A severe centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages

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Abstract: We present evidence from a variety of physical and biological proxies for a severe drought that affected the mid-continent of North America between 4.1 and 4.3 ka. Rapid climate changes associated with the event had large and widespread ecological effects, including dune reactivation, forest fires and long-term changes in forest composition, highlighting a clear ecological vulnerability to similar future changes. Drought is also documented in the Middle East and portions of Africa and Asia, where it was similar in timing, duration and magnitude to that recorded in the central North American records. Some regions at high latitudes, including northern Europe and Siberia, experienced cooler and/or wetter conditions. Widespread mid-latitude and subtropical drought, associated with increased moisture at some high latitudes, has been linked in the instrumental record to an unusually steep sea surface temperature (SST) gradient between the tropical eastern and western Pacific Ocean (La Niña) and increased warmth in other equatorial oceans. Similar SST patterns may have occurred at 4.2 ka, possibly associated with external forcing or amplification of these spatial modes by variations in solar irradiance or volcanism. However, changes in SST distribution bracketing the 4.2 ka event are poorly known in most regions and data are insufficient to estimate magnitude of changes in solar and volcanic forcing at this time. Further research is needed to delineate geographical patterns of moisture changes, ecological responses, possible forcing mechanisms and climatology of this severe climatic event.

Key words: Holocene climate, North America, abrupt climate change, drought, 4.2 ka.

Introduction

Palaeoclimate records show that Earth's climatic system is subject to abrupt, severe and widespread changes, with large and sometimes devastating effects on ecosystems and civilizations (Alley *et al.*, 2003). Abrupt climate changes are particularly well documented during the last deglaciation; temperature changes associated with the Younger Dryas (12.9–11.6 ka) and 8.2 ka events occurred in less than a decade (Alley *et al.*, 2003). These events had large and long-lasting effects on terrestrial ecosystems (Yu, 2000; Ammann, B. *et al.*, 2000; Tinner and Lotter, 2001; Shuman *et al.*, 2002; Williams *et al.*, 2002). Abrupt climate changes during the middle and late Holocene have been less severe, and many appear to represent hydroclimatic changes that are still poorly understood. Droughts spanning several years to several decades are documented throughout the late Holocene, and many of these had substantial ecological and socioeconomic effects (Hodell *et al.*, 1995; Woodhouse and Overpeck, 1998; Stahle *et al.*, 2000; DeMenocal, 2001). Abrupt changes are

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clearly part of the natural variability of Earth's climate, but human activities may alter their probability (Alley *et al*., 2003), lending urgency to understanding abrupt changes of the past. Knowledge of patterns, mechanisms and impacts of abrupt climate change, particularly during non-glacial time periods, is needed as context for considering possible future abrupt climate changes and possible ways to mitigate their effects (Overpeck and Webb, 2000). We present evidence from mid-continental North America for a widespread drought that occurred between 4.3 and 4.1 ka, evaluate some of the ecological responses and discuss larger Northern Hemispheric patterns and mechanisms.

Temporal and spatial dimensions of the 4.2 ka drought

Abrupt climate changes centred on 4.2 ka have been documented from various regions of the world, ranging from the North Atlantic to northern Africa and southern Asia, and it has been suggested that these changes may have been global in extent (Bond *et al*., 2001; Thompson *et al*., 2002). However, climate changes in North America at 4.2 ka have not been well established, and global patterns have not been well delineated. A recently developed high-resolution record of moisture variability from South Rhody Peatland, a closed-basin peatland in the Upper Peninsula of Michigan (Figure 1), clearly documents severe drought at 4.2 ka (Booth *et al*., 2004). The palaeohydrological record was inferred from testate amoebae (Protozoa: Rhizopoda), which are sensitive indicators of moisture conditions, and assemblage composition is strongly correlated with water-table depth (Woodland *et al*., 1998). Testate amoebae have provided reconstructions of past climate variability at subcentennial timescales in Europe and North America (Charman and Hendon, 2000; Booth and Jackson, 2003a). Water-table depths at South Rhody Peatland were reconstructed using a transfer function developed from a modern calibration dataset (Booth, 2002). The inferred water-table in the peatland reached its lowest levels of the last 5000 years between 4.2 and 4.0 ka (Figure 2). *Hyalosphenia subflava* and *Bullinularia indica*, which are reliable indicators of very dry peatland conditions (Woodland *et al*., 1998, Booth, 2002), are abundant during this time period (Booth *et al*., 2004). Seven radiocarbon dates constrain the last 5000 years of record at South Rhody, and one of these dates was obtained from *Pinus* (pine) needles that were deposited immediately after the drought interval (Booth *et al*., 2004). Dry conditions at South Rhody persisted for at least two centuries, and the drought occurred between relatively wet periods, indicating that it was a discrete event and not part of a long-term gradual change.

