Medieval megadroughts in the Four Corners region: Characterization and causes

Richard Seager and Edward R. Cook
Lamont Doherty Earth Observatory of Columbia University
Palisades, New York

Presentation before:
The Society for American Archaeology
Austin, Texas

April 2007

1. Introduction

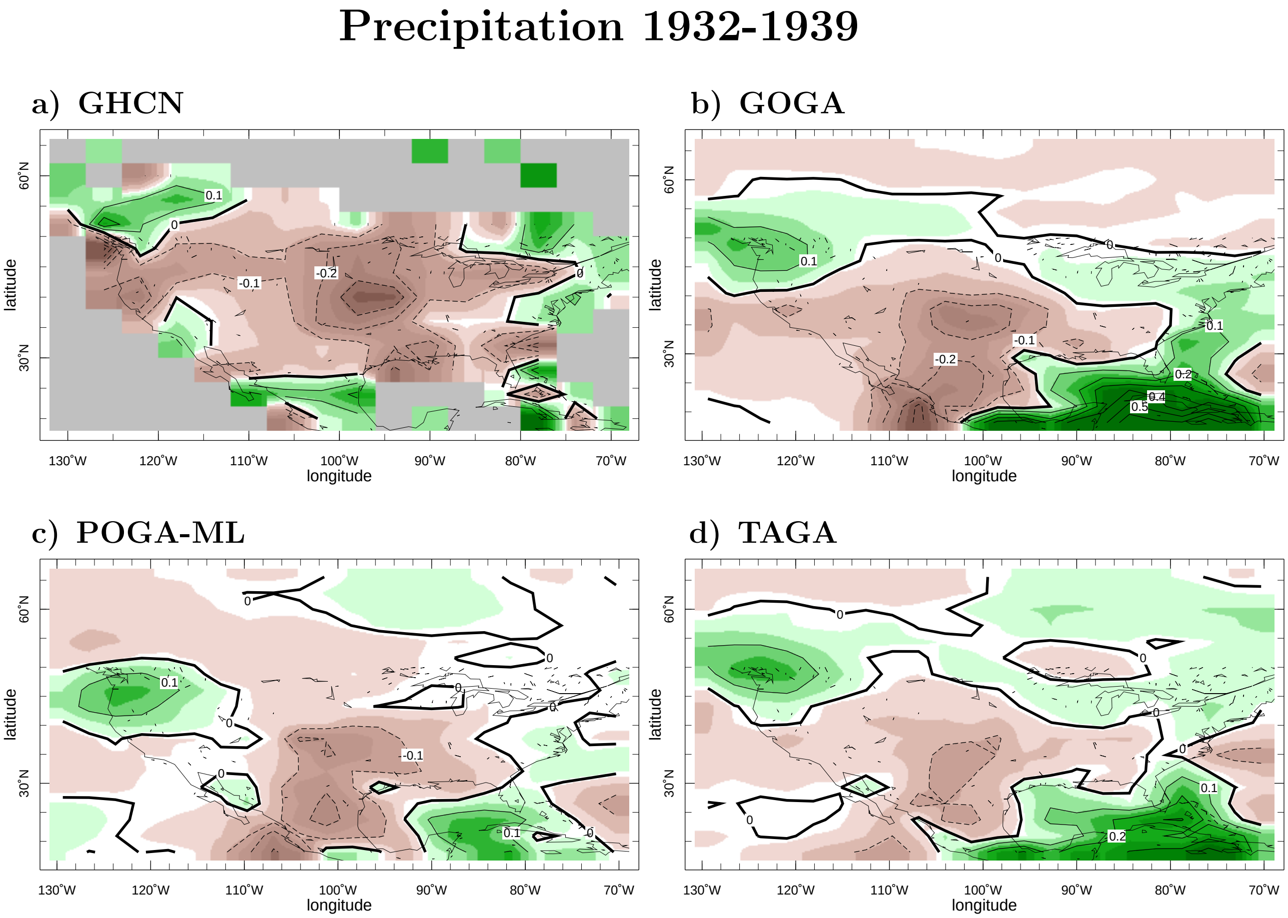
Analyses of tree rings across North America make very clear that between about 800A.D. and 1400 A.D. the American West experienced one severe multidecadal drought after another, with only brief respite, that amounted to a more arid climate during the Medieval period than in subsequent centuries or now (Cook et al., 2004). One of these 'megadroughts', at the end of the 13^{th} Century is the 'Great Drouth' originally identified by Douglass (1929, 1935) and which has been linked to a population decrease in the Puebloan societies of the Four Corners region or even an abandonment of well developed settlements (e.g. Benson et al. (2007)). Here we attempt to characterize these droughts in space and time and offer ideas as to what caused them.

2. Understanding past persistent North American droughts

Understanding the megadroughts begins with an attempt to understand the much better observed droughts in the instrumental climate record. The Dust Bowl drought of the 1930s was one of the worst environmental disasters of the 20^{th} Century, anywhere in the world (Worster, 1979). Until Hurricane Katrina it held the record within the United States for the most number of people displaced by an environmental event, about a third of a million. Unlike pre-instrumental droughts there is no doubt that this one led to widespread abandonment of agricultural settlements.

