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The role of the Atlantic Multidecadal Oscillation on medieval drought in North America: Synthesizing results from proxy data and climate models

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ABSTRACT

During medieval times (900–1300 AD; henceforth MT), persistent drought ('megadrought') was a ubiquitous feature for much of North America. To better understand the mechanisms for these droughts, relationships between specific sea surface temperatures (SSTs) and drought in North America have been synthesized from previous studies using modern observations, proxy paleo-data, and simulations from multiple climate models. Particular focus is on the role of the Atlantic Multidecadal Oscillation (AMO), a roughly 60–80 year fluctuation in the North Atlantic between relatively warm ('warm phase') and cool ('cold phase') SSTs. Present-day relationships, for which instrumental observations can be used, indicate that persistent droughts in the U.S. Great Plains and Southwest are closely related to AMO. During AMO warm (cold) phases, most of North America is dry (wet). The MT drought is closely related to AMO-like warm phases in the North Atlantic. However, the MT drought is just one of numerous droughts on centennial timescales affected by the AMO that new results from the proxy record indicate impacted North America during the Holocene. The influence of North Atlantic SST on modern North American drought is examined using simulations made by global climate models. When forced by warm North Atlantic SST anomalies, all models captured significant drying over North America, despite some regional differences. Overall, the ensemble of the 5 models could well reproduce the statistical relationship between the dry/wet fluctuations in the North America and North Atlantic SST anomalies. Using one particular climate model, we further demonstrated that warm North Atlantic SST anomalies might have played a major role in the MT drought over much of North America. The MT drought could be simulated either by perpetual La Niña-like conditions in the eastern Pacific or warm phase of the AMO in the North Atlantic. Best match to proxy reconstructions was obtained, however, when both La Niña and warm phase AMO conditions were imposed. During the warm phase of AMO, the subtropical high is displaced north and east of its mean location, reducing moisture transport into the US except along the mid-Atlantic coast. During the cool phase, the subtropical high strengthens and pushes westward, allowing for more moisture transport into the central and western US. In summary, the AMO modulates the large-scale circulation to be more (less) conducive to precipitation over the central and western U.S. during cold (warm) phases. Its effects must be considered along with other, shorter time-scale factors such as ENSO, or PDO, as well as local effects that affect land surface–atmosphere interactions, such as soil moisture.

1. Introduction

The proxy record clearly indicates that so-called 'megadroughts' affected North America during the medieval times (MT) that lasted from approximately 900–1300 AD (The term 'megadroughts' refers to periods of drought much more prolonged than what has occurred during the historic record e.g., Woodhouse and Overpeck, 2000). Tree-ring records in particular show that droughts were particularly frequent and persistent throughout much of the western US (30–50°N, 90–125°W) during the MT (Fig. 1a). These droughts usually lasted for decades, indeed, sometimes for most of a given century (Fig. 1b). Dry conditions during MT are also recorded by terrestrial eolian deposits and alluvial stratigraphic evidence, as well as chemical and salinity reconstructions from lake sediments (Gray et al., 2003; Cook et al., 2007; Graham et al., 2007; McCabe et al., 2007; Seager et al., 2007; Feng et al., 2008). These episodic droughts had tremendous impacts on ecosystems and past civilizations. The incidence of wildfires during the MT was very high along the Pacific coast (Schoenagel et al., 2004; Kitzberger et al., 2006; Graham et al., 2007). The prolonged droughts drove Native American populations into abandoning their homes and migrating to areas with more reliable water supplies (Benson et al., 2007). In the Great Plains, the grassland cover of the sand dunes was destroyed, and the dunes became mobilized, indicating drought conditions much more severe

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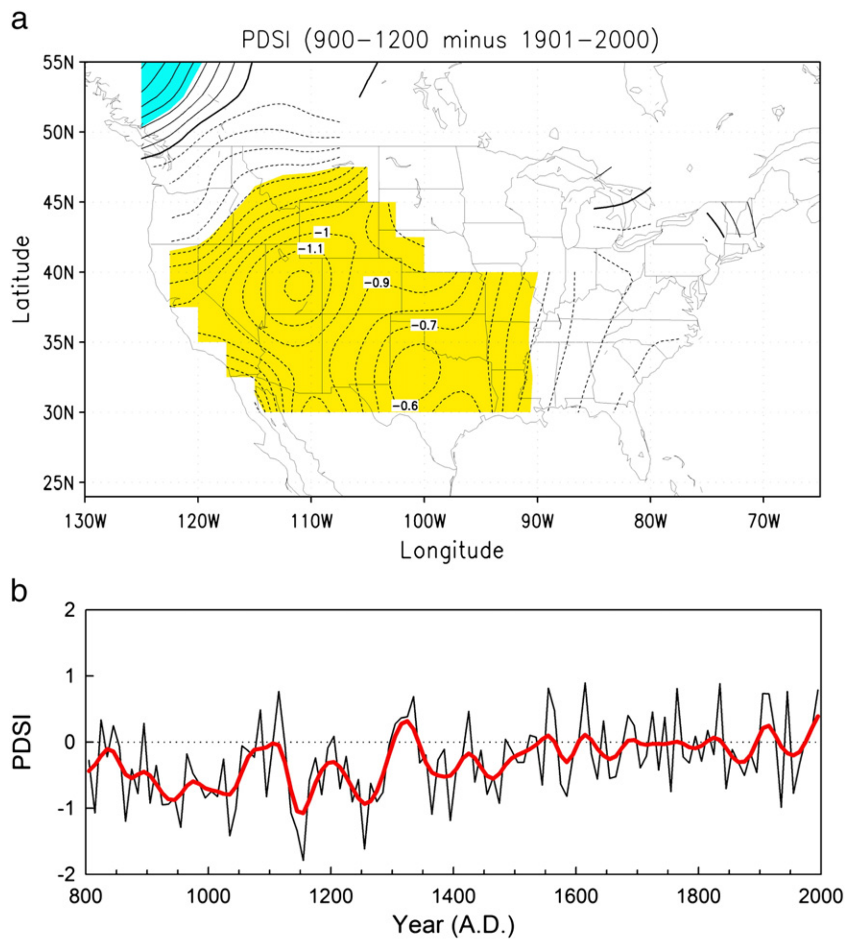