Severe multiyear droughts (e.g., 1930s) and multidecadal droughts (e.g., late sixteenth century) affected much of the mid-continental USA (Woodhouse and Overpeck, 1998; Stahle *et al*., 2000; Fye *et al*., 2003). The 4.2 ka drought had similarly broad impacts from the Great Lakes to the Central Plains. In Minnesota, a sharp increase in clastic sediments from aeolian sources, associated with pronounced drying, is registered in the sediments of Elk Lake at *c*. 4.3–4.1 ka (Dean, 1993, 1997). Diatom influx reaches its highest levels at 4.2 ka, suggesting high lake productivity. The diatom flora alternates between species characteristic of clear and turbid water, the latter probably resulting from regional aeolian episodes (Bradbury and Dieterich-Rurup, 1993). Sediment bulk density at Elk Lake peaks at 4.2 ka, and a prominent spike in magnetic susceptibility occurs between 4.4 and 4.2 ka, consistent with high lake productivity and increased clastic sediments (Figure 2). Varve thickness at Elk Lake increases at 3.9 ka, which corresponds temporally with the rapid increase in moisture documented at South Rhody Peatland after the drought (Figure 2).

Drought-induced aeolian activity in many currently stabilized dune systems across the mid-continent (Forman *et al*., 2001) provides additional information on the magnitude and extent of the 4.2 ka drought. The Ferris Dune Field in eastern Wyoming shows widespread reactivation *c*. 4.3–4.0 ka ago (Stokes and Gaylord, 1993), as do parabolic dune systems in eastern Colorado (Forman *et al*., 1995) (Figure 2). Persistent and pervasive aridity in Nebraska at *c*. 4.3 ka is indicated by dune movements that spanned tens of kilometres, altering surface hydrology (Loope *et al*., 1995; Stokes and Swinehart, 1997; Mason *et al*., 1997). Regional aridity extended at least as far east as west-central Illinois, where a sand sheet dated at 4.2 ka is banked against parabolic dune forms from the last glacial maximum (Figure 2). This Holocene sand sheet deposit is unique for the region, indicating a drop in mean annual precipitation sufficient to decrease vegetation cover for aeolian entrainment (Forman *et al*., 2001).

Other high-resolution palaeoclimate records provide additional evidence for widespread drought in the Midwest at this time. A speleothem record from northeastern Iowa documents a brief negative spike in $\delta^{18}O$ at 4.1 ka (Denniston *et al*., 1999) suggesting a shift in seasonality of precipitation and a change to more distal sources of moisture, consistent with drought climatology (Woodhouse and Overpeck, 1998). A pollen record from alluvial sediments in the same region shows a brief spike in *Ambrosia* (ragweed) and corresponding decrease in *Quercus* (oak) (Baker *et al*., 2002), indicating transient drought. Another record of moisture balance, which provides a more regional perspective on climate variability, is the sedimentologically derived water-level history of Lake Michigan, which integrates the net water budget of Lakes Superior, Michigan and Huron, a watershed encompassing more than 575 000 km^2 (Baedke and Thompson, 2000; Booth and Jackson, 2003a). Lake Michigan water levels fell between 4.5 and 4.0 ka, at a rate at least five times that attributable to isostatic rebound (Baedke and Thompson, 2000). Although the water-level drop may be related to non-climatic factors (e.g., erosion of the Port Huron outlet), the timing of the rapidly decreasing water levels coincides with a decrease in flood magnitudes in the upper Mississippi River catchment (Knox and Kundzewicz, 1997).