The causes of the Dust Bowl are no longer a meteorological mystery. Modeling studies (Schubert et al., 2004b,a; Seager et al., 2005b) have shown that atmosphere general circulation models (GCMs), when forced with the time history of observed sea surface temperatures (SSTs), produce severe droughts over North America in the 1930s. By conducting series of model simulations in which the observed SSTs are specified only in some parts of the world ocean, it is possible to determine what parts of the global SST pattern forced the drought. These model studies agree that a persistent weak La Niña in the tropical Pacific Ocean was the dominant cause, with a warm subtropical North Atlantic Ocean also playing a role (Figure 1). As such the Dust Bowl drought was a low frequency version of the types of seasonal to interannual variability of North American hydroclimate associated with the El Niño-Southern Oscillation (ENSO). As part of this work, modeling studies have also shown that persistent La Niña-like states were the cause of the three mid to late 19^{th} Century droughts (Herweijer et al., 2006), the 1950s drought (Seager et al., 2005b) and the 1998-2002 period of the one that began after the 1998 El Niño (Seager, 2007). This association of La Niña-like conditions in the tropical Pacific during all the droughts, and with the Atlantic sometimes playing a supporting role by being warm, is also clear in the observations (figure 2).

The dynamics that link tropical SSTs to North American droughts are also reasonably well understood. Well established Rossby wave teleconnection mechanisms are one means, but it has also been noted that the droughts fit into a pattern with noticeable hemispheric and zonal symmetry. Symmetric dynamics based on interactions between tropically-forced changes in the subtropical jets, the impact this has on transient eddy propagation and the resulting impact on the eddy-driven mean meridional circulation (MMC) (Seager et al., 2003), have been invoked to explain the patterns of atmospheric moisture transport variability that underly the droughts (Seager et al., 2005a). The dynamics of a subtropical Atlantic influence are much less clear but appear real (see also Sutton and Hodson (2005)).



Precipitation 1932-1939

a) GHCN

b) GOGA

c) POGA-ML

d) TAGA

Figure 1: The change in precipitation, averaged over 1932-1939, relative to 1856 to 2005 climatologies for observations (top left) and three ensemble mean model simulations. The simulations are with global sea surface temperature (SST) forcing (top right), tropical Pacific SST forcing alone (bottom left) and tropical Atlantic SST forcing alone (bottom right). Units are in mm per day.

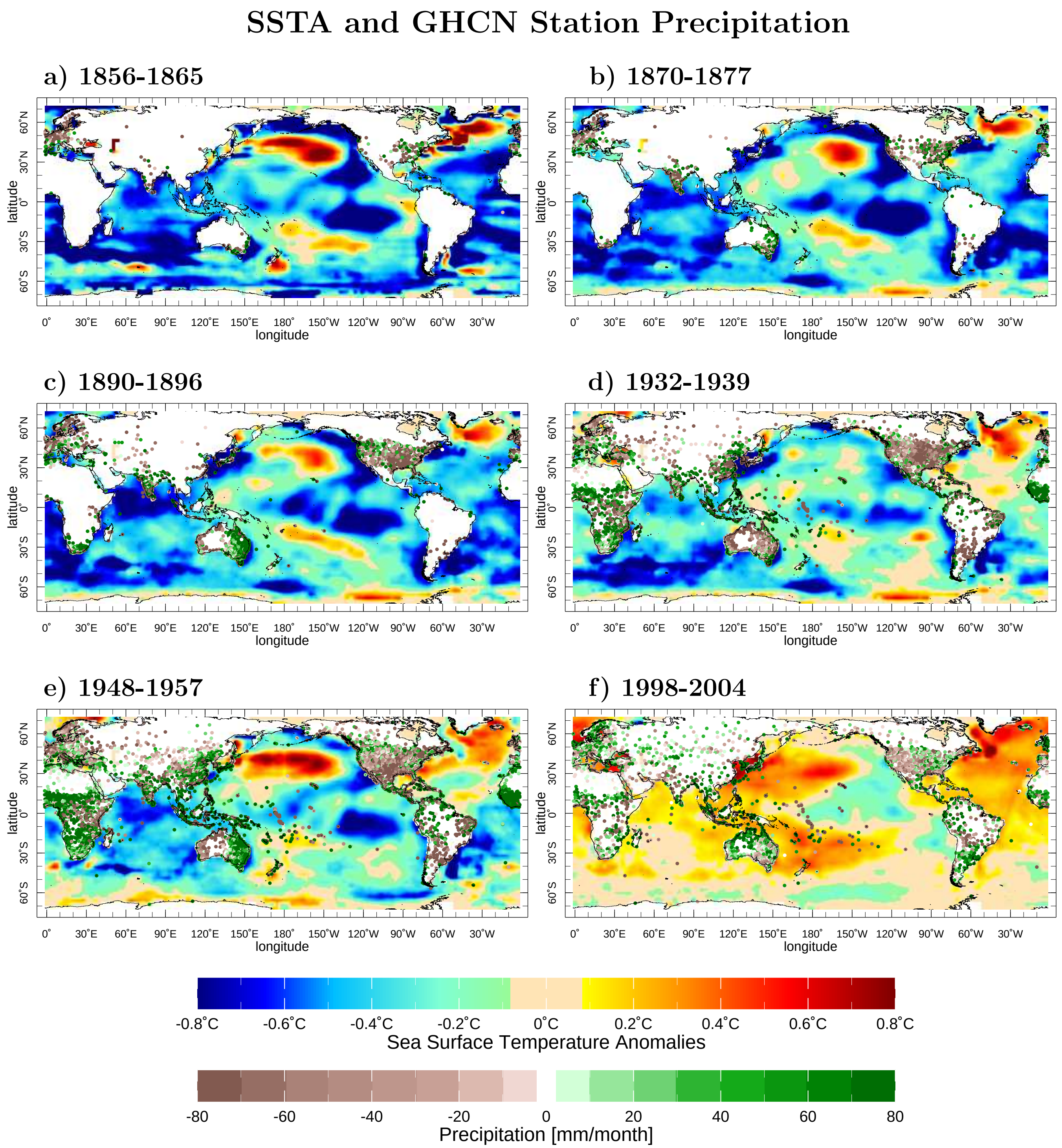


Figure 2: The sea surface temperature (SST) anomaly and station precipitation anomaly averaged over all seasons of the six periods of persistent North American drought within the instrumental record. Anomalies are relative to a climatology for the January 1979 to April 2005 period. Units are K for SST and mm/month for precipitation. Taken from Seager (2007)

3. Comparing modern droughts and Medieval megadroughts

The megadroughts occurred during a period of several hundred years from at least 800AD until around the 15th Century and added up to make the climate of the West more arid than it has been in subsequent centuries (Cook et al., 2004). During the Medieval period there was a succession of droughts of Dust Bowl severity that lasted not years but decades at a time (Herweijer et al., 2007) and which had possible impacts on ancestral Puebloan Indian civilizations (Benson et al., 2007).

