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# Medieval drought in North America: The role of the Atlantic Multidecadal Oscillation

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**The sea surface temperature anomalies associated with the Atlantic Multidecadal Oscillation may have been a major factor contributing to widespread drought in North America during Medieval times.**

### The role of the Atlantic Multidecadal Oscillation

Medieval times (900-1330 AD; hereafter referred to as MT) in central and western North America were, according to proxy data reconstructions, generally warm, and especially dry (Fig. 1), with numerous decadal or longer "megadroughts" that were the worst of the past 2000 years (Woodhouse and Overpeck, 2000). Considerable attention has been paid to the role of sea surface temperature (SST) anomalies in forcing these prolonged periods of drought, especially that of the La Niña-like condition in the eastern tropical Pacific (e.g., Graham et al., 2007; Seager et al., 2007). Compelling recent evidence suggests that North Atlantic SST, through the Atlantic Multidecadal Oscillation (AMO), may also have a strong effect on persistent summertime drought in North America (Fig. 1b). At present, the AMO expresses a 60-80 year cycle between relatively warm (warm phase) and cool (cold phase) SST (Kerr, 2000; Enfield et al., 2001).

We investigated the role of the AMO in MT drought in North America using modern (present-day) observations, proxy paleo-data, and simulations from multiple climate models (Feng et al., 2010). Considering present-day relationships, for which instrumental observations can be used, the results show that persistent summertime droughts in the U.S. Great Plains and southwest North America are closely related to multidecadal variations of North Atlantic SST (AMO). During the AMO warm (cold) phases, most of North America is dry (wet).

