Comparisons of simulated and observed Northern Hemisphere temperature variations during the past millennium – selected lessons learned and problems encountered

By ANDERS MOBERG*, Department of Physical Geography and Quaternary Geology, Bolin Centre for Climate Research, Stockholm University, SE-10691 Stockholm, Sweden
(Manuscript received 19 October 2012; in final form 5 January 2013)

ABSTRACT

Comparison of simulated and reconstructed past climate variability within the last millennium provides an opportunity to aid the understanding and interpretation of palaeoclimate proxy data and to test hypotheses regarding external forcings, feedback mechanisms and internal climate variability under conditions close to those of the present day. Most such comparisons have been made at the Northern Hemispheric scale, of which a selection of recent results is briefly discussed here. Uncertainties in climate and forcing reconstructions, along with the simplified representations of the true climate system represented by climate models, limit our possibility to draw certain conclusions regarding the nature of forced and unforced climate variability. Additionally, hemispheric-scale temperature variations have been comparatively small, wherefore the last millennium is apparently not a particularly useful period for estimating climate sensitivity. Nevertheless, several investigators have concluded that Northern Hemispheric-scale decadal-mean temperatures in the last millennium show a significant influence from natural external forcing, where volcanic forcing is significantly detectable while solar forcing is less robustly detected. The amplitude of centennial-scale variations in solar forcing has been a subject for much debate, but current understanding of solar physics implies that these variations have been small – similar in magnitude to those within recent sunspot cycles – and thus they have not been a main driver of climate in the last millennium. This interpretation is supported by various comparisons between forced climate model simulations and temperature proxy data. Anthropogenic greenhouse gas and aerosol forcing has been detected by the end of Northern Hemispheric temperature reconstructions.

Keywords: Palaeoclimate, climate proxy data, climate models, climate forcings, external climate variability, internal climate variability, Northern Hemisphere, temperature, last millennium

This paper is part of a Thematic Cluster in honor of the late Professor Bert Bolin for his outstanding contributions to climate science.

1. Introduction

Attempts to simulate past climate conditions and variability by the use of climate models help to understand the interpretation of palaeoclimate proxy data and to test hypotheses regarding external forcings, feedback mechanisms and internal climate variability under a range of possible past climate conditions (Schmidt, 2010). The last millennium provides an opportunity to examine natural and emerging anthropogenic climate variability under conditions close to those of the present day (Jansen et al., 2007; Hegerl et al., 2007b; Braconnot et al., 2012). All such model versus data comparisons, however, heavily rely on proxy information because direct instrumental observations – both of the climate itself and of the forcing factors that are assumed to have affected climate and which are needed to drive the simulations – are only available for a
Stockholm University

This is a published version of a paper published in *Tellus. Series B, Chemical and physical meteorology*.

Citation for the published paper:
Moberg, A. (2013) "Comparisons of simulated and observed Northern Hemisphere temperature variations during the past millennium - selected lessons learned and problems encountered" *Tellus. Series B, Chemical and physical meteorology*, 65(19921)
URL: [http://dx.doi.org/10.3402/tellusb.v65i0.19921](http://dx.doi.org/10.3402/tellusb.v65i0.19921)

Access to the published version may require subscription.

Permanent link to this version:
[http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-87837](http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-87837)

[http://su.diva-portal.org](http://su.diva-portal.org)
short period. This situation leads to substantial statistical uncertainties in the results. Nevertheless, the Fourth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC AR4) was able to draw the conclusion that ‘A substantial fraction of the reconstructed Northern Hemisphere (NH) inter-decadal temperature variability of the seven centuries prior to 1950 is very likely attributable to natural external forcing, and it is likely that anthropogenic forcing contributed to the early 20th-century warming evident in these records’ (Hegerl et al., 2007b). Here, I will illustrate some difficulties encountered and expose some selected significant recent results and controversies in this context.

