Opinion

A noodle, hockey stick, and spaghetti plate: a perspective on high-resolution paleoclimatology

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The high-resolution reconstruction of hemispheric-scale temperature variation over the past-millennium benchmarks recent warming against more naturally driven climate episodes, such as the Little Ice Age and the Medieval Warm Period, thereby allowing assessment of the relative efficacies of natural and anthropogenic forcing factors. Icons of past temperature variability, as featured in the Intergovernmental Panel on Climate Change (IPCC) reports over nearly two decades, have changed from a schematic sketch in 1990, to a seemingly well-solved story in 2001, to more explicit recognition of significant uncertainties in 2007. In this article, we detail the beginning of the movement to reconstruct large-scale temperatures, highlight major steps forward, and present our views on what remains to be accomplished. Despite significant efforts and progress, the spatial representation of reconstructions is limited, and the interannual and centennial variation are poorly quantified. Research priorities to reduce reconstruction uncertainties and improve future projections, include (1) increasing the role of expert assessment in selecting and incorporating the highest quality proxy data in reconstructions (2) employing reconstruction ensemble methodology, and (3) further improvements of forcing series. We suggest that much of the sensitivity in the reconstructions, a topic that has dominated scientific debates, can be traced back to the input data. It is perhaps advisable to use fewer, but expert-assessed proxy records to reduce errors in future reconstruction efforts. *WIREs Clim Change* 2010 1 507–516

Constraining the climate sensitivity[1] and the reconstruction of large-scale temperature[2] may be regarded as key goals to help predict consequences of anthropogenic activity. The former quantifies how global temperature will change due to shifts in external (e.g., solar, volcanic, and anthropogenically emitted greenhouse gases and aerosols) forcing. The latter characterizes variability of the climate system due to changes in natural external forcing and internal climate variability (e.g., ENSO, meridional overturning circulation) in absence of significant anthropogenic forcing. Both of these objectives serve in parallel to quantify climate system behavior. A large natural variability may imply a large climate sensitivity and underscore the consequences of anthropogenic emissions.[3] However, respecting uncertainties in both the temporal course and efficacy of solar and volcanic activity,[4] a large amplitude over the past millennium may equally well indicate a greater role of natural factors in dictating past (and future) climate variation.[5] In addition to the direct assessment of the climate sensitivity to a doubling of CO_2, the amplitude of past temperature change is also intimately linked with the modulation of climate drivers of many earth system processes, such as the positive feedback between temperature and atmospheric CO_2 concentrations as mediated by a variety of oceanic and terrestrial processes.[2,6]

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To help address these issues, over the last 30 years, more than two dozen large-scale reconstructions of past temperature have been produced—most since the late 1990s. These reconstructions have placed the twentieth century warmth within the context of preceding climatic phases, such as the Medieval Warm Period (MWP) and Little Ice Age (LIA), and arrived at the broad consensus of the unusual nature of late twentieth century warming. The sheer number of reconstructions testifies to their scientific and societal importance. But simultaneously, this number of reconstructions, and continued efforts for still more, clearly demonstrate that not all questions of large-scale climate variability are solved. In this article, we (1) briefly review the beginning of this reconstruction movement, (2) describe the 'consensus view' for the large-scale temperature evolution over the past millennium as illustrated in IPCC reports, and (3) present what we have learned in the past decade or so and what, in our opinion, still remains to be answered. We conclude with our view on research agendas that should help reduce remaining uncertainties.

EARLY RECONSTRUCTIONS

In a 1979 article, Brian Groveman (doctoral student) and Helmut Landsberg (advisor) presented the first quantitative reconstruction of Northern Hemisphere (NH) annual mean temperatures in Geophysical Research Letters.[7] The authors compiled 20 time-series of mostly instrumental and a few proxy records (including two tree-ring series) that individually correlated between 0.28 and 0.62 with NH temperatures, and using a nested multiple regression to take into account the different temporal coverage of the predictors, provided a reconstruction and associated measures of uncertainty back to 1579. Groveman and Landsberg called this a 'short cut method to estimate NH temperature' based upon a demonstration that nine instrumental stations could sufficiently represent the mean of an extensive gridded network of instrumental series.[8] Aside from the fact that this short publication (2 tables, 1 figure, 10 references) is the first quantitative reconstruction of NH temperatures, novel methodological aspects of the paper appear to have only recently been re-discovered. Such aspects include: separate calibration for all predictor subsets, time-varying error bars, and mention of the (small) large-scale amplitude of reconstructed temperatures derived from their approach. This groundbreaking reconstruction showed evidence that the Maunder Minimum was not appreciably cooler than neighboring periods and that the twentieth century was rather warm.

Remaining untouched for about a decade, Jacoby and D'Arrigo, re-approached quantitative reconstructions for the NH and developed the first NH reconstruction[9] based entirely upon noninstrumental sources: tree-rings. Building upon the quantitative traditions of dendroclimatology,[10] Jacoby and D'Arrigo presented calibration/verification statistics and mitigated potential problems due to multicollinearity of the predictors by performing principal components regression. Even though the suite of techniques to preserve long-term climate signals in tree-ring records were not so well developed at that time, they pointed out that low-frequency variance must be preserved in the proxy records for them to contribute usefully to global change studies. This reconstruction also showed that twentieth century warmth was anomalous back to at least 1671.

