Climate during the past millennium

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To determine whether twentieth-century climate change is unusual, it is essential to place it in a longer-term context. Since instrumental climate records prior to the twentieth century are sparse, indirect 'proxy' indicators are required for a description of large-scale climate variability in past centuries. The determination of annual patterns of climate, furthermore, requires high-resolution proxy climate indicators such as tree rings (*e.g.* Fritts 1991), laminated sediment cores (*e.g.* Lamoureux and Bradley 1995; Hughen *et al.* 1996), ice cores (*e.g.* Fisher *et al.* 1998), and corals (*e.g.* Dunbar and Cole 1999), and the few early instrumental and historical documentary records (*e.g.* Bradley and Jones 1995; Pfister *et al.* 1998) which contain seasonal or annual climate information.

A number of recent studies have employed global 'multiproxy' networks of such high-resolution proxy climate indicators to reconstruct spatial and temporal patterns of climate change and variability in past centuries. Such reconstructions include large-scale temperature patterns (Briffa *et al.* 1998; Mann *et al.* 1998, 1999, 2000a,b; Jones *et al.* 1998), multidecadal and century-scale patterns of atmospheric circulation and drought (*e.g.* Woodhouse and Overpeck 1998), indices of climate phenomena such as the North Atlantic Oscillation (NAO) (*e.g.* Luterbacher *et al.* 1999; Cullen *et al.* 2001) and the El Niño Southern Oscillation (ENSO) (*e.g.* Stahle *et al.* 1998; Mann *et al.* 2000a), and the histories of externally forced temperature variability (Crowley and Kim 1999; Free and Robock 1999; Crowley 2000). I review here the most recent findings in these areas, and the implications for our understanding of past climate variability and change.

Large-scale temperature trends

Building on earlier, preliminary work (*e.g.* Jacoby and D'Arrigo 1989; Bradley and Jones 1993; Hughes and Diaz 1994; Mann *et al.* 1995; Fisher 1997; Overpeck *et al.* 1997), numerous recent studies have sought to combine multiple types of high-resolution proxy climate indicators in the reconstruction of large-scale temperature changes in past centuries. Jones *et al.* (1998) estimated extratropical Northern (and, more tentatively, Southern) Hemisphere warm-season temperature trends during the past millennium based on a modest number of proxy temperature climate indicators and a simple compositing approach similar to that of Bradley and Jones (1993). Mann *et al.* (1998, 1999, 2000a,b) presented reconstructions of annual global surface temperatures over the past millennium which are based on the 'calibration' (*i.e.* the construction of a statistical relationship over a reference period, the 'calibration period') of a combined terrestrial (tree ring, ice core, and historical documentary indicator) and marine (coral) multiproxy climate network against the dominant patterns of twentieth-century global surface temperatures. Averaging these patterns, they obtained an estimate of Northern Hemisphere mean temperature back to AD 1000, skilfully resolving an estimated 70–80% of the Northern Hemisphere mean temperature variance back to 1820, and about 50% back to AD 1000, based on analyses from both the twentieth-century calibration interval and an independent nineteenth-century 'cross-validation' interval (a time-interval distinct from the calibration period during which the reconstructions can be independently tested for validity). Calibration residuals (the differences between the reconstruction and actual data during the calibration period) were used to provide a self-consistent estimation of the uncertainties in the reconstruction. Prior to AD 1600, the uncertainty estimates were modified to reflect potentially enhanced uncertainty in century-scale and longer time-scale variability relative to the nominal self-consistent uncertainty estimates with the sparser network available prior to AD 1600 (see Mann *et al.* 1999). Since the instrumental data used for calibration are themselves quite sparse poleward of the Southern Hemisphere tropics (see Mann *et al.* 1998), estimates of global mean temperature in past centuries are necessarily more tentative. However, to the extent that such estimates are possible over the past few centuries, they show a broadly similar trend to that for the Northern Hemisphere (Mann *et al.* 2000b).

The Northern Hemisphere mean reconstruction of Mann *et al.* (1999) is shown in Fig. 1. The reconstruction exhibits a modest irregular long-term cooling from AD 1000 to around 1900, followed by an abrupt warming during the twentieth century. The uncertainties expand considerably prior to AD 1600 as discussed above. Taking into account these substantial uncertainties, it can nonetheless be

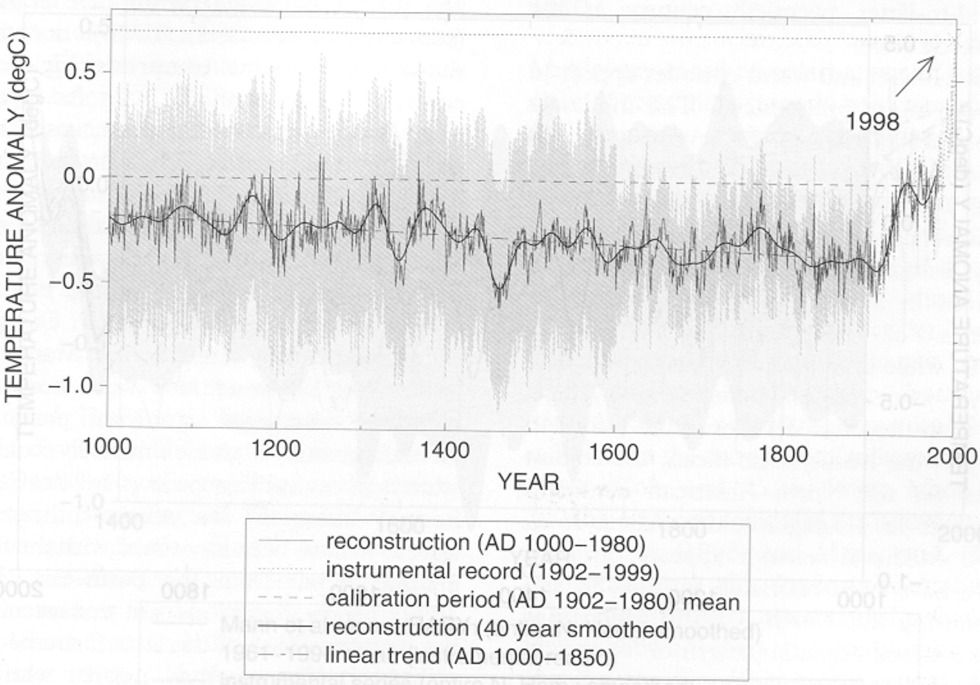


Fig. 1 Northern Hemisphere mean annual temperature reconstruction (AD 1000–1980) and instrumental series (1902–99) (from Mann et al. *1999). The shaded band indicates 95% confidence limits. Note that uncertainties increase back in time. The figure has been updated from Mann* et al. *(1999) to reflect a modest correction of the 1998 value, and to update the instrumental record to 1999.*

concluded that the decade of the 1990s (nearly a 2 standard error positive outlier relative to all other decades in the reconstruction) and the year 1998 (nearly a 2.5 standard error positive outlier relative to all other years) are probably the warmest decade and year respectively of the millennium.