2. Requisites

To compare observed and simulated past climate, we need estimates of past climate variations and of the external climate forcings, as well as climate models driven by the estimated past forcings. We also need analysis methods that permit the drawing of conclusions from the comparisons. Thus, four principal requisites are demanded:

First, to reconstruct (i.e. to estimate) past climate variations before the period when instrumental observations are available (mostly before the late 19th century), the information has to be deduced from proxy data. The most important and geographically widespread proxy used to reconstruct climate in the last millennium is annual growth rings in trees but other proxies, in particular from ice cores, lake sediments and speleothems, have also been used (Jansen et al., 2007; Jones et al., 2009). Whatever type of proxy is used, or what the target climate variable is, the collected data need to be compiled and calibrated against instrumental observations of climate. This is a statistical calibration exercise and the resulting climate reconstructions are associated with a certain degree of uncertainty (Tingley et al., 2012). This uncertainty typically increases back in time as the number of proxy records become fewer and fewer.

Second, we need a climate model. A variety of models have been used for studies of climate in the last millennium, ranging in complexity from two-dimensional energy balance models (EBMs) to comprehensive Earth system models with fully coupled atmosphere and oceans linked to biosphere and carbon cycle models (Jansen et al., 2007; Hegerl et al., 2007b; Fernández-Donado et al., 2013). No model, however, – no matter how advanced it is – can fully and correctly represent all aspects of the real climate system.

Third, to produce model simulations that in some sense represent past climate variations, we need reconstructions of the external forcings that are assumed to have caused variations of the real past climate (Schmidt et al., 2011). Most types of forcings need to be estimated from proxy data and then converted to some unit that is required for driving a climate model. As with climate proxies, this is typically a statistical exercise associated with a degree of uncertainty.

Fourth, we need some method for comparing the estimated past climate with output obtained from simulations driven by the reconstructed external forcings. To this end, formal statistical methods such as the regression-based fingerprinting technique used in detection and attribution studies (Hegerl et al., 2007a) or statistical distance-based data assimilation (Goosse et al., 2006, 2010) and simulation ranking techniques (Sundberg et al., 2012; Hind and Moberg, 2012), have been developed. Quite often, however, the method is as simple as a graph or map where time series or spatial patterns of simulated and reconstructed past climate variations are visually compared (e.g. Mann et al., 2009; Jungclaus et al., 2010; Feulner, 2011).

Most model-data comparisons for the last millennium have, so far, been made on the Northern Hemispheric scale and for annual mean temperatures (Fernández-Donado et al., 2013). In my brief overview of selected recent investigations, I will therefore mainly consider temperatures averaged over the entire or large part of the NH.

3. NH temperature reconstructions

In the IPCC AR4, Jansen et al. (2007) discussed efforts by several research teams to reconstruct mean temperatures for the entire or large parts of the NH. These reconstructions agree that NH temperatures were on average warmer at the beginning of the past millennium compared to in the 1600–1800s, and that there has been a warming since then, particularly throughout the 20th century and which has continued into the beginning of the current century. The amplitude of the centennial variations, as well as the character of the shorter-term variability, differs among the reconstructions depending on the choice of input data and data compilation and calibration technique. Several Northern Hemispheric-scale temperature reconstructions have been published more recently (e.g. Mann et al., 2008; Christiansen and Ljungqvist, 2012a). These new reconstructions have not changed the overall picture, although some show amplitudes of variations larger than those with the largest temperature amplitudes used in AR4. This larger amplitude is mainly a result of a particular choice of calibration technique and it is debated whether the resulting reconstruction has more low-frequency variance than in the real temperature variations (Moberg, 2012; Christiansen and Ljungqvist, 2012b). On the contrary, most previous methods have been shown to potentially result in too little variance (Christiansen et al., 2009). A few attempts have also been made to use climate proxy
data to reconstruct spatial patterns of temperature changes within the NH in the last millennium (Ljungqvist et al., 2012) or even within both hemispheres (Mann et al., 2009). Although the analysis by Mann et al. (2009) included an interesting comparison of reconstructed temperature patterns with patterns observed in climate model simulations, I will not consider this type of spatially explicit comparison in my discussion.

4. Climate forcings

The climate forcings considered in simulations of the pre-industrial part of the past millennium are mainly variations in greenhouse gas levels, orbital change, changes in land use/land cover, volcanic forcing and solar variability. The Paleoclimate Model Intercomparison project Phase III (PMIP3) has specified forcing histories to be used by the participating modelling groups (Schmidt et al., 2011). However, some other pre-industrial forcings that are assumed to have played a role in reality, such as dust or other natural aerosols, could not be sufficiently specified for use in PMIP3. Earlier modelling efforts may not have used all types of forcings considered in PMIP3, or they may have made alternative choices for some of the forcing histories (Fernández-Donado et al., 2013).