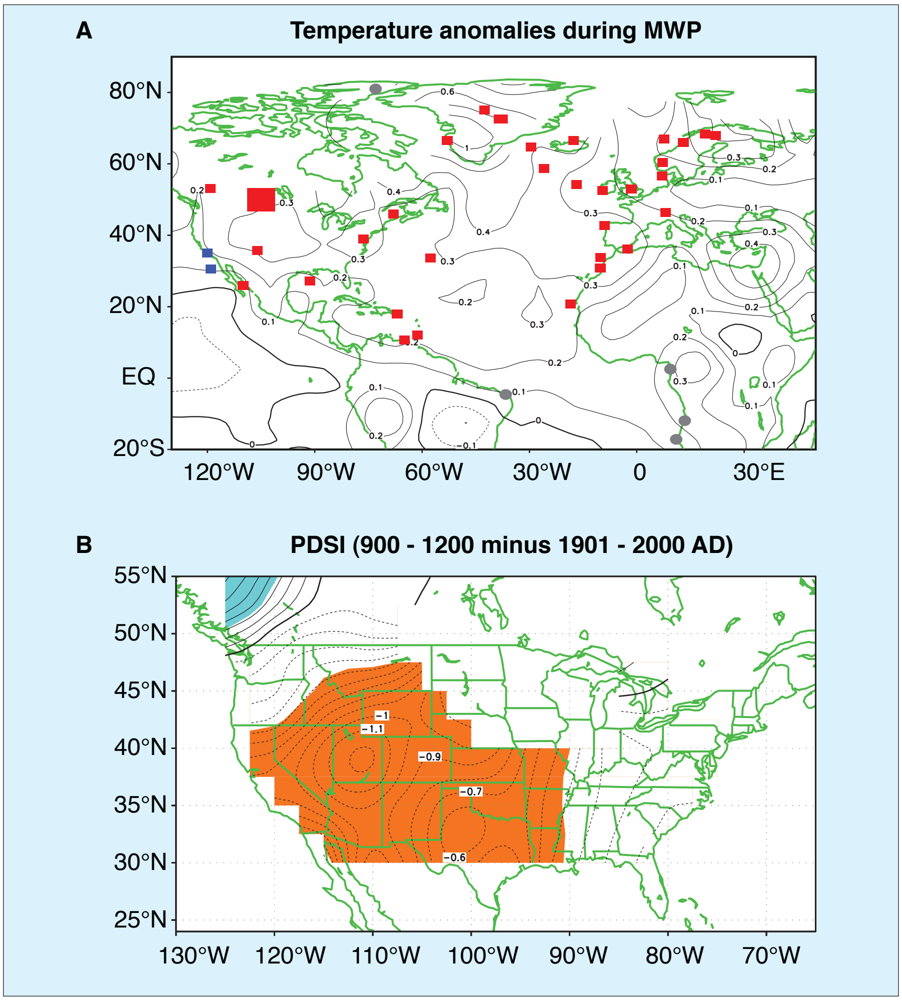

*Figure 1: **A**) Spatial distribution of the proxy data of temperature changes during MT. Blue squares, gray dots and red squares indicate cooling, no changes and warming during Medieval Times, respectively. The contour lines are the observed temperature anomalies associated with AMO warm phases for the period 1901-2006 AD. The contour interval is 0.1°C. Details of the proxy data can be found in Feng et al. (2009). **B**) Difference in tree ring reconstructed Palmer Drought Severity Index (PDSI) for 900-1200 minus 1901-2000 AD. Shadings indicate the differences are significant at 95% confidence level by two-tailed student-test. The figure is adapted from Feng et al. (2010).*

Next, the influence of North Atlantic SST on modern North American drought was examined using simulations made by five global climate models (Feng et al., 2010). When forced by warm North Atlantic SST anomalies, all models captured significant drying over North America despite some regional differences. Specifically, all the models simulate dry summers in the Great Plains and southwestern North America. The response of precipitation to a cold North Atlantic is much weaker, with greater disagreement among the models. Overall, the ensemble of the five models reproduced the statistical relationships between dry/wet fluctuations in North Amer-