Drought at 4.2 ka is not evident in all palaeoclimate records from the North American mid-continent. Sites and proxies differ in their sensitivity, response time and temporal resolution, and the short duration of the 4.2 ka event makes it likely that it has been overlooked in some records. For example, the drought spans only 5 cm of sediment at South Rhody Peatland (Booth *et al*., 2004), and most studies of lake and peatland sediments in the region have been carried out at coarser sampling intervals. This may account for the paucity of records of this event from other parts of North America. Palaeoclimate studies of potentially sensitive sites with high temporal resolution should be directed at this time period to delineate the spatial extent, nature and magnitude of the event in North America.

Ecological impacts of the drought

High-resolution pollen and charcoal analyses at South Rhody peatland and other sites indicate the drought was of sufficient magnitude to cause widespread ecological change in northern

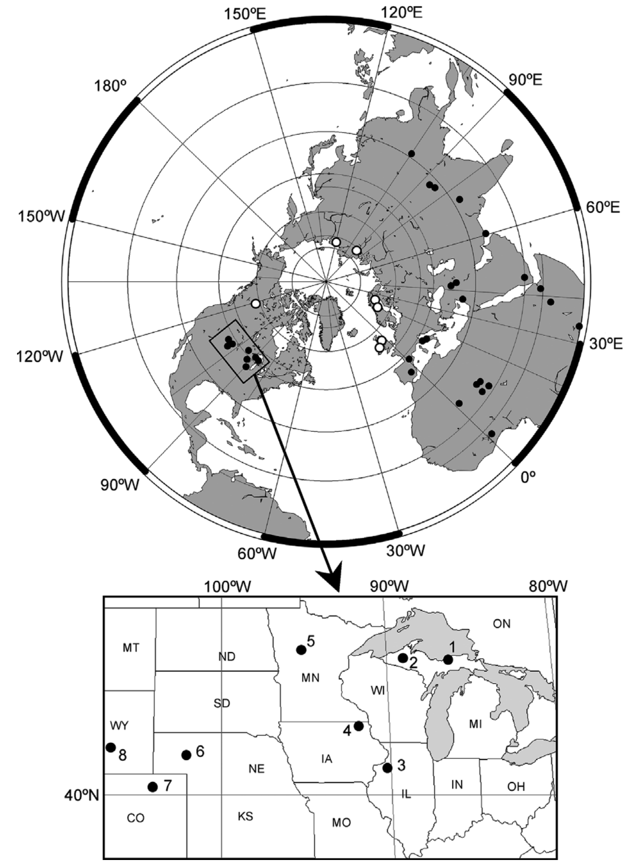

Figure 1 Map showing sites mentioned in text where climatic changes centring on 4.2 ka (4.4–4.0 ka) have been documented, with inset showing location of sites in the continental USA. Solid circles indicate severe drought and open circles indicate increased moisture. Sites in the USA include: (1) South Rhody Peatland, Michigan (Booth *et al.*, 2004); (2) Sylvania Wilderness, Michigan (Davis *et al.*, 1998); (3) Western Illinois sand sheet; (4) Coldwater Cave Speleothem (Denniston *et al.*, 1999); (5) Elk Lake, Minnesota (Dean, 1993; Dean, 1997); (6) Sand Hills, Nebraska (Mason *et al.*, 1997); (7) Eastern Colorado dunes (Forman *et al.*, 1995); (8) Ferris/Seminoe dune field, Wyoming (Stokes and Gaylord, 1993). In Africa, Asia and Europe, dots represent generalized locations of studies cited in the text. The maps do not represent comprehensive surveys of all available palaeoclimate records, but rather portray sites where clear anomalies centring on 4.2 ka have been documented. The spatial pattern of wet and dry anomalies resembles that of the mid-latitudinal drought that occurred June 1998–May 2002 (see Hoerling and Kumar, 2003).