Fig. 1. (a) Difference in tree-ring reconstructed PDSI for 900–1200 AD minus 1901–2000. Negative values indicate the regions were dryer in MT. Shadings indicate the differences are significant at 95% confidence level by two-tailed Student *t*-test. (b) Regional averaged PDSI for the western U.S. (30–50°N, 90–125°W). To retain the low frequency variations in PDSI, only the 10-yr average values of PDSI were shown. The red lines show the low frequency variations of PDSI by low pass binomial filter. (adapted from Feng et al., 2008).

than that during the 20th century (Sridhar et al., 2006). In summary, multiple lines of evidence suggest that *during the MT, drought was the dominant feature of climate rather than the exception.*

The physical processes that contribute to relatively short duration drought during the instrumental period in North America have been extensively studied (e.g., Lyon and Dole, 1995; Trenberth and Guillemot, 1996; Hong and Kalnay, 2000). These generally include remote effects such as forcing by sea surface temperatures (SSTs) and local effects such as land surface feedbacks due to soil moisture or snow cover. How, and even if, these processes also contribute to the long duration, persistent 'megadroughts' of the past, especially those that occurred during the MT remains unclear. SST anomalies in the tropical Pacific and North Atlantic Ocean have frequently been related to droughts in North America (e.g., Trenberth and Guillemot, 1996; Enfield et al., 2001; Hu and Feng, 2001; Hoerling and Kumar, 2003; Schubert et al., 2004, 2008, in press; Seager et al., 2005; Herweijer et al., 2006, 2007; Seager, 2007; McCabe et al., 2007; Lau et al., 2008; Mo et al., 2009; Conroy et al., 2009b; Cook et al., 2009, 2010; Kushnir et al., 2010). The major North America droughts of the instrumental record during the 1850–1860s, 1870s, 1890s, and 1930s are coincident with cool SST anomalies in the tropical Pacific (La Niña condition) (Seager et al., 2005, 2007; Herweijer et al., 2006, 2007). Additionally, the major droughts in the 1930s, 1950s and the recent drought during 1998–2005 are also associated with a warm North Atlantic Ocean (the warm phase of the Atlantic Multidecadal Oscillation, AMO) (Enfield et al., 2001; McCabe et al., 2004, 2007, 2008; Sutton and Hodson, 2007; Curtis, 2008; Feng et al., 2010). On the other hand, present-day drought is not ubiquitous during the warm phase of the AMO, as periods with normal and above-normal precipitation have also occurred during the most recent warm phase. This suggests that something else must be at work in addition to merely warm AMO phases and/or La Nina conditions. All we can do is speculate — perhaps a conjunction of extremal AMO and La Nina events is required, or perhaps land surface feedbacks become crucial to prolonging the drought.

Previous studies of the impacts of SST on medieval drought in North America mainly focused on the tropical Pacific Ocean. Mann et al. (2005) showed that simulations using a low-order (Zebiak–Cane) model of tropical Pacific coupled ocean–atmosphere dynamics reproduces coral evidence of a La Niña-like MT. Medieval droughts in North America were related to cool conditions in the tropical Pacific (Herweijer et al., 2006; Cook et al., 2007; Graham et al., 2007; Seager et al., 2007; Conroy et al., 2009b). Graham et al. (2007) showed that the Community Climate Model (CCM3; Kiehl et al., 1998) is able to simulate the medieval drought by prescribing strong cool SST anomalies in the eastern Tropical Pacific as the forcing. Seager et al. (2008) analyzed the role of tropical Pacific SST on the North America drought during 1320 to 1462 AD. They first reconstructed the SST variations during that period using the fossil coral records from Palmyra Island. Their model results suggest that, when forced by reconstructed SSTs, the NCAR/CCM3 could simulate two previously identified persistent droughts during 1360–1400 AD and 1430–1460 AD. Though the work of Seager et al. is focused on the transition period between the MT and Little Ice Age, their results and those of Graham et al. (2007) clearly suggest that the cool conditions in the Eastern tropical Pacific may have played an important role on medieval droughts in North America. Recent global surface temperature reconstructions by Mann et al. (2009b) which suggest a La Niña-like pattern during the MT provide further support for this interpretation, as do sediment-based reconstructions of past Atlantic hurricane activity which suggest an active MT (Mann et al., 2009a).

The roles of North Atlantic SST on medieval drought are not nearly as well established by previous work, although some studies argued that the North Atlantic likely impacted North America drought during the MT (e.g. Booth et al., 2006; Benson et al., 2007; Seager et al., 2007; Feng et al., 2008; Conroy et al., 2009b). In the remainder of this synthesis paper, we describe the Atlantic Multidecadal Oscillation (AMO) as it is known from the modern observational record, and why it can strongly influence summer precipitation over North America. To provide a context for the importance of the AMO through time, we present new results for a Holocene SST reconstruction for the North Atlantic that emphasize the long-term existence of the AMO. Clearly, the AMO is a potentially major player on decadal to centennial and millennial time scales. We further present a preliminary explanation in terms of the dynamical response of the atmosphere to the thermodynamic SST forcing, but emphasize this is still an active area of exploration. Furthermore, the AMO does not operate by itself, but in conjunction with other key SST phenomena, especially El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). We describe what little is currently known about the interactions between these various SST phenomena, concluding this is a key area for future research.

2. The AMO and modern drought in North America

Instrumental records show that SSTs in the North Atlantic have risen and fallen in a roughly 60- to 80-year cycle during the past 150 years (Schlesinger and Ramankutty, 1994) (Fig. 2b). This variability has been named the Atlantic Multidecadal Oscillation, or AMO (Kerr, 2000). According to Enfield et al. (2001), the AMO index is defined as the detrended, regionally-averaged, summer SST anomalies (red line) over the North Atlantic Ocean (0–60°N, 7.5–75°W). During the AMO warm (cold) phases, SSTs over the entire North Atlantic show positive (negative) anomalies (Fig. 2a). These basin-wide SST variations are also recorded by tree rings around the Atlantic (Delworth and Mann, 2000; Gray et al., 2003, 2004), coral records from the Red Sea, and varved sediments on the continental shelf of Venezuela (Grosfeld et al., 2007). While the warm/cold phases reflect behavior over the entire basin, distinct spatial patterns nonetheless exist. In particular, a horseshoe pattern is seen, with warmings largest

