Climate Over the Past Two Millennia

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climate change, radiative forcing, volcanic forcing, solar forcing, anthropogenic forcing, greenhouse gas forcing, NAO, ENSO, climate reconstruction, paleoclimate modeling

Abstract

To assess the significance of modern climate change, it is essential to place recent observed changes in a longer-term context. This review assesses the evidence from both "proxy" climate data and theoretical climate model simulations with regard to the nature and causes of climate variability over a time interval spanning roughly the past two millennia. Evidence is reviewed for changes in temperature, drought, and atmospheric circulation over this timescale. Methods for reconstructing past climate from proxy data are reviewed and comparisons with the results of climate modeling studies are provided. The assessment provided affirms the role of natural (solar and volcanic) radiative forcing in past changes in large-scale mean temperature changes and in dynamical modes of climate variability such as the North Atlantic Oscillation (NAO) and El Niño/Southern Oscillation (ENSO) influencing large-scale climate. At hemispheric scales, late twentieth century warmth appears unprecedented in the context of at least the past 2000 years. This anomalous warmth can only be explained by modern anthropogenic forcing.

INTRODUCTION

Earth's climate exhibits variations on all resolvable timescales, from the interannual (year to year) to the geological (millions of years and longer). This variability is known to result from both internal and external factors, the latter associated with both natural and anthropogenic influences. A good review is provided by Ruddiman (2001). It is generally believed that modern (e.g., nineteenth to twenty-first century) climate change is due primarily to anthropogenic factors, including increased greenhouse gas concentrations owing to fossil fuel burning and the more regionally limited offsetting cooling influence of anthropogenic tropospheric aerosols. On longer timescales, a variety of natural processes, both internal (e.g., intrinsic modes of variability in the atmosphere and ocean) and external (e.g., solar and volcanic radiative forcing changes and, to a lesser extent, Earth-orbital changes) are believed to have been important over the past one to two millennia.

Over the past two millennia, the basic boundary conditions of Earth's climate (e.g., the continental arrangement, orography, Earth-orbital parameters, and the spatial extent of continental ice sheets) have not changed significantly. This time interval thus provides an appropriate context for estimating the envelope of natural climate variability within which modern climate change should be interpreted. Because the instrumental record can only provide information regarding large-scale (e.g., hemispheric) climate changes over only the past one-and-a-half centuries, and selected regions for only the past few centuries, it is essential that we turn to other lines of evidence to evaluate the longer-term changes over the past one or two millennia. One line of evidence is provided by so-called proxy climate data, natural or historical archives of information that describe, albeit imperfectly, climate variations in prior centuries. Those proxy data with relatively high (decadal or better) resolution, such as tree rings, corals, ice cores, historical records, and in some cases speleothems, and lake and marine sediments [see e.g., the review by Bradley (1999)] can be used to reconstruct climate variations over past centuries and, in some cases, as far back as the past two millennia. In addition, it is possible to use independent proxy and historical sources to estimate the actual external "forcings" of climate over this time interval (specifically, volcanic and solar natural radiative forcing, and anthropogenic greenhouse gas, aerosol, and land-use forcing). These estimates can be used to drive theoretical climate model simulations of the past millennium or longer (Jones & Mann 2004). A comparison of proxy-based reconstructions with such model simulation results can provide insight into the roles of various external and internal factors behind the variability of past centuries to millennia.

CLIMATE IN PAST CENTURIES

Building on pioneering earlier work (e.g., Lamb 1965, Fritts et al. 1971), a considerable body of more recent work (Bradley & Jones 1993; Hughes & Diaz 1994; Mann et al. 1995, 1998, 1999, 2003; Overpeck et al. 1997; Jones et al. 1998; Luterbacher et al. 1999; Crowley & Lowery 2000; Huang et al. 2000; Briffa et al. 2001; Folland et al. 2001; Esper et al. 2002; Mann & Jones 2003; Cook et al. 2004; Luterbacher et al.

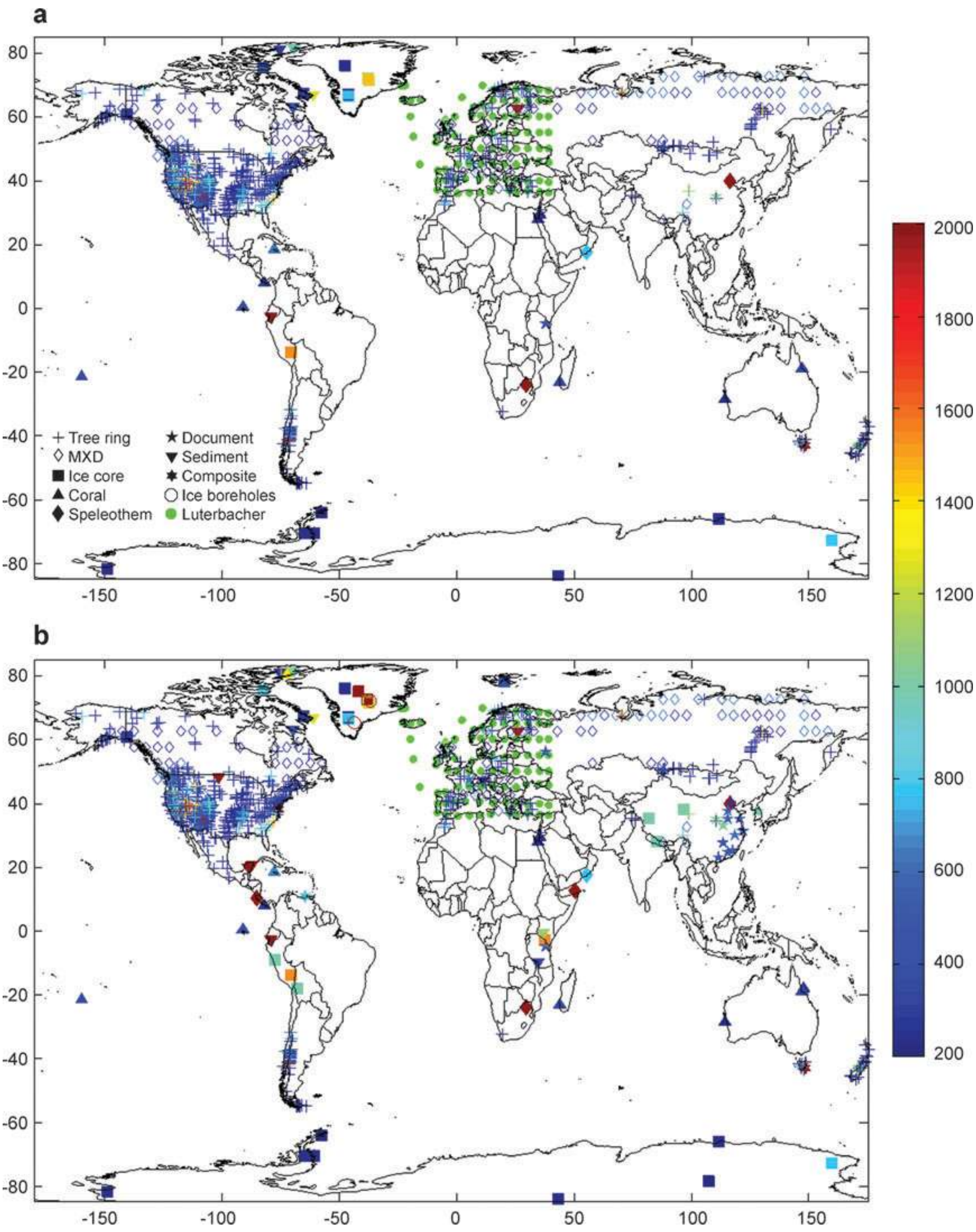
2004; Moberg et al. 2005; Oerlemans 2005; Rutherford et al. 2005) has focused on reconstructing large-scale climate changes over the period of the past one to two millennia during which widespread high-resolution, generally well-dated proxy records are available for large regions of the Northern Hemisphere (NH), and some parts of the Southern Hemisphere [see Jones & Mann (2004) for a review]. A number of model simulation studies of this period have also recently been performed (Rind & Overpeck 1993; Crowley & Kim 1996; Cubasch et al. 1997; Free & Robock 1999; Crowley 2000; Delworth & Mann 2000; Shindell et al. 2001, 2003, 2004; Bertrand et al. 2002; Bauer et al. 2003; Braganza et al. 2003; Gerber et al. 2003; Bell et al. 2003; Gonzalez-Rouco et al. 2003; Crowley et al. 2003; Schmidt et al. 2004; Mann et al. 2005a). Below, we review the recent work in these areas, including discussions of (*a*) the proxy data that are available for paleoclimate reconstructions of past centuries, (*b*) the methods used in these reconstructions, (*c*) an assessment of the performance of these methods based on tests using climate model simulation data, and (*d*) a comparison of proxy reconstructions of past climate with model simulation predictions.