Michigan (Figure 2) (Booth *et al.*, 2004). Wildfires increased in frequency and/or intensity, and transient increases in *Pteridium* (bracken fern) populations indicate widespread disturbance of forest vegetation (Figure 2). Similar changes in charcoal and *Pteridium* occurred at Ackerman Lake, located 60 km southwest of South Rhody peatland (Booth and Jackson, 2003b). Transient increases in charcoal and/or *Pteridium* spores, along with a brief decrease in *Betula* (birch) pollen, are also recorded in small hollows in western Upper Michigan (Davis *et al.*, 1998). During the rapid onset of wetter conditions after the drought, *Betula alleghaniensis* (yellow birch) and *Tsuga canadensis* (hemlock) populations expanded in Upper Michigan (Booth and Jackson, 2003b; Booth *et al.*, 2004). Drought-induced disturbance of incumbent forest vegetation may have facilitated the expansion of these species. Mesic tree populations persisted on the landscape after their post-drought rapid expansion, suggesting that the abrupt climate shifts associated with the drought event led to the establishment of a new equilibrium state in forest ecosystems. High-resolution palaeoecological records are needed from other regions within the continental interior to assess the response of different ecosystem types to the drought and associated climate changes.

A megadrought 4200 years ago?

Widespread, persistent drought events spanning several years are well documented in the instrumental record of the past century, and these droughts can span several continents (Hoerling and Kumar, 2003). High-resolution palaeoclimate records indicate that widespread, multidecadal megadroughts have occurred at various times in the late Holocene, spanning large portions of North America (Woodhouse and Overpeck, 1998; Stahle *et al.*, 2000, Gray *et al.*, 2003). Lower-resolution palaeoclimate records indicate that the mid-continent of North America experienced an abrupt, severe and persistent drought within 100–200 years of 4.2 ka (Figure 2). This drought persisted for at least several decades, perhaps centuries, and its magnitude is unmatched in the last 5000 years. Although the spatial extent of drought within North America has not been adequately delimited, severe droughts at or near 4.2 ka are recorded at multiple mid-latitude and subtropical sites on all other continents of the Northern Hemisphere (Figure 1). The records from Africa, Europe and Asia, together with the records from the North American mid-continent, suggest that much of the Northern Hemisphere may have experienced persistent drought at low to middle latitudes at 4.2 ka. Severe drought is clearly recorded at *c.* 4.2 ka in the Middle East and northern Africa (e.g., Gasse, 2000; Cullen *et al.*, 2000; Thompson *et al.*, 2002). For example, a 200–300 year drought centred on 4.2 ka has been inferred from dust in marine sediments of the Gulf of Oman (Figure 2) (Cullen *et al.*, 2000), and this drought has been linked to the collapse of the Akkadian Empire and early civilizations in Greece, Egypt and the Indus Valley of Pakistan (Weiss *et al.*, 1993; Dalfes *et al.*, 1997; Cullen *et al.*, 2000; Staubwasser *et al.*, 2003). Sediment and speleothem records from Israel, Turkey and Yemen also document drought during this time period (Bar-Matthews *et al.*, 1997; Dalfes *et al.*, 1997; Frumkin *et al.*, 2001).

Pronounced drought also occurred in other areas of Africa, Asia and the Mediterranean (e.g., Gasse and Van Campo, 1994; Gasse, 2000; Thompson *et al.*, 2002; Wenxiang and Tungsheng, 2004). Drying at 4.2 ka is associated with abrupt deforestation in the western Mediterranean region, and an increased influx of *Cedrus* pollen of African origin reaching central Italy suggests that extraregional air masses coming from the south were associated with the drought (Magri and Parra, 2002). This drying was widespread, reactivating dune systems on the margin of the Saharan Desert in North Africa (Swezey, 2001) and causing increases in Saharan-derived aeolian particle flux to lakes in central Italy (Narcisi, 2000). Increased dust content in glacier ice on the summit of Mount Kilimanjaro (Thompson *et al.*, 2002) and widespread lowered lake levels *c.* 4.2 ka (Gasse and Van Campo, 1994; Damnati, 2000; Gasse, 2000) indicate pervasive and severe drought extended across central and east Africa. A large increase in sediment flux from new sources into the lower Nile River 4.0–4.5 ka, is attributable to a decrease in vegetation cover in contributing catchments (Stanley *et al.*, 2003). Drought conditions extended to the Mediterranean and southern Europe, where dessication of lakes and vegetation changes indicate drying at *c.* 4.2 ka (Jalut *et al.*, 2000; Carrion, 2002; Pantaleon-Cano, 2003).

