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

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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 simulate the main characteristics of this signal at the right time.

Combining model results and proxy data through data assimilation

Data assimilation provides a way to partly bypass this latter problem. The goal of this technique is to optimally combine data with model results in order to obtain a state of the system that is compatible with both, taking into account the uncertainties on all the elements (for a recent review of applications of data assimilation devoted to the last millennium, see Widmann et al., 2010). As the obtained model state reproduces the observed signal, it is then possible to describe the origin of this signal by analyzing all the model variables.

However, data assimilation should be used in conjunction with simulations without data assimilation. In simulations with data assimilation, it is not possible to determine if a simulated event is related to a particular forcing or just to the internal variability of the system. By contrast, the average of an ensemble of simulations without data assimilation can be used to estimate the response of the system to the forcing. It is then tempting to consider that the differences between the simulations with and without data assimilation are related to the internal variability of the system. Nevertheless, this step should be made with caution since it assumes that the contributions of forced and internal variability linearly add to each other without any interactions between them and that the forced response estimated from models is perfect. This is of course only a first order approximation and data assimilation also compensates for uncertainties in the estimates of forcing reconstructions, as well as for errors in the model response to this forcing to an extent that is usually difficult to estimate.

The data assimilation technique that has been selected in our studies is a particle filter (Sequential Monte Carlo method, e.g., van Leeuwen, 2009) because it is relatively intuitive to use and because it is well adapted to strongly non-linear systems. Starting from an ensemble of initial conditions (96 in our case) obtained for instance from simulations without data assimilation, simulations are performed for one year using the climate model LOVECLIM (Goosse et al., 2010). The likelihood of each model state is then estimated from a comparison with proxy-based reconstructions. The simulations that show the largest disagreement with the proxies are stopped while the ones that are in better agreement are maintained. In order to keep the same number of particles (i.e., of members in the ensemble of simulations), the simulations that display the highest likelihood are duplicated, the number of copies being proportional to the likelihood, and then a small perturbation to the model state is added. The procedure is then prolonged for an additional year until the end of the period of interest. This technique guides the model results to follow the signal recorded in proxies. One of the limitations of the particle filter is that it requires a large number of members to reproduce the development of the system. Consequently, it is generally necessary to focus on a particular region or, when interested in a larger scale, to apply a spatial filter to remove high frequency spatial variations and to reduce the number of degrees of freedom of the system.

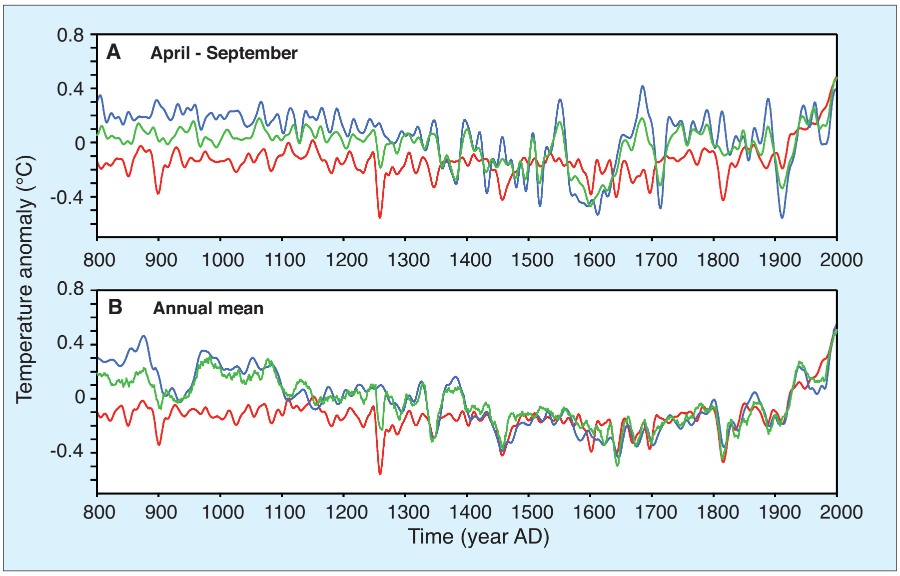

*Figure 1: **A**) Anomaly of growing season temperature (April to September) averaged over Europe (25°-65°N, 0-70°E) in the reconstruction of Guiot et al. (2010, blue), in simulations with the climate model LOVECLIM without data assimilation (red), and in simulations with LOVECLIM with data assimilation constrained by the Guiot et al. (2010) reconstruction (green). The reference period is 1900-1995. The time series has been filtered using an 11-year running mean. **B**) Same as (A) for annual mean except that the reconstruction is now the one of Mann et al. (2009) (blue) and the simulation with data assimilation is driven by this reconstruction (green).*

Application to the study of the MCA in Europe

Using this technique, it is possible to directly constrain the model to follow the relatively large number of proxy records available for the past millennium (e.g., Jones et al., 2009), eventually using forward proxy models and regionalization techniques. However, as a first step, we found it easier to use spatial reconstructions either of annual mean temperature over a large part of the world (Mann et al., 2009) or of summer temperature over Europe (Guiot et al., 2010) since they provide fields that are easy to compare with model results (Fig. 1).

In summer and winter, both reconstructions and simulations with data assimilation show a clear warm period in Europe between 900 and 1050 AD during the Medieval Climate Anomaly (MCA). This contrasts with the ensemble mean of the simulations without data assimilation (i.e., the forced response of the model), which shows only a small decrease between the early part of the millennium and the 16th-18th century (often referred to as the Little Ice Age). This weak forced response has also been found in other models driven by similar forcing as the one used here (Jungclaus et al., 2010). The analyses of the origin of the larger warming in the simulation with data assimilation shows that, in the simulation constrained by the Mann et al. (2009) reconstruction, the atmospheric circulation displays stronger westerly winds bringing warm air to northern Europe during the MCA, mainly in winter. In the simulation driven by the Guiot et al. (2010) reconstruction, westerlies are weaker in summer and a northward flow transports air from Africa to the central Mediterranean Sea and southern Europe during the MCA, contributing to the simulated warming.

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