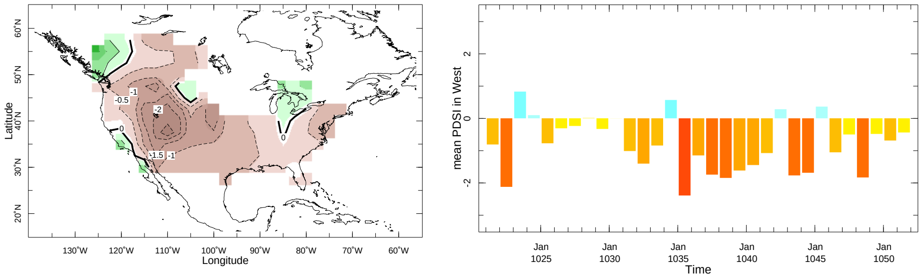
Herweijer et al. (2007) have compared tree ring records of modern droughts and Medieval droughts (see Figures 3 and 4). It is quite remarkable how similar the spatial patterns of the droughts are: drought afflicts almost all of western North America from Mexico to the US-Canada border with wetter conditions to the north and south and more modest changes in the east. For the Medieval droughts, the drought severity (as measured here by reconstructions of the Palmer Drought Severity Index), averaged over the West, in any one year was not more severe than in the historical records. What makes the term 'megadrought' apt is the duration: while modern droughts last at most a decade the Medieval droughts could last a few decades at a time.

The similar spatial patterns of modern and Medieval droughts suggests a similar cause and, for now, the reigning paradigm for the causes of the droughts lies with tropical SSTs. This is based on both a handful of SST proxies from the Pacific (see Figures 5 and 6) and Atlantic, limited modeling studies (Graham et al., 2007), and the fact that the global pattern of Medieval hydroclimate (Figure 5) has some similarities to what would be expected for a combination of a very persistent La Niña and a warm subtropical North Atlantic (Herweijer et al., 2007; Seager et al., 2007). Limited coral based SST evidence from the tropical Pacific Ocean (an example is shown in Figure 6) does in fact shows cooler SSTs during the Medieval period (Cobb et al., 2003).

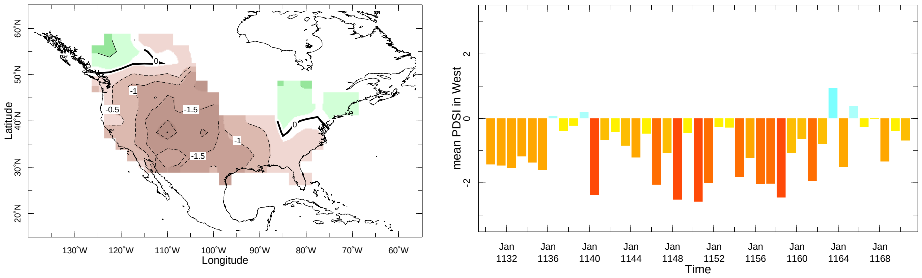
Arguments exist for why the tropical Pacific Ocean would have been more La Niña-like (cold eastern equatorial Pacific) during the Medieval period. This is though to have been a time of relatively high solar irradiance and weak volcanic activity both of which increase downward solar radiation at the ocean surface. However the SST response will not be the same in the east and the west because of strong upwelling of water at the equator, and hence poleward movement of water away from the equator, in the east. In the western tropical Pacific waters will warm until evaporation increases to balance the increased downward solar