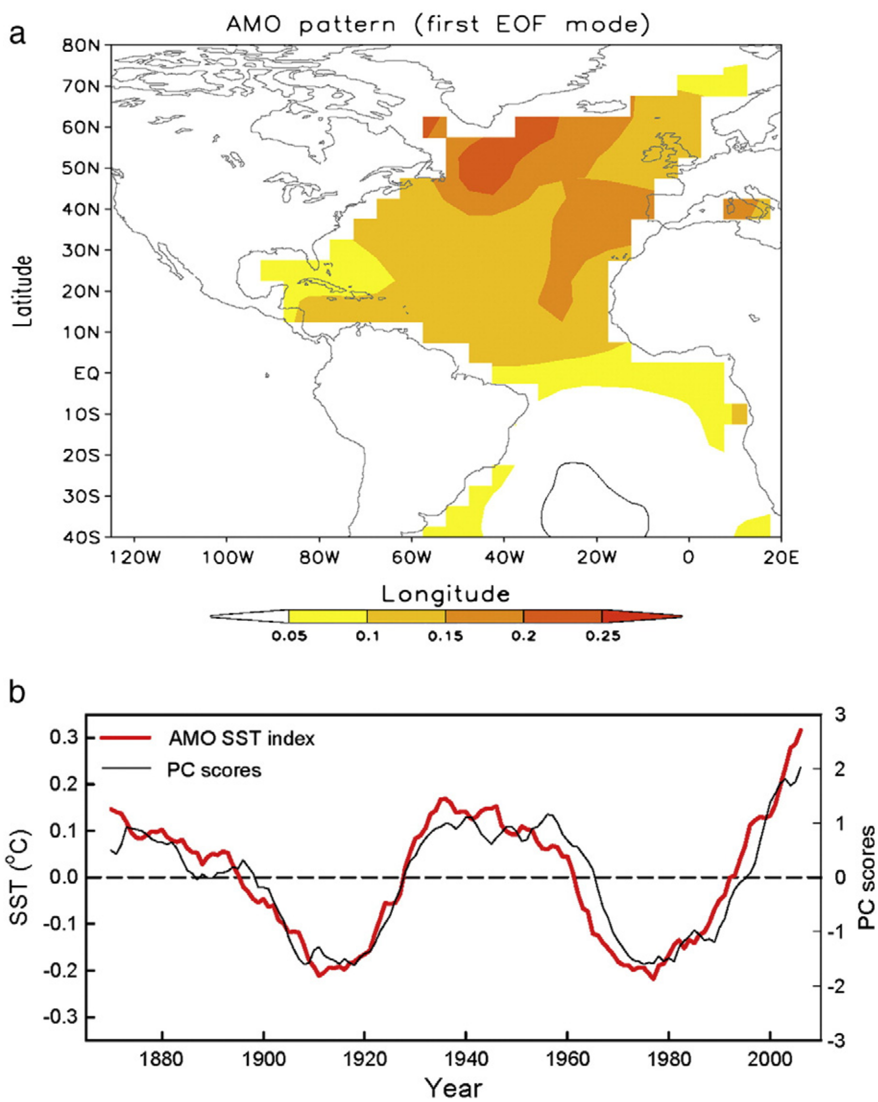

Fig. 2. Observed summer (June–August) SST pattern associated with AMO and the temporal variations of the AMO index. (a) The first EOF of the SST in the North Atlantic Ocean. Before EOF analysis, the SST in each grid point was first detrended and then smoothed with a 9-point equal-weight low pass filter. (b) Temporal variations of the first principal component (PC) associated with the EOF mode (black line), and the regional averaged summer detrended SST anomalies (red line) over the North Atlantic Ocean (0–60 N, 7.5–75 W).

to the north and south, and least in the west-central portions. The fact that this pattern is also expressed in past reconstructions (as we will show in more detail later on) suggests that it represents a natural mode of variability, as opposed to a modern artifact (or purely a 'global warming' signal).

The Atlantic Ocean is typically considered as a key source of internal variability for climate through interactions between the near-surface poleward heat and salt fluxes and the deep convective activity in the subpolar Atlantic (associated with the thermohaline circulation, THC), as well as export of sea ice from the Arctic (Delworth et al., 1997; Dima and Lohmann, 2007). Modeling studies suggest that the strength of the THC is closely related to the AMO, and further suggest a possible oscillatory component to this behavior (Delworth and Mann, 2000; Knight et al., 2006; Grosfeld et al., 2007).

The AMO has been linked to recent multidecadal climate changes over North America (Enfield et al., 2001; McCabe et al., 2004, 2007; Hu and Feng, 2008). Observational studies of the effects due to AMO (e.g., Hu and Feng, 2008) show that each phase of the AMO is associated with a different regional circulation regime in North America. During the cold phase of AMO, more frequent northwesterly wind anomalies in the North American monsoon region confine the monsoon rainfall to the south of the southwestern U.S. (Hu and Feng, 2008). Meanwhile, a strong southerly low-level flow from the Gulf of Mexico, associated with the SST anomalies in the western tropical Atlantic Ocean, enhances moisture transport and summer precipitation in the central U.S. (Wang et al., 2006; Feng et al., 2008, 2010). This anomaly pattern changes during the warm phase of the AMO, resulting in below average precipitation for most of North America. These changes effectively describe an alternating monsoon regime that follows the phases of AMO (Hu and Feng, 2008).

The AMO does not act in isolation. In particular, interactions with other phenomena such as PDO and ENSO affect the end result — precipitation over North America. Additionally, the AMO (and PDO and ENSO) are all defined based on ocean phenomena. This raises the question of their relationship with *atmosphere-based* phenomena, such as the North Atlantic Oscillation/Arctic Oscillation (NAO/AO), which many researchers feel represent the same underlying phenomenon. Observational and modeling studies showed that the warm (cold) AMO can induce a sea level pressure (SLP) pattern that resembles the negative (positive) phases of NAO (Robertson et al., 2000; Grosfeld et al., 2007; Feng et al., 2009), suggesting that the AMO and NAO may be manifestations of the same basic climate system phenomenon, just manifested somewhat differently for the atmosphere and the ocean. The observational findings of the direct influence of AMO on the North American monsoon regime indicate that differing and persistent large-scale circulation regimes exist at multidecadal timescales in association with multidecadal variations of SST in both the North Pacific and the North Atlantic Ocean. These circulation regimes affect especially the location and intensity of subtropical high-pressure zones, thereby favoring specific precipitation anomaly patterns in North America. They also condition particular circulation environments for interannual time-scale forcing, e.g., ENSO and NAO/AO, and decadal ones, e.g., PDO, to further affect precipitation. Collectively, they, along with local surface effects and interactions, determine the precipitation distributions in North America. Understanding the combined interactions of these various SST anomalies is an area of active current investigation, but is complicated by the diverse time scales (from the observational record) over which they appear to operate.