NH: Northern Hemisphere

Paleoclimate Proxy Data

Proxy climate data used in reconstructing climate over recent past centuries fall into two distinct categories. The first category comprises annually or perhaps decadally resolved high-resolution proxy records, such as tree rings, corals, ice cores, laminated sediments, and historical documentary proxy information. Such records can potentially be calibrated against the shorter available instrumental records to yield quantitative climate reconstructions [see, e.g., reviews by Bradley (1999) and Jones & Mann (2004)]. The second category includes records that cannot be explicitly calibrated in this manner because they are less well resolved in time, have less precise age models, or both. Nonetheless, the records can often provide meaningful insights into centennial-scale climate changes in the past. Examples are nonlaminated marine lake and marine sediments (Keigwin 1996, Laird et al. 1996, Keigwin & Pickart 1999, Verschuren et al. 2000, Moy et al. 2002, Noren et al. 2002), fossil corals with annual resolution but floating chronologies (Cobb et al. 2003), mountain glacier moraines (Oerlemans 2005) and ice (Dahl-Jensen et al. 1998), and terrestrial (Huang et al. 2000, Mann et al. 2003) borehole ground temperature estimates.

Mann et al. (1998, 1999) used a network of 415 annually resolved proxy data (with dense data networks represented by a smaller number of representative summaries) to reconstruct temperature patterns over the past thousand years. Zhang et al. (Z. Zhang, M. Mann, S. Rutherford, R. Bradley, M. Hughes et al., manuscript in preparation) have more recently assembled a much larger network of 1232 annually resolved proxy data consisting of tree rings, corals and sclerosponge series, ice cores, lake sediments, and speleothems combined with reconstructions of European seasonal surface temperatures back to 1500 CE based on a composite of proxy, historical, and early instrumental data (Luterbacher et al. 2004). The resulting spatial distribution of annually resolved proxy data are shown in **Figure 1**. The additional inclusion of non-annually resolved, but still relatively high (e.g., decadal), resolution proxies (e.g., nonlaminated lake and ocean sediments) with high enough resolution


a
b
Tree ring
MXD
Ice core
Coral
Speleothem
Document
Sediment
Composite
Ice boreholes
Luterbacher
2000
1800
1600
1400
1200
1000
800
600
400
200

and accurate enough age models to calibrate at decadal resolution leads to an even larger network of 1302 proxy series (**Figure 1**).

NAO: North Atlantic Oscillation

AO: Arctic Oscillation

PDO: Pacific Decadal Oscillation

AMO: Atlantic Multidecadal Oscillation

SOI: Southern Oscillation Index

ENSO: El Niño/Southern Oscillation

CPS: composite plus scale

CFR: climate field reconstruction

PCA: principal component analysis

METHODS FOR RECONSTRUCTING PAST CLIMATE

Alternative Reconstruction Approaches

Most past attempts to model climate variations in past centuries have used proxy data to reconstruct time series representing global or hemispheric mean temperatures or selected climate indices of phenomena such as the North Atlantic Oscillation (NAO) and related Arctic Oscillation (AO), the so-called Pacific Decadal Oscillation (PDO), and Atlantic Multidecadal Oscillation (AMO), and indices such as the Southern Oscillation Index (SOI) and Niño3 index which attempt to describe the variability in the El Niño/Southern Oscillation (ENSO) phenomenon. These reconstructions have typically employed the so-called composite plus scale (CPS) methodology [see Jones & Mann (2004) for a review] wherein a selection of proxy series such as tree rings, ice cores, or corals are first standardized then composited to form a regional or hemispheric mean temperature series. In some cases, proxies are selected specifically for their retention of low-frequency variability (Esper et al. 2002, Mann & Jones 2003), and in other cases low-resolution (decadal or centennial-scale) proxy records are used to reconstruct long-term trends (Huang et al. 2000, Moberg et al. 2005). In the latter case, however, biases can arise from the difficulty in properly calibrating proxy records against instrumental data (Mann et al. 2003, 2005b).

It is arguably preferable to reconstruct not just single time series but the actual spatial patterns of past climate variation, which can provide better insights into dynamical modes of climate variability or the signatures of responses to particular climate forcings (Mann et al. 1998; Delworth & Mann 2000; Briffa et al. 2001; Shindell et al. 2001, 2003, 2004; Braganza et al. 2003; Luterbacher et al. 2004; Schmidt et al. 2004; Rutherford et al. 2005). In some cases, spatial pattern reconstructions are attempted through a spatially distributed set of local reconstructions (Cook et al. 1999, Briffa et al. 2001). In many other cases the spatial reconstructions specifically target the large-scale patterns through what is referred to as a climate field reconstruction (CFR) approach. CFR approaches have been applied to the reconstruction of large-scale surface temperature patterns (Mann et al. 1998, Rutherford et al. 2005) and regional (Evans et al. 2002, Luterbacher et al. 2004) surface temperature fields, and other fields such as regional sea level pressure (Luterbacher et al. 2002), precipitation (Pauling et al. 2006), and continental drought (Zhang et al. 2004). Earlier studies used a truncated principal component analysis (PCA) approach to proxy-based CFR

Figure 1

Spatial distribution of (*a*) annually resolved climate proxy data. Nine different proxy types are denoted with different symbols. Length of proxy is represented by cold color (shorter proxies) and warm color (longer proxies). (*b*) Same as (*a*) but for low-frequency predictors (which includes all annually resolved proxies and additional proxies with decadal to centennial resolution).

SST: sea surface temperature

SNR: signal-to-noise amplitude ratio

(Mann et al. 1998, 1999; Luterbacher et al. 1999; Evans et al. 2002; Luterbacher et al. 2002). Mann and coworkers have more recently adapted the RegEM algorithm introduced into the climate literature by Schneider (2001) to the problem of proxy-based CFR (Mann & Rutherford 2002; Rutherford et al. 2003, Zhang et al. 2004; Mann et al. 2005b, 2006; Rutherford et al. 2005). RegEM employs an objective regularization scheme and an explicit statistical modeling of errors, addressing a putative weakness of truncated PCA-based approaches claimed by Burger & Cubasch (2005).

In the CFR approach, hemispheric or global means, as well as any climate indices of interest, are computed directly from the spatial reconstructions of the underlying spatial field, just as they would be for, for example, modern gridded instrumental climate records. CFR methods do not require that a proxy indicator used in the reconstruction exhibit any local correlation with the climate field of interest, but instead make use of both local and nonlocal information by relating predictors (i.e., the long-term proxy climate data) to the temporal variations in the large-scale patterns of the spatial field. Indeed, this represents a primary advantage of CFR approaches to climate reconstruction because a greater amount of information contained within a diverse set of proxy data can potentially be used in climate reconstruction. For example, with respect to surface temperature reconstructions, coral and tree-ring precipitation proxies in the western tropical Pacific or parts of Mexico are excellent predictors of eastern tropical Pacific sea surface temperatures (SSTs) through their relationship with the ENSO phenomenon. Annual accumulation measurements or oxygen isotopes from Greenland ice cores, on the other hand, are excellent predictors of European and eastern North American winter temperatures through their relationship with the NAO.

CFR approaches depend more heavily on assumptions regarding the stationarity of relationships between proxy indicators and large-scale climate patterns than do simpler methods, such as the CPS method. However, investigations using synthetic proxy data (so called pseudoproxies), as discussed below, find that CFR methods are likely to perform well given the range of variability inferred for past centuries and the signal versus noise characteristics that appear to apply to actual proxy data networks.

Testing Reconstruction Methods Using Pseudoproxies

Experiments using synthetic proxies, or pseudoproxies, have been used to test the performance of both the CPS (Mann et al. 2005b) and CFR (Mann & Rutherford 2002; Rutherford et al. 2003; Pauling et al. 2003; Mann et al. 2005b, 2006; Von Storch et al. 2004; Burger et al. 2006) methods of paleoclimate surface temperature reconstruction. In these experiments, pseudoproxy time series are formed by summing a selected gridbox temperature series (either from a climate model simulation or from actual observational temperature data) with an independent realization of noise representative of the processes that degrade the climate signals contained within proxy records. Various relative amplitudes of noise can be considered, characterized for example by a signal-to-noise amplitude ratio (SNR). Typically (Mann & Rutherford 2002; Mann et al. 2005b, 2006), this is defined as the ratio of the amplitudes (in degrees Celsius) of the added noise and the gridbox temperature series (i.e., the signal). Some studies (Von Storch et al. 2004, Burger et al. 2006) instead express signal versus noise attributes in terms of the % noise, defined as the fraction of the variance in the pseudoproxy series accounted for by the noise component alone. For example, the following five different values of SNR, 0.25, 0.4, 0.5, 1.0, and ∞ (i.e., no added noise), correspond to the following % noise variance values, 94%, 86%, 80%, 50%, and 0%, respectively.