MCA droughts

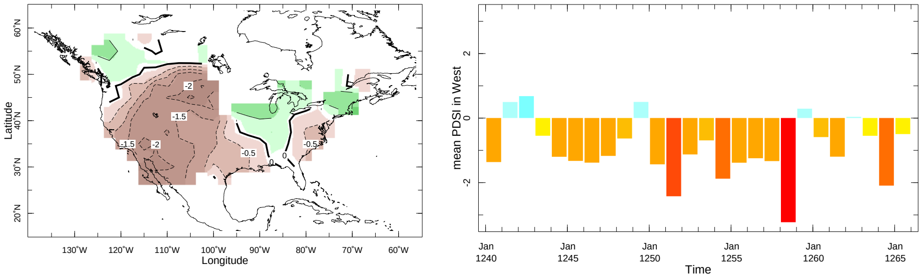
AD 1021-1051



AD 1130-1170



AD 1240-1265



AD 1360-1382

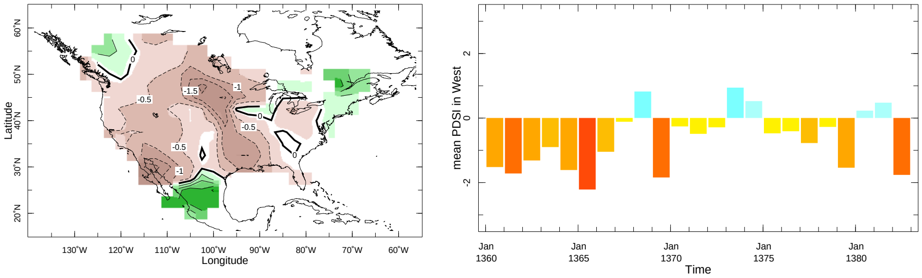
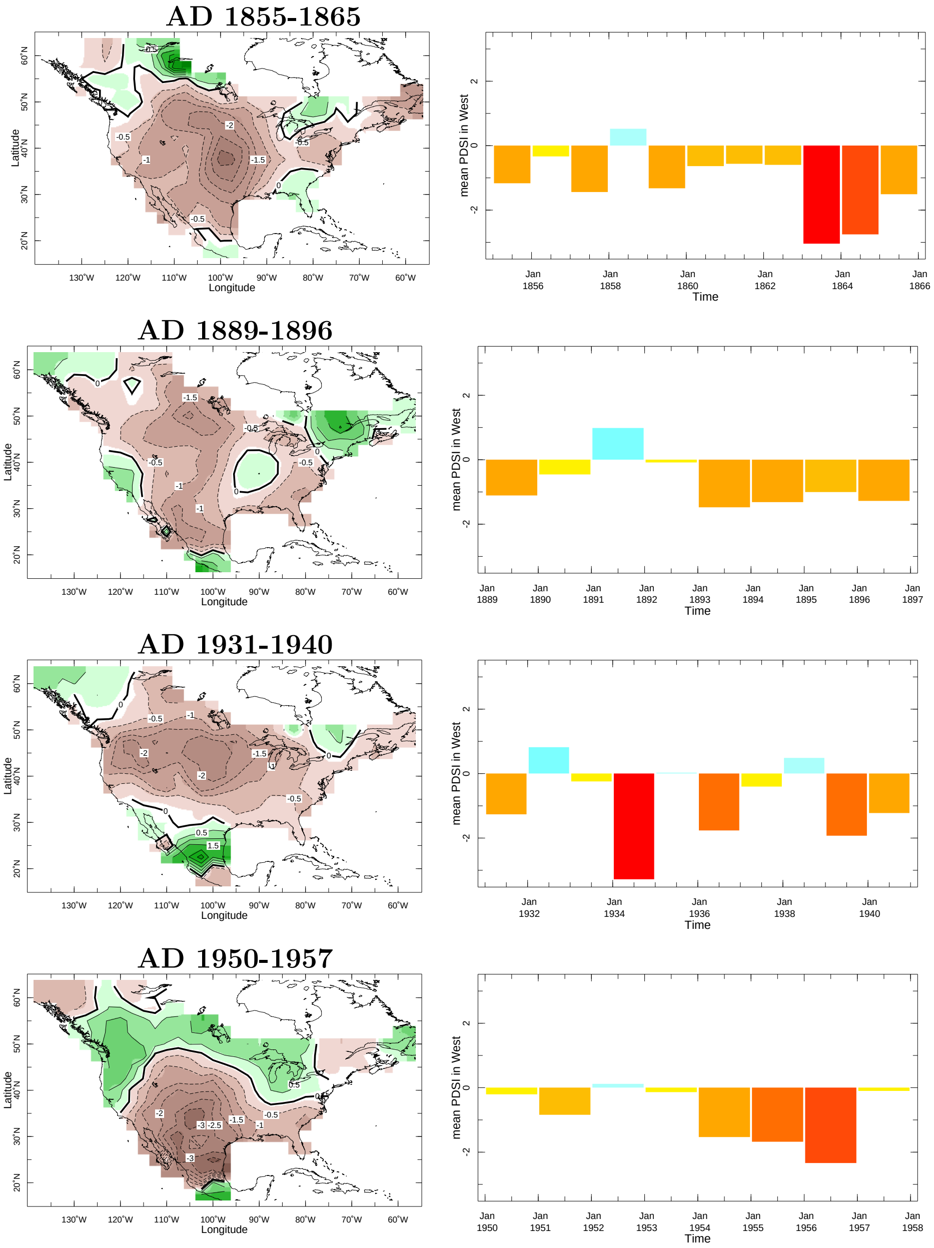


Figure 3: Some Medieval megadroughts. The maps show the spatial pattern of tree ring-reconstructed summer Palmer Drought Severity Index (PDSI) averaged over the indicated period and the right column shows time series during the megadrought of the PDSI averaged over the West. From Herweijer et al. (2007).

Modern-day droughts


AD 1855-1865

AD 1889-1896

AD 1931-1940

AD 1950-1957

Figure 4: The modern droughts. The maps show the spatial pattern of tree ring-reconstructed summer Palmer Drought Severity Index (PDSI) averaged over the indicated period and the right column shows time series during the drought of the PDSI averaged over the West. From Herweijer et al. (2007).