Finally, when the tropical Pacific has a strong La Nina-like pattern, annual precipitation in the High Plains and the western U.S. is about 10–20% less than present-day conditions as defined by climate norms (Feng et al., 2008). The eastern U.S. is also somewhat drier. When the North Atlantic Ocean has a warm anomaly, annual precipitation in the High Plains and the western U.S. is about 5–20% less than climate norms. The Pacific Northwest and the northeastern U.S. are slightly wetter. When both a relatively cool tropical Pacific and warm North Atlantic Ocean are combined, the entire U.S., except the Pacific Northwest and New England, are significantly drier (Feng et al., 2008). We also note that the US CLIVAR Drought Working Group has conducted a series of model runs using five climate models to better understand the roles of both Pacific and Atlantic SST on North American drought during modern times (Schubert et al., 2009). When forced by warm North Atlantic SST anomalies, all models captured significant drying over North America, despite some regional differences. Overall, the ensemble of the 5 models could reproduce well the statistical relationship between the dry/wet fluctuations in the North America and North Atlantic SST anomalies obtained from observational and proxy analyses by Feng et al. (2010), as detailed in Sections 3 and 4.

3. The AMO and medieval time drought in North America

The focus of this special issue is on the climate during medieval times, with a particular emphasis on the warm conditions that prevailed over much of the Northern Hemisphere from about 900–1300 AD. These warm conditions also coincided with extended periods of megadroughts over North America. Therefore, the key thrust of this report is: What role may the AMO have played in causing or at least influencing the warm, dry conditions that prevailed most of the time over North America? Our focus is on hydroclimatic effects associated with the dry conditions, though we note prolonged drought also tends to lead to warming conditions, most notably due to reduced soil moisture and consequent enhanced surface heating (Oglesby and Erickson, 1989; Oglesby et al., 2002). In a recent study (Feng et al., 2008), we used the NCAR Community Atmospheric Model (CAM3) to investigate and compare the role of SST anomalies from the North Atlantic and the tropical Pacific Ocean on North American MT drought. We focused on model simulations, rather than observational analyses because the latter, while strongly suggestive of relationships between AMO and drought, are both short in duration (at most 150 years; much less in many locations) and contain every influence on climate. This makes attribution of specific effects and their influences extremely difficult. With model simulations we can isolate specific effects (e.g., SST anomalies) and determine what their influence may be, with the caveat that the model is a simplification of the real climate system, and does not provide a perfect simulation of the present-day climate.

The SST anomalies were derived from a variety of proxy reconstructions for that time period (for details, see Feng et al., 2008). Several CAM3 experiments with prescribed SST anomalies in the tropical Pacific and/or North Atlantic Ocean, and modern-day climatological SST elsewhere, were then made. The model experiments otherwise used all present-day control parameters (e.g., CO_2, land use, etc.) along with the Community Land Model (CLM) land surface scheme. The use of prescribed SST does somewhat restrain air–sea interactions, but allows isolation of the effects on the atmosphere due to SST anomalies consistent with AMO and ENSO, as that is our aim. If we computed SST, the air–sea interactions might be handled a bit more realistically, but we would inevitably be trying to simulate the causes of the SST anomalies, not the subsequent impacts on the atmosphere. Finally, CAM3, when driven by climatological SST imposed globally, does quite a satisfactory job in simulation the present-day atmospheric climate (e.g., Collins et al., 2006).

As indicated in Fig. 3, the CAM3 simulations captured the major dry features that occurred during medieval times in North America. The region of drought related to a strong La Niña-like pattern in the tropical Pacific is generally similar to the drought pattern reconstructed by tree-ring data. The intensity of the drought also appears to be even better matched. However, the evidence for medieval SST patterns in the tropical Pacific appears less clear than that for the