Variations in greenhouse gases have been derived from ice cores in Antarctica and Greenland (MacFarling Meure et al., 2006). A substantial increase in radiative forcing, amounting to about 2.5 W m\(^{-2}\) compared to the pre-industrial period, has been caused by the anthropogenic emissions of greenhouse gases in the industrial period (Forster et al., 2007). Small variations in pre-industrial greenhouse gas levels are related to natural feedbacks in the carbon and nitrogen cycles to changes in climate (Gerber et al., 2003; Scheffer et al., 2006).

Orbital change is the most well constrained forcing and the only one that can be calculated analytically or numerically from astronomical considerations (Berger and Loutre, 1991; Laskar et al., 2004). Globally and averaged over the entire year, the change in orbital forcing has had very little influence over the last millennium. However, at a given latitude and season, the change in orbital forcing can have been about as large as the current level of anthropogenic greenhouse gas forcing. For example, a progressive decrease in incoming solar radiation in late summer at latitudes north of 60°N has led to a decrease in late summer radiative forcing there of about ~2 W m\(^{-2}\) since AD 850, while the corresponding change in spring is an increase by about +1.5 W m\(^{-2}\) (Schmidt et al., 2011).

Reconstructions of land use/land cover have been made based on published maps of agricultural areas for the last three centuries and a country-based approach for earlier times that uses population data as a proxy for agricultural activity (Pongratz et al., 2008). Globally, the effect of this forcing is very small in the pre-industrial period, but an increasing negative radiative forcing has occurred in the last three centuries associated with an increased albedo. This corresponds in magnitude to about a tenth of the current anthropogenic greenhouse gas forcing, but of the opposite sign (Pongratz et al., 2009). Larger forcing changes have occurred already in the pre-industrial period over populated areas such as Europe, America, India and China.

Solar variability is possibly the most uncertain forcing and also the one associated with the largest controversies. If changes in the shape of the emitted solar spectrum are neglected, the solar variations can be quantified as the total solar irradiance (TSI). TSI has been directly measured using instruments on satellites since the mid-1970s, and it shows an amplitude of about 0.1% in phase with the ~11-yr sunspot cycle (Gray et al., 2010). Before this period TSI must be reconstructed based on proxy indices of solar irradiance found to correlate with TSI variations during the instrumental period, in particular sunspot numbers back to the early 1600s and variations in measurements of the cosmogenic isotope \(^{10}\text{Be}\) in polar ice cores and \(^{14}\text{C}\) in trees which go beyond the last millennium (Steinhilber et al., 2009; Gray et al., 2010). Partly due to the short overlap with the satellite record, there is large uncertainty in estimates of long-term TSI variations. Such variations are often quantified as the hypothesized increase between the Maunder Minimum period (AD 1645–1715) and the most recent solar minima. Current understanding of solar physics imply that this increase has been on the order 0.1% or less, while a value of about 0.24% or perhaps more was an often held view in the late 1990s (Gray et al., 2010; Lockwood, 2011). A change in TSI by 0.1% roughly corresponds to a tenth of the current anthropogenic greenhouse gas forcing (Lockwood, 2011). Recent input into this debate claims that the change since the Maunder Minimum may be as much as 0.4% (Shapiro et al., 2011) or, on the contrary, that it could potentially be...
entirely negligible (Schrijver et al., 2011). The PMIP3 consortium initially agreed on using a set of alternative solar forcing histories with increases since the Maunder Minimum in the range 0.04–0.1% (Schmidt et al., 2011), while earlier modelling efforts have often used a history with a change by about 0.24%, or both the 0.1% and the 0.24% alternatives for comparative purposes (Jungclaus et al., 2010; Fernández-Donado et al., 2013). Recently, PMIP3 also included (Schmidt et al., 2012) the large-amplitude TSI history suggested by Shapiro et al. (2011) for completeness of their forcing database. Notably, the PMIP3 consortium did not endorse one solar forcing reconstruction over another. They rather presented them as a range to give a sense of the structural uncertainty. However, Schmidt et al. (2012) also pointed out that there is magnetic field evidence that supports only a modest increase of solar activity over the 20th century.