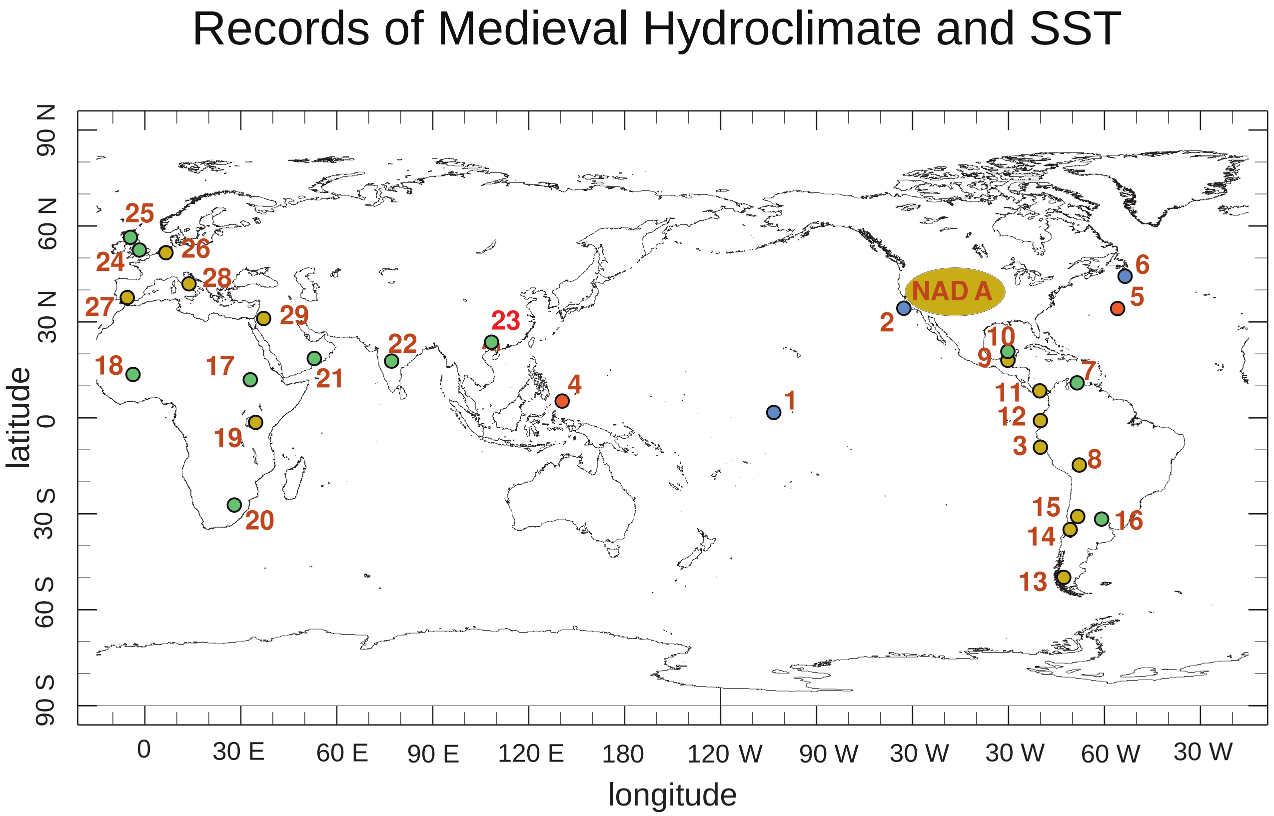


Figure 5: Records of Medieval hydroclimate and SST. Four SST records are plotted as red or blue dots depending on whether they show the Medieval period to be warm or cold relative to succeeding centuries. Green and brown dots over land indicate a proxy record of wet or dry Medieval hydroclimate. The numbers cross reference the records to the references in the text and Table 1 of Seager et al. (2007). The Medieval period is taken to be, approximately, from 800 A.D. to 1400 A.D. NADA refers to the North American Drought Atlas of Cook and Krusic (2004). From Seager et al. (2007).

radiation. However in the east some of the added solar radiation, after absorption as heat, is moved away by the upwelling and poleward moving water. Hence the west warms more than the east. This strengthens winds that blow from east to west which, in turn, drives stronger ocean upwelling which ends up cooling the waters in the east: a La Niña-like state (Clement et al., 1996; Cane et al., 1997; Emile-Geay et al., 2007; Mann et al., 2005). In turn a persistent La Niña-like state in the tropical Pacific could force changes in winds around the world that would drive a stronger North Atlantic meridional ocean overturning thus warming the subtropical North Atlantic (Seager et al., 2007). It is a matter of active research in climate dynamics to determine whether these links are correct and that a small positive solar radiative forcing could induce a La Niña-like state and a warm Atlantic: the perfect ocean for western North American drought.