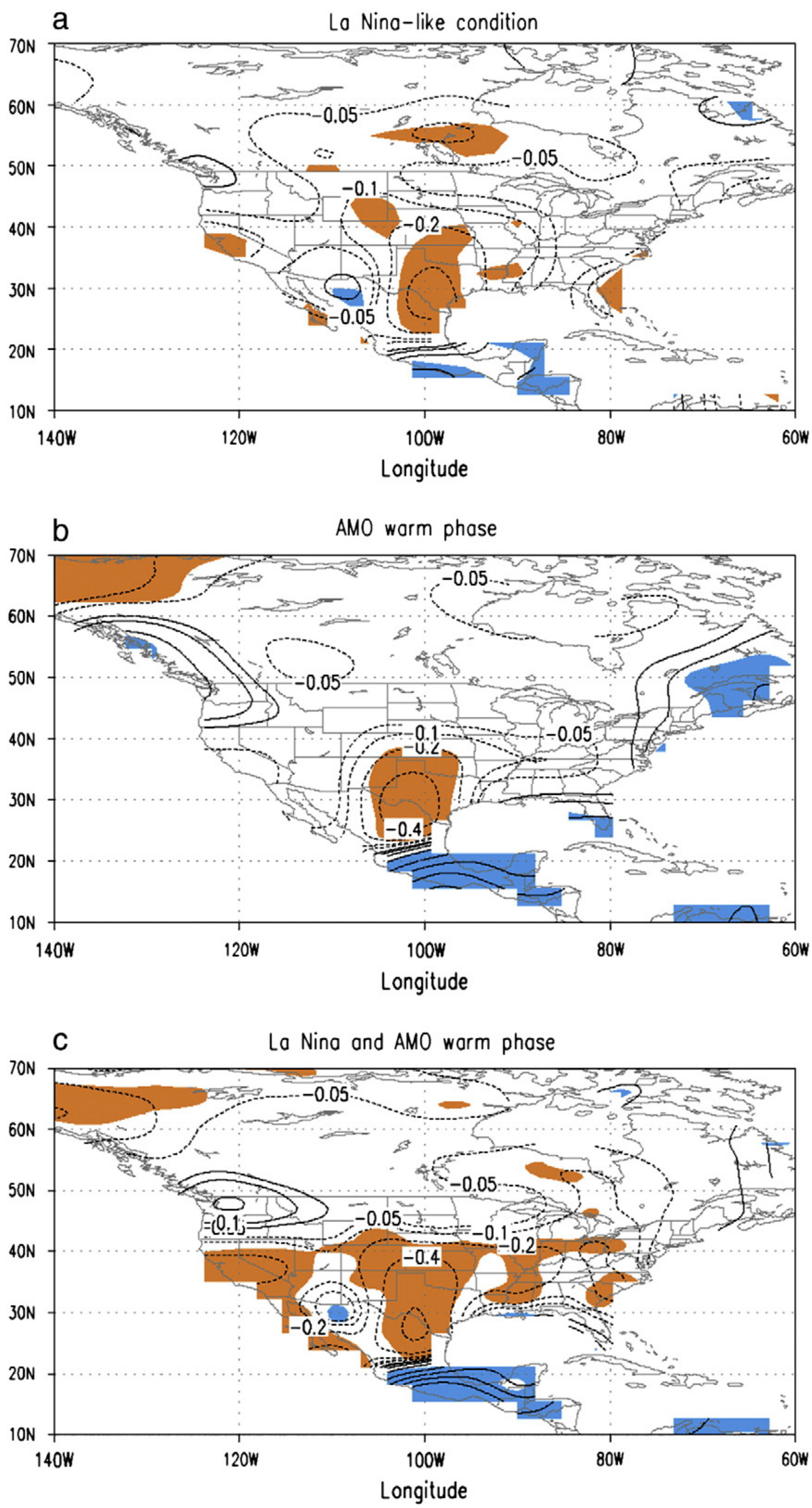

Fig. 3. Influences of (a) La Niña-like condition in eastern tropical Pacific Ocean, (b) AMO warm phase SST in the North Atlantic and (c) both La Niña-like SST in the tropical Pacific and AMO warm Phase SST in the North Atlantic on the annual averaged daily precipitation (mm/day). Detail of those model simulations can be found at Feng et al. (2008).

Atlantic, and different reconstructions produce somewhat differing results (Moy et al., 2002; Cobb et al., 2003; Lachniet et al., 2004; Conroy et al., 2008, 2009a). Our results suggest that the impact of the Pacific Ocean SST anomalies on medieval drought in North America could be overestimated if the La Niña-like cooling in tropical Pacific Ocean was not as strong as some studies suggest. On the other hand, the areal extent of drought is very well simulated by the warm phase AMO pattern, though the intensity not as well as in the Pacific case. The two SST phenomena working together can best explain the severity and longevity of the drought (Feng et al., 2008). For example, during April–May–June (AMJ) (period of greatest precipitation in the Great Plains of the Central US), the cool tropical Pacific, or the warm North Atlantic, or both, results in less moisture transport to the High Plains, with a 15–40% decrease in rainfall. In the July–August summer season (period of greatest precipitation in the US Southwest), on the other hand, precipitation increased by up to 20% with either the cool tropical Pacific or warm North Atlantic. Precipitation in the Great Plains continued to decrease (though not by as much as in AMJ), consistent with the observed out-of-phase relationship between summer monsoon precipitation, and that in the central Great Plains (Hu and Feng, 2008).

The SST variations in the tropical Pacific and North Atlantic could also have interacted with each other during medieval times. Some scientists (e.g., Seager et al., 2007) argue that a medieval La Niña-like pattern could induce a stronger meridional overturning circulation, and hence a warm North Atlantic Ocean. Other observational and modeling studies, however, suggest that the North Atlantic played a more active role in influencing the tropical Pacific Ocean (e.g., Wang et al., 2006, 2007, 2010; Xie et al., 2007). Therefore, it is possible on physical grounds to argue that the warm North Atlantic in medieval times should result in a tropical Pacific warming. This mechanism could also explain the warm North Atlantic and proxy records indicating a relatively warm tropical Pacific Ocean (Moy et al., 2002; Lachniet et al., 2004). If this mechanism operated, the North Atlantic could play a dominant role on the medieval drought in North America because the warm tropical Pacific by itself should lead to wet conditions in the western and central US. These two mechanisms (the cool tropical Pacific inducing a warm North Atlantic, and the warm North Atlantic inducing a warm tropical Pacific) demonstrate the agreed-upon warming in North Atlantic Ocean, but would require controversial SST anomalies in the tropical Pacific Ocean during medieval times (Feng et al., 2008). However, it must be emphasized that both mechanisms, at this point, are ideas that need to be proven or disproven. Links between the North Atlantic and the tropical Pacific Ocean remain poorly understood at this time, because diverse results have been obtained by previous modeling studies.

Overall, the cold tropical Pacific alone can simulate essentially the drought intensity, while the warm North Atlantic alone can simulate the drought areal extent (Fig. 3a, b). The two working together can explain the severity and longevity of the drought (Fig. 3c). The importance of the Atlantic Ocean on medieval drought in North America suggests that attention should be paid not only to the tropical Pacific Ocean, but also to the North Atlantic Ocean in understanding the North America drought variability and predictability, both at present and during the past (Feng et al., 2008).

Also potentially important is the Pacific Decadal Oscillation (PDO), which manifests largely in the North Pacific. Statistical results suggest that the PDO plays an important role on climate in North America. However, model studies (e.g., Lau, 1997) showed that, when forced just by SST over the North Pacific, the model cannot simulate the observed relationship between North Pacific SST and North America circulation. The model show similar results when forced by 1) merely SST anomalies in the tropical Pacific, and 2) SST anomalies in both tropical and North Pacific. Therefore, the PDO itself likely played a fairly minor role and is best thought of as modulating ENSO.

Sridhar et al. (2006) identified a change in surface wind direction during medieval times by comparing the orientation of sand dunes in the Sand Hills of central and western Nebraska (approximately 98–103°W and 40–43°N) with that expected from modern surface winds. They concluded that the prevailing warm season surface wind was southwesterly during medieval times, markedly different from the southerly to southeasterly wind at present. Though the dry conditions of the medieval drought in North America were simulated quite well by the cool tropical Pacific and/or warm North Atlantic Ocean SST anomalies, the wind direction change revealed by sand dune orientation in the Nebraska Sand Hills (Sridhar et al., 2006) was not reproduced by any of the model experiments. The circulation simulated in all of the model runs was broadly similar to that at present; less moisture is transported into this region and environmental lift decreases as well (Feng et al., 2008). The model resolution may possibly be too coarse to distinguish this more local effect from the overall large-scale circulation. More likely, however, is that land cover changes associated with the activated dunes provided a feedback that allowed southwesterlies aloft to be brought down to the surface, replacing the southerly to southeasterly winds that occur today (Sridhar et al., 2006). This is the focus of continuing study.