The Northern Hemisphere temperature reconstructions of Jones *et al.* (1998), and Mann *et al.* (1999) are compared in Fig. 2, along with an entirely independent (extra-tropical, warm-season) tree-ring density-based Northern Hemisphere temperature estimate of Briffa (2000). The uncertainties for the smoothed Mann *et al.* series are shown for comparison. Statistically significant differences between the different temperature reconstructions are evident during the seventeenth and early nineteenth centuries. These are probably associated with the different latitudinal and seasonal sampling contributing to the different estimates. The Mann *et al.* surface temperature reconstruction, averaged only over the extra-tropical (30–70°N) region of the Northern Hemisphere, for example, shows greater similarity to the Jones *et al.* reconstruction (Fig. 2), though residual differences remain which are probably associated with different seasonal emphases of the two estimates. These differences emphasise the importance of considering regional and seasonal distinctions when characterising climate changes in past centuries. Such distinctions are further discussed in the next section.

Estimates of past ground surface temperatures from networks of boreholes have also been used to reconstruct hemispheric and global terrestrial temperature trends in past centuries (*e.g.* Huang *et al.* 2000). These estimates suggest even lower Northern Hemisphere mean temperatures in the sixteenth–eighteenth centuries or, equivalently, greater warming during the past two centuries, than is indicated above. However, a number of factors may complicate such a direct comparison with borehole-based ground surface temperature trends. The borehole estimates are associated with a significant loss of temporal resolution back in time, so that important century-scale temperature changes may be smoothed over in

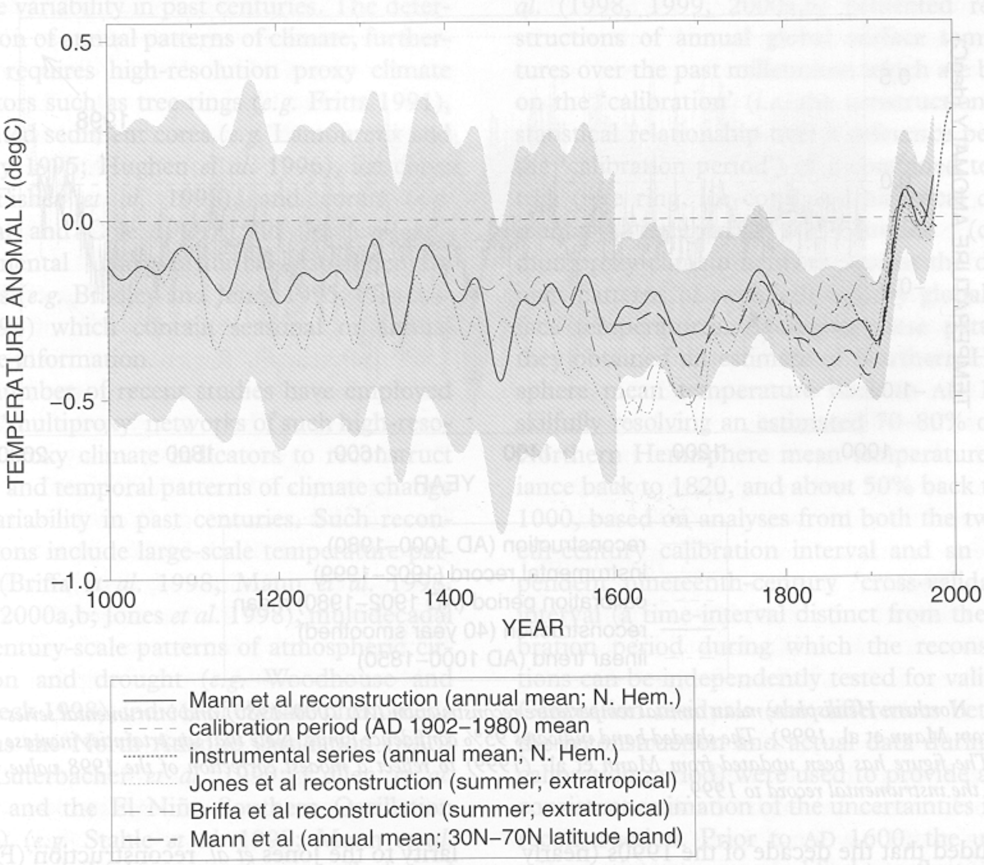


Fig. 2 Northern Hemisphere temperature reconstructions of Mann et al. *(1998, 1999), Briffa* et al. *(1998), and Jones* et al. *(1998), along with recent instrumental record (Jones* et al. *1999), smoothed to highlight variations on time-scales greater than 40 years. The 2 standard error uncertainty range for the Mann* et al. *reconstruction is shown by the shaded region.*

past centuries. Moreover, ground surface temperatures may be insulated from winter surface air temperature changes by seasonal snow-cover in extratropical regions, and such seasonal snow-cover may itself exhibit significant changes over time. Perhaps most importantly, a significant component of the enhanced warming evident in the borehole data may be due to anthropogenic land-usage changes which change the radiative and thermal properties of the ground surface, rather than any actual warming of surface air temperatures (see Mann 2000). In support of this argument, Skinner and Majorowicz (1999) show that ground temperature warming as measured by boreholes exceeds by more than 2 degC the instrumentally recorded surface air warming over substantial portions of North America – regions which in fact dominate the borehole network used by Huang *et al.* (2000). I investigate the implications of assuming that land-usage changes are responsible for (i) 0.5 degC, (ii) 0.75 degC, and (iii) 1.0 degC of the Northern Hemisphere mean ground temperature warming trend as estimated by Huang *et al.* (2000) (Fig. 3). The borehole-estimated ground surface temperature trend over the past few centuries is seen to be consistent with the Mann *et al.* temperature trend (based on averaging the Mann *et al.* surface temperature reconstructions only over the terrestrial regions of the Northern Hemisphere for an appropriate comparison) if the mid-range value of 0.75 degC warming due to land-usage changes is assumed. The remaining discrepancy during the nineteenth century might be attributed to the fact that the abrupt early twentieth-century warming is split between the nineteenth and