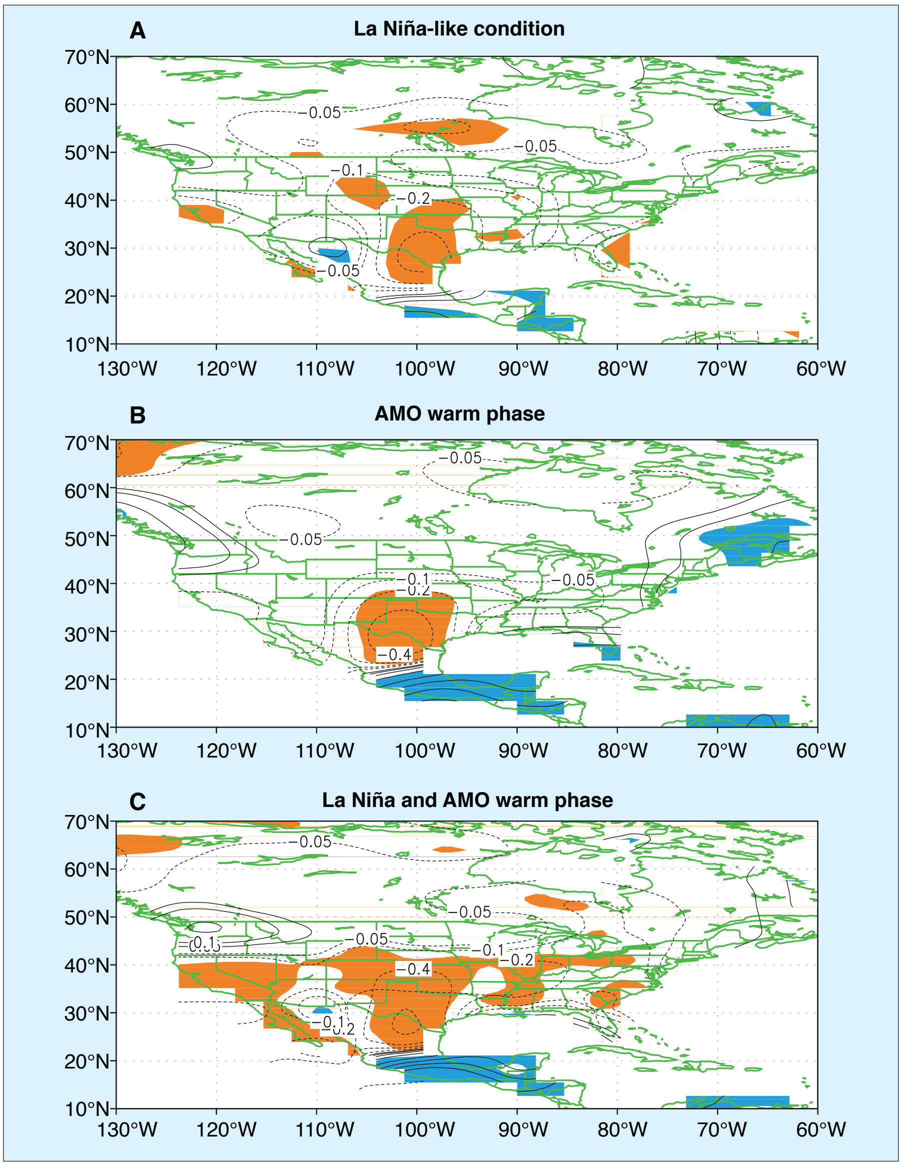

*Figure 2: Influences of (**A**) La Niña-like conditions in the eastern tropical Pacific Ocean, (**B**) AMO warm phase SST in the North Atlantic and (**C**) both La Niña-like SST in the tropical Pacific and AMO warm phase SST in the North Atlantic on the annual averaged daily precipitation (mm/day; solid lines are positive and dotted lines are negative anomalies with respect to the control run). Shadings indicate the anomalies are significant at the 95% confidence level based on a two-tailed student-test. Figure adapted from Feng et al. (2008).*

ica, and North Atlantic SST anomalies (Feng et al., 2010) quite well.

## The AMO during Medieval times

Investigations of proxy SST records in both the tropical Pacific and North Atlantic (Feng et al., 2008, 2009) found a consistent basin-wide warming in the North Atlantic Ocean during MT (Fig. 1), supporting previous studies that there were generally warm periods in the North Atlantic realm (Lamb, 1977). The proxy records from the Pacific Ocean, however, yielded opposite results about SST changes in the eastern tropical Pacific during MT, with some suggesting La Niña-like conditions, while others suggest neutral or even El Niño-like conditions (Feng et al., 2008).

Using one particular model, the NCAR Community Atmosphere Model (CAM3), we further demonstrated that warm North Atlantic SST anomalies might have played a major role in the MT drought over much of North America (Feng et al., 2008). The MT drought could be simulated either by perpetual La Niña-like conditions in the eastern Pacific or by the warm phase of the AMO in the North Atlantic. La Niña conditions alone resulted in the best simulation of the intensity of MT drought (Fig. 2a), while simulation with a warm phase AMO alone reproduced well its areal extent (Fig. 2b). The two together can explain both the severity and longevity of the droughts (Feng et al., 2008) as shown in Figure 2c.

## The AMO throughout the Holocene

To provide a longer-term perspective, we analyzed SST variations in the North Atlantic Ocean for the last 10 ka using empirical orthogonal functions (EOF). The first spatial mode (EOF1) accounts for 52.5% of the variance of the Holocene SST and demonstrates a basin-wide structure in the North Atlantic that clearly resembles the AMO pattern recorded during the recent instrumental period (Feng et al., 2009). The first principal component (PC1) associated with EOF1 is thus a good index that represents the temporal variations of the AMO-like SST pattern during the Holocene. The proxy record indicates that the MT drought is just one of many previous droughts on centennial timescales that impacted North America. We further demonstrated that these centennial droughts appear closely related to the AMO-like SST variations in the North Atlantic (Feng et al., 2010).

## How does the AMO affect North American drought?

Clearly, the AMO or AMO-like SST had the capacity to strongly modulate precipitation and drought over North America throughout the Holocene. But the evidence presented above is all essentially statistical in nature, i.e., over a variety of timescales the AMO appears highly correlated with precipitation (and drought) over North America. The question arises: through what physical processes and mechanisms do the SST patterns reflected by AMO affect North American precipitation? Preliminary analyses from a suite of long model simulations made with the CAM3 suggest some intriguing and even surprising results (Hu et al., unpublished). A primary connection is through the influence of the AMO on the subtropical high-pressure zone in the North Atlantic (Wang et al., 2007). In summer, the poleward flow on the western side of this high-pressure system funnels moisture into the central and western US, providing a source for most of the summertime precipitation in those regions. 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. Similar mechanisms appear to be at play during MT (Feng et al., 2008).

## Future directions

The above results are intriguing, but still very preliminary. Proxy reconstructions and modern observations suggest that the AMO is associated with drought in North America. Understanding the physical mechanisms by which the AMO affects this drought remains, however, less clear. Furthermore, the AMO acts along with other phenomena, especially El Niño Southern Oscillation and the Pacific Decadal Oscillation. A much deeper understanding is required of how these various phenomena act together, over a variety of timescales.