4. Reconstructing the AMO throughout the Holocene

So we have now identified the AMO as a potentially important player in both modern drought in North America, and megadroughts during the MT. Just how ubiquitous *is* the influence of the AMO on North American precipitation and drought? To better understand Holocene SST variations in the Atlantic Ocean, published records of proxy SST were collected (Fig. 4). Because different proxy datasets record SST variations for different seasons, we used the following criteria for selection: 1) The records spanned the last 10 ka with sufficient chronological control and sample quantity to provide sub-millennial resolution, and 2) the proxy data recorded either boreal summer or annual mean, but weighted toward boreal summer SST. Based on these criteria, the alkeneone-derived SSTs in mid- and high-latitude North Atlantic are included because they represent boreal summer temperature (Leduc et al., 2010). In the tropical Atlantic, the alkenone-derived SSTs are excluded because they represent boreal winter temperature (Leduc et al., 2010). Instead, the Mg/Ca-derived SSTs are used, as they represent summer or the average of summer and annual mean temperature (Nürnberg et al., 2008; Oppo et al., 2009; Leduc et al., 2010). Applying these criteria results in 11 alkenone-derived SST records in the mid- and high-latitude North Atlantic Ocean, 4 alkenone-derived SST records in the Mediterranean and the Red Sea, and 4Mg/Ca-derived SST records in the tropical Atlantic. Because there are no other SST records available for the middle North Atlantic, SST reconstructed by planktonic isotopes ($\delta^{18}O$) in the Sargasso Sea (site 11 in Fig. 4) was also used. Keigwin (1996) suggested that the $\delta^{18}O$ in this region represents annual mean temperature.

We analyzed SST variations from these proxy SST records using empirical orthogonal functions (EOF) (von Storch and Zwiers, 1999). This method decomposes the SST records into spatial variations (EOF modes) and temporal variations (principal components). Importantly for our purposes, it also “serves as a data-filtering procedure to smooth the (spatial) noise and uncertainties in the age models of individual SST records” (Kim et al., 2004). This feature of the EOF method also has proven useful for the evaluation of the co-variability and consistency of records for different periods during the Holocene (Marchal et al., 2002; Kim et al., 2004, 2007).

Spatial features in the North Atlantic Ocean are displayed by leading EOF modes of the Holocene SST variations. The first EOF (EOF01) accounts for 57.6% of the total SST variance during the Holocene (Fig. 5a), and shows a coherent pattern of SST variations from the subtropical to the mid- and high-latitude North Atlantic. The tropical Atlantic shows weak SST variations, and the eastern Mediterranean and the Red Sea show SST anomalies opposite to that in the North Atlantic. High scores for EOF01 reflect positive loading from individual sites in the mid- and high-latitude Atlantic Ocean, whereas the scores in the tropical and low latitude are relatively small. The temporal variations associated with EOF01 described by the first principal component (PC01) for the last 10 ka are shown in Fig. 5b, and the detrended time series in Fig. 5c. The ‘warmest’ peak of PC01 occurred before 9.0 ka BP and then decreased slowly during the Holocene. This variation suggests that SSTs in the North Atlantic Ocean have been primarily decreasing over the last 10 ka, a result also indicated in previous studies using only alkenone-based SST reconstructions from the eastern North Atlantic, Mediterranean and Red Sea (Marchal et al., 2002; Kim et al., 2004, 2007). This cooling trend can best be explained by decreasing boreal summer

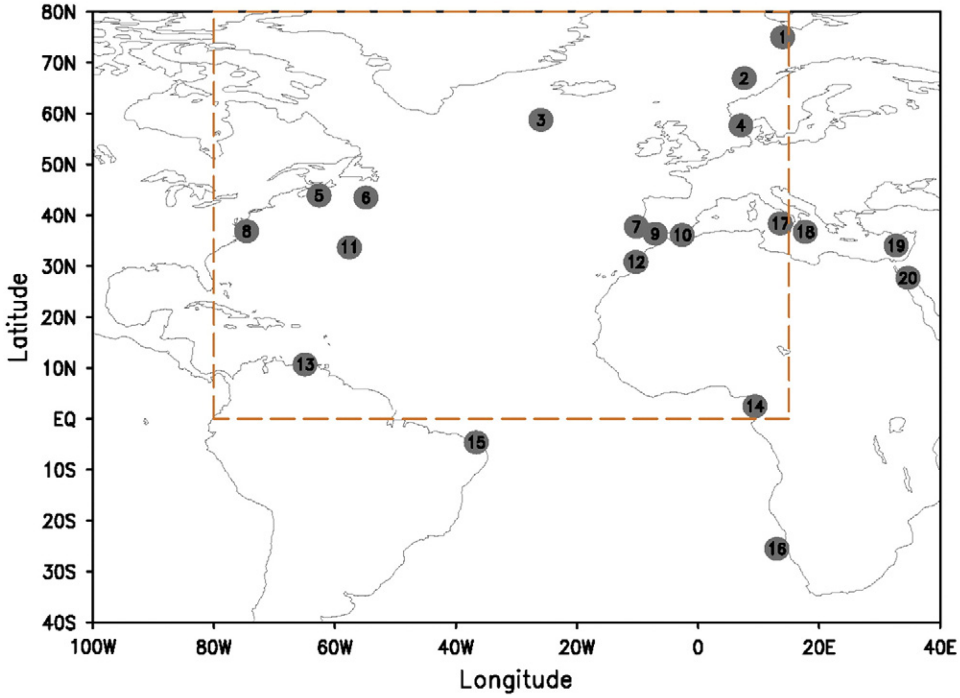

Fig. 4. Spatial distribution of the proxy SST records used in this study. The (numbered) gray dots in the Atlantic Ocean mark the 20 sites where proxies for SST were obtained (details of those sites and the temporal SST variations in individual site are shown in Feng et al. (2009). Dashed rectangle shows the regions dominated by basin-wide AMO signal during the instrumental period.

insolation during the Holocene as suggested in Berger and Loutre (1991) and Lorenz et al. (2006).