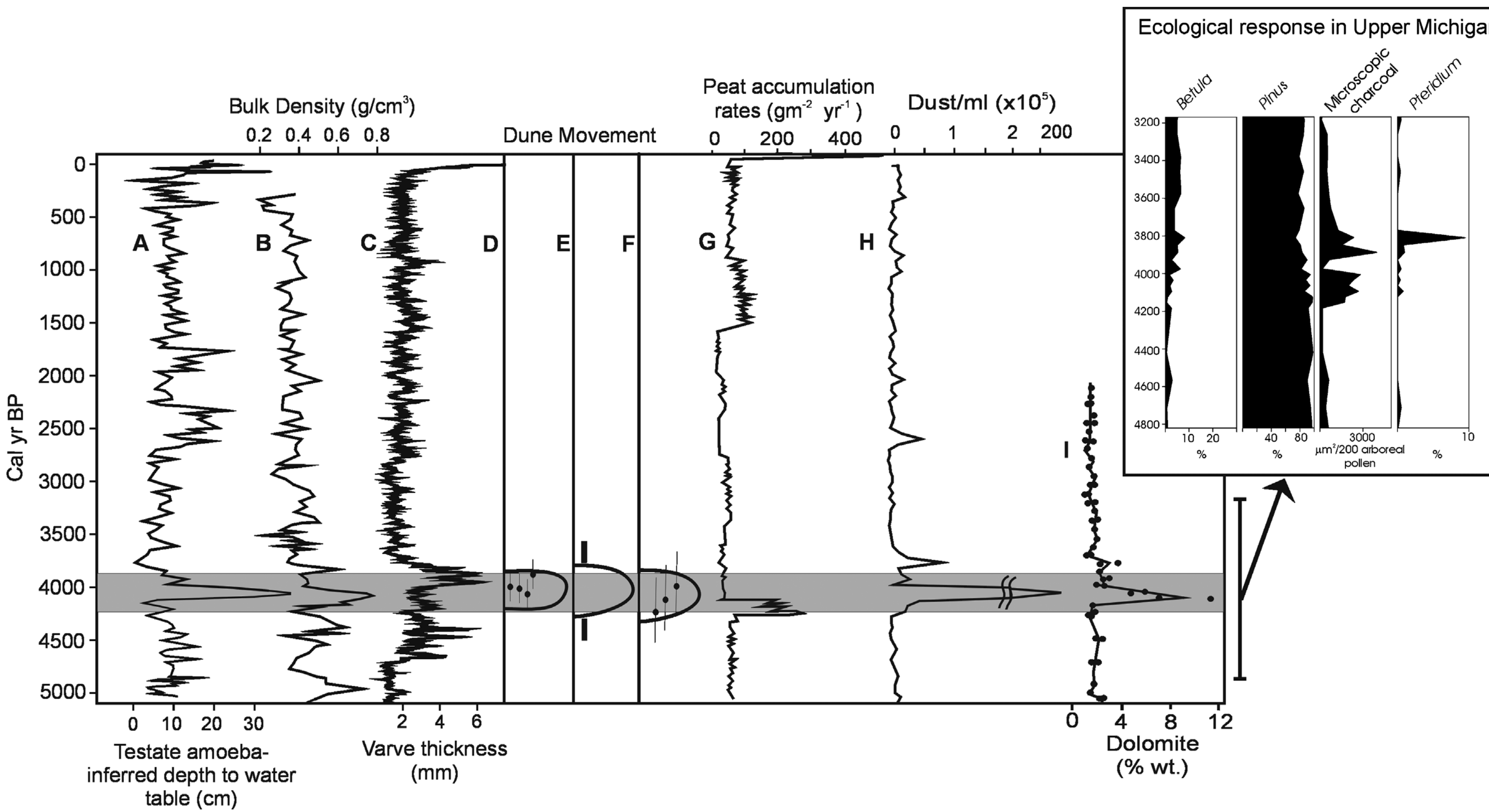

Figure 2 Selected records of the 4.2 ka climatic event in North America, Africa and the Middle East. (A) Testate amoeba-inferred water-table depth history of South Rhody peatland in Upper Michigan (Booth *et al.*, 2004). (B) Sediment bulk density of Elk Lake, Minnesota. Mass accumulation rates of eolian-derived minerals at Elk Lake show a similar spike at 4.2 ka (Dean, 1993; Dean, 1997). (C) Varve thickness record from Elk Lake, Minnesota (Dean, 1993; Dean, 1997). (D) Optically stimulated luminescence ages on quartz grains constrain deposition of aeolian sand for Ferris Dune Field, Wyoming (Stokes and Gaylord, 1993). (E) Radiocarbon ages on bounding organic matter constrain the damming of a drainage in the western Sand Hills, Nebraska by dune migration (Mason *et al.*, 1997). (F) Optically stimulated luminescence ages on a sand sheet deposit in western Illinois (Kreig *et al.*, 2004). (G) Accumulation rates for a peatland in Alberta, Canada (Yu *et al.*, 2003). (H) Dust concentration from the Kilimanjaro ice core record, equatorial Africa (Thompson *et al.*, 2002). (I) Percentage aeolian detrital dolomite for a core from the Gulf of Oman (Cullen *et al.*, 2000). Inset shows ecological responses to the drought near South Rhody Peatland in central Upper Michigan, including profiles of microscopic charcoal and selected pollen/spores (Booth *et al.*, 2004).

The palaeoclimate records indicate that low to mid-latitudes of much of the Northern Hemisphere experienced severe drought conditions centring on 4.2 ka (Figures 1 and 2). A similar pattern of multiyear, mid-latitude drought occurred in 1998–2002 and was described by Hoerling and Kumar (2003); however, Hoerling and Kumar do not show results equatorward of 20°N, so the records from tropical Africa cannot be compared with their results. The 1998–2002 drought was accompanied