The CPS method. CPS reconstructions of hemispheric mean temperatures (see, e.g., Jones & Mann 2004 for a review) are typically based on approximately a dozen long-term proxy series believed to be indicative specifically of past local surface temperature variations. Mann et al. (2005b) used a simulation of the NCAR CSM 1.4 coupled model over the interval 850–1999 CE forced with combined natural (solar and volcanic) and anthropogenic (greenhouse gas and sulphate aerosol) forcing to test the performance of the CPS method given such a modest network of proxy information. They found that the CPS method is likely to produce faithful reconstructions of long-term climate histories under these circumstances provided that SNRs are in the range of SNR = 0.5 or higher (i.e., 80% noise or less), whereas there is evidence of a bias associated with an underestimation of amplitude for significantly lower SNR values. For the reconstruction of Mann & Jones (2003), the average decadal correlation between the eight proxies used and the closest available instrumental annual mean surface temperature gridpoint record during the twentieth century is $r = 0.47$. This corresponds to SNR > 0.5, a condition as discussed above under which the CPS method should produce a faithful reconstruction of long-term temperatures histories.

The CFR method. Because a primary interest in reconstructing past climate is on spatial patterns of change and not just, for example, hemispheric mean changes, I henceforth focus attention on tests of the CFR approach, which provides spatial reconstructions of past climate from which hemispheric means or simple indices such as the Niño3 can readily also be diagnosed. As discussed above, CFR methods can make use of both local and nonlocal relationships between proxies and the climate field (e.g., surface temperature) for which a reconstruction is sought because proxies related to other variables (e.g., precipitation) connected with atmospheric circulation carry information about other fields, such as surface temperature. For these reasons, an appropriate estimate of the SNR of multiproxy networks used in, for example, surface temperature field reconstruction should not only consider the correlation of proxy data with annual or seasonal temperatures but also with measures of the large-scale circulation (e.g., winter sea level pressure), which may better be recorded by the proxy. Based on this criterion, the average value for the Mann et al. (1998, henceforth MBH98) network of 112 indicators is $r = 0.41$ at annual timescales (and higher, at decadal and longer timescales) (Mann et al. 2006a). This corresponds to SNR > 0.4 (or % noise < 86%). By contrast, the average nearest instrumental gridpoint temperature correlation for the MXD tree-ring proxy data set used by Rutherford et al. (2005) and considered a priori to reflect local warm-season surface temperatures variations is $r = 0.49$, which corresponds to SNR > 0.5 (or % noise < 85%). In either of these two cases, the value SNR = 0.4 (86% noise) can be considered a conservative measure of the SNR for proxy data networks that have been used in actual proxy CFR studies such as MBH98 and Rutherford et al. (2005).

A number of studies have used pseudoproxies to specifically examine the robustness and reliability of multiproxy surface temperature field reconstructions such as MBH98. Mann & Rutherford (2002) formed pseudoproxies based on resampling of actual annual mean instrumental surface temperature gridbox series and used split calibration/validation experiments over the interval 1856–1998 by alternatively using the first half of the data for calibration and the second half for validation. They found that multiproxy networks with the same distribution as the full MBH98 network yielded similar validation statistics to those found by MBH98 at SNR ≈ 0.5. Moreover, they found that CFR approaches using proxy data with such SNR levels are likely to yield reliable annual mean reconstructions whether using the full MBH98 network of 112 indicators or the sparse network used by Mann et al. (1999) back to 1000 CE; whether using proxy indicators that reflect annual mean conditions or a mix of annual and seasonal conditions; and whether the "spectrum" of the proxy noise component is white (proxies reconstruct climate equally well at all frequencies), red (i.e., proxies selectively lose information at lower frequencies), or blue (i.e., proxies selectively lose information at higher frequencies). Pauling et al. (2003) performed similar tests to determine the influence of degradation back in time in the reliability of historical documentary evidence used in reconstructions of past European climate. Rutherford et al. (2003) tested the influence of nonstationarity in CFR by analyzing both anthropogenic forced and control simulations of the Princeton Geophysical Fluid Dynamics Laboratory (GFDL)-coupled model. They concluded that the potential nonstationarity owing to anthropogenic forcing during the modern period used for calibrating proxy networks against the instrumental record is unlikely to produce any substantial bias in reconstructing past surface temperatures.

Appearing to contradict these previous studies, a more recent study by Von Storch et al. (2004) claimed to present evidence that CFR approaches, such as that used by MBH98, are prone to significant underestimation of long-term variations. A number of problems with the Von Storch et al. (2004) study have now been identified, however, which appear to undermine the conclusions of the study: (*a*) The authors incorrectly implemented the MBH98 procedure, introducing an inappropriate (see Mann et al. 2006, Wahl et al. 2006) detrending procedure [this same procedure has since been adopted by their collaborator Cubasch in follow-up work (Burger & Cubasch 2005, Burger et al. 2006) undermining the conclusions of these studies too]. The use of such a procedure in CFR has been shown to produce poor results when, as in the real world, substantial trends are present over the calibration period (Mann et al. 2006a,b). (*b*) The model simulation used by the authors, the so-called Erik simulation of the GKSS "ECHO-G" model, was compromised by an artificial long-term drift of several degrees in amplitude due to erroneous model initialization (Osborn et al. 2006). The simulation moreover did not include a first-order anthropogenic forcing (twentieth-century tropospheric aerosol cooling), leading to a sizeable overestimate of recent warming in the simulation (Osborn et al. 2006). (*c*) The authors' conclusions based on the ECHO-G simulation do not hold up in a parallel analysis they performed (but did not shown in their article) using a different (HadCM3) simulation (Rahmstorf 2006).

Independent subsequent studies by Mann et al. (2005b, 2006a,b) have yielded very different findings from those reported by Von Storch et al. (2004). These studies demonstrate that CFR methods are likely to yield realistic reconstructions and uncertainty estimates given the estimated statistical attributes of actual proxy data networks, refuting the criticisms of proxy-based CFR approaches made by Von Storch, Cubasch, and collaborators (Burger & Cubasch 2005; Burger et al. 2006; Von Storch et al. 2004, 2006). Mann et al. (2005b, 2006a,b) created pseudoproxy networks using a simulation of the climate of the past millennium (850–1999 CE) with the NCAR Climate System Model 1.4 coupled ocean-atmosphere model driven by estimated long-term natural and anthropogenic radiative forcing histories. A modest long-term spatial drift was removed from the model fields prior to analysis. The simulation produced NH temperature variations in past centuries that are modestly greater in amplitude than most other simulations (see e.g., Jones & Mann 2004), providing a challenging, but importantly, realistic test for climate reconstruction methods.

The pseudoproxy networks were constructed from the model surface temperature field to have similar spatial distributions and a range of SNR values, including those that are both lower than and higher than that estimated value (e.g., SNR $\approx$ 0.4–0.5) for actual multiproxy networks used in previous work (Mann et al. 1998, 1999; Rutherford et al. 2005). Using these pseudoproxy networks, they tested the performance of the RegEM CFR method favored by Mann and coworkers. They found that the CFR method produced skillful reconstructions at SNR values even substantially lower (e.g., SNR $=$ 0.25) than those estimated above for the actual multiproxy networks. The reconstructions showed no systematic underestimate of low-frequency variability such as has been argued by Von Storch et al. (2004), producing reconstructed temperature histories that agree with the true model history prior to the calibration period, within estimated uncertainties.

Von Storch et al. (2006) responded with the argument that they can still force CFR methods to underestimate low-frequency variability if they assume that the noise component of proxies is red (i.e., that proxies selectively lose low-frequency climate information) and the calibration interval is short (1900–1980). This claim has now also been tested and rejected by Mann et al. (2006a,b), as discussed below.