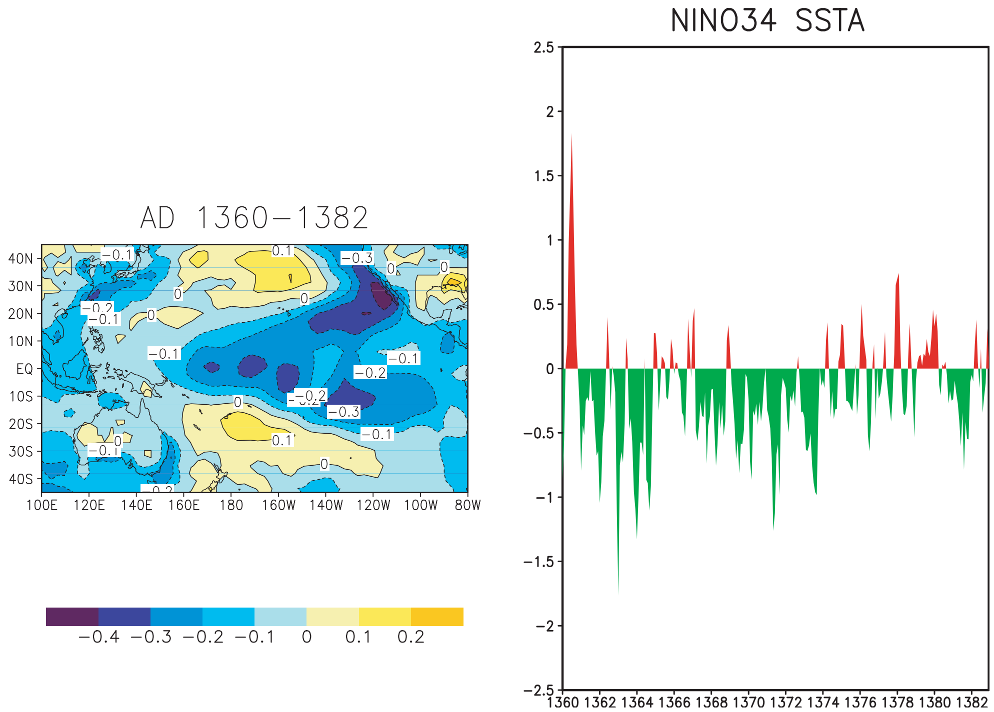


Figure 6: The SST anomaly and time series of the NINO3.4 SST index in the equatorial Pacific Ocean computed from the Cobb et al. (2003) coral oxygen isotope record during one of the Medieval megadroughts identified by Herweijer et al. (2007) indicating sustained la Niña conditions. Reconstruction performed by R. Burgman and A. Clement (RSMAS, U. Miami) with the author. Units are °C.

4. An improved tree ring drought record for the Four Corners region

Recently the Lamont Tree Ring Lab has developed a new high spatial resolution tree ring reconstruction of PDSI using all available dendroclimatic records for the Four Corners area of Utah, Colorado, Arizona and New Mexico. The reconstructions were produced for the May-July season on a 64-point one-half degree regular grid of instrumental PDSIs covering the period 1901-2002. The method of reconstruction used was the point-by-point regression method that had been used to successfully reconstruct PDSI over most of North American (see Cook et al. (2007)). In this case, only those tree-ring chronologies that fell within 50 km of each grid point (roughly equal to the grid spacing) were used to reconstruct drought at that grid point. Doing so produced a set of reconstructions that preserved much of local drought variability in the region. Fifty-six of the 64 tree-ring reconstructions extended back before the abandonment of settlements in the Four Corners area in the late 13th century.

This new record shows that the megadroughts struck the entire Four Corners region at once, that is, no wetter havens existed, which is consistent with the prior analysis that the

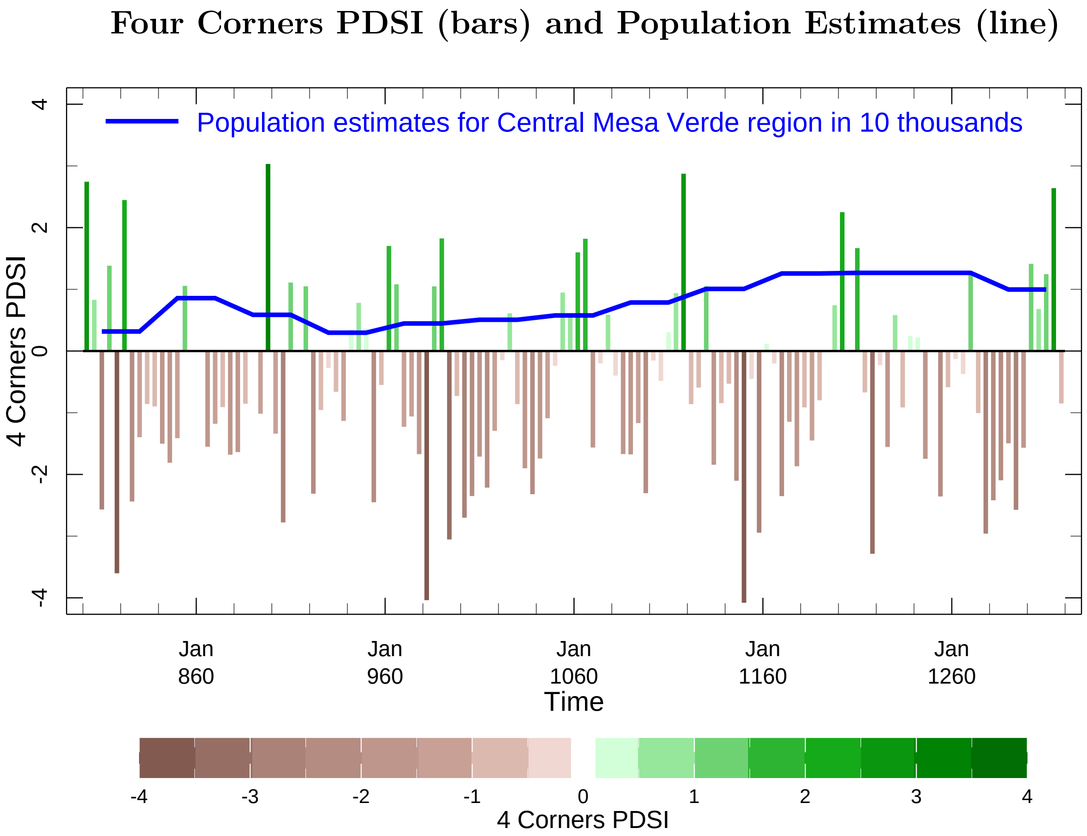


Figure 7: The new tree ring based May-July PDSI reconstructed specifically for the Four Corners region using all available records (and many not in the earlier North American Drought Atlas) covering 800 A.D to 1300 A.D. (bars). The blue line is the population estimate for this region from Wilshusen (2002) plotted in segments of 40 years length.

droughts were, in fact, near continental in scale.