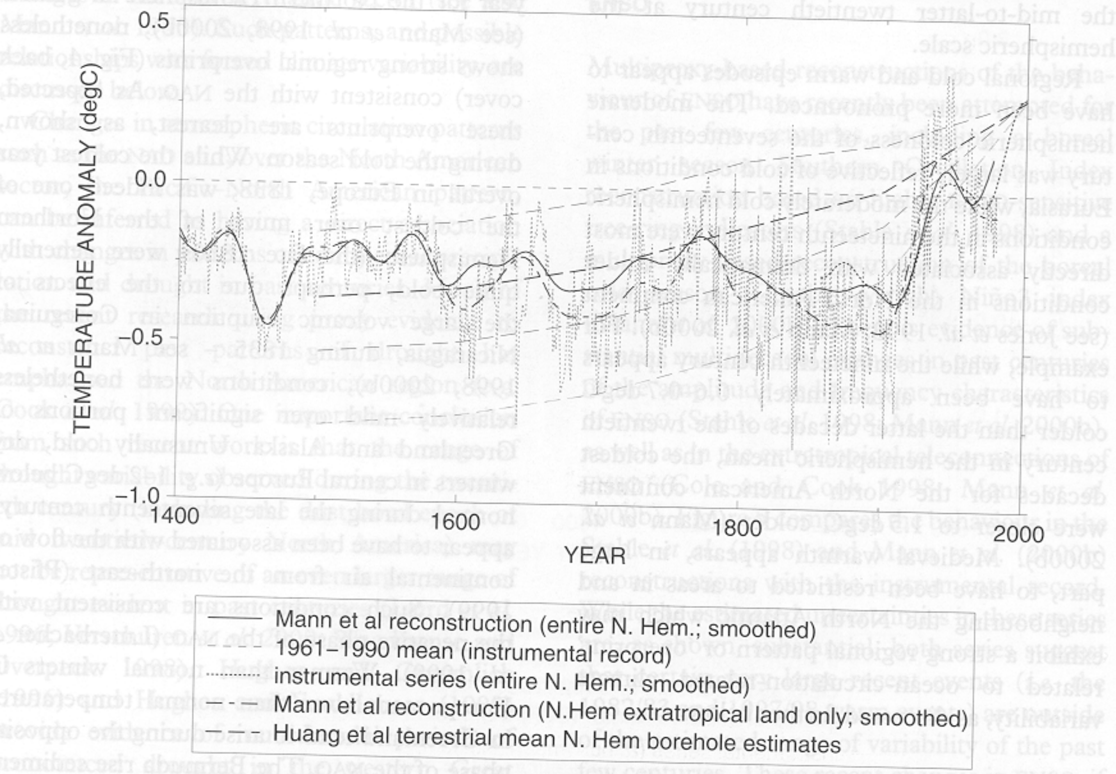


Fig. 3 Comparison of smoothed Mann et al. *Northern Hemisphere mean (smoothed as in Fig. 2) and Northern Hemisphere terrestrial mean (both smoothed and raw annual mean values) temperature reconstruction with borehole Northern Hemisphere terrestrial mean temperature estimates. The dashed lines represent adjusted versions of the borehole series corresponding to the assumption that 0.6 degC (top), 0.4 degC (second from top, bold), and 0.2 degC (second from bottom) of the warming recorded by the boreholes over the past two centuries is due to land-usage changes, while the lowest dashed line corresponds to the unadjusted borehole estimates.*

twentieth centuries in the parametrization of century-long trends used by Huang *et al.* (2000).

The terms 'Little Ice Age' and 'Medieval Warm Period' have conventionally been used to describe past inferred climate anomalies in Europe and neighbouring regions (see Lamb 1965). The timing of cold and warm periods in past centuries, however, has been demonstrated to be highly regionally variable based on more globally expansive data (Bradley and Jones 1993; Hughes and Diaz 1994) than were available to Lamb (1965). Regional anomalies thus tend to cancel out in a hemispheric average, leading to muted temperature changes in hemispheric mean temperature. The analyses of Mann *et al.* (1998) and Jones *et al.* (1998), which incorporate globally extensive data, and objective statistical methods for averaging these data, both indicate that the fifteenth–nineteenth centuries were the coldest of the millennium for the Northern Hemisphere on the whole. However, if defined as a large-scale event, the Little Ice Age is observed to represent only a modest cooling of the Northern Hemisphere from the mid-fifteenth to the late nineteenth century of less than 1 degC relative to modern (typical late twentieth-century) levels. Likewise, the Medieval Warm Period, if it is applied to the interval spanning the eleventh–fourteenth centuries, describes a period during which Northern Hemisphere mean temperatures only occasionally breached early-to-mid twentieth-century levels. Using yet a different mix of proxy temperature indicators (including those which do not have annual or seasonal resolution), and a simple compositing approach, Crowley and Lowery (2000) reach the very similar conclusion that Medieval temperatures were almost certainly not higher than the mid-to-latter twentieth century at the hemispheric scale.