Red noise can be characterized by the temporal autocorrelation coefficient ρ of the noise. The ratio of the lowest (i.e., in this case, centennial-scale) and broadband (i.e., frequency-averaged) noise variance is given by the factor $(1 + \rho)/(1 - \rho)$. The amplitude ratio is correspondingly given by $\alpha = [(1 + \rho)/(1 - \rho)]^{1/2} \cdot \alpha = 1$ for white noise pseudoproxies ($\rho = 0$). Although it is plausible that some proxy data (e.g., tree-ring data) do suffer such selective losses of low-frequency variance [see, e.g., the discussion in Jones & Mann (2004)], Von Storch et al. (2006) assumed an unrealistically large autocorrelation coefficient $\rho = 0.71$, which gives $\alpha \approx 6$, an inflation of variance of the lowest-frequency (i.e., century-scale) noise by a factor of six relative to average noise variance across all timescales. The true value of ρ can in fact be estimated from the proxy data themselves, and Mann et al. (2006a) have estimated the average value of ρ for the full network of 112 proxy multiproxy indicators used by MBH98 to be $\rho = 0.29 \pm 0.03$. The value $\rho = 0.32$ therefore constitutes an appropriate upper limit for the actual multiproxy network used by MBH98 in past surface temperature

LIA: Little Ice Age

MWP: Medieval Warm Period

reconstructions. Mann et al. (2006a,b) investigated the influence of red proxy noise on CFR performance using pseudoproxy networks with the spatial distribution and the estimate $\rho = 0.32$ of the proxy noise autocorrelation in the MBH98 proxy network. They performed experiments using both the NCAR CSM model discussed above and the (admittedly flawed) ECHO-G Erik simulation used by Von Storch et al. (2004, 2006). In both cases, even using a short (1900–1980) calibration interval and a lower signal-to-noise ratio (0.4 versus 0.5) than Von Storch et al. (2006), Mann and co-authors found that the RegEM reconstructions closely reproduced the actual model temperature histories, with the reconstructions lying entirely within the self-consistently estimated uncertainties of the true NH mean series (**Figure 2**). The most striking feature in both simulations—the cold temperatures of the fifteenth to nineteenth centuries associated with a combination of solar irradiance reduction and active explosive volcanic aerosol forcing—is well captured. It is thus clear that more recent, independent analyses refute the claims by Von Storch et al. (2004, 2006) that CFR methods intrinsically underestimate low-frequency variability, given the estimated statistical attributes of actual proxy data networks. Careful tests with model-simulated pseudoproxies using even the worst case scenarios (i.e., the flawed GKSS "Erik" simulation) instead actually validate the reliability of CFR methods to reconstruct past patterns of climate variability given suitable quality proxy data networks. These findings suggest that meaningful spatial reconstructions are possible from the application of CFR methods to available climate proxy data and that meaningful comparisons are possible between these reconstructions and the results from climate model simulations. Such reconstructions and model/data comparisons are discussed in detail below.

Reconstructions of Past Surface Temperature

Numerous past studies have used climate proxy data to reconstruct past large-scale surface temperatures. Regional temperature reconstructions demonstrate that much of the surface temperature variation in past centuries is characterized by a complex pattern of regional and seasonal variation that belies (see Mann et al. 2003) simplistic labels such as the Little Ice Age (LIA) and Medieval Warm Period (MWP), which arose primarily in the context of historical climatological studies (e.g., Lamb 1965) of European climate change. Indeed, the best available evidence suggests that substantial

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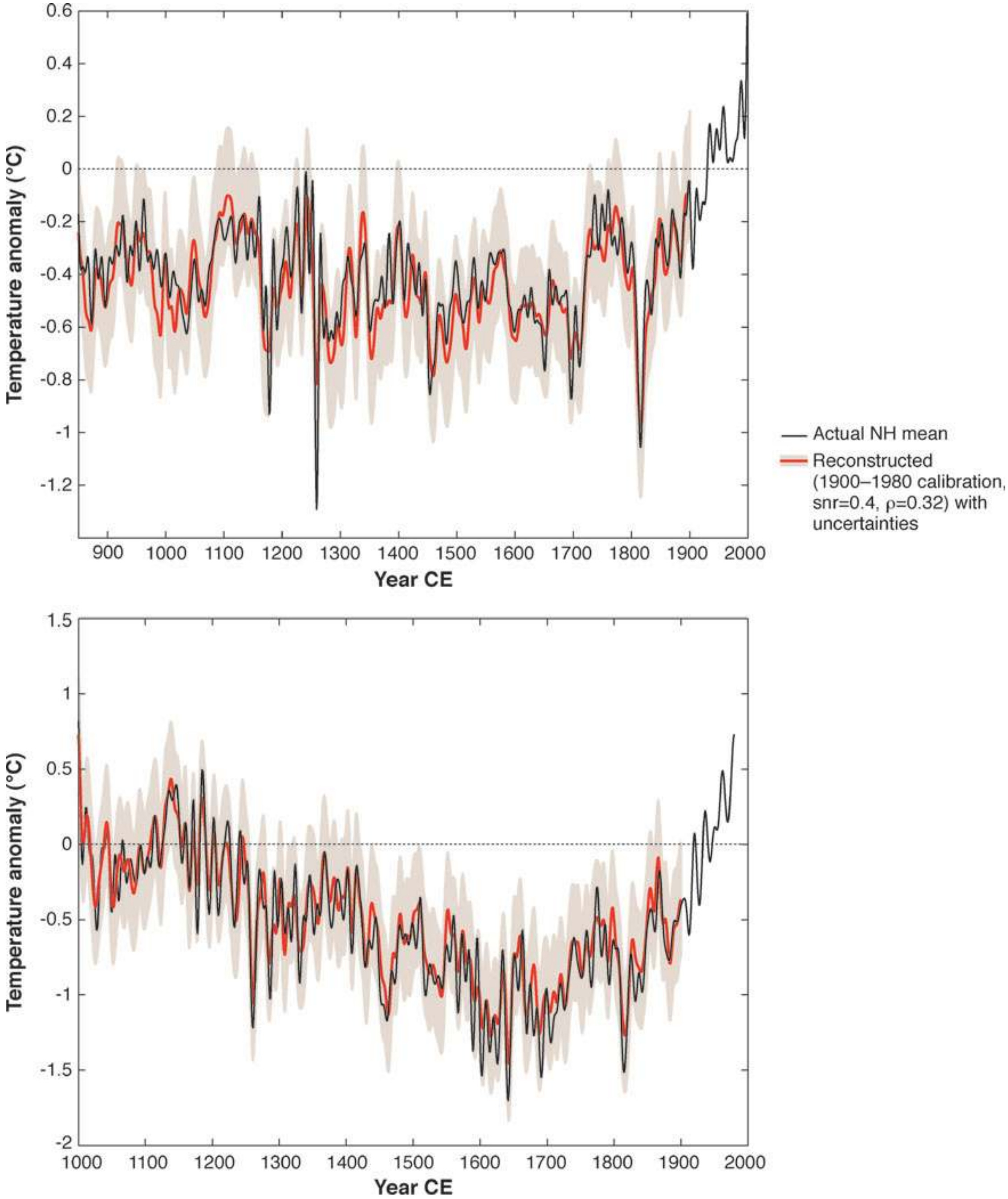
Figure 2

Reconstruction of Northern Hemisphere mean temperature based on RegEM CFR reconstructions using 'pseudoproxy' networks taken from (*a*) NCAR CSM 1.4 and (*b*) GKSS ECHO-G Erik simulations. In both cases, the pseudoproxy network locations correspond to the 104 unique locations used by MBH98, a proxy signal-to-noise ratio SNR = 0.4, red proxy noise with noise autocorrelation $\rho = 0.32$, and a 1900–1980 calibration interval is used. Self-consistent uncertainties in the reconstructions are estimated from the unresolved residual variance during an 1856–1899 validation interval, and are indicated by shading (95% uncertainty region). Actual model NH series is shown for comparison (*black*). All series are decadally smoothed. From Mann et al. (2006b), © AMS.



Temperature anomaly (°C)
Year CE
Actual NH mean
Reconstructed (1900–1980 calibration, snr=0.4, ρ=0.32) with uncertainties
Temperature anomaly (°C)
Year CE