5. Selected results from Northern Hemispheric model versus proxy data comparisons

5.1. Forcing fingerprints

The fingerprint method seeks to establish regression relationships between, on the one hand, the observed or reconstructed climate variability and, on the other hand, the patterns of climate variability simulated by climate models driven by one-forcing-only at a time. Each simulation is performed to provide a fingerprint of a particular forcing, i.e. the spatial and/or temporal pattern in climate that is the result of the forcing under consideration. Once the fingerprints have been established they are used in a multiple regression, where the observed or reconstructed temperatures are regressed on the fingerprints. If a regression coefficient for a particular fingerprint is significantly different from zero, then this fingerprint can be said to be detected in the observations. An assumption underlying this approach is that the individual forced components of climate variability can be linearly combined, which is an approximation to reality that is generally thought to be reasonable in this kind of studies (IDAG, 2005; Hegerl et al., 2007b). Another implicit assumption is that the time lag between a particular forcing and the response to this forcing is the same in the real and simulated climates. This assumption, however, may not hold if a climate model does not well enough represent those mechanisms that can cause a delayed response to a forcing. If this is the case, it may lead to less significant regression relationships when the fingerprint method is used.

Only a few published formal fingerprint studies have been based on temperature proxy data for the last millennium. Hegerl et al. (2007a) used fingerprints defined by simulations with a two-dimensional EBM driven with solar, volcanic and a combination of anthropogenic greenhouse gas and aerosol forcing. The solar forcing history they used has a 0.24% increase in TSI since the Maunder Minimum. They also used NH temperature reconstructions from four different author teams to account for a range of alternative temperature histories and they concluded that hemispheric-scale decadal-mean temperature has been largely driven by external forcing, typically amounting to 60–75% of the variance. They could clearly detect the influence of volcanism on hemispheric temperatures, but a response to solar forcing could not be robustly distinguished. Their analysis also revealed that anthropogenic greenhouse gas and aerosol forcing is detectable by the end of the records and supports the finding that most of the late 20th-century warming has been anthropogenic. In their selection of temperature reconstructions, anthropogenic forcing explains about a third of the warming trend over the first half of the 20th century, while 15–40% could be explained by a decrease in volcanic forcing and roughly 30% by internal variability. Due to the mostly non-significant solar fingerprint, they could only vaguely state that there was an uncertain contribution to the early 20th-century warming from an increase in solar forcing.

5.2. Visual and other types of comparisons

Jungclaus et al. (2010) presented results from the first ensemble simulations over the last 1200 yr with a Comprehensive Earth System Model including a fully interactive carbon cycle. They used recent reconstructions of all essential external forcings discussed in Section 4, including two alternative solar forcing histories; one with a 0.1% TSI increase since the Maunder Minimum and one with 0.24% increase. All of their multiple-forced simulated NH temperatures differ significantly from the range of simulated internal variability over time intervals from decades to centuries. Strong volcanic eruptions, particularly the cumulative effect of several subsequent eruptions clustered around the most severe ones leave a long-lasting imprint on NH temperatures, in accordance with the fingerprint result of Hegerl et al. (2007a). Modulation by changing solar irradiance is more pronounced in the ensemble with the larger solar forcing amplitude, where the largest pre-industrial temperature anomalies occur in the 15th century in association with both a large eruption and a solar minimum at about the same time in the middle of that century. Most NH temperature reconstructions also show a cool period around this time; but less pronounced and more in line with simulated temperatures from the ensemble using the smaller solar forcing. The temperature reconstructions rather tend to have their coldest period in the 17th century, when they are on average relatively colder even than the simulations using the larger solar forcing.
Thus, none of the two simulation ensembles are able to well capture the coldest interval seen in the temperature proxy data. The reasons for this are not clear, but possible explanations could be that the applied forcing reconstructions do not sufficiently represent the real changes in forcing that have occurred, or that unforced real internal temperature variability occurring on centennial timescales can be of relatively large importance (Goosse et al., 2012).