by positive moisture anomalies at high latitudes in North America and Eurasia (Hoerling and Kumar, 2003), a pattern matched by the palaeoclimate records at 4.2 ka (Figure 1). For example, in northwestern Canada a prominent increase in peat accumulation rate occurred at 4.2 ka, suggesting a brief (~200 year) wet event (Yu *et al.*, 2003) (Figure 2). Moister and/or cooler conditions at 4.2 ka are also indicated by proxy-climate records in northern England (Hughes *et al.*, 2000), Ireland (Barber *et al.*, 2003; Plunkett *et al.*, 2004), northern Scandinavia (Korhola *et al.*, 2000, 2002; Rosen *et al.*, 2001), central Europe (Magny, 2004), northwest Siberia (Laing and Smol, 2003) and possibly northeast Siberia (Porinchu and Cwynar, 2002) (Figure 1). Therefore, the 1998–2002 event is worth exploring as a potential model to help assess mechanisms underlying the event of 4.2 ka.

Possible causal mechanisms

Abrupt climate changes during the early Holocene and last glacial period were driven by ice-sheet dynamics and their effects on ocean circulation (Alley *et al.*, 2003). The 4.2 ka anomaly occurred when continental glaciers were absent from most of the Northern Hemisphere, similar to the situation today, so other mechanisms must be sought. Potential mechanisms include non-linear responses to Milankovitch forcing, solar variation, volcanic events and variability in the ocean–atmosphere system.

Milankovitch orbital parameters were changing at a very slow rate during the mid- to late Holocene; nevertheless, changes in the base-state climate associated with altered orbital forcing may have played a role in this event. However, except for models of intermediate complexity (e.g., Claussen *et al.*, 1999), climate models have not been run for several millennia of Holocene climate to assess the likely magnitude and frequency of abrupt decadal- and centennial-scale changes.