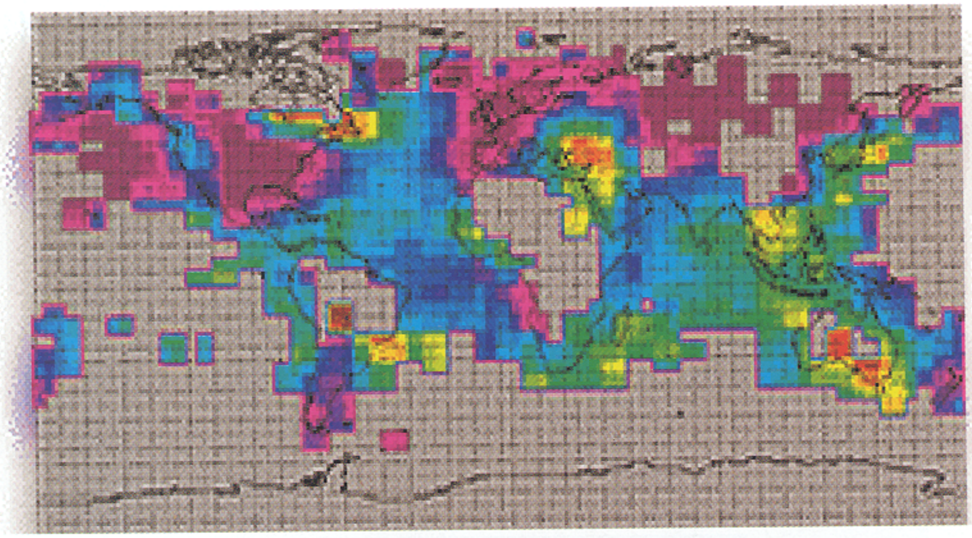
Regional cold and warm episodes appear to have been more pronounced. The moderate hemispheric coldness of the seventeenth century was largely reflective of cold conditions in Eurasia, while the moderately cold hemispheric conditions in the nineteenth century were most directly associated with dramatically colder conditions in the North American continent (see Jones *et al.* 1998; Mann *et al.* 2000b). For example, while the nineteenth century appears to have been approximately 0.6–0.7 degC colder than the latter decades of the twentieth century in the hemispheric mean, the coldest decades for the North American continent were closer to 1.5 degC colder (Mann *et al.* 2000b). Medieval warmth appears, in large part, to have been restricted to areas in and neighbouring the North Atlantic which may exhibit a strong regional pattern or 'overprint' related to ocean-circulation-related climate variability, as discussed further below.

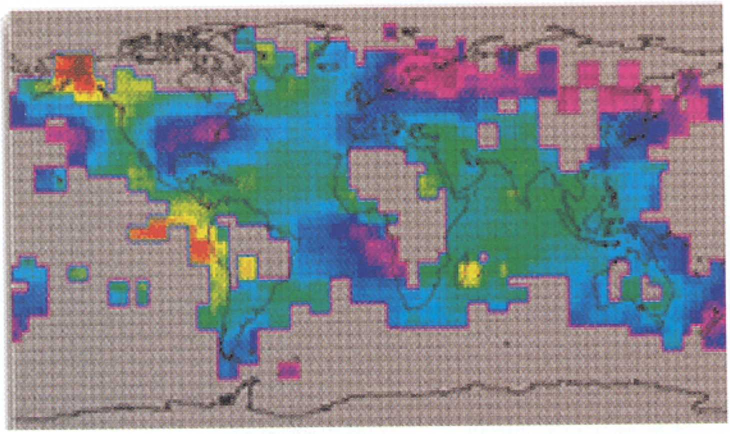
Patterns of atmospheric circulation and drought

The considerable variability in the timing, magnitude, and sign of temperature changes in past centuries in different regions of the Northern Hemisphere and globe can be interpreted in terms of regional temperature overprints due to changes in patterns of atmospheric circulation. Indeed, much of the regional variability evident in the Northern Hemisphere during the Little Ice Age and Medieval Warm Period of Europe can be understood in terms of changes in the NAO. For example, a distinct onset of Little Ice Age conditions of the fifteenth century is evident in measures of atmospheric circulation patterns of the North Atlantic, such as a 'polar atmospheric circulation' index determined from ice-core chemical species measurements (O'Brien *et al.* 1995). The influence of such regional atmospheric circulation anomalies on Europe underscores why it is perilous to extrapolate information regarding early European climate conditions to the hemispheric, let alone global, scale.

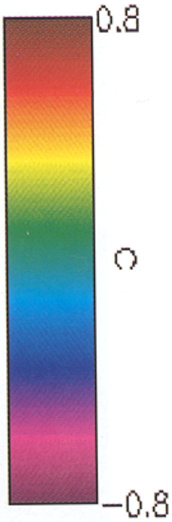
'The year without a summer', 1816, a cold year for the Northern Hemisphere in general (see Mann *et al.* 1998, 2000b), nonetheless shows strong regional overprints (Fig. 4, back cover) consistent with the NAO. As expected, these overprints are clearest, as shown, during the cold season. While the coldest year overall in Europe, 1838, was indeed one of the coldest over much of the Northern Hemisphere (the late 1830s were generally quite cold, perhaps due to the effects of the large volcanic eruption in Coseguina, Nicaragua, during 1835 – see Mann *et al.* 1998, 2000b), conditions were nonetheless relatively mild over significant portions of Greenland and Alaska. Unusually cold, dry winters in central Europe (*e.g.* 1–2 degC below normal during the late seventeenth century) appear to have been associated with the flow of continental air from the north-east (Pfister 1999). Such conditions are consistent with the negative phase of the NAO (Luterbacher *et al.* 1999). Warmer than normal winters in Europe and lower than normal temperatures in Greenland tend to arise during the opposite phase of the NAO. The Bermuda rise sediment core record of Keigwin (1996) suggests warm Medieval conditions and cold seventeenth–nineteenth-century conditions in the Sargasso Sea of the tropical North Atlantic. A sediment record just south of Newfoundland (Keigwin and Pickart 1999), in contrast, indicates opposite, cold Medieval, and warm sixteenth–nineteenth-century upper-ocean temperatures. Keigwin and Pickart (1999) infer these temperature contrasts as being associated with changes in ocean currents in the North Atlantic, and argue that the Little Ice Age and Medieval Warm Period in the Atlantic may in large part be manifestations of century-scale changes in the NAO. There is also evidence, however, that basin-scale changes in North Atlantic sea surface temperatures distinct from the NAO (De Menocal *et al.* 2000) may also play a role in these changes. Black *et al.* (1999) emphasise the persistence of decadal tropical Atlantic variability in past centuries, while Delworth and Mann (2000) highlight (see also Kerr 2000) the importance of an intrinsic multidecadal mode of North Atlantic climate variability related to the thermohaline circulation of the ocean on past climate

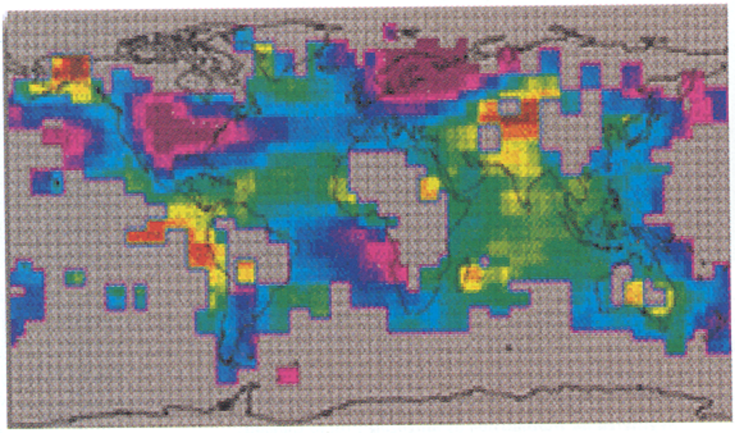
1816
("A Year Without A Summer")





1816 - Warm Season





1816 - Cold Season

changes in the North Atlantic sector (see also Mann *et al.* 1995). Such patterns, and possible relationships with forced climate variability, are discussed below.