The EOF01 of the Holocene SST is very similar to the first EOF of the observed SST related to the AMO, except, of course, that the PC01 of Holocene SST contains variations on much longer time scales. In other words, we suggest that SST in the North Atlantic during the Holocene and during the instrumental period (and the MT) had similar spatial patterns of variability (Fig. 5a, denoted as the AMO-like pattern), while the temporal SST variations (PC01) associated with this AMO-like pattern varied on different timescales and are (presumably) controlled by different physical processes (Feng et al., 2009). Lorenz et al. (2006) in their modeling study suggest that, when forced by orbital insolation changes during the Holocene, the model could simulate a basin-wide cooling in the North Atlantic, a pattern that resembles the EOF01.

Superimposed on the decreasing trend of the temporal SST variations (PC01) associated with this AMO-like pattern are centennial-scale variations, presumably due to orbital-induced summer insolation changes. After removing this trend, by applying local weighted regression (Cleveland, 1979), the centennial time-scale variations in PC01 clearly stand out. A distinct warm period occurred roughly 1000 years ago, consistent with the basin-wide AMO-like warm SST pattern during the MT (Feng et al., 2009). Feng et al. (2010) further note that the centennial variations in PC01 seem closely related to centennial time-scale dry/wet variations in the Midwest and the southern Great Plains during the last 7000 years. Major centennial warm periods in the North Atlantic all correspond to dry conditions in the Midwest and the southern Great Plains. They also argued that the megadrought during MT is just one of several such droughts on centennial timescales that affected North America.

5. A mechanism for AMO forcing of North American summer precipitation

We have now identified the AMO as a potentially important player in North American drought on a variety of time scales, including the megadroughts of medieval times. Just *how* does the AMO influence precipitation over North America? Understanding this influence involves identifying the *key physical processes* involved, which in turn requires examining the atm\ospheric circulation and how it responds to the SST anomalies. We summarize, and place in context, results from Hu et al. (2011), who conducted model experiments with the CAM3 that focus on elucidating the physical processes and mechanisms by which the AMO actually impacts precipitation over North America during the summer. We relied on model simulations, rather than purely observational analyses for the reasons described above.

A primary way by which SST anomalies can affect the atmosphere is by differential heating, with consequent effects on atmospheric pressure (Hu et al., 2011). They find the largest differences in the North Atlantic subtropical high-pressure system (NASH). Compared to the control run, the NASH enhanced and shifted its center westward by nearly 20° in the cold phase of the AMO. All of North America is effectively under the influence of the western portion of this enhanced high-pressure system. During the warm phase of the AMO, on the other hand, the NASH diminishes substantially, and its center shifts eastward by about 20° and also northward by 20°. Strong negative SLP anomalies occur over the subtropical North Atlantic, extending to the eastern subtropical Pacific. Negative SLP anomalies also occur over most of North America. Less clear is whether or not these changes in the NASH could account for the wind shift that, as described above, is clearly indicated for the Nebraska Sand Hills.

Why do these results occur? When SSTs in the North Atlantic Ocean are warmer than average, the warmed air rises, and, now aloft, expands and spreads downstream to northeastern portions of the North Atlantic region. The resultant decrease in air mass lowers the SLP, effectively diminishing the size and influence of the NASH. This contraction in the NASH would leave the land areas in North America to more freely develop their own pressure and associated circulation anomalies. Because heated land areas in summer favor thermal low pressure, low-pressure anomalies tend to develop and prevail in North America following the contraction of the NASH during the warm phase of the AMO. Support for this concept is provided by the overall warmer surface air temperatures and lower summertime surface pressure that occur during the warm phase of the AMO.