Some evidence exists for changed solar forcing at 4.2 ka. Bond *et al.* (2001) document a cold event in the North Atlantic at 4.2 ka, one of several such Holocene events, and a corresponding increase in cosmogenic isotopes suggests reduced solar radiation at this time. A possible link between late Holocene drought cycles in south Asia and cosmogenic ^{14}C production rates has also been documented (Staubwasser *et al.*, 2003). However, although climate models are being used to investigate the climatic response to solar variability, particularly the period of reduced insolation during the Maunder Minimum (Shindell *et al.*, 2003; Rind *et al.*, 2004), they have primarily focused on simulating temperature and circulation changes rather than changes in precipitation or drought. Discussion of precipitation responses to changes in solar forcing has been limited to the tropics (Meehl *et al.*, 2003).

Volcanic forcing may have changed at 4.2 ka, and a record of volcanic activity compiled from radiocarbon-dated volcanic eruptions shows a peak in volcanic activity at this time (Bryson, 1988). However, ice-core records have not yet shown a significant global-scale volcanic signal at 4.2 ka (Zielinski, 2000), and most detailed observational studies of ice cores have been limited to the past millennium (Crowley, 2000; Ammann and Naveau, 2003). Potential impacts of volcanism on large-scale drought have also not been evaluated fully in general circulation models and, similar to models assessing the climatic response to solar forcing, most have focused on simulating temperature and circulation changes (Amman, C.M. *et al.*, 2003; Shindell *et al.*, 2003; Rind *et al.*, 2004).

Many severe drought events of the past century have been linked to internal variability in the ocean–atmosphere system (Enfield *et al.*, 2001, McCabe *et al.*, 2004, Schubert *et al.*, 2004a, b), raising the question of whether such intrinsic variability in the Earth system is capable of inducing the event of 4.2 ka. Recent research has demonstrated linkages between SST patterns and drought, particularly widespread droughts such as those of 1998–2002 (Hoerling and Kumar, 2003), the 1950s and 1930s (e.g., Enfield *et al.*, 2001; McCabe *et al.*, 2004, Schubert *et al.*, 2004a, b) and the sixteenth century (Stahle *et al.*, 2000; Gray *et al.*, 2003). Widespread occurrence of mid-latitude, Northern Hemisphere drought in 1998–2002 has been connected with an enhanced thermal gradient between the tropical eastern and western Pacific Ocean and warm SSTs in the other equatorial oceans (Hoerling and Kumar, 2003). Increasing SSTs in equatorial basins may be related in part to greenhouse gas forcing (Hoerling and Kumar, 2003). The 1998–2002 SST pattern resulted in a persistent belt of higher pressure aloft at Northern Hemisphere middle latitudes, providing a scenario for widespread, synchronous drought (Hoerling and Kumar, 2003). Some regions at mid to high latitudes received more moisture under this SST forcing (Hoerling and Kumar, 2003), similar to the pattern at 4.2 ka (Figure 1). SST anomalies may also have played a role in the drought over the Great Plains during the Dust Bowl period (1932–38) (Schubert *et al.*, 2004b), and bear some resemblance to the SST patterns of 1998–2002. Both periods had colder SSTs in the central and eastern equatorial Pacific and warmer SSTs in the equatorial Atlantic. However, there were also some differences: the 1998–2002 interval had warmer SSTs in the western equatorial Pacific and the Indian Ocean relative to the 1932–1938 period, and the 1932–1938 period had large warm SST anomalies in the northern North Atlantic. The strong association between SST patterns and drought during the instrumental record suggests that SST patterns at 4.2 ka should be investigated.