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# Reconstructed and simulated Medieval Climate Anomaly in southern South America

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**An austral summer temperature reconstruction for southern South America for the last millennium is compared to paleoclimate simulations provided by two Atmosphere-Ocean General Circulation Models with special emphasis on the Medieval Climate Anomaly.**

The understanding of the current and future processes, and dynamics of the climate system can greatly benefit from the knowledge of past spatial patterns, trends, amplitudes, and frequencies of climatic variations (Jones et al., 2009, and references therein). Until recently, the rather low number and uneven spatial distribution of temporally highly resolved proxies from the Southern Hemisphere did not allow reliable continental scale reconstructions at interannual-to-interdecadal timescales (Neukom et al., 2010). Given the importance of the potential seesaw mechanism between the Northern and Southern Hemisphere (NH and SH) and the driving role of the SH oceans in regulating global climate variability, South America is a key region for the study of climate processes and dynamics. Climate in South America is influenced by a variety of oceanic and atmospheric patterns, such as the El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM; Garreaud et al., 2009). Thus, SH climate reconstructions covering the past centuries to millennia can provide insights into the underlying mechanisms of climate variability and forcing imprints. Such reconstructions are essential for data/climate model comparisons. Here, we present results from a new multiproxy-based austral summer (DJF) temperature reconstruction that covers the last 1000 years in southern South America (SSA) (Neukom et al., 2010). Special emphasis is given to the temperature difference between the periods 1001-1350 ("Medieval Climate Anomaly", MCA) and 1400-1700 ("Little Ice Age", LIA). Furthermore, austral summer temperature reconstructions are also compared with two coupled atmosphere-ocean general circulation models (AOGCMs): The two ECHO-G simulations Erik1 and Erik2 using identical external forcings, but different initial conditions (i.e., the initial conditions used in year 1000 AD in Erik2 where cooler than in Erik1; González-Rouco et al., 2006), and one simulation with CCSM3 (Hofer et al., 2010). The models use slightly different anthropogenic and natural forcings, including different levels of atmospheric concentrations of carbon dioxide, methane, and nitrous oxide, of solar activity, and of volcanic aerosols. We also provide austral summer temperature difference patterns (MCA minus LIA; 1001-1350 minus 1400-1700 AD) for both the multiproxy reconstruction with their associated uncertainties and the corresponding simulations from the three model simulations.

## Austral summer temperature reconstructions back to the MCA and comparison with two AOGCMs

Figure 1 shows the austral summer (DJF) land-surface air temperature anomalies (with respect to the 1001-1700 AD reference period) for SSA (south of 20°S) both for the principal component-multiple regression based reconstructions (Neukom et al., 2010) and the three model simulations spanning the period 1001-1990 AD. The reconstruction generally points to warmer conditions during the MCA. A strong decrease in temperature is visible in the second half of the 14th century. The climate reconstruction for this period mainly relies on tree-ring information from the Andes, lake sediments from Central Chile and an ice core from the tropical Andes (Neukom et al., 2010; see Fig. 1 bottom left). Cooler conditions prevail throughout the late 17th century (LIA). The difference in mean austral summer temperature between the two periods (1001-1350 minus 1400-1700 AD) is approximately 0.39°C in the reconstruction, 0.14°C and 0.49°C in CCSM3 and Erik1, respectively. A possible explanation for the rather small difference in the CCSM3 simulation compared to the Erik1 simulation is the lower equilibrium climate sensitivity of CCSM3. The associated ±2 Standard Error (SE) uncertainties of this difference (based on the uncalibrated variance in the 20th century calibration period; see Neukom et al., 2010, for more details) for the MCA and the LIA are of the order of ± 0.3°C (shaded parts in Fig. 1 top panel). The interpretation for the sudden drop in the mean temperature during the "MCA-LIA" transition is not known yet.

The reconstructions (Neukom et al., 2010) point to positive temperature anomalies in the 18th century, followed by a cooling phase that starts in the early 19th century. Since approximately the 1850s, SSA has experienced a long-term warming trend with superimposed shorter cooling periods. The multiproxy-based reconstruction and the AOGCMs generally agree on the centennial-scale warm and cold phases and their amplitude. However, there are differences between the reconstruction and the models in the timing of the MCA-LIA transition, which appears around 60 years later in the models. Additionally, the simulated transition is a two step process: a first step is initiated with