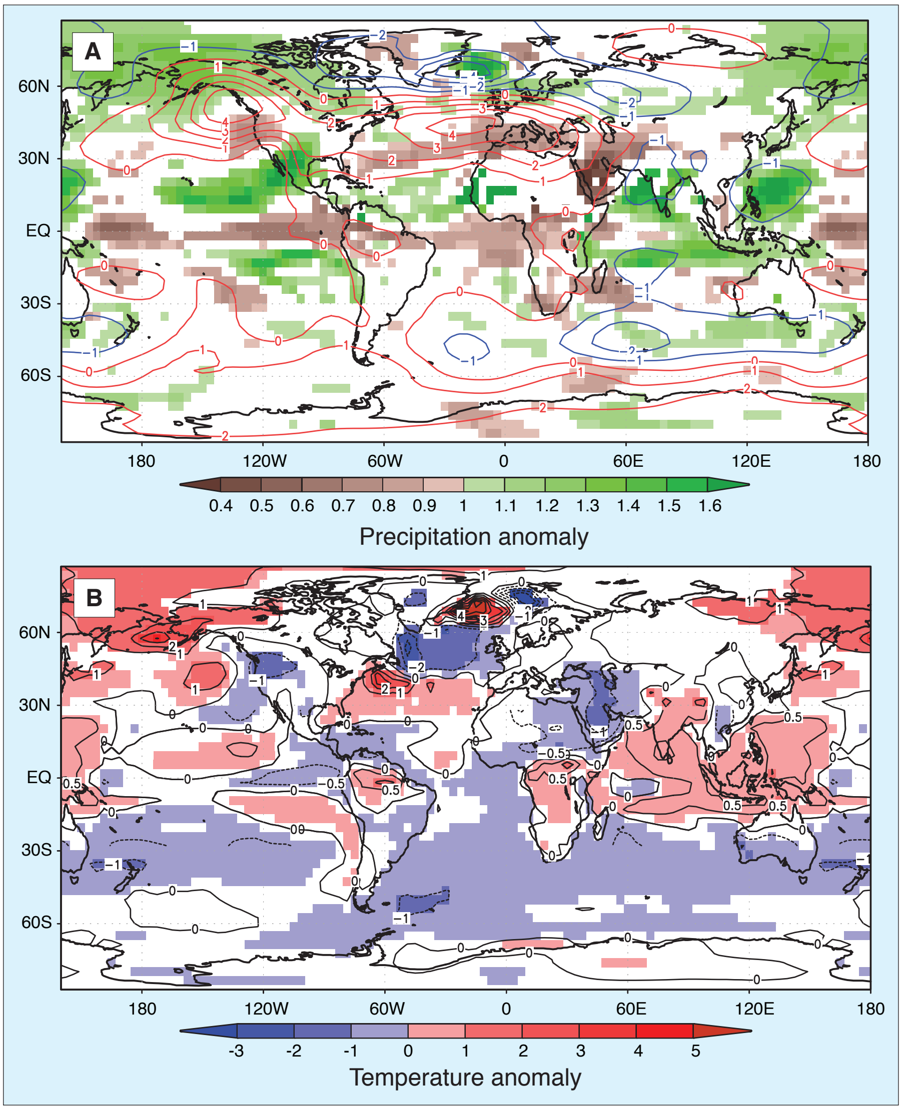

*Figure 2: **A**) Changes in December-March precipitation (fraction of control simulation climatology; color) and sea level pressure (difference with control simulation climatology; hPa, contours) for a simulation with increased tropical Indian and western Pacific SST; precipitation changes are shown only where the differences exceed the 95% confidence level. **B**) As in (A), but for December-March temperature (°C, color; values are SST over ocean and 2-meter temperature over land). Colors are shown only where temperature differences exceed the 95% confidence level. Lined contour interval is 0.5°C between 30°N and 30°S and 1°C elsewhere. Global average temperature change has been subtracted.*

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Medieval hydroclimate revisited

Richard Seager[1] **and Robert J. Burgman**[2]

[1]Lamont Doherty Earth Observatory, Columbia University, Palisades, USA; seager@ldeo.columbia.edu
[2]Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, USA

Can the global pattern of Medieval hydroclimate be explained by a persistent La Niña-like state and a persistent positive North Atlantic Oscillation (NAO) and, if so, why did this happen?