Changes in atmospheric circulation patterns such as the NAO and, over the North American sector, the Pacific–North American pattern, can be inferred as having a direct association with changes in patterns of continental precipitation and drought in past centuries. Much of the recent research using proxy evidence to reconstruct past patterns of drought has emphasised the North American region (*e.g.* Cook *et al.* 1999). One important conclusion from such recent work is that the range of drought variability observed during the twentieth century (including the dust bowl epoch of mid twentieth-century North America) may not be representative of an even larger range of drought evident in past centuries (Laird *et al.* 1996; Verschuren *et al.* 2000; Woodhouse and Overpeck 1998). Hughes and Graumlich (1996) and Hughes and Funkhouser (1999) provide evidence of multidecadal periods of pronounced drought in the western Great Basin of North America in the tenth–fourteenth centuries, while Swetnam and Betancourt (1998) argue that recent spring wetness in the American Southwest is greater than that observed in at least 1000 years. There is also evidence of significant changes in regional hydroclimatic patterns in South America in past centuries (Stine 1994; Thompson 1996). The relationship with such past changes in regional drought and precipitation patterns and large-scale atmospheric circulation patterns associated with ENSO is an area of active current research (*e.g.* Cole and Cook 1998). It is evident, for example, that regions such as equatorial east Africa, which are currently influenced by ENSO, have undergone significant changes in drought/wetness during the past 1000 years (Verschuren *et al.* 2000). In addition, multidecadal modulation of atmospheric circulation, and drought in North America (Woodhouse and Overpeck 1998) may be associated with the impacts of a significant pattern of multidecadal climate variability originating in the North Atlantic sector (Delworth and Mann 2000), as discussed below.

ENSO

Multiproxy-based reconstructions of the behaviour of ENSO have recently been attempted for the past few centuries, including a boreal winter season Southern Oscillation Index reconstruction based on highly ENSO-sensitive tree-ring indicators (Stahle *et al.* 1998) and a multiproxy-based reconstruction of the boreal cold season (October–March) Niño3 index (Mann *et al.* 2000b). There is evidence of substantial multidecadal changes in past centuries of the amplitude and frequency characteristics of ENSO (Stahle *et al.* 1998; Mann *et al.* 2000b), as well as in the extratropical teleconnections of ENSO (Cole and Cook 1998; Mann *et al.* 2000b). Figure 5 compares the behaviour in the Stahle *et al.* (1998) and Mann *et al.* (2000b) reconstructions with the instrumental record. While the estimated uncertainties in these series are, as shown, substantial, both series suggest that certain very large recent events (*i.e.* the 1982/83 and 1997/98 warm events) are outside of the estimated range of variability of the past few centuries. These recent changes in ENSO, if anthropogenic in nature (*e.g.* Timmermann *et al.* 1999), may have more dramatic impacts on regional temperature and precipitation patterns than any associated mean large-scale warming.

Forced variability

Recent studies invoking statistical comparisons of reconstructions of surface temperature with time-series estimates of natural (solar and volcanic) radiative forcing during past centuries (*e.g.* Lean *et al.* 1995; Overpeck *et al.* 1997; Mann *et al.* 1998; Damon and Peristykh 1999; Crowley and Kim 1996) find that both solar and volcanic influences have had a detectable influence on large-scale temperature in past centuries. Similar conclusions have been reached in studies that have used these forcing time-series to drive energy balance models (EBMs), producing surface temperature estimates that can be compared to empirical temperature reconstructions (Crowley and Kim 1999; Free and Robock 1999; Crowley 2000). Using such an EBM simulation, Crowley (2000) has shown that between 40 and 60% of