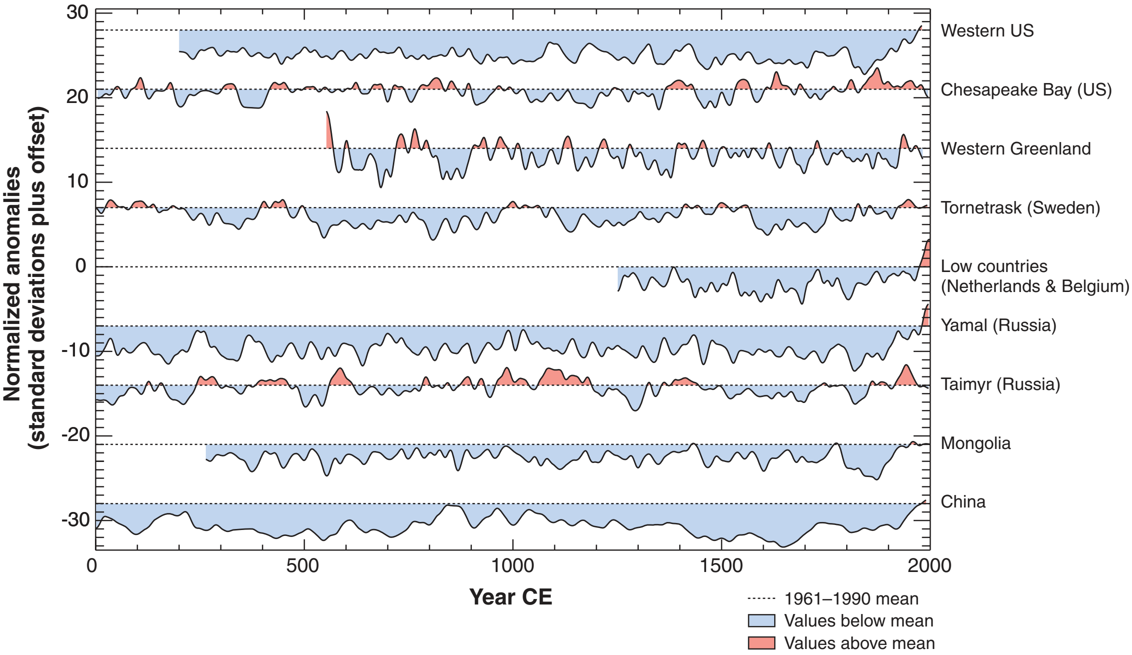


Figure 3

Temporal histories of nine temperature-sensitive proxy records, chosen to illustrate a variety of proxy types, NH locations, and spatial and seasonal representation. All series have been smoothed with a 40-year low-pass filter, then normalized so that the filtered series have unit standard deviation over 1251–1980 (when all series have data) and have zero mean over 1961–1990. Blue (*red*) shading indicates filtered values below (*above*) the 1961–1990 means (the latter are shown by thin horizontal lines). From Mann et al. (2003), © AGU.

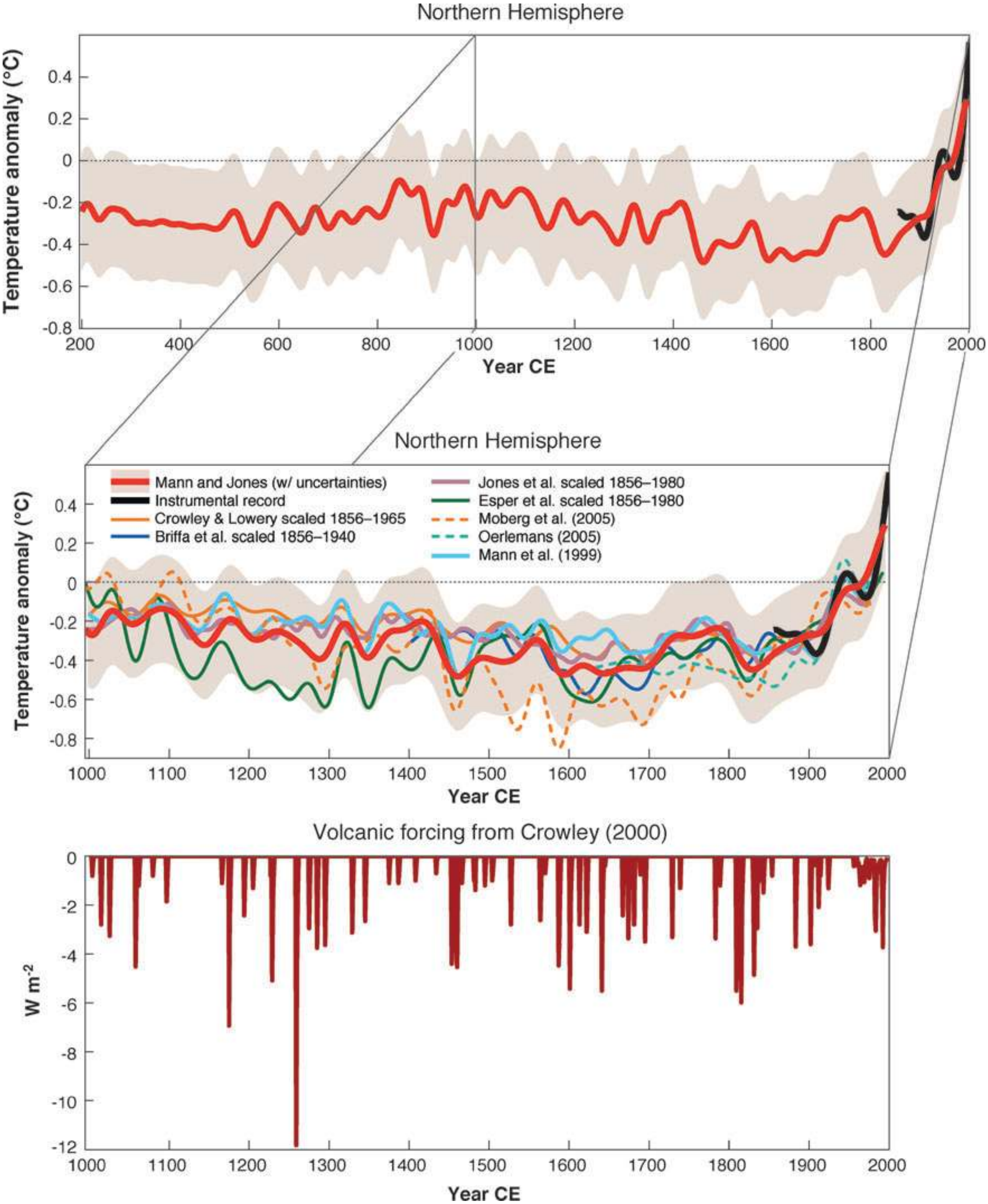
regional cold and warm anomalies can be found spanning the intervals often included within broad definitions of the LIA and MWP (Bradley & Jones 1993, Hughes & Diaz 1994). The best available proxy evidence (Hendy et al. 2002, Cobb et al. 2003) suggests relatively warm conditions in the tropical Pacific within the conventional LIA (e.g., in the seventeenth century) and relatively cold conditions during the conventional MWP (e.g., the eleventh century), calling into question the usefulness of these terms as descriptors of global-scale climate changes. Comparisons (**Figure 3**) of estimated regional temperature histories in different locations over the past 1000 years indicate that the specific periods of cold and warmth differ considerably from region to region. The only obvious common feature is the indication of anomalous warmth at many locations during the latter half of the twentieth century (Bradley et al. 2003, Osborn & Briffa 2006). These differences, as discussed below, follow from the complex influence of dynamical climate changes in past centuries, in particular substantial changes in atmospheric circulation that tend, in large part, to redistribute heat over the surface of the Earth rather than raise or lower the global mean temperature.

Owing to the considerable spatial variability described by past temperature variations, which is characterized by substantial but often opposite sign (warm versus cold) regional anomalies that tend to cancel in large-scale averages, it is essential to assimilate diverse proxy records over large-scale scales in the estimation of large-scale (i.e., hemispheric or global), long-term mean surface temperature trends. A number of studies (Bradley & Jones 1993; Overpeck et al. 1997; Mann et al. 1998, 1999; Jones et al. 1998; Crowley & Lowery 2000; Briffa et al. 2001; Esper et al. 2002; Mann & Jones 2003; Moberg et al. 2005; Oerlemans 2005; Rutherford et al. 2005) over the past decade have sought to produce hemispheric reconstructions of NH mean temperature changes over the past 500–2000 years based on the various types of proxy evidence and various statistical reconstruction methods discussed earlier. A smaller number of studies have also sought to reconstruct Southern Hemisphere and global surface temperature trends (Jones et al. 1998, Mann & Jones 2003), but the uncertainties are far more substantial owing to the relative paucity of long-term proxy records in the Southern Hemisphere (see e.g., Jones & Mann 2004). Although there are significant differences between the various published NH mean temperature reconstructions (**Figure 4**), every reconstruction performed to date indicates that large-scale late-twentieth-century warmth is anomalous in the context of at least the past 1000–2000 years. Some of the differences between different reconstructions are likely due to their different spatial and seasonal emphases and the implications this has for the impact of external radiative forcing influences on the estimates. For example, comparing the various reconstructions over the past 1000 years (**Figure 4**, middle panel), it can be seen that the Esper et al. (2002) reconstruction (green curve), which emphasizes the continental centers of the extratropical NH continents during summer, indicates greater variability than other reconstructions that are more indicative of the entire NH (extratropics and tropics, continent and oceans) over the full year. The increased variability, however, is observed primarily during those time intervals of intense explosive volcanic activity (**Figure 4**, bottom panel). These considerations are discussed in more detail below.

Reconstructions of Atmospheric Circulation and Drought

The substantial cooling in certain regions such as Europe during the late seventeenth and early eighteenth century often associated with the LIA appears to be related to long-term changes in the NAO (e.g., Luterbacher et al. 1999, 2002; Shindell et al. 2001; Keigwin & Pickart 1999; Jansen & Koc 2000; Rimbu et al. 2003), a pattern of atmospheric circulation variability that appears to vary on interannual and longer timescales. The prolonged tendency from much of the late sixteenth through early nineteenth century for the negative phase of the NAO (**Figure 5**) is associated with a tendency for cold, continental air mass influences over much of Europe during that time interval.