North American megadroughts

The hydroclimate of the Medieval period (here loosely defined as the period from about the 9th Century to the end of the 15th Century) features some dramatic anomalies with respect to the modern climate. Perhaps the most remarkable are the series of multidecadal "megadroughts" that struck vast areas of Southwest North America which combined to create a generally more arid climate in the region that lasted centuries. These are well documented from tree-ring records (Herweijer et al., 2007; Cook et al., 2007, 2010). In addition, there is evidence for a strong Asian monsoon during the Medieval period, wet conditions over much of tropical South America, dry conditions in equatorial East Africa, wet in South Africa, a dry western Mediterranean region and wet northwest Europe (see compilation of proxy data in Seager et al., 2007, Burgman et al., 2010 and Figure 1). What could have caused such a global reorganization of hydroclimate for such a long period of time? The North American megadroughts immediately suggest a link to tropical ocean sea surface temperatures (SSTs). Climate modeling has clarified that the historical droughts of the 19th and 20th centuries were forced by small variations in tropical SSTs. All were forced, wholly or in part, by a cold, La Niña-like tropical Pacific Ocean. In addition, a warm subtropical North Atlantic Ocean played a role in forcing the 1930s and 1950s droughts. The tree-ring data clarified that the spa-

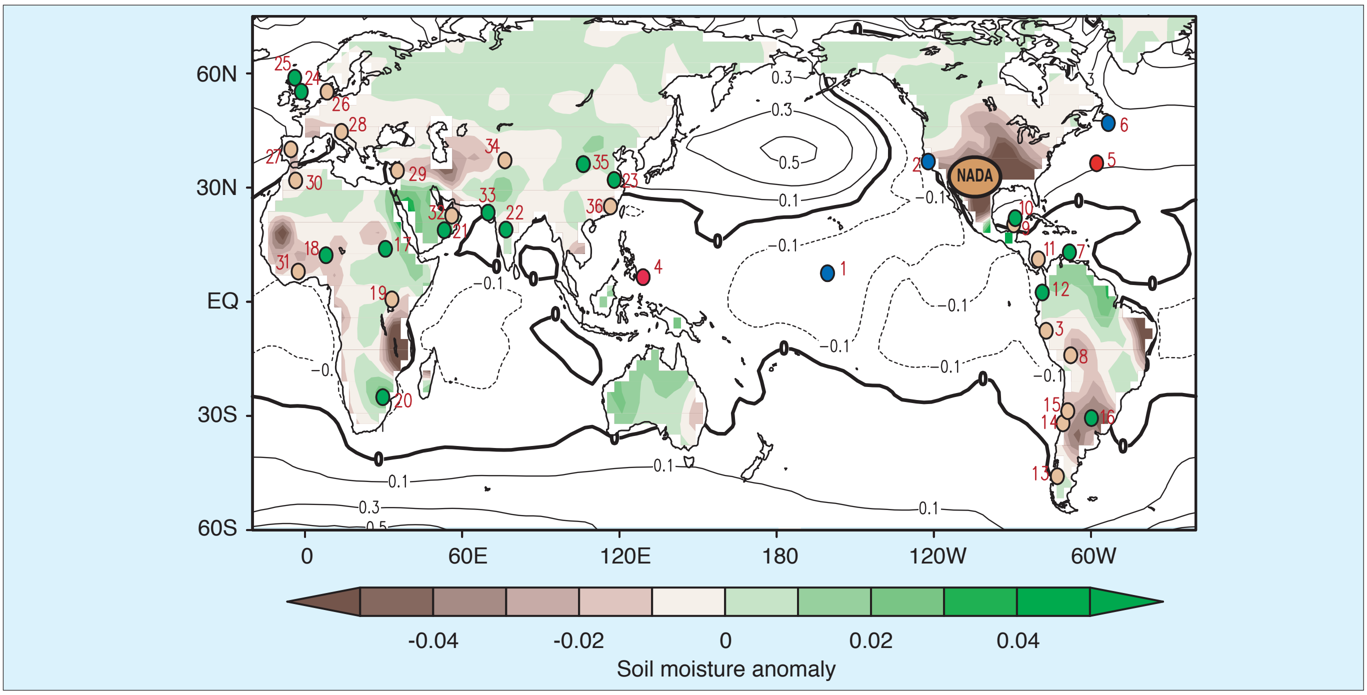

Figure 1: Global hydroclimate information from model simulations and proxy data. Brown and green dots indicate proxy records that show the 1320-1462 AD period to be drier or wetter than the subsequent Little Ice Age and modern periods. NADA (North American Drought Atlas, Cook et al., 2007) refers to dry conditions over North America. The colors over land show the soil moisture difference (soil water volume per soil volume) between the ensemble means of simulations forced by coral-reconstructed tropical Pacific SSTs for 1320-1462 AD and a simulation forced by modern observed SSTs. Contours over the ocean are the specified SST in the tropical Pacific and calculated (with an ocean mixed layer model) SSTs elsewhere. Blue and red dots over the ocean indicate proxy evidence of relatively cold and warm SSTs for this period. See Seager et al. (2008a) and Burgman et al. (2010) and supplementary material for more details including plots of the proxy data.

tial patterns of the modern and Medieval droughts were essentially the same extending from Mexico up to Oregon and from the Pacific coast into the Great Plains and sometimes as far as the Atlantic coast of the eastern USA. Persistent, multi-year La Niñas force modern droughts. Likewise, past shifts of the tropical Pacific to a more La Niña-like state for multiple decades at a time could, conceivably, have forced changes in atmospheric circulation that created the megadroughts.

Modeling of tropical Pacific Ocean forcing of North American megadroughts