The full-forcing ensemble with the larger solar amplitude shows a centennial warm interval peaking in the late 1100s, in parallel with the peak in the corresponding solar forcing history. However, most temperature reconstructions show a warming peak about a century earlier, so there is a mismatch in timing also between the reconstructed and simulated warmth in medieval times. A recently published analysis of more than 100 millennial temperature proxy series by Ljungqvist et al. (2012) suggests that NH warmth in Medieval times extended over all of the 9th–11th centuries, i.e. well before the large-amplitude solar forcing history had its maximum. This kind of temporal mismatch between reconstructed and simulated peak NH warmth has been discussed by several other authors (e.g. Servonnat et al., 2010), and illustrates a still poorly understood aspect of climate of the last millennium. Based on results from a data assimilation experiment, Goosse et al. (2012) argue that internal atmospheric circulation dynamics might explain some of the discrepancy. The larger insolation in high-latitude boreal summer, due to the changed orbital forcing, can also have contributed to the comparatively high temperatures in the first centuries of the past millennium, at least in summer at high latitudes as argued based on results from both proxy data and forced simulations (Kaufman et al., 2009; Esper et al., 2012).

Feulner (2011) undertook a climate model-data comparison with the explicit goal to investigate if the most recent conflicting views of solar forcing amplitude are consistent with the reconstructed NH temperatures. He used the coupled intermediate-complexity model CLIMBER-3x driven by greenhouse gas forcing, anthropogenic aerosol and volcanic forcing along with three alternative solar forcing histories – the 0% one by Schrijver et al. (2011), the 0.4% one by Shapiro et al. (2011) and one with 0.04% increase since the Maunder minimum; similar to the smallest-amplitude alternative in PMIP3. Feulner compared his three simulated NH temperatures with the temperature reconstruction by Frank et al. (2010), which includes an uncertainty estimate emerging from alternative calibration data. The two small solar forcing amplitudes clearly provide a better match of the simulated and reconstructed NH temperatures compared to the simulation that used the large solar forcing. The hypothesized large solar amplitude, by Shapiro et al. (2011), gives temperature multi-decadal to centennial variations that are too large and consistently too cold temperature anomalies during periods coinciding with the past grand minima of solar activity. However, as Feulner (2011) points out, it remains a difficult task to determine an upper limit for the TSI amplitude due to the uncertainties also in other climate forcings, climate sensitivity and reconstruction of temperatures from proxy data.

5.3. Distance-based model ranking

Hind and Moberg (2012) used the statistical framework of Sundberg et al. (2012) to compare the two full-forcing simulation ensembles by Jungclaus et al. (2010) with a selection of six alternative Northern Hemispheric-scale temperature reconstructions. Their purpose was to investigate whether it was possible to judge with certainty which of the two alternative solar forcing amplitudes, in the presence of other important forcings, provides the best fit to the temperature reconstructions. They observed a statistically significant correlation between Northern Hemispheric-scale temperatures in both types of all-forcings simulations and the reconstructions, indicating that the simulated and reconstructed temperatures share a common forced signal; which in turn means that a comparative ranking of the two types of simulation ensembles is meaningful. The ranking exercise led to the observation that the higher solar forcing amplitude results in a poorer match with the hemispheric-scale temperature reconstructions and lends stronger statistical support for the lower-amplitude case of solar forcing. However, the authors pointed out that their results are likely conditional upon the sensitivity of the climate model used and that they are strongly dependent on the choice of temperature reconstruction, implying that a greater consensus is needed regarding the reconstruction of past temperatures as this currently provides a great source of uncertainty.

5.4. Climate sensitivity estimates

Climate sensitivity is a concept used to denote the global mean equilibrium surface warming after a doubling of atmospheric CO₂ conditions. Estimates of the climate sensitivity can be obtained from comprehensive climate models and process studies, or by using constraints from the instrumental period or palaeoclimatic evidence. Knutti and Hegerl (2008) reported that various observations favour a climate sensitivity value of about 3°C and a likely range of 2°C–4.5°C was identified in IPCC AR4 (Hegerl et al., 2007b). However, the physics of the response and uncertainties in forcing led to fundamental difficulties in ruling out substantially higher values. Only a few attempts have been made to use palaeoclimate reconstructions
from the past millennium to quantify climate sensitivity. Hegger et al. (2006) undertook one such experiment for the last seven centuries. They used a large ensemble of EBM simulations, where they specified a range of plausible values for the climate sensitivity and forced the model by estimated changes in past solar, volcanic, greenhouse gas and sulphate aerosol forcing. To account for the uncertainty in the forcings, they used a range of amplitudes of the solar, volcanic and anthropogenic aerosol forcing. The rationale for such an approach is that some combination of climate sensitivity and forcing amplitudes gives the best fit to the reconstructed NH temperatures, as given by a specified distance measure. By analysing the distribution of these distance measures, they could estimate a probability distribution of the climate sensitivity.

