated Solvent Extractor 200 (Dionex). Acid fractions were isolated, methylated, and purified. A HP 6890 GC interfaced to a Finnigan Delta+ XL stable isotope spectrometer through a high-temperature pyrolysis reactor was used for hydrogen isotopic analysis. The precision (1σ) of triplicate analyses was <±2‰. The accuracy was routinely checked by measuring laboratory isotopic standards every six measurements. The δD value of the added methyl group was determined by acidifying and then methylating (along with the samples) the disodium salt of succinic acid with a predetermined δD value (using TC/EA-IRMS) (Huang et al., 2002).

Results and discussion

Early-Holocene climate revealed by Blood Pond δD_{BA}

Our new decadal to multidecadal δD_{BA} record during the early Holocene reveals six distinct negative isotopic excursions centered at 10.6, 10.2, 9.5, 9.2, 8.8 and 8.4 ka (Figure 2). The largest and longest of these isotopic excursions occurs around 9.2–9.3 ka with ~ 30‰ δD_{BA} shift, and two significant δD_{BA} shifts (~15‰) occur around 10.2 and 8.4 ka. The isotopic shift at 9.2 ka is, within the chronological uncertainties, concurrent with changes seen in Greenland ice core $\delta^{18}O$ (Vinther et al., 2006), European lake sediment $\delta^{18}O$ (von Grafenstein et al., 1999) and tree ring width (Spurk et al., 2002), Baffin Island Chironomid data (Kurek et al., 2004), East Asian and Arabian speleothem $\delta^{18}O$ records (Dykoski et al., 2005; Fleitmann et al., 2008), and Alaskan lake biogenic silica (Hu et al., 2003). Recent data from isotopic ratios of oxygen gas preserved in the Siple dome ice core display a clear 9.2 ka shift (Severinghaus et al., 2009), strongly supporting a near-global 9.2 ka event (Fleitmann et al., 2008). The freshwater input responsible for the 9.2–9.3 ka cooling event might come from Lake Superior as lake level rapidly dropped for 45 m at the same time, which was delivered into the North Atlantic Ocean via Lake Huron–North Bay–Ottawa River–St Lawrence River valleys (Yu et al., 2010). Our results are also supported by regional paleoclimate data from New England (Figure 2). Cooling events in the early Holocene inferred by our isotopic records are closely associated with overall drier conditions as indicated by shifts in sediment facies (increase in grain sizes) at nearby Rocky and New Long Ponds, Massachusetts (Newby et al., 2009). A modern analog for such a cold-dry scenario is the AD 1962–1965 drought, which was the most severe historic drought in the northeastern USA (Namias, 1966). During AD 1962–1965 a band of cool sea-surface temperatures extending from Maine to Ireland severely reduced regional summer precipitation by drawing cold Arctic air masses into the region. These air masses also led to unusually low temperatures, especially during the winter. The cooler and drier climate around 9.2 ka, as demonstrated by δD_{BA} data, also coincides with a broad interval of elevated *Ambrosia* pollen reflecting

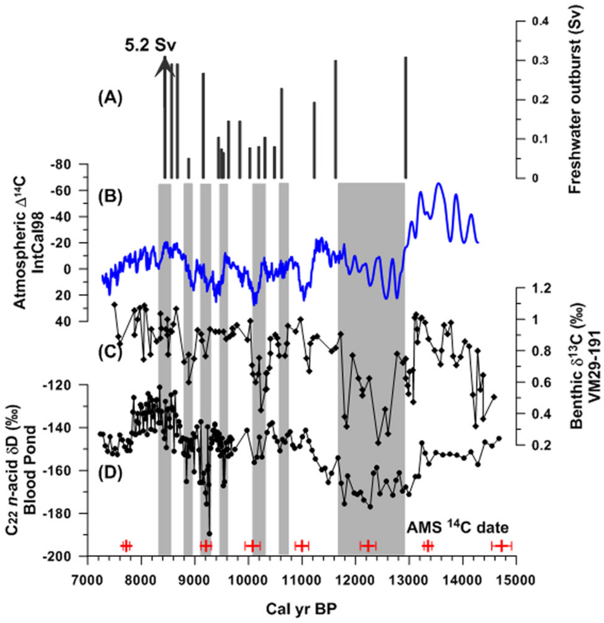

Figure 3. Comparison of Blood Pond δD_{BA} records with records inferring changes in the AMOC. (A) Freshwater release to North Atlantic Ocean (Teller and Leverington, 2004). (B) Detrended $\Delta^{14}C$ from tree rings (Stuiver et al., 1998). (C) $\delta^{13}C$ records from VM29-191 (Bond et al., 2001) and Blood Pond δD_{BA} records. The climate reversals at Blood Pond are strongly correlated with inferred AMOC changes, possibly induced by freshwater outbursts from Laurentide Ice Sheet

more open land in northeastern North America (Faison et al., 2006).