Recent work also suggests that the tropical Pacific Ocean–atmosphere dynamics associated with the ENSO may play an important role in the large-scale variability of the climate in past centuries (**Figure 5**). Statistical analyses show a significant influence of explosive volcanic eruptions on the ENSO based on volcano/El Niño


Northern Hemisphere
Temperature anomaly (°C)
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
200
400
600
800
1000
1200
1400
1600
1800
2000
Year CE
Northern Hemisphere
Mann and Jones (w/ uncertainties)
Instrumental record
Crowley & Lowery scaled 1856–1965
Briffa et al. scaled 1856–1940
Jones et al. scaled 1856–1980
Esper et al. scaled 1856–1980
Moberg et al. (2005)
Oerlemans (2005)
Mann et al. (1999)
Temperature anomaly (°C)
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Year CE
Volcanic forcing from Crowley (2000)
W m-2
0
-2
-4
-6
-8
-10
-12
Year CE

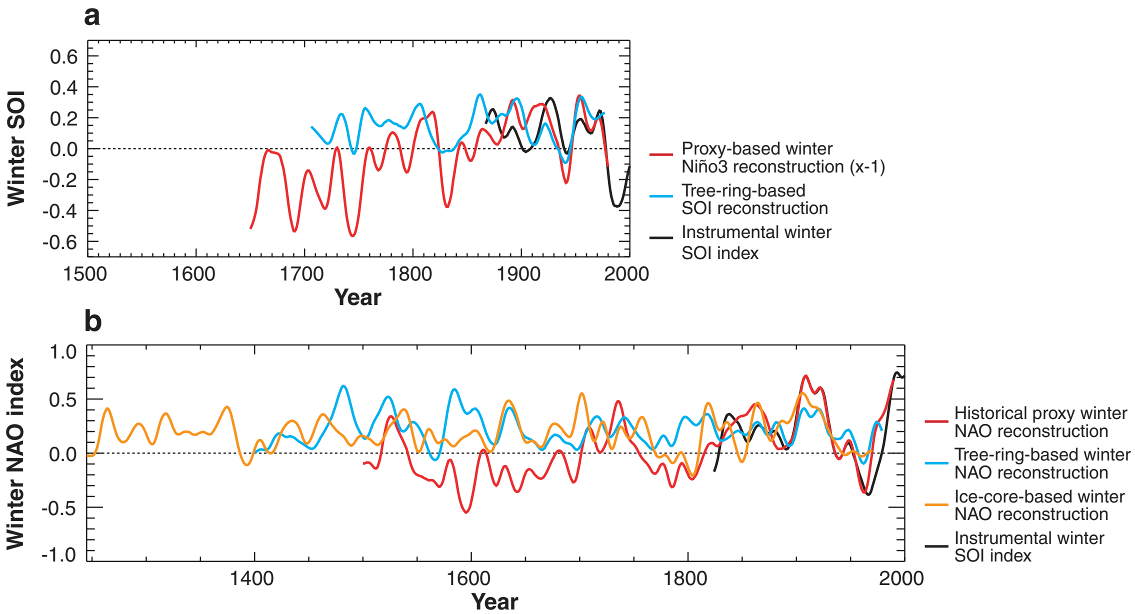


Figure 5

Proxy-based reconstructions of two key atmospheric indices: (*a*) the Southern Oscillation Index (SOI) and (*b*) the North Atlantic Oscillation (NAO). Series are smoothed to emphasize variations on 30-year and longer timescales. From Jones & Mann (2004), © AGU.

relationships (Adams et al. 2003) determined from reconstructions of ENSO indices spanning the past few centuries (Stahle et al. 1998, Mann et al. 2000). Fossil corals from the central tropical Pacific (Cobb et al. 2003) indicate a cold La Niña–like state during the eleventh to twelfth centuries, typically associated with the MWP, and a warm, El Niño–like state during the seventeenth century, typically associated with the LIA.

Changes in drought and precipitation patterns in past centuries appear, in many regions, to represent a response to the changing state of the tropical Pacific inferred above. Lake level evidence from eastern equatorial Africa (Verschuren et al. 2000) indicates dry conditions (typically associated with La Niña) and wet conditions

Figure 4

Comparison of various NH mean temperature reconstructions of the past 1000 years. Instrumental NH mean series 1856–2005 (centered over the 1961–1990 interval) is shown for comparison. Mann & Jones (2003) reconstruction is as in Jones & Mann (2004), but it is rescaled to have same decadal variance as actual instrumental NH series over 1856–1995 interval. All series have been smoothed with a 40-year, low-pass filter and are aligned to have the same mean as the overlapping instrumental record. Also shown for comparison is Crowley (2000) volcanic forcing series back to 1000 CE.

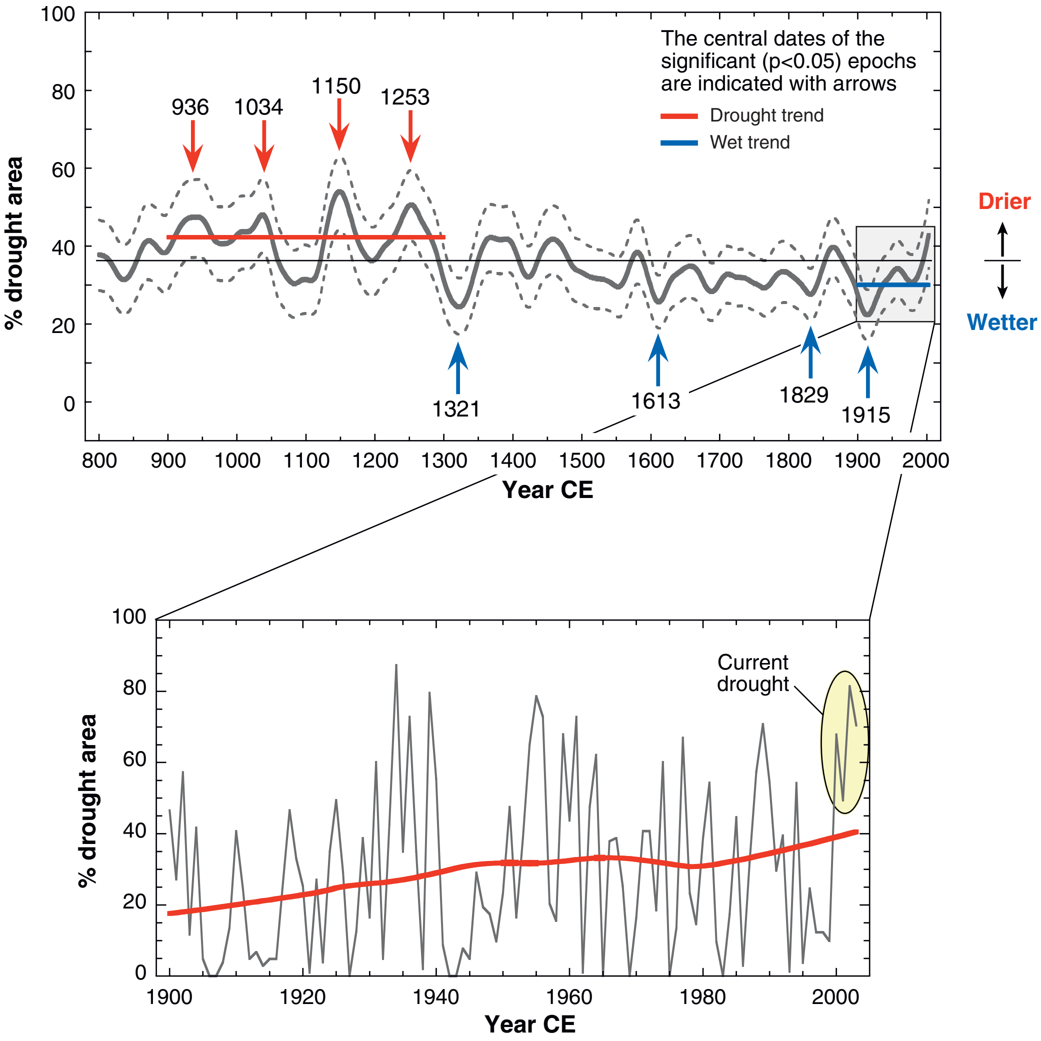


Figure 6

Reconstruction of drought area index from tree-ring data, indicative of changes in the extent of drought over the western United States during the past millennium [reprinted with permission by American Association for the Advancement of Science (AAAS) from Cook et al. (2004)].