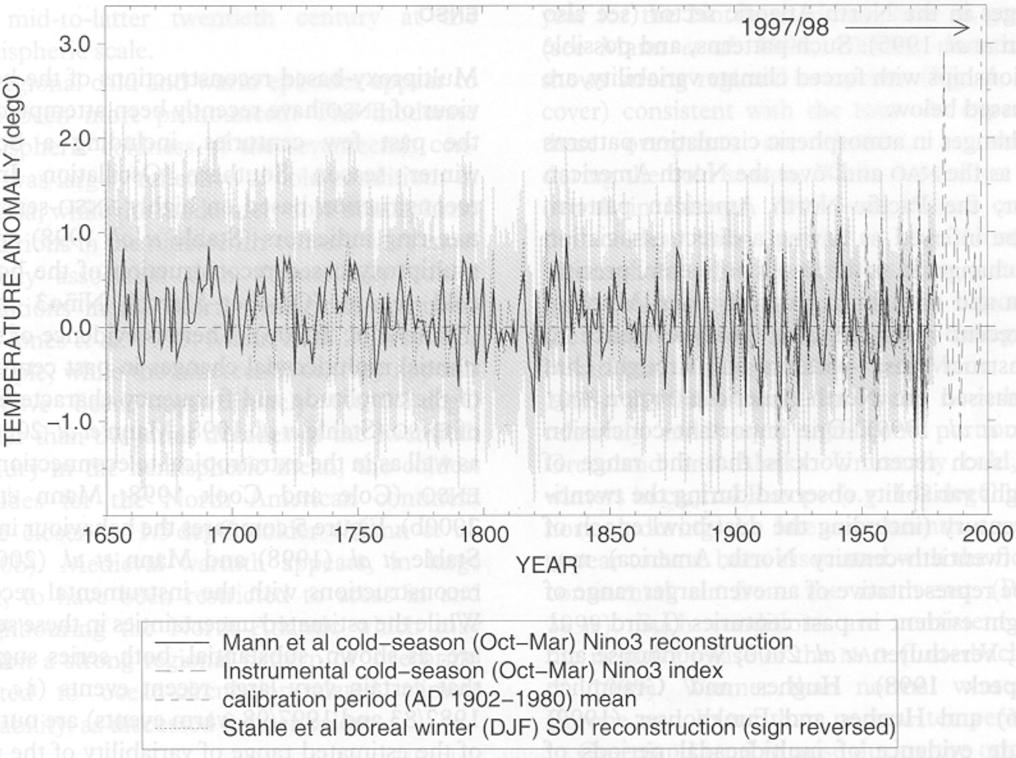


Fig. 5 Cold-season Niño3 temperature index reconstruction (AD 1650–1980) and instrumental series (1902–98) (from Mann et al. *2000b). The shaded band indicates 95% confidence limits for the Niño3 reconstruction. The Southern Oscillation Index (SOI) reconstruction has been rescaled to have the same sign and the same standard deviation as the Niño3 reconstruction; the two reconstructions, based on independent methods and partially independent data, have a linear correlation of 0.64 during the pre-calibration interval of mutual overlap (1707–1901). The magnitude of the 1997/98 event is shown for comparison.*

the low-frequency variability in the Northern Hemisphere temperature reconstructions of both Mann *et al.* (1999) and Crowley and Lowery (2000) can be explained in terms of the response to a combination of natural and anthropogenic forcing (Fig. 6). The twentieth-century warming, however, can be explained only by anthropogenic (greenhouse gas plus sulphate aerosol) forcing. Crowley's model prediction underpredicts the observed cooling of the late nineteenth century, which may arise from albedo changes associated with anthropogenic land-cover changes which are not incorporated in his analysis (see Mann 2000). Equally importantly, Crowley shows that the spectrum of the residuals (*i.e.* the remaining component after this forced variability is accounted for) agrees almost precisely with that of unforced variability from control runs of coupled models, reinforcing the notion that coupled ocean–atmosphere climate models used for 'fingerprint detection' of anthropogenic climate change (*i.e.* Intergovernmental Panel on Climate Change 1996) provide reasonable estimates of the amplitude of unforced variability.

Furthermore, Waple *et al.* (2001) find compelling similarities between the results of experiments with a coupled model forced with estimated solar irradiance variations in past centuries (Cubasch *et al.* 1997) and the spatial patterns of correlation between empirical temperature reconstructions and reconstructions of solar radiative forcing during the period 1650–1850 preceding the apparent emergence of an anthropogenic climate change signal (*i.e.* Mann *et al.* 1998). A coupling of solar forcing to the intrinsic multidecadal North Atlantic mode discussed earlier is found in both the empirical and model-based analyses. Enhanced temperature anomalies in certain regions of the North Atlantic (*e.g.* the relatively more pro-

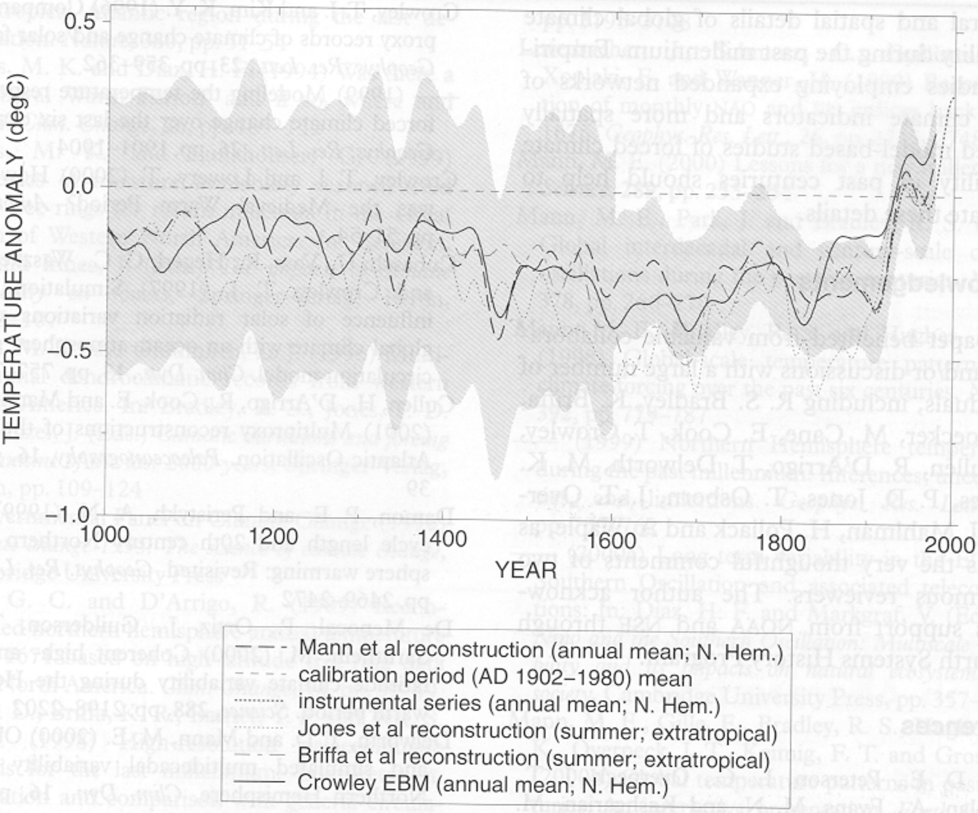


*Fig. 6 Comparison of empirical and energy balance model (*EBM*)-estimated millennial changes in Northern Hemisphere annual mean temperatures during the past millennium, smoothed to highlight variations on time-scales greater than 40 years. The 2 standard error uncertainty range for the Mann* et al. *reconstruction is shown by the shaded region.*

nounced European Little Ice Age and Medieval Warm Period) could, as discussed earlier, represent a regional pattern resulting from ocean circulation changes. Thus, it is possible (*e.g.* Mann 2000) that such regional anomalies are synchronised with the more modest hemispheric warming and cooling because both represent possible hemispheric and spatial responses, respectively, to the same solar radiative forcing changes.