Because of a weak signal and large uncertainties in reconstructions and forcing data, however, their analysed time horizon yielded only a weak constraint on the climate sensitivity, arising mainly from low-frequency temperature variations associated with changes in the frequency and intensity of volcanism, with little additional help by the solar variations. Their 5–95th percentile range for the climate sensitivity was 1.5–6.2°C. Hence, it appears that the past millennium is not a particularly useful period for estimating climate sensitivity. Due to comparatively small changes in temperature during the last millennium, in combination with the uncertainty in both reconstructed temperature and forcings, the last millennium is not a particularly useful period for estimating climate sensitivity (Knutti and Hegerl, 2008).

6. Conclusions

- There are large uncertainties in both temperature reconstructions and forcing reconstructions for the last millennium. Moreover, climate models are simplified representations of the true climate system. This needs to be considered when comparing reconstructed and simulated climate in the last millennium.
- Northern Hemispheric-scale decadal-mean temperatures show a significant influence from natural external forcing imposed upon the internal temperature variations.
- Volcanic forcing is significantly detectable on Northern Hemispheric-scale temperatures in the last millennium.
- There have been substantial controversies on the centennial-scale amplitude of solar forcing, but both simple visual inspection of time series, fingerprinting studies and other statistical investigations suggest that solar forcing has not been a main driver of climate in the last millennium.
- Anthropogenic greenhouse gas and aerosol forcing is detectable by the end of Northern Hemispheric-scale temperature reconstructions.
- Due to comparatively small changes in temperature during the last millennium, in combination with the uncertainty in both reconstructed temperature and forcings, the last millennium is not a particularly useful period for estimating climate sensitivity.

7. Acknowledgement

Financial support from the Swedish Research Council (VR): grant 90751501, ‘Reconstructing Climate in the last Millennium’.

References

Berger, A. and Loutre, M.-F. 1991. Insolation values for the climate of the last 10 million years. Quat. Sci. Rev. 10, 297–317. DOI: 10.1016/0277-3791(91)90033-Q.

Braconnot, P., Harrison, S. P., Kageyama, M., Bartlein, P. J., Masson-Delmotte, V. and co-authors. 2012. Evaluation of climate models using palaeoclimatic data. Nat. Clim. Change 2, 417–424. DOI: 10.1038/nclimate1456.

Christiansen, B. and Ljungqvist, F. C. 2012a. The extra-tropical NH mean temperature in the last two millennia: Reconstructions of low-frequency variability. Clim. Past 8, 765–786. DOI: 10.5194/cp-8-765-2012.

Christiansen, B. and Ljungqvist, F. C. 2012b. Reply to “comments on ‘reconstruction of the extra-tropical NH mean temperature over the last millennium with a method that preserves low-frequency variability’”. J. Clim. 25, 7998–8003. DOI: 10.1175/JCLI-D-11-00642.1.

Christiansen, B., Schmith, T. and Thejll, P. 2009. A surrogate ensemble study of climate reconstruction methods: Stochasticity and robustness. J. Clim. 22, 951–976. DOI: 10.1175/2008JCLI2301.1.

Esper, J., Frank, D. C., Timonen, M., Zorita, E., Wilson, R. J. S. and co-authors. 2012. Orbital forcing of tree-ring data. Nat. Clim. Change 2, 862–886. DOI: 10.1038/nclimate1589.

Fernández-Donado, L., González-Rouco, J. F., Raible, C. C., Ammann, C. M., Barriopedro, D. and co-authors. 2013. Large-scale temperature response to external forcing in simulations and reconstructions of the last millennium. Clim. Past 9, 393–421. DOI: 10.5194/cp-9-393-2013.

Feulner, G. 2011. Are the most recent estimates for Maunder Minimum solar irradiance in agreement with temperature reconstructions? Geophys. Res. Lett. 38, L16706. DOI: 10.1029/2011GL048529.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R. and co-authors. 2007. Changes in Atmospheric Constituents and
in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. and co-authors). Cambridge University Press, Cambridge, United Kingdom, pp. 129–234.