Marine proxy data are quite sparse for the Medieval period. However Cobb et al. (2003, and updates at the Lisbon symposium, September 2010; http://mwplisbon2010.fc.ul.pt/) used coral oxygen isotope data from Palmyra in the central equatorial Pacific Ocean and showed that SSTs were quite likely reduced throughout most of the Medieval period they were able to sample. However more work is needed to be certain since the coral oxygen isotopic composition could also be influenced by changes in salinity. Graham et al. (2007) examined other marine proxies from the Pacific and showed that they were consistent with a Medieval La Niña-like state. The Cobb et al. (2003) record has been used to create tropical Pacific SST fields for 1320-1462 AD that were imposed as forcing for an ensemble of 16 atmosphere GCM simulations (Seager et al., 2008a). The coral-reconstructed tropical Pacific SSTs were sufficiently cool and persistent to create multidecadal megadroughts over North America that had comparable spatial pattern and amplitude to the tree-ring reconstructed megadroughts during this 1320-1462 AD period. However, the model did not track the year-to-year evolution of the reconstructed North American hydroclimate very well.

Possible tropical Atlantic Ocean role on North American Medieval hydroclimate

In the last few years, climate modeling has shown that North American drought is also influenced by tropical North Atlantic SST variations, either via an indirect influence that involves the Pacific in winter or directly by forced stationary Rossby waves in summer (Kushnir et al., 2010; Seager et al., 2008b). Hence part of the model vs. tree-ring reconstruction discrepancy for 1320-1462 AD could be attributed to the neglect of the influence of Atlantic SST variations. Indeed Feng et al. (2008) have argued that the North Atlantic was warm during the Medieval period (in a pattern resembling the Atlantic Multidecadal Oscillation) and that this, in combination with the cold tropical Pacific, forced the North American megadroughts (see Oglesby et al., this issue). It is highly likely that the decade-to-decade and century-to-century evolution of North American hydroclimate during the Medieval period (including the succession of megadroughts interrupted briefly by wetter periods more akin to the current climate) was forced by the evolution of tropical Pacific and Atlantic SSTs acting in concert at some time and in opposition at other times. The extent to which the Pacific and the Atlantic Oceans themselves interacted is not known but it has been speculated that the two oceans can vary in a coordinated manner with possibilities for each to force and respond to the other.

Explaining the global pattern of Medieval hydroclimate: La Niña and a positive NAO

Turning to Medieval hydroclimate beyond North America, Herweijer et al. (2007), Seager et al. (2007) and Burgman et al. (2010) found around 30 proxy records from various types of archive (tree rings, speleothems, sediment cores, etc.) that showed evidence of a well defined Medieval hydroclimate anomaly (extending into the 14th and 15th centuries) relative to the subsequent Little Ice Age and modern periods. These were simply characterized as wet or dry following the interpretation of the original authors. These were then plotted together with the 1320-1462 AD time-averaged soil moisture anomalies from the ensemble mean of the model simulations forced with the tropical Pacific coral-reconstructed SST. Figure 1 presents an update of that figure.