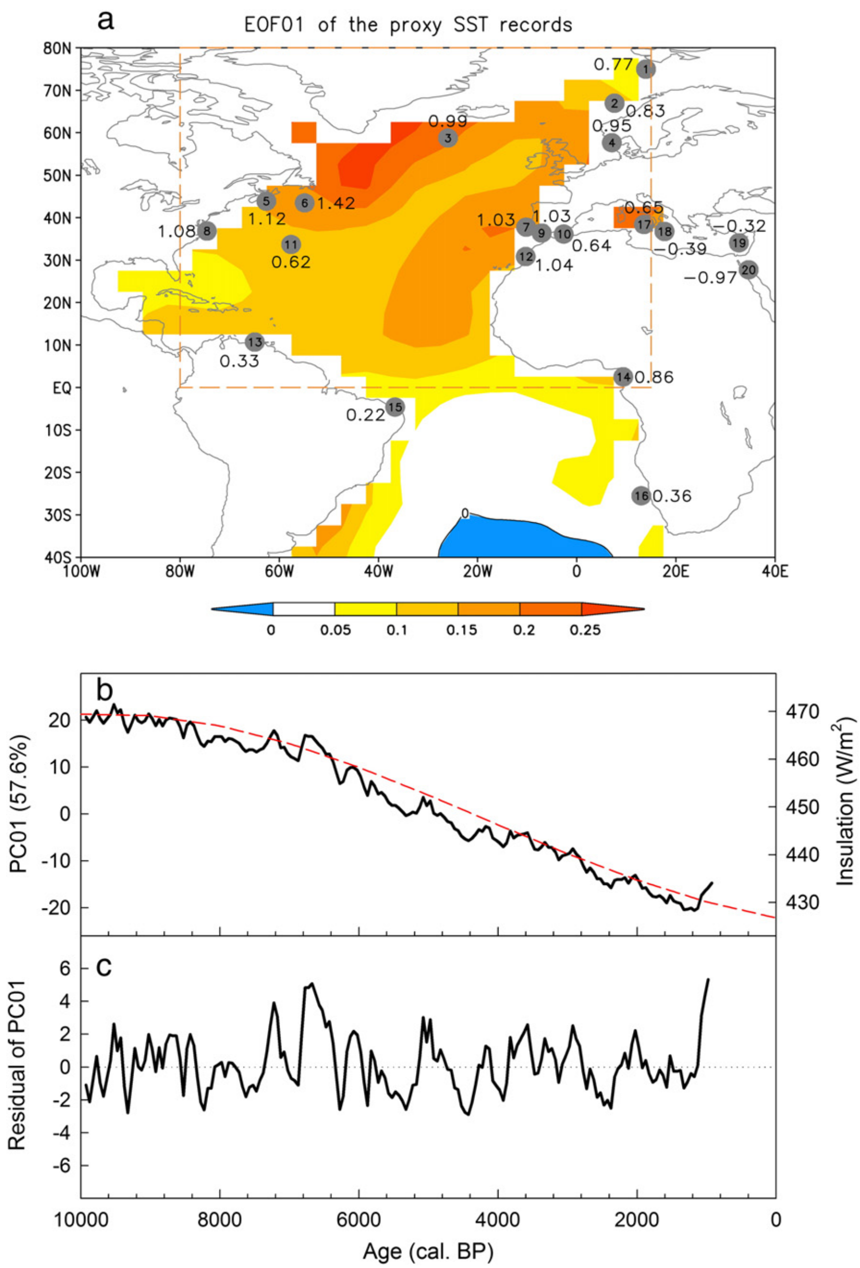

Fig. 5. EOF results of the proxy SST records. (a) Spatial distribution of the first EOF. The (numbered) gray dots show the 20 sites where proxy SST records were obtained (see Fig. 4). The value by each site is the eigenvector of the first EOF of the proxy SST record. (For illustration purposes, shading shows the first EOF of the observed summer SST in the North Atlantic Ocean on decadal and longer timescales, essentially the AMO pattern as defined from observations. The decadal and longer time-scales variations in detrended summer SST are smoothed using a 9-year equal-weight filter, which remove the SST variations shorter than 9 years.). Dashed rectangle shows the regions dominated by basin-wide AMO signal during the instrumental period. (b) PC01 of the 20 proxy SST records (thick line) and July insolation at 65°N during the Holocene (dashed line). (c) Detrended time series of PC01. Details of the results can be found at Feng et al. (2009).

During the cold phase of the AMO a different three-cell pattern is observed (Hu et al., 2011). An anomalous low-pressure cell remains over the North America, though with a more north–south orientation from that in the AMO warm phase. The two cells in the subtropical North Atlantic and the eastern subtropical Pacific are reversed from that in the warm phase, with high-pressure anomalies in the SLP and the lower troposphere. A plausible explanation for the sustained low-pressure anomalies in SLP and the lower troposphere in the western US in both phases of the AMO is the strong "heat island" effect of the Rockies, which provide an elevated summer heat source in the lower troposphere. This topography and surface heterogeneity obviously plays an important role in the regional circulation during boreal summer.

These contrasting circulation anomalies between the cold and warm phases of AMO contribute to, and enhance, the different precipitation anomalies and their spatial variations over North America. During the cold phase of AMO, a zone of strong horizontal shear occurs across mid-latitude North America. On the north and south sides of this shear zone the air masses are quite different, with an oceanic origin for the air on the south and more continental origin for the air to the north. These air masses interact actively across this upper level frontal zone, leading to vertical ascent and above average precipitation. Such an upper level frontal zone and associated air mass interaction and exchange are absent during the warm phase of the AMO. The relatively stable air mass of continental origin over divergent flow anomalies in the lower troposphere yields an environment conducive to fewer storms and less precipitation in most of North America (Hu et al., 2011).

We emphasize that these results do not suggest that the cold phase of AMO has a greater influence than that of the warm phase. *In both cases* they act to affect the hemispheric circulation to be more, or less, conducive to precipitation over North America. The fact that in one phase the influence of the NASH is strengthened while in the other it is reduced does not mean the AMO is more or less important. It plays a crucial role in either phase.

6. Summary and future work

The results summarized in previous sections suggest that the SST pattern associated with AMO likely played a strong and persistent effect on dry/wet fluctuations in North America. It should be emphasized that the AMO does not operate by itself; instead its effects are modulated by, and it in turn modulates, the effects due to other ocean–atmosphere phenomena such as the PDO and ENSO. For example, in previous work we showed that the ENSO effects on summer rainfall variations in the central US were very strong during the periods 1880–1916 and 1948–79. The ENSO effects weakened and disappeared from 1917 to 48 and 1980 onward. These multidecadal variations of ENSO effects appear to be modulated by the PDO (Hu and Feng, 2001). Also, the PDO has been found to strongly influence ENSO effects on North America (Zhang et al., 1997). These lines of evidence suggest that the PDO effect on North American summertime precipitation and drought is primarily through regulating the intensity of El Niño and La Niña, amplifying interannual variations in summertime precipitation (e.g., Hu and Feng, 2001). But, what about the AMO? As an even longer time-scale phenomenon, it may well modulate the PDO and ENSO and, importantly, how they in turn affect each other. In general, longer time-scale phenomena tend to modulate the shorter-term phenomena; the effects of the latter tend to dominate records, be they from observations or paleoclimate proxy data. Furthermore, there are times when the long-term (e.g., AMO) and short-term (e.g., PDO; La Nina) are coupled, and other times when they are decoupled. Schubert et al. (in press) conducted a series of model runs to better understand the roles of both Pacific and Atlantic SST on North American drought during modern times (Schubert et al., in press). Their modeling studies, however, are based on imposed SST anomalies in the tropical Pacific that are twice as large as the anomalies imposed in the North Atlantic Ocean. Proxy records suggested that the SST in the North Atlantic Ocean during MT was about 1 °C warmer than in modern times (Feng et al., 2008), which is about the same magnitude as modern SST anomalies associated with ENSO cycles. Therefore, the model experiments by Schubert et al. (in press) may have underestimated the role of the North Atlantic SST anomaly on North American droughts. Much work remains to be done to clarify this crucial issue. The results described here are intriguing, but still very preliminary. A much deeper understanding is required of how these various phenomena act together, over a variety of time scales.

Other important physical processes that may influence medieval drought are regional land surface–atmosphere interactions and resultant feedbacks. The importance of land use, vegetation, and soil moisture conditions in causing regional/local rainfall anomalies is supported by a large number of observational and model studies (e.g., Shukla et al., 1990; Namias, 1991; Bell and Janowiak, 1995; Huang et al., 1996; Hong and Kalnay, 2000; Malhi et al., 2008; Cook et al., 2009; Koster et al., 2009). Koster et al. (2000), GLACE Team (2004) and Wang et al. (2007) showed that the Great Plains is a region where rainfall is particularly sensitive to changes in soil moisture. Hong and Kalnay (2000) suggest that while drought is usually initiated by SST anomalies, soil moisture anomalies then act to extend the drought. Cook et al. (2009) showed that the inclusion of forcing from land degradation due to human activities, in addition to the anomalous SSTs, is necessary to reproduce the anomalous features of the Dust Bowl drought. These previous results have demonstrated mainly the importance of soil moisture and land surface processes on droughts during modern times. Work on the role of land-use changes and soil moisture feedbacks on medieval droughts in North America, however, remains to be done.

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