Frank, D. C., Esper J., Raible, C. C., Böttgen, U., Trouet, V. and co-authors. 2010. Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. Nature. 463, 527–530. DOI: 10.1038/nature08769.

Gao, C., Robock, A. and Ammann, C. 2008. Volcanic forcing of climate over the past 1500 years: An improved ice core-based index for climate models. J. Geophys. Res. [Atmos.]. 113, D23111. DOI: 10.1029/2008JD010239.

Gerber, S., Joos, F., Brügger, P. P., Stocker, T. F., Mann, M. E. and co-authors. 2003. Constraining temperature variations over the last millennium by comparing simulated and observed atmospheric CO2. Clim. Dyn. 20, 281–299. DOI: 10.1007/s00382-002-0270-8.

Goosse, H., Crespin, E., de Montety, A., Mann, M., Renssen, H. and co-authors. 2010. Reconstructing surface temperature changes over the past 600 years using climate model simulations with data assimilation. J. Geophys. Res. [Atmos.]. 115, D09108. DOI: 10.1029/2009JD012737.

Goosse, H., Crespin, E., Dubinkina, S., Loutre, M.-F., Mann, M. E. and co-authors. 2012. The role of forcing and internal dynamics in explaining the "medieval climate anomaly". Clim. Dyn. 39, 2847–2866. DOI: 10.1007/s00382-012-1297-0.

Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M. and co-authors. 2010. Solar influences on climate. Rev. Geophys. 48, RG4001. DOI: 10.1029/2009RG000282.

Hegerl, G. C., Crowley, T. J., Allen, M., Hyde, W. T., Pollack, H. N. and co-authors. 2007a. Detection of human influence on a new, validated 1500-year temperature reconstruction. J. Clim. 20, 650–666. DOI: 10.1175/JCLI4011.1.

Hegerl, G. C., Crowley, T. J., Hyde, W. T. and Frame, D. J. 2006. Climate sensitivity constrained by temperature reconstructions over the past seven centuries. Nature. 440, 1029–1032. DOI: 10.1038/nature04679.

Hegerl, G. C., Zwiers, F. W., Braccionnot, P., Gillett, N. P., Luo, Y. and co-authors. 2007b. Understanding and Attributing Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, and co-authors) Cambridge University Press, Cambridge, United Kingdom, pp. 663–745.

Hind, A. and Moberg, A. 2012. Past millennial solar forcing magnitude. A statistical hemispheric-scale climate model versus proxy data comparison. Clim. Dyn. DOI: 10.1007/s00382-012-1526-6.

IDAG – The International Ad Hoc Detection and Attribution Group. 2005. Detecting and attributing external influences on the climate system: A review of recent advances. J. Clim. 18, 1291–1314. DOI: 10.1175/JCLI3329.1.

Jansen, E., Overpeck, J., Briffa, K. R., Duplessy, J. C., Joos, F. and co-authors. 2007. Palaeoclimate. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, and co-authors). Cambridge University Press, Cambridge, United Kingdom, pp. 443–497.

Jones, P. D., Briffa, K. R., Osborn, T. J., Lough, J. M., van Ommen, T. D. and co-authors. 2009. High-resolution palaeoclimatology of the last millennium: A review of current status and future prospects. Holocene. 19, 3–49. DOI: 10.1177/09596836080988952.

Jungclaus, J. H., Lorenz, S. J., Timmreck, C., Reick, C. H., Brovkin, V. and co-authors. 2010. Climate and carbon-cycle variability over the last millennium. Clim. Past. 6, 723–737. DOI: 10.5194/cp-6-723-2010.

Kaufman, D. S., Schneider, D. P., McKay, N. P., Ammann, C. M., Bradley, R. S. and co-authors. 2009. Recent warming reverses long-term Arctic Cooling. Science. 325, 1236–1239. DOI: 1126/science.1173983.

Knutti, R. and Hegerl, G. C. 2008. The equilibrium sensitivity of the Earth’s temperature to radiation changes. Nat. Geosci. 1, 735–743. DOI: 10.1038/ngeo337.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. and co-authors. 2004. A long-term numerical solution for the insolation quantities of the Earth. Astron. Astrophys. 428, 261–285. DOI: 10.1051/0004-6361:20041335.