Conclusions

The latest assessments of past large-scale climate variability from palaeoclimatic indicators provide a key perspective regarding climate variability and climate change during the twentieth century. Such assessments show, for example, that late twentieth-century temperatures are probably unprecedented in at least a millennium, at hemispheric or global scales. Proxy evidence also provides important insights into regional patterns of climate change, including natural phenomena such as ENSO.

If defined as large-scale climate anomalies, the Little Ice Age and Medieval Warm Period represent relatively modest changes in hemispheric mean temperature of less than 1 degC peak to peak in amplitude, with slightly greater estimates from borehole data apparently explainable in terms of the effects of anthropogenic land-usage changes on these estimates. Temperature anomalies of considerably greater amplitude occur in particular regions, but tend to cancel in a hemispheric average. An NAO or related North Atlantic overprint may have enhanced warmth and cold regionally during the European Medieval Warm Period and Little Ice Age, respectively. It is likely that significant natural and forced changes in ENSO, NAO, and multidecadal and longer-term patterns of climate variability are superimposed on any hemispheric or global mean temperature changes, potentially explaining both the temporal and spatial details of global climate variability during the past millennium. Empirical studies employing expanded networks of proxy climate indicators and more spatially detailed model-based studies of forced climate variability in past centuries should help to elucidate these details.

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References

Black, D. E., Peterson, L. C., Overpeck, J. T., Kaplan, A., Evans, M. N. and Kashgarian, M. (1999) Eight centuries of North Atlantic Ocean atmosphere variability. *Science*, **286**, pp. 1709–1713

Bradley, R. S. and Jones, P. D. (1993) 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. *Holocene*, **3**, pp. 367–376

—— (1995) Climate since AD 1500: Introduction. In: Bradley, R. S. and Jones, P. D. (Eds) *Climate since A.D. 1500* (revised edition), Routledge, London, pp. 1–16

Briffa, K. R. (2000) Annual climate variability in the Holocene: Interpreting the message of ancient trees. *Quaternary Sci. Rev.*, **19**, pp. 87–105

Briffa, K. R., Jones, P. D., Schweingruber, F. H. and Osborn, T. J. (1998) Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years. *Nature*, **393**, pp. 350–354

Cole, J. E. and Cook, E. R. (1998) The changing relationship between ENSO variability and moisture balance in the continental United States. *Geophys. Res. Lett.*, **25**, pp. 4529–4532

Cook, E. R., Meko, D. M., Stahle, D. W. and Cleaveland, M. K. (1999) Drought reconstructions for the continental United States. *J. Clim.*, **12**, pp. 1145–1162

Crowley, T. J. (2000) Causes of climate change of the last 1000 years. *Science*, **289**, pp. 270–277

Crowley, T. J. and Kim, K. Y. (1996) Comparison of proxy records of climate change and solar forcing. *Geophys. Res. Lett.*, **23**, pp. 359–362

—— (1999) Modeling the temperature response to forced climate change over the last six centuries. *Geophys. Res. Lett.*, **26**, pp. 1901–1904

Crowley, T. J. and Lowery, T. (2000) How warm was the Medieval Warm Period? *Ambio*, **29**, pp. 51–54

Cubasch, U., Voss, R., Hegerl, G. C., Waszkewitz, J. and Crowley, T. J. (1997) Simulation of the influence of solar radiation variations on the global climate with an ocean–atmosphere general circulation model. *Clim. Dyn.*, **13**, pp. 757–767

Cullen, H., D'Arrigo, R., Cook, E. and Mann, M. E. (2001) Multiproxy reconstructions of the North Atlantic Oscillation. *Paleoceanography*, **16**, pp. 27–39

Damon, P. E. and Peristykh, A. N. (1999) Solar cycle length and 20th century Northern Hemisphere warming: Revisited. *Geophys. Res. Lett.*, **26**, pp. 2469–2472

De Menocal, P., Ortiz, J., Guilderson, T. and Sarnthein, M. (2000) Coherent high- and low-latitude climate variability during the Holocene warm period. *Science*, **288**, pp. 2198–2202

Delworth, T. D. and Mann, M. E. (2000) Observed and simulated multidecadal variability in the Northern Hemisphere. *Clim. Dyn.*, **16**, pp. 661–676

Dunbar, R. B. and Cole, J. E. (1999) *Annual Records of Tropical Systems (ARTS): A PAGES/CLIVAR Initiative: Recommendations for research*

Fisher, D. A. (1997) High resolution reconstructed Northern Hemisphere temperatures for the last few centuries: using regional average tree ring, ice core and historical annual time series. Paper U32C-7 in Supplement to *EOS*, **78**, No. 46

Fisher, D. A., Koerner, R. M., Bourgeois, J. C., Zielinski, G., Wake, C., Hammer, C. U. H., Clausen, H. B., Gundestrup, N., Johnsen, S. J., Goto-Azuma, K., Hondoh, T., Blake, E. and Gerasimoff, M. (1998) Penny Ice Cap, Baffin Island, Canada, and the Wisconsinan Foxe Dome connection: Two states of Hudson Bay ice cover. *Science*, **279**, pp. 692–695

Free, M. and Robock, A. (1999) Global warming in the context of the Little Ice Age. *J. Geophys, Res.*, **104**, pp. 19057–19070

Fritts, H. (1991) *Reconstructing large-scale climatic patterns from tree ring data*. The University of Arizona Press, Tucson, Arizona, USA

Huang, S., Pollack, H. N. and Shen, P. Y. (2000) Temperature trends over the past five centuries reconstructed from borehole temperature. *Nature*, **403**, pp. 756–758

Hughen, K. A., Overpeck, J. T., Peterson, L. C. and Trumbore, S. (1996) Rapid climate changes in the tropical Atlantic region during the last deglaciation. *Nature*, **380**, pp. 51–54

Hughes, M. K. and Diaz, H. F. (1994) Was there a 'Medieval Warm Period' and if so, where and when? *Clim. Change*, **26**, pp. 109–142

Hughes, M. K. and Funkhouser, G. (1999) Extremes of moisture availability reconstructed from tree rings for recent millennia in the Great Basin of Western North America. In: Beniston, M. and Innes, J. (Eds.) *The impacts of climatic variability on forests*, Springer-Verlag, Berlin, pp. 99–107