Correlation with AMOC variability

The abrupt climate reversals revealed at Blood Pond correspond strongly to the early-Holocene AMOC changes inferred from foraminifera $\delta^{13}C$ values as well as detrended atmospheric $\Delta^{14}C$ record from tree rings (Stuiver et al., 1998) (Figure 3). The benthic foraminifera $\delta^{13}C$ values at site VM29-191 essentially reflect the convective overturning rate of AMOC, with lower $\delta^{13}C$ implying reduced overturning (Bond et al., 1999; Clark et al., 2001). The definitive identification of a 10.2 ka climate excursion at Blood Pond, which coincides with the most severe lake low stand at Rocky Pond (Newby et al., 2009), is particularly important, because the 10.2 ka $\delta^{13}C$ change at VM29-191 is as large as 0.6‰, accounting for ~70% amplitude of the $\delta^{13}C$ excursions during the YD and suggesting substantial AMOC reductions. The increase in $\Delta^{14}C$ at the abrupt climate reversals could also indicate AMOC slowdowns during the early Holocene (Clark et al., 2001). The fact that all the abrupt hydrogen isotopic excursions during the early Holocene at Blood Pond have counterparts within the $\delta^{13}C$ and/or $\Delta^{14}C$ data suggests a consistent, causal relationship between AMOC strength and climate variability in New England. Likewise, the evidence for cool, dry climate in New England when AMOC slowed is consistent with historic responses to North Atlantic conditions (Namias, 1966).

The 10.2 and 9.2 ka events

Blood Pond provides the first isotopic record from North America to register abrupt climatic changes at 9.2 and 10.2 ka. However, directly applying the δD_{BA}–temperature relationship (δD_{BA} = 4.3T −208.4‰) (Hou et al., 2006) established from a transect of eastern North American lakes yields an unexpectedly large maximum temperature drop of nearly ~7°C around 9.2 ka, only slightly smaller than that estimated for the YD (Hou et al., 2007). It is thus unlikely that the isotopic shift at 9.2 kyr BP represents mean annual temperature change alone. Precipitation seasonality must have also changed, with an increase in the ratio of cool to warm season precipitation. This is consistent with early-Holocene lake-level low stands in New England, which have been attributed to reduced summer precipitation and relatively high winter precipitation (Shuman and Donnelly, 2006). The modern-day precipitation δD values at Blood Pond are ~ −40‰ for June to August and ~ −82‰ for November to January, with precipitation amounts evenly distributed throughout the year (Bowen and Revenaugh, 2003). A 20% decrease in summer relative to winter precipitation would produce a ~13‰ reduction in the δD values of mean annual precipitation. Likewise, the historic analog to these events produced a severe reduction in summer precipitation (Namias, 1966). If temperature declines were primarily a wintertime feature, as models have inferred for AMOC induced temperature decreases (Seager and Battisti, 2007), the lower δD values of the colder winter precipitation will further reduce annual mean precipitation D/H ratios. Therefore, temperature derived from δD_{BA} changes should be more appropriately defined as precipitation-weighted temperature (PWT), taking into consideration seasonal shifts in precipitation and temperature. Moreover, the large size of the Laurentide Ice Sheet at 9.2 ka (two times the modern Greenland) (Dyke and Prest, 1987) and relative proximity to our study site may have been particularly important for the very different seasonality in precipitation and unusually large 9.2 ka isotope excursion.