(typically associated with El Niño) during the conventional timeframes associated with the MWP and LIA, respectively. Estimates of the regional extent of drought in the western United States over the past 1000 years (Cook et al. 2004) indicate a substantial tendency for drought during the eleventh to thirteenth centuries, and wet conditions during the sixteenth to nineteenth centuries, consistent with a tendency for La Niña–like and El Niño–like conditions, respectively (**Figure 6**).

Comparisons of Reconstructions with Model Simulation Results

EBM: energy-balance model

AOGCM: atmosphere-ocean general circulation model

Complementing the numerous proxy-based reconstructions of large-scale temperature changes over the past 1000 years (e.g., **Figure 4**), a number of computer model simulations of the past 1000 years have been performed over the past decade (Crowley & Kim 1999, Crowley 2000, Free & Robock 1999, Bertrand et al. 2002, Bauer et al. 2003, Crowley et al. 2003, Gerber et al. 2003, Gonzalez-Rouco et al. 2003, Andronova et al. 2004, Mann et al. 2005b, Goosse et al. 2006b), based on the full hierarchy of available climate models, from simple energy-balance models (EBMs) to fully coupled atmosphere-ocean general circulation models (AOGCMs). These simulations make use of varying estimates of past natural and anthropogenic radiative forcing histories. Given the different characteristics of the model simulations used (which differ in their sensitivities to radiative forcing) and the sometimes very different forcing estimates that have been used in these experiments, it is difficult to interpret the spread of the results of the different simulations. Nonetheless, comparisons of the simulated NH mean temperature histories with empirical proxy-based reconstructions of NH mean temperature indicate a favorable comparison overall, with the various simulation results falling largely within the uncertainties of the reconstructions (**Figure 7**). One exception is the GKSS Erik simulation (orange dashed curve in **Figure 7**) of Von Storch et al. (2004), which, for reasons discussed above, does not provide a realistic simulation of the past millennium owing to errors in

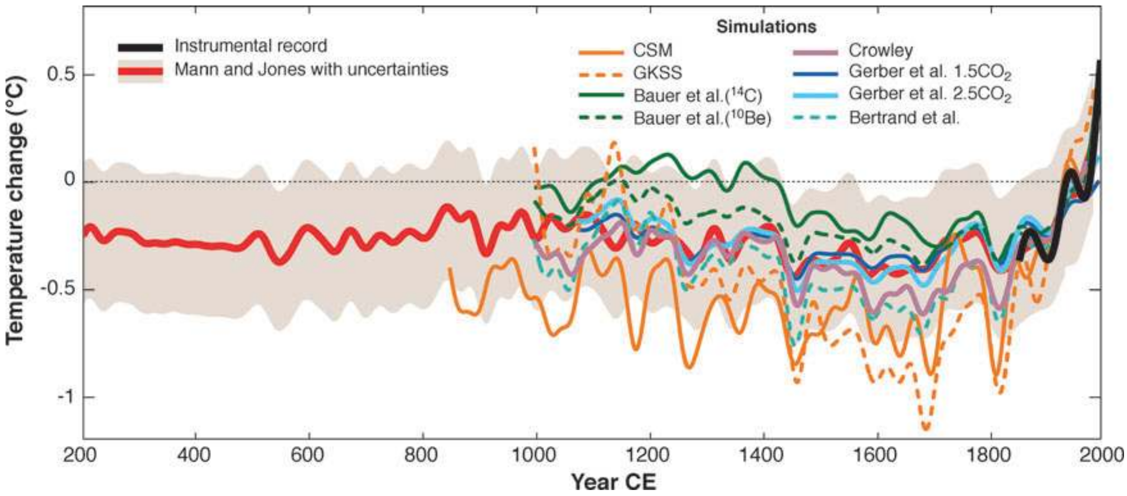


Figure 7

Model-based estimates of NH temperature variations over the past two millennia. Series have been smoothed to highlight variations on timescales greater than 40 years. The simulations employ a range of climate models with differing sensitivities to radiative forcing and employ various different estimates of radiative forcing histories, including natural (solar + volcanic) and modern anthropogenic (greenhouse gas and sulfur aerosol) impacts. Shown for comparison are the instrumental NH record 1856–2003 and an empirical proxy-based estimate of NH mean temperature changes with its 95% uncertainty band (*shading*). From Jones & Mann (2004), © AGU.

the model initialization and the prescription of forcings. The comparisons indicate that natural (solar and volcanic) forcing can explain reasonably the major large-scale mean surface temperature changes of the past millennium through the nineteenth century. Only anthropogenic (greenhouse gas plus sulfate aerosol) forcing of climate, however, can explain the recent anomalous large-scale warming in the late twentieth century. Several of the simulations overpredict the net warming that has occurred since the early/mid-nineteenth century, as evident from the instrumental record (and reconstructions), leading to the appearance of colder temperatures in past centuries when aligned with the modern instrumental record, as in **Figure 7**. Simulations such as that of Bauer et al. (2003) (green curves in **Figure 7**) that take into account nineteenth to twentieth century anthropogenic land use changes, however, more closely match the observations, suggesting that this forcing has played an important role in large-scale surface temperature changes over at least the past two centuries.

At regional scales, a number of considerations other than the global mean response to forcing become important. Purely internal variability can have a similar or even greater influence on surface temperature variations than forced variability at regional scales (Shindell et al. 2003, 2004; Goosse et al. 2006b). Although anthropogenic land-surface impacts appear to play an important role in large-scale surface temperature changes only during the past two centuries, in some regions and during certain seasons (e.g., over Europe during the summer), land surface forcing appears to have played an important regional role much earlier, in association with large-scale deforestation that was well underway more than 1000 years ago. The associated land surface changes appear to explain, in particular, Medieval European summer warmth around the eleventh century that was comparable to summer warmth around the late twentieth century (Goosse et al. 2006a).

Regional climate variability is also strongly influenced by dynamical modes of climate variability, which have an important influence on the large-scale atmospheric circulation, particularly during the winter or cold season. Some of this dynamical variability may also be associated with past radiative forcing changes as they influence the behavior of particular modes of climate variability, such as the NAO and ENSO.

The substantial cooling in large parts of Europe at the height of the conventionally defined European LIA during the late seventeenth and early eighteenth century appear to be related in large part to long-term variations in the NAO, discussed above, which in turn appear to have been associated (**Figure 8**) with a large-scale dynamical response of the climate system to natural radiative forcing by explosive volcanic activity (Shindell et al. 2003, 2004) and solar output (Shindell et al. 2001, 2003). The influence of this forcing on the vertical and meridional atmospheric temperature gradients leads to a change in the strength of the midlatitude westerlies characterized by the NAO (or related AO) pattern. The moderate apparent lowering of solar irradiance during the seventeenth-century Maunder Minimum period, for example, appears to have lead to only moderate decreases in hemispheric mean temperature, but a substantial annual mean cooling in certain regions, such as Europe, owing to a prolonged tendency toward the negative phase of the NAO (Shindell et al. 2001). The seasonal and spatial response of the climate to volcanic forcing is especially