There is general agreement on the dry conditions in the extratropical Americas and wet in the tropical Americas, typical of a La Niña-state. The model also agrees with proxy evidence for dry conditions in equatorial East Africa and wet conditions in southern Africa. There is some indication of a stronger monsoon. The model also produces a dry Mediterranean region in agreement with some proxies. However, the model does not capture the wet conditions that proxy data indicate for northwest Europe. Data presented at the Lisbon symposium supported the dry western Mediterranean-wet northwest Europe dipole. This would not be expected from La Niña-forcing and is more likely to have been caused by a persistently positive North Atlantic Oscillation (NAO; Trouet et al., 2009). With the exception of Europe and perhaps North Africa, much of the global pattern of Medieval hydroclimate can be explained as a response to a Medieval La Niña-like state.

What caused Medieval La Niña and positive NAO states?

Why might a persistent Medieval La Niña and positive NAO have occurred? One argument is that relatively high solar irradiance and weak volcanism could have forced the tropical Pacific into a more La Niña-like state (Emile-Geay et al., 2007) with a positive NAO then being forced as a teleconnected response. Other arguments have been made that high irradiance could directly force a positive NAO (e.g., Rind et al., 2008). Recently Marchitto et al. (2010) have presented sedimentary evidence from the Soledad Basin off Baja California that La Niña-like states have coincided with increased solar irradiance throughout the Holocene, with the Medieval period being the most recent of these events. Should Medieval hydroclimate be externally forced, it would raise two important issues. The presumed amplitude of the external forcing is very small and the Medieval response would indicate a surprisingly high regional climate sensitivity. That regional climate sensitivity comes from a strong projection of forcing onto the patterns of the ENSO and NAO modes of climate variability. On the other hand, it is possible that these atmosphere-ocean states could arise from internal variability of the climate system on timescales longer than generally considered possible and potentially including as yet unknown interbasin couplings that act to persist certain preferred states. Either way, global Medieval hydroclimate is a fascinating and important challenge to our understanding of climate variability and change.

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The Medieval Climate Anomaly in Europe in simulations with data assimilation

Hugues Goosse[1], J. Guiot[2], M.E. Mann[3], S. Dubinkina[1] and Y. Sallaz-Damaz[1]

[1]Georges Lemaître Centre for Earth and Climate Research, Earth and Life Institute, Catholic University of Louvain, Belgium; hugues.goosse@uclouvain.be

[2]CEREGE, Aix-Marseille Universities / CNRS, Europole Mediterraneen de l'Arbois, Aix-en-Provence, France; [3]Department of Meteorology and Earth and Environmental Systems Institute, Pennsylvania State University, University Park, USA

Data assimilation improves our understanding of the origins of climate changes during the past millennium in Europe.

Model data-comparison in the presence of large internal variability

The analyses of past climate changes are based on two main sources of information. First, proxy records provide qualitative and quantitative estimates of the changes. Second, the knowledge of the physical processes governing climate allows us to propose interpretations of the observed signals and possible explanations of their origin. This understanding of the system is generally formalized in models, ranging from conceptual models to sophisticated general circulation models. A successful study needs to stand on those two pillars and thus requires an efficient way to compare model results with proxy records.

However, such a comparison is not straightforward, in particular for the past millennium for several reasons. First, as for any paleoclimate study whatever the timescale is, proxy records covering the last millennium and model outputs do not represent the same quantity. Proxies include non-climatic signals and are generally influenced by local climate, while models simulate physical, and sometimes biogeochemical quantities averaged over thousands of square kilometers. Forward proxy models (where the variable recorded in the archive is directly estimated from the model output instead of using a calibration of the proxy in terms of simple physical variables like annual mean temperature) and regionalization techniques will certainly contribute to reduce the uncertainties associated with those issues in the near future (Hughes et al., 2010).

A second problem for the last millennium is the large role of the internal variability of the system during this period, in particular at continental and regional scales (Goosse et al., 2005). If a signal recorded in proxies is related to a known forcing such as a change in the insolation in summer or a decrease in greenhouse gas concentration, then a model that includes the adequate physics and is driven by this forcing should ideally reproduce the observed signal at the right time. However, even a perfect model cannot simulate at the right moment an event that has its origin internally in the non-linear dynamics of the climate system. Instead, a similar event may occur in the simulations earlier or later in time but never with identical temporal and spatial structure. Therefore, any difference between model results and observations can be due to model deficiencies but also simply due to a different realization of internal variability. This strongly reduces the constraints that model-data comparison could put on the realism of models. Furthermore, using a model to interpret an observed signal is nearly impossible if the model does not sim-