Ljungqvist, F. C., Krusic, P. J., Brattström, G. and Sundqvist, H. S. 2012. Northern Hemisphere temperature patterns in the last 12 centuries. Clim. Past. 8, 227–249. DOI: 10.5194/cp-8-227-2012.

Lockwood, M. 2011. Shining a light on solar impacts. Nat. Clim. Change. 1, 98–99. DOI: 10.1038/nclimate1096.

MacFarling Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R. and co-authors. 2006. Law Dome CO2, CH4 and N2O ice core records extended to 2000 years BP. Geophys. Res. Lett. 30, L14810. DOI: 10.1029/2003GL018252.

Mann, M. E., Zhang, Z., Hughes, M. K., Bradley, R. S., Miller, S. K. and co-authors. 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. Proc. Natl. Acad. Sci. USA. 105, 12352–12357. DOI: 10.1073/pnas.0805721105.

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K. and co-authors. 2009. Global signatures and dynamical origins of the little ice age and medieval climate anomaly. Science. 326, 1256–1260. DOI: 10.1126/science.1177303.

Moberg, A. 2012. Comments on “reconstruction of the extratropical NH mean temperature over the last millennium with a method that preserves low-frequency variability”. J. Clim. 25, 7991–7997. DOI: 10.1175/JCLI-D-11-00404.1.

Pongratz, J., Raddatz, T., Reick, C. H., Esch, M. and Claussen, M. 2009. Radiative forcing from anthropogenic land cover
change since AD 800. *Geophys. Res. Lett.* **36**, L02709. DOI: 10.1029/2008GL036394.

Pongratz, J., Reick, C. H., Raddatz, T. and Claussen, M. 2008. A reconstruction of global agricultural areas and land cover for the last millennium. *Global. Biogeochem. Cycles.* **22**, GB3018. DOI: 10.1029/2007GB003153.

Scheffer, M., Brovkin, V. and Cox, P. M. 2006. Positive feedback between global warming and atmospheric CO₂ concentration inferred from past climate change. *Geophys. Res. Lett.* **33**, L10702. DOI: 10.1029/2005GL025044.

Schmidt, G. A. 2010. Enhancing the relevance of palaeoclimate model/data comparisons for assessments of future climate change. *J. Quat. Sci.* **25**, 79–87. DOI: 10.1002/jqs.1314.

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P. and co-authors. 2011. Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0). *Geosci. Model Dev.* **4**, 33–45. DOI: 10.5194/gmd-4-33-2011.

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P. and co-authors. 2012. Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.1). *Geosci. Model Dev.* **5**, 185–191. DOI: 10.5194/gmd-5-185-2012.

Schrijver, C. J., Livingston, W. C., Woods, T. N. and Mewaldt, R. A. 2011. The minimal solar activity in 2008–2009 and its implications for long-term climate modeling. *Geophys. Res. Lett.* **38**, L06701. DOI: 10.1029/2011GL046658.

Servonnat, J., Yiou, P., Khodri, M., Swingedouw, D. and Denvil, S. 2010. Influence of solar variability, CO₂ and orbital forcing between 1000 and 1850 AD in the IPSLCM4 model. *Clim. Past.* **6**, 445–460. DOI: 10.5194/cp-6-445-2010.

Shapiro, A. I., Schmutz, W., Rozanov, E., Schoell, M., Haberreiter, M. and co-authors. 2011. A new approach to the long-term reconstruction of the solar irradiance leads to large historical solar forcing. *Astron. Astrophys.* **529**, A67. DOI: 10.1051/0004-6361/201016173.

Sundberg, R., Moberg, A. and Hind, A. 2012. Statistical framework for evaluation of climate model simulations by use of climate proxy data from the last millennium – Part 1: Theory. *Clim. Past.* **8**, 1339–1353. DOI: 10.5194/cp-8-1339-2012.

Steinhilber, F., Beer, J. and Fröhlich, C. 2009. Total solar irradiance during the Holocene. *Geophys. Res. Lett.* **36**, L19704. DOI: 10.1029/2009GL040142.

Tingley, M. P., Craigmile, P. F., Haran, M., Li, B., Mannshardt, E. and Rajaratnam, B. 2012. Piecing together the past: Statistical insights into paleoclimatic reconstructions. *Quat. Sci. Rev.* **35**, 1–22. DOI: 10.1016/j.quascirev.2012.01.012.