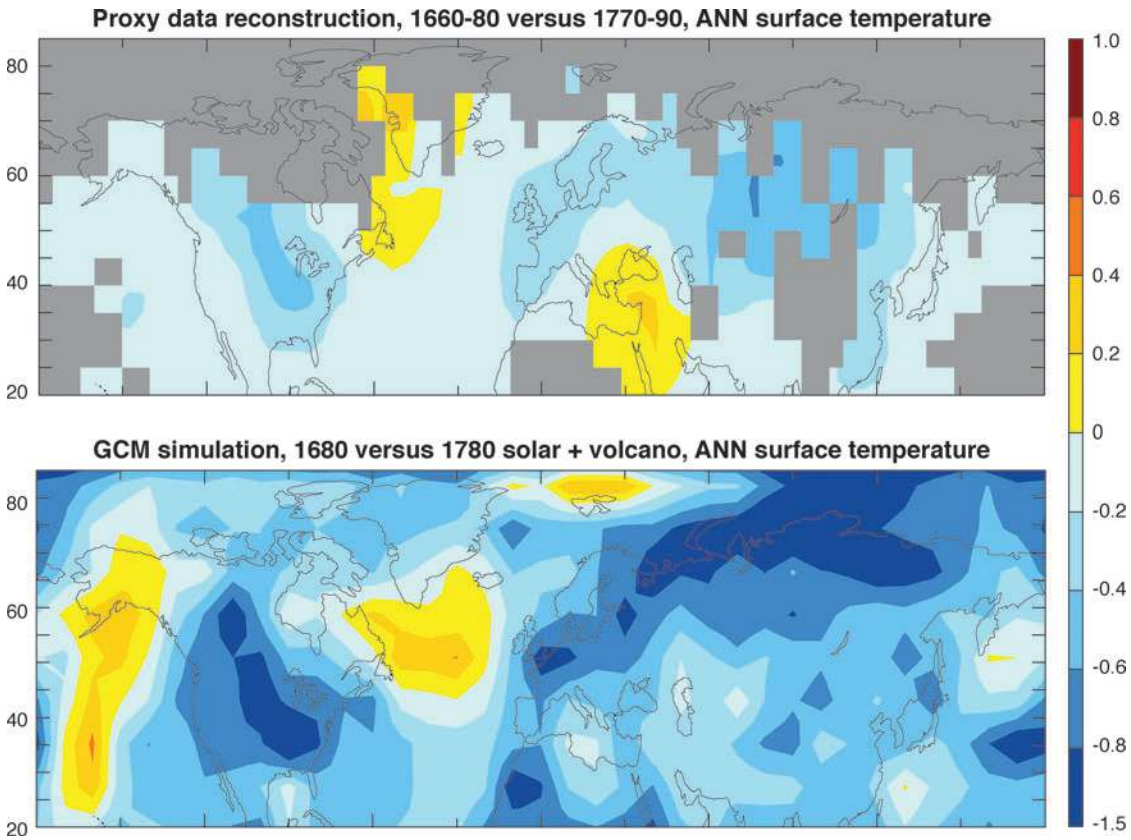


Figure 8

Reconstructed (*top*) and simulated (*bottom*) annual average temperature difference between 1660–80 and 1770–90. The reconstructed surface temperatures are based on a multiproxy estimate using tree rings, ice cores, corals, and historical data. Model results are based on the sum of the response in two simulations: one incorporating reconstructed solar irradiance changes during this period and one using volcanic forcing scaled to changes over this period. From Schmidt et al. (2004).

important from the standpoint of interpreting paleoclimate proxy data. Modeling studies (Shindell et al. 2003, 2004) suggest a tendency for a substantial cooling over the continents, but they also suggest a tendency for a dynamically induced, offsetting winter warming over the continents during the first couple of years following an explosive tropical eruption. In continental regions, therefore, there is a tendency for cancellation of summer cooling and winter warming in the surface temperature response to volcanic forcing. This observation implies that regionally and seasonally restricted proxy data may provide a biased estimate of actual large-scale annual surface temperature changes. For example, as noted previously (**Figure 4**), the greater cooling evident in proxy reconstructions of NH mean temperature that emphasize the summer and the continental regions during intervals of intense explosive volcanic forcing is likely due to the restricted spatial and seasonal sampling implicit in those reconstructions (Shindell et al. 2003).

Recent work also suggests that that the ENSO may be an important component of the response of the climate to forcing over the past 1000 years. Model simulations using simple models of the coupled tropical ocean-atmosphere to study the response of ENSO to solar and volcanic forcing (Mann et al. 2005a) indicate a counter-intuitive tendency toward El Niño–like (warm eastern and central tropical Pacific) conditions in response to negative radiative forcing (past explosive tropical volcanic eruptions or decreases in solar irradiance) and a tendency for La Nina–like conditions in response to positive radiative forcing (i.e., increases in solar irradiance). This prediction explains (**Figure 9**) the empirical connection between past explosive tropical volcanic

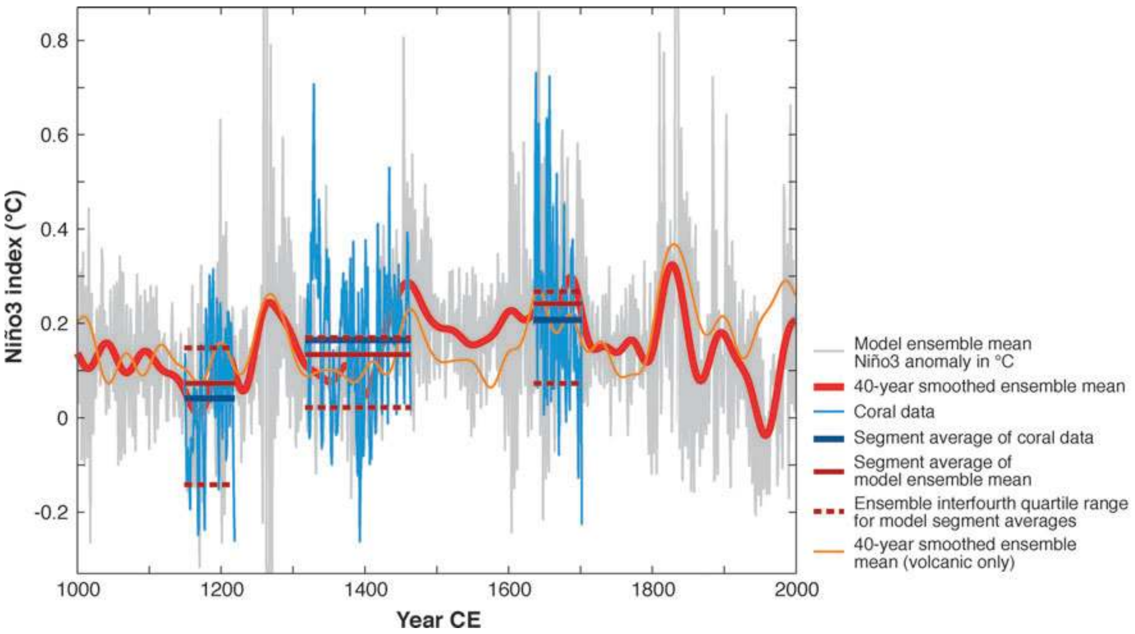


Figure 9

Comparison of the ensemble annual mean Niño3 response to combined natural radiative forcing (volcanic + solar) over the interval 1000–1999 CE (*gray*: anomaly in degrees Celsius relative to 1950–1980 CE reference period; 40-year smoothed values shown by *thick red curve*) with reconstructions of ENSO behavior from Palmyra coral oxygen isotopes (*light blue*: the annual means of the published monthly isotope data are shown). The coral data are scaled as described in the text, with warm-event (cold-event) ENSO conditions associated with negative (positive) isotopic departures. Thick horizontal lines indicate averages of the scaled coral data for the three available time segments (*dark blue*) and the ensemble-mean averages from the model (*dark red*) for the corresponding time intervals. The associated interfourth quartile range for the model means (the interval within which the mean lies for 50% of the model realizations) is also shown (*dark red dashed lines*). Also shown (*orange curve*) is the 40-year smoothed model result based on the response to volcanic forcing only, with the overall mean shifted to match that of the overlapping coral segments. From Mann et al. (2005a), © AMS.

activity and El Nino reconstructions found by Adams et al. (2003) and the widespread evidence discussed above from tropical Pacific corals (Cobb et al. 2003), equatorial east African Lake records (Verschuren et al. 2000), and western North American drought reconstructions (Cook et al. 2004) for La Niña–like conditions during the MWP (when solar irradiance was relatively high and there were few explosive tropical volcanic eruptions) and El Niño–like conditions during the LIA (when solar irradiance was relatively low and there were many explosive tropical volcanic eruptions). The conclusion that the tropical Pacific appears to have been in a cold La Niña–like state during the MWP and a warm El Niño–like state during the LIA implies that surface temperature changes in the tropical Pacific may have offset extratropical temperature changes (where these periods were relatively warm and cold respectively), reducing the amplitude of global or hemispheric-mean temperature changes from what would be deduced based on extratropical proxy data alone.

SUMMARY POINTS

1. Proxy reconstructions and model simulations both suggest that late twentieth century warmth is anomalous in the context of the past 1000–2000 years.
2. Forced changes in large-scale atmospheric circulation, such as the NAO, and internal dynamics related to El Niño may play an important role in explaining regional patterns of variability and change.
3. Important differences between estimates of extratropical and full (combined tropical and extratropical) hemispheric mean temperature changes in past centuries appear consistent with seasonally and spatially specific responses to climate forcing.
4. Tests with synthetic pseudoproxy networks derived from climate model simulations indicate that statistical methods used for reconstructing past climate from proxy data are likely to yield reliable reconstructions back at least 1000 years within estimated uncertainties, given the statistical properties estimated for actual proxy networks.

FUTURE ISSUES

1. Future efforts at large-scale climate reconstruction methods should address the reconstruction of fields other than surface temperature (e.g., measures of atmospheric circulation, such as sea level pressure, and hydroclimatic variables, such as precipitation and drought).
2. Continued investigations of climate field reconstructions should focus on the use of teleconnected local climate responses and the stability of the associated long-term relationships.

3. There is a need for longer, high-quality proxy climate records from key regions (e.g., the tropical Pacific and Southern Hemisphere) to reduce the current sizable uncertainties in climate reconstructions over the past 1000–2000 years.
4. There is a need for more reliable estimates of long-term radiative forcing histories (e.g., solar and volcanic radiative forcing) to constrain the currently sizable spread in model simulations of climate changes over the past 1000–2000 years.

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