The 8.2 ka and other events

In addition to 9.2 and 10.2 ka climatic reversals, the δD_{BA} record also shows a clear abrupt decrease from 8.45 to 8.3 kyr BP (Figure 2), with a ~3–4°C decline in PWT change. This temperature shift slightly precedes the well-known 8.2 ka event in the ice cores and speleothems by about 200 years (Alley and Agustsdottir, 2005). Currently, it is unclear whether the timing discrepancy results from chronological inaccuracies or actual difference in timing of the continental climatic response. We adopted a linear interpolation between the neighboring ^{14}C ages to assign the ages of individual samples during the early Holocene. The sedimentation rate might have changed between the two neighboring ^{14}C ages, which would cause the small age offsets. However, the timing of the negative δD_{BA} shift between 8.45 and 8.3 kyr BP is consistent with climatic and ecological records from northeastern North America (Kurek et al., 2004; Lutz et al., 2007; Shuman et al., 2002). Ellison et al. (2006) suggest the presence of two distinct cooling events centered at 8.5 and 8.1 kyr BP, respectively, in the subpolar North Atlantic Ocean (Ellison et al., 2006). The chronological uncertainties of the Blood Pond sediment core make it difficult to assign the δD_{BA} shift between 8.45 and 8.3 kyr BP to one of these two events. Aditionally, the precipitation seasonality during the 8.2 ka event may differ from that during the 9.2 ka event because of the final collapse of Laurentide Ice Sheet. The collapse of the LIS may have resulted in a more evenly distributed precipitation throughout the year, which may explain the relatively small δD_{BA} shift during the 8.2 ka event. At 10.6 ka, δD_{BA} decreased by ~ 10‰ with a duration of about a century, which corresponds to a similar $\delta^{13}C$ variation (Clark et al., 2001). In addition to the above four clearly identified century-scale climatic reversals, we also found two relatively short-lived δD_{BA} excursions at 8.8 and 9.5 ka, lasting only a couple of decades. Of these brief excursions, only the one at 8.8 ka has a corresponding carbon isotopic excursion in VM29-191. Definitive identification of abrupt climate events of such short duration will require higher resolution isotopic records.

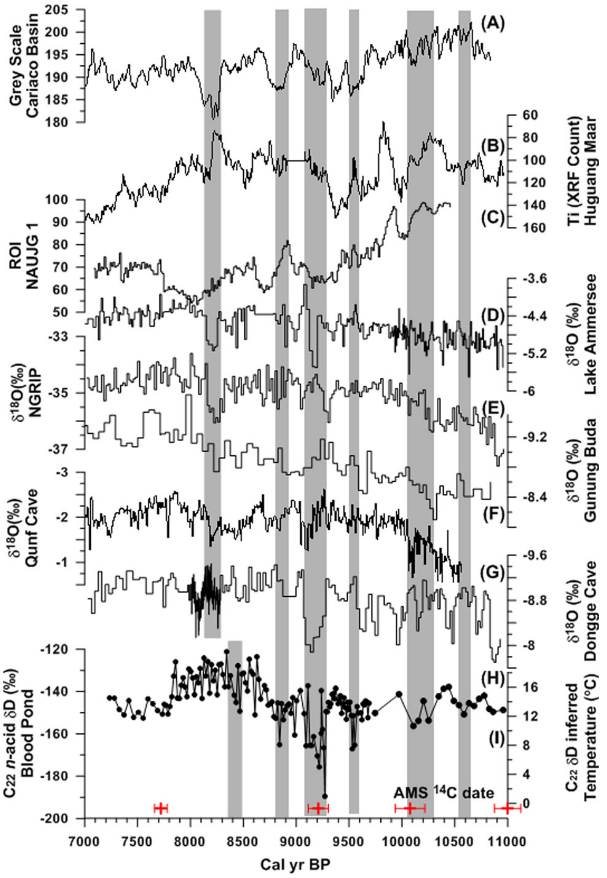

Figure 4. Compilation of selected records showing the abrupt climate reversals during the early Holocene at 8.2 ka, 8.8 ka, 9.2 ka, 9.6 ka, 10.2 ka and 10.6 ka. (A) Grey scale from Cariaco Basin (Hughen et al., 2000). (B) Ti concentration from Huguangyan Maar Lake (Yancheva et al., 2007). (C) Residue on ignition (ROI) from NAUJH1 (Willemse and Tornqvist, 1999). (D) $\delta^{18}O$ records from Lake Ammersee (von Grafenstein et al., 1999). (E) $\delta^{18}O$ records from NGRIP (Vinther et al., 2006). (F) $\delta^{18}O$ records from Gunnug Buda cave. (G) $\delta^{18}O$ records from Qunf Cave (Fleitmann et al., 2008). (H) $\delta^{18}O$ records from Dongge Cave (Dykoski et al., 2005). (I) Blood Pond δD_{BA} records