Figure 7 shows the time series of this new summer PDSI reconstruction, averaged over a 400km wide area centered on the Four Corners, for the 900 A.D. to 1300 A.D. period. Also shown are the population estimates, in 40 year intervals, as reported by Wilshusen (2002). Severe and long droughts, by modern standards, occurred throughout this period. Overall it would have been harder to practice agriculture then in this region than it would be now using similar techniques. That ancestral Puebloan societies were nonetheless able to flourish is quite remarkable. It is not clear that the population estimates match up with the drought record. The population estimates are of coarse temporal resolution but, to paraphrase Wilhusen, suggest a very late 13^{th} Century depopulation of the region. This did coincide with a severe and long drought, the 'Great Drouth' of Douglass, but it is equally striking that population increased during 12^{th} Century (and earlier) droughts that were every bit as bad.

The same PDSI reconstruction is shown in Figure 8 together with an alternative measure

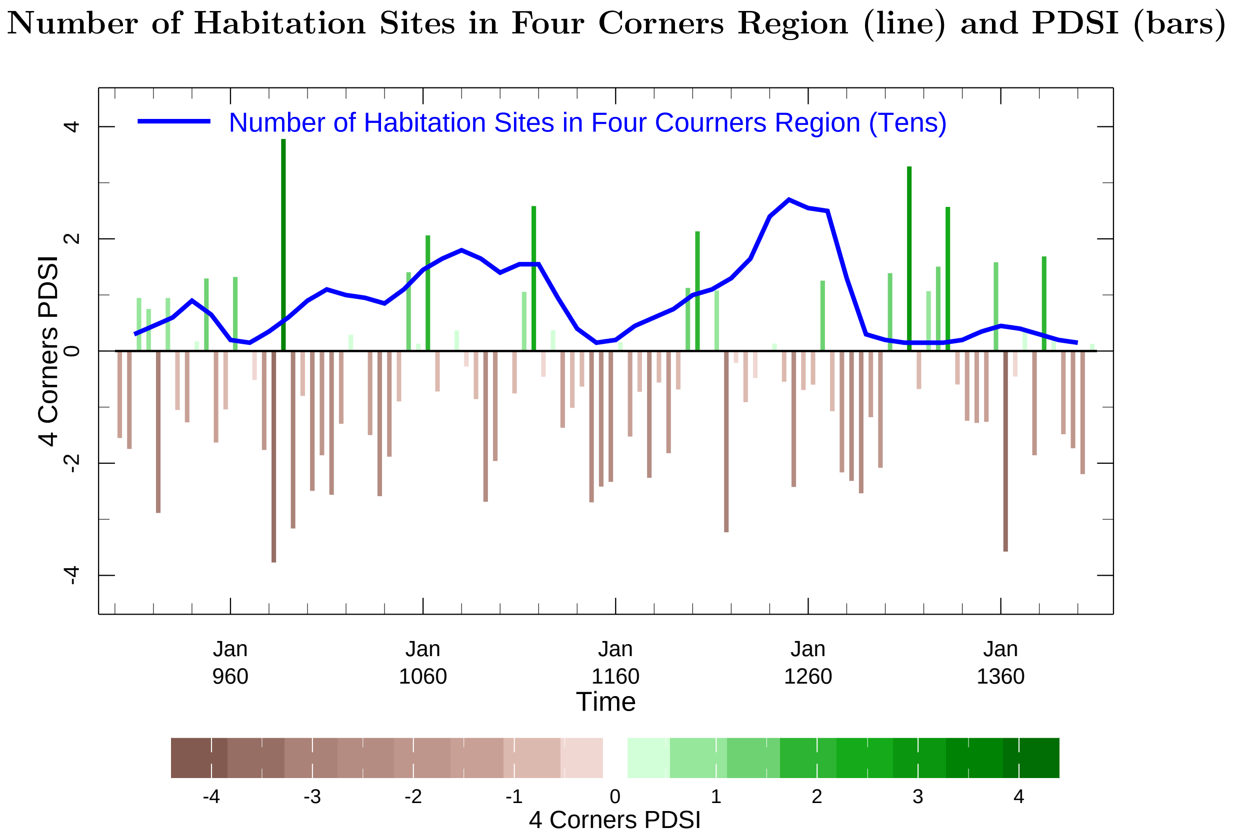


Figure 8: The new tree ring based May-July PDSI reconstructed specifically for the Four Corners region using all available records (and many not in the earlier North American Drought Atlas) covering 900 A.D to 1400 A.D. (bars). The blue line is the estimated number of habitation sites (an unknown nonlinear function of population) from Barry (1982) as recorded by Benson et al. (2007).

of the population: the number of habitation sites in the Four Corners area as estimated by Barry and reported by Benson et al. (2007). In this case there is a precipitous drop in habitation sites in the late 13^{th} Century during the 'Great Drouth'. There is a also a drop during a drought in the early to mid 12^{th} Century but habitation sites increased during drought from 960 to 1020 and from 1160 to 1200. Wetter conditions promptly returned in 1300 but the number of habitation sites did not increase.

5. Conclusions

The droughts in the historical record (such as the the Dust Bowl and the 1950s Southwest drought) were forced by small changes in tropical ocean surface temperatures that most likely arose due to natural variations of the tropical atmosphere-ocean system. A relatively cold tropical Pacific (La Niña-like state)-warm subtropical North Atlantic is ideal for creating drought conditions over western North America. The Medieval megadroughts have a very similar spatial pattern to modern droughts, but remarkable persistence. This suggests that the coupled tropical atmosphere-ocean system became stuck in the La Niña-warm North Atlantic state for decades at a time and, overall, for most of the centuries of the Medieval period. Theories exist, focused on the forced response of the tropical Pacific and communication worldwide via the atmosphere circulation, for why this global climate regime could have arisen as a response to relatively high solar irradiance and weak volcanic activity. A near perpetual La Niña during the Medieval period is supported to a limited extent by coral records of ocean temperatures and by the global pattern of Medieval hydroclimate, which is La Niña-like.