Although records of past SST patterns are limited in spatial coverage, we can infer SST patterns at 4.2 ka in some regions. For example, lake sediments of southern Ecuador suggest less frequent warm ENSO events *c*. 4.0–4.3 ka ago (Moy *et al.*, 2002). Weaker ENSO variability may have been associated with more persistent La Niña conditions, and persistent or enhanced La Niña conditions (i.e., colder SSTs in the central/eastern equatorial Pacific) have been linked to other times of prolonged North American drought in the Holocene (Forman *et al.*, 2001; Menking and Anderson, 2003), as well as the 1998–2002 drought (Hoerling and Kumar, 2003) and the Dust Bowl drought (Schubert *et al.*, 2004b). Northern North Atlantic SST was probably cold, compared with the present, at 4.2 ka (Bond *et al.*, 2001). Simulations suggest that cooling of the northern North Atlantic might also contribute to drought in continental North America (Benson *et al.*, 1997; Peteet *et al.*, 1997), and some arid time periods during the late Holocene of the Great Plains have been correlated with cold conditions in the North Atlantic region (Yu *et al.*, 2002). However, correlations observed during the historical time period have linked continental droughts with warm phases of the Atlantic Multidecadal Oscillation (AMO) (Enfield *et al.*, 2001; McCabe *et al.*, 2004), an index averaged for the entire North Atlantic (0–70°N), and the Dust Bowl drought was associated with an anomalously warm northern North Atlantic. Because Holocene SST patterns are poorly known across the entire North Atlantic, direct comparison with the historical record is difficult. There is also evidence for changes in the tropics or subtropics at 4.2 ka that could be linked to SST changes in the Indian Ocean. For example, a reduction in the Indian Ocean Summer Monsoon has been inferred at approximately 4.2 ka from Arabian Sea sediments (Gupta *et al*., 2003), and a similar but larger reduction in monsoon strength has been inferred from a peatland-derived $\delta^{13}C$ cellulose record on the Tibetan Plateau (Hong *et al*., 2003). High-resolution proxy records of past SST variability are needed before firm conclusions can be reached.

In summary, our knowledge of changes in external forcing at 4.2 ka is still limited and, although the response of temperature and circulation patterns to changes in solar or volcanic forcing during recent centuries is now being studied, the response of precipitation has not been documented, especially outside the tropics. The role of SST changes, either caused by external forcing changes and feedbacks or as part of an internal mode, cannot be fully assessed until more SST data are available for the period bracketing the 4.2 ka event. Nevertheless, several modelling studies indicate that tropical SST anomalies are an important component of the climate anomalies that accompany drought. Although we cannot yet isolate the causal mechanisms of the 4.2 ka event, the likelihood that ice sheet dynamics did not play a role makes the event a prime target for modelling studies once base-state changes, solar or volcanic forcing changes or internal dynamical modes can be simulated for this period.

Conclusions

Temporal resolution of the available paleoclimate records is insufficient to assess whether drought was experienced synchronously within and among continents, but it is clear that extraordinary and persistent drought occurred on all Northern Hemisphere continents within a century or two of 4.2 ka, amounting to a hemisphere-wide megadrought far surpassing the droughts of the past millennium in severity and/or duration. In mid-continental North America, rapid climate changes associated with the event had large and widespread ecological effects, including dune reactivation, forest fires, and long-term changes in forest composition. Emergence of a persistent climate anomaly similar to that of 4.2 ka would have devastating societal and ecological impacts. The mechanisms forcing the event, whether externally caused and/or related to an internal mode involving SST changes, are unclear.

The spatial extent, forcing mechanisms and ecological responses to the abrupt climatic changes at 4.2 ka need to be further characterized. The causes of the event, why it persisted with such intensity for so long, and what caused it to end, still need to be investigated. More continuous records of hydroclimatic changes are needed across 4.2 ka, particularly to better delineate the spatial pattern of drought throughout the North American continent, and these records should be coupled with records of ecological response. Studies of proxies with annual to decadal precision are needed to determine spatiotemporal patterns of drought, particularly whether it was synchronous across the Northern Hemisphere or displayed temporal and spatial heterogeneity. We also need high-resolution proxy records of SST from various regions of the world, and modelling efforts aimed at developing and testing hypotheses regarding the climatic response to possible changes in external forcing mechanisms or internal dynamical models.

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