Hughes, M. K. and Graumlich, L. J. (1996) Multimillennial dendroclimatic records from western North America. In: Bradley, R. S., Jones, P. D. and Jouzel, J. (Eds.) *Climatic variations and forcing mechanisms of the last 2000 years*, Springer-Verlag, Berlin, pp. 109–124

Intergovernmental Panel on Climate Change (1996) *Climate change 1995: The science of climate change*, Cambridge University Press

Jacoby, G. C. and D'Arrigo, R. (1989) Reconstructed northern hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. *Clim. Change*, **14**, pp. 39–59

Jones, P. D., Briffa, K. R., Barnet, T. P. and Tett, S. F. B. (1998) High-resolution palaeoclimatic records for the last millennium: Interpretation, integration and comparison with general circulation model control run temperatures. *Holocene*, **8**, pp. 477–483

Jones, P. D., New, M., Parker, D. E., Martin, S. and Rigor, J. G. (1999) Surface air temperature and its changes over the past 150 years. *Rev. Geophys.*, **37**, pp. 173–199

Keigwin, L. (1996) The Little Ice Age and Medieval Warm Period in the Sargasso Sea. *Science*, **274**, pp. 1504–1508

Keigwin, L. D. and Pickart, R. S. (1999) Slope water current over the Laurentian Fan on interannual to millennial time scales. *Science*, **286**, pp. 520–523

Kerr, R. A. (2000) A North Atlantic climate pacemaker for the centuries. *Science*, **288**, pp.1984–1986

Laird, K. R., Fritz, S. C., Maasch, K. A. and Cumming, B. F. (1996) Greater drought intensity and frequency before AD 1200 in the northern Great Plains. *Nature*, **384**, pp. 552–554

Lamb, H. H. (1965) The early Medieval warm epoch and its sequel. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, **1**, pp. 13–37

Lamoureux, S. F. and Bradley, R. S. (1995) A 3300 year varved sediment record of environmental change from northern Ellesmere Island, Canada. *J. Paleolimnology*, **16**, pp. 239–255

Lean, J., Beer, J. and Bradley, R. S. (1995) Reconstruction of solar irradiance since 1610: Implications for climatic change. *Geophys. Res. Lett.*, **22**, pp. 3195–3198

Luterbacher, J., Schmutz, C., Gyalistras, D., Xoplaki, E. and Wanner, H. (1999) Reconstruction of monthly NAO and EU indices back to AD 1675. *Geophys. Res. Lett.*, **26**, pp. 2745–2748

Mann, M. E. (2000) Lessons for a new millennium. *Science*, **289**, pp. 253–254

Mann, M. E., Park, J. and Bradley, R. S. (1995) Global interdecadal and century-scale climate oscillations during the past five centuries. *Nature*, **378**, pp. 266–270

Mann, M. E., Bradley, R. S. and Hughes, M. K. (1998) Global-scale temperature patterns and climate forcing over the past six centuries. *Nature*, **392**, pp. 779–787

—— (1999) Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophys. Res. Lett.*, **26**, pp. 759–762

—— (2000a) Long-term variability in the El Niño Southern Oscillation and associated teleconnections: In: Diaz, H. F. and Markgraf, V. (Eds.) *El Niño and the Southern Oscillation: Multiscale variability and its impacts on natural ecosystems and society*, Cambridge University Press, pp. 357–412

Mann, M. E., Gille, E., Bradley, R. S., Hughes, M. K., Overpeck, J. T., Keimig, F. T. and Gross, W. (2000b) Global temperature patterns in past centuries: An interactive presentation. *Earth Interactions*, **4–4**, pp. 1–29

O'Brien, S., Mayewski, P. A., Meeker, L. D., Meese, D. A., Twickler, M. S. and Whitlow, S. I. (1995) Complexity of Holocene climate as reconstructed from a Greenland ice core. *Science*, **270**, pp. 1962–1964

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolfe, A. and Zielinski, G. (1997) Arctic environmental change for the last four centuries. *Science*, **278**, pp. 1251–1256

Pfister, C. (1999) *Wetternachhersage. 500 Jahre Klimavariationen und Naturkatastrophen 1496–1995.* Paul Haupt, Bern

Pfister, C., Luterbacher, J., Schwarz-Zanetti, G. and Wegmann, M. (1998) Winter air temperature variations in central Europe during the early and high Middle Ages (A.D. 750–1300). *Holocene*, **8**, pp. 547–564

Skinner, W. R. and Majorowicz, J. A. (1999) Regional climatic warming and associated twentieth century land-cover changes in north-western North America. *Clim. Res.*, **12**, pp. 39–52

Stahle, D. W., D'Arrigo, R. D., Krusic, P. J., Cleaveland, M. K., Cook, E. R., Allan, R. J., Cole, J. E., Dunbar, R. B., Therrell, M. D., Gay, D. A., Moore, M. D., Stokes, M. A., Burns, B. T., Villanueva-Diaz, J. and Thompson, L. G. (1998) Experimental dendroclimatic reconstruction of the Southern Oscillation. *Bull. Am. Meteorol. Soc.*, **79**, pp. 2137–2152

Stine, S. (1994) Extreme and persistent drought in California and Patagonia during medieval time. *Nature*, **369**, pp. 546–549

Swetnam, T. W. and Betancourt, J. L. (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *J. Clim.*, **11**, pp. 3128–3147

Thompson, L. G. (1996) Climate changes for the last 2000 years inferred from ice core evidence in tropical ice cores. In: Jones, P. D., Bradley, R. S. and Jouzel, J. (Eds) *Climate variations and forcing mechanisms of the last 2000 years*, NATO ASI Series I, Vol. 41, pp. 281–297

Timmermann, A., Oberhuber, J., Bacher, A., Esch, M., Latif, M. and Roeckner, E. (1999) Increased El Niño frequency in a climate model forced by future greenhouse warming. *Nature*, **398**, pp. 694–697

Verschuren, D., Laird, K. R. and Cumming, B. F. (2000) Rainfall and drought in equatorial east Africa during the past 1,100 years. *Nature*, **403**, pp. 410–414

Waple, A., Mann, M. E. and Bradley, R. S. (2001) Long-term patterns of solar irradiance forcing in model experiments and proxy-based surface temperature reconstructions. *Clim. Dyn.* (In Press)

Woodhouse, C. A. and Overpeck, J. T. (1998) 2000 years of drought variability in the central United States. *Bull. Am. Meteorol. Soc.*, **79**, pp. 2693–2714

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