New tree ring records from the Four Corners region emphasize that the period from 800 A.D. to 1300 A.D. was one of greater aridity than today and that the multidecadal periods of most severe aridity were regional - even subcontinental - in spatial scale. The 'Great Drouth' at the end of 13th Century was severe and persistent and may have seriously impacted societies in the region. What is remarkable is that ancestral Puebloan societies were able to survive in this area for centuries given a more arid climate than today and that they were able to weather through, albeit with some setbacks, earlier severe droughts such as those in the 12th century.

Acknowledgements. Thi work was supported at LDEO by the NOAA ARCHES grant to LDEO for abrupt climate change research and by the NSF Climate Dynamics and Earth System History programs.

Correspondence. Richard Seager, Lamont Doherty Earth Observatory of Columbia University, Palisades, New York 10964; seager@ldeo.columbia.edu

References

Benson, L., M. S. Berry, E. A. Jolie, J. D. Spangler, D. W. Stahle, and E. M. Hatton: 2007, Possible impacts of early eleventh, middle twelfth and late thirteenth century droughts on western Native Americans and the Missippian Cahokians. *Quat. Sci. Rev.*, **26**, 336–350.

Cane, M. A., A. C. Clement, A. Kaplan, Y. Kushnir, D. Pozdnyakov, R. Seager, S. E. Zebiak, and R. Murtugudde: 1997, Twentieth Century sea surface temperature trends. *Science*, **275**, 957–960.

Clement, A. C., R. Seager, M. A. Cane, and S. E. Zebiak: 1996, An ocean dynamical thermostat. *J. Climate*, **9**, 2190–2196.

Cobb, K., C. D. Charles, H. Cheng, and R. L. Edwards: 2003, El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. *Nature*, **424**, 271–276.

Cook, E. R. and P. J. Krusic: 2004, North American Summer PDSI Reconstructions. Technical Report 2004-045, IGBP PAGES/World Data Center for Paleoclimatology Data Contribution Series, Boulder, CO, USA.

Cook, E. R., R. Seager, M. A. Cane, and D. W. Stahle: 2007, North American droughts: Reconstructions, causes and consequences. *Earth. Sci. Rev.*, **81**, 93–134.

Cook, E. R., C. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle: 2004, Long term aridity changes in the western United States. *Science*, **306**, 1015–1018.

Douglass, A. E.: 1929, The secrets of the Southwest solved by talkative tree rings. *Nat. Geogr..*, **54**, 737–770.

— 1935, Dating Pueblo Bonito and other ruins of the southwest. Technical Report Pueblo Bonito Series No. 1, National Geographic Society, Washington D.C. 74pp.

Emile-Geay, J., M. A. Cane, R. Seager, A. Kaplan, and P. Almasi: 2007, ENSO as a mediator for the solar influence on climate. *Paleoceanogr.*, accepted pending revision.

Graham, N., M. K. Hughes, C. M. Ammann, K. M. Cobb, M. P. Hoerling, D. J. Kennett, J. P. Kennett, B. Rein, L. Stott, P. E. Wigand, and T. Xu: 2007, Tropical Pacific-Mid latitude teleconnections in Medieval times. *Climatic Change*, in press.

Herweijer, C., R. Seager, and E. R. Cook: 2006, North American droughts of the mid to late Nineteenth Century: History, simulation and implications for Medieval drought. *The Holocene*, **16**, 159–171.

Herweijer, C., R. Seager, E. R. Cook, and J. Emile-Geay: 2007, North American droughts of the last millennium from a gridded network of tree ring data. *J. Climate*, **20**, 1353–1376.

Mann, M., M. A. Cane, S. E. Zebiak, and A. Clement: 2005, Volcanic and solar forcing of the tropical Pacific over the past 1000 years. *J. Climate*, **18**, 447–456.

Schubert, S. D., M. J. Suarez, P. J. Region, R. D. Koster, and J. T. Bacmeister: 2004a, Causes of long-term drought in the United States Great Plains. *J. Climate*, **17**, 485–503.

— 2004b, On the cause of the 1930s Dust Bowl. *Science*, **303**, 1855–1859.

Seager, R.: 2007, The turn-of-the-century North American drought: dynamics, global context and prior analogues. *J. Climate*, in press.

Seager, R., N. Graham, C. Herweijer, A. Gordon, Y. Kushnir, and E. R. Cook: 2007, Blueprints for Medieval hydroclimate. *Quat. Sci. Rev.*, accepted pending revision.

Seager, R., N. Harnik, Y. Kushnir, W. Robinson, and J. Miller: 2003, Mechanisms of hemispherically symmetric climate variability. *J. Climate*, **16**, 2960–2978.

Seager, R., N. Harnik, W. A. Robinson, Y. Kushnir, M. Ting, H. P. Huang, and J. Velez: 2005a, Mechanisms of ENSO-forcing of hemispherically symmetric precipitation variability. *Quart. J. Roy. Meteor. Soc.*, **131**, 1501–1527.

Seager, R., Y. Kushnir, C. Herweijer, N. Naik, and J. Velez: 2005b, Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856-2000. *J. Climate*, **18**, 4068–4091.

Sutton, R. T. and D. L. R. Hodson: 2005, Atlantic Ocean forcing of North American and European summer climate. *Science*, **309**, 115–118.

Wilshusen, R. H.: 2002, Estimating population in the central Mesa Verde region. *Seeking the Center Place: Archaeology and Ancient Communities in the Mesa Verde region*, M. D. Varien and R. H. Wilshusen, eds., The University of Utah Press, pp 81-99.

Worster, D.: 1979, *Dust Bowl: The Southern Plains in the 1930s*. Oxford University Press, New York, 277 pp.