Comparison with global climate records

The abrupt climate reversals revealed in the Blood Pond records can also be tentatively found in other high-resolution proxy records of climate around the globe (Figures 4 and 5). Other than the Greenland ice cores, most other quantitative climate records are derived from speleothem $\delta^{18}O$ values. To improve the comparability with our hydrogen isotopic records, we converted the δD_{BA} excursions at Blood Pond into oxygen isotopic variations using the slope of the global meteoric water line (i.e. $\delta D = 8\delta^{18}O + 10$) (Craig, 1961), and plotted the scale of isotopic changes from all sites in Figure 5. Interestingly, except for the 8.2 ka event, the isotopic excursions in New England appear to display the largest signal in the world, especially for the largest and longest 9.2 ka and 10.2 events when the isotopic changes in New England are several times greater than corresponding changes in Greenland, Asia and Europe. The isotopic signal of the 8.2 ka event in New England is modest compared with other records, which may be related to the different routing (i.e. Hudson Bay) of freshwater outburst at the final collapse of the LIS. The high amplitude of climate response to AMOC changes in eastern north America is consistent with model results (Shindell et al., 1999).

Summary

The variability of decadal- to multidecadal-scale hydrogen isotope records from the northeastern USA coincides with key intervals of weakened AMOC, demonstrating the profound impact of AMOC oscillations on the abrupt continental climate changes in eastern North America. Our high resolution hydrogen isotopic records indicate that New England is highly sensitive to AMOC variations, and thus likely to experience significant climatic variations should the predicted major disturbance of AMOC occur in the coming century due to anthropogenic gas emissions.

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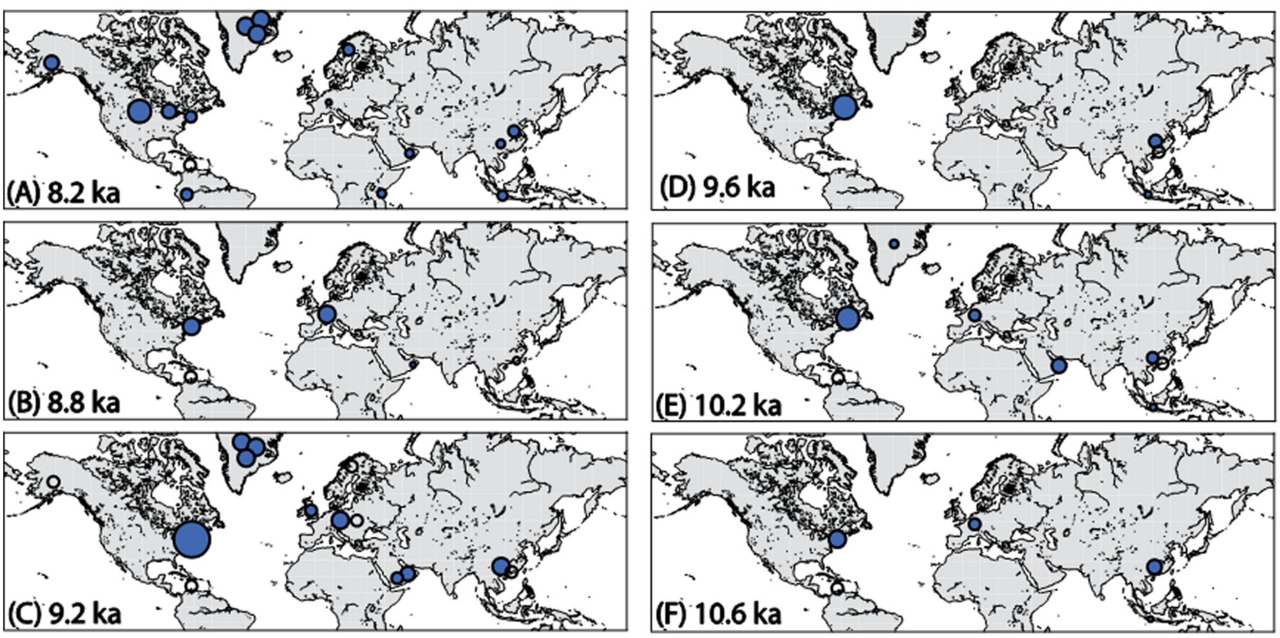

Figure 5. Compilation of selected isotope records showing the abrupt climate reversals during the early Holocene around the world, at (A) 8.2 ka, (B) 8.8 ka, (C) 9.2 ka, (D) 9.6 ka, (E) 10.2 ka and (F) 10.6 ka. Solid circles represent stable isotope records ($\delta^{18}O$ and δD). The size of the solid circles represents the amplitude of isotope reversal of individual records. Open circles represent non-isotope records

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