CLIMATE CHANGE ICONS

Following in the footsteps of these initial efforts[7,9] and bolstered by the increased recognition of the relevance of global change research and development of new proxy records and techniques, numerous large-scale temperature reconstructions in the following two decades were produced.[11–36] It was not until the late 1990s that such reconstructions extended far enough back to place recent temperature change in the context of the perhaps temporally nearest natural warm analog: the MWP. Such analyses are of relevance as they allow the forcing and variability responsible for natural warm and cool conditions to be understood and contrasted with the current and more diverse forcing cocktail. However, the IPCC reports took an early stance on this topic in the first report published in 1990,[37] and followed this up in the 2001 third[38] and 2007[39] fourth assessments. In Figure 1, we show snapshots of the evolving 'consensus view' of large-scale temperature change over the past millennium. It should be noted that this figure (and related text) only represents a small percentage of the knowledge in the various IPCC reports related to past-millennium temperature change. For example, the 1995 IPCC report displayed a submillennial length record that extended back to A.D. 1400[12] and the 2001 report also depicted a harbinger of the 2007 spaghetti plate by showing three reconstructions.[14,16,18] Past regional warming, cooling, and the general level of climatic hetero/homogeneity as evidenced by the text of the IPCC volumes is also not captured by such figures.

IPCC 1990: 'Eurocentric Cartoon'

In the first IPCC report, presentation of temperatures over the past millennium appears to be a hand-drawn

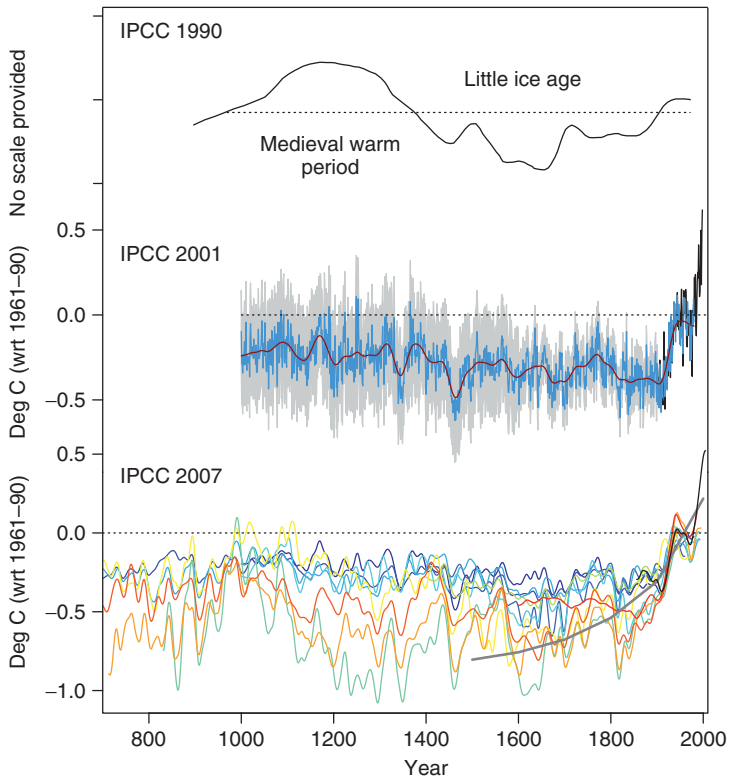

FIGURE 1 | IPCC icons of temperatures over the past millennium. Sequence of the pre-industrial to industrial temperatures as expressed in the 1990 (upper), 2001 (middle), and 2007 (lower) IPCC reports. Dashed lines represent mean temperatures at 1900 in the upper panel and for 1961–1990 in the middle and lower panels. The upper panel was graphically recreated, whereas the middle and lower panels are based upon data obtained at the NCDC webpage (http://www.ncdc.noaa.gov/paleo/recons.html). Curves illustrate the evolution of the 'consensus views' for large-scale temperature change in the IPCC reports. See text for details.

sketch of how climate varied. A prominent MWP, followed by a cold period—the LIA—are observed with clear indications for high natural variability of the climate system. It was demonstrated[40] that this figure was derived from the groundbreaking work of H. H. Lamb[41] representing temperature change over Central England, but the chosen smoothing and figure description suggested more of an illustration, rather than quantification, of past temperatures. This curve presenting a Eurocentric schematic view of climate change, left room open for a completely new temperature history.

IPCC 2001: 'Anthropogenic Admission'

The 1990 sketch was replaced 11 years later by a quantitative reconstruction for the entire NH by Mann et al.[16] Annual precision and *y*-axis in degrees Celsius contrasted strongly with the 1990 figure and suggested a marked increase of knowledge. The little varying, yet slowly declining temperatures over about 900 years of natural variability, reversed by the strong upward trend over the past century, served as a symbol for human impact on temperature change. The existence of an MWP and LIA were hinted at, but only as part of an almost negligible pre-anthropogenic temperature change. Even though this reconstruction was presented with calibration uncertainties, their common omission in subsequent discussion, may have led to an overly optimistic assessment of the degree to which past temperatures were understood.

IPCC 2007: 'Stepping Back'

In the most recent IPCC report, further consideration of existing and the development of new reconstructions, methodological disputes, and analysis called for a retreat from the 2001 position that reconstructed temperatures were well understood. Numerous, smoothed reconstructions in the 2007 report testify to significant remaining uncertainty. The superposition of the instrumental data still demonstrate the extreme warmth of the most recent decades, but the wide-scatter in the reconstructions in defining pre-industrial temperature variability showed that an understanding of natural variability remains poorly constrained. The pre-1000 A.D. period hints at a rise of temperatures into the MWP, with the convergence of most reconstructions toward peak values ~1000 years ago suggesting for some sort of large-scale MWP. However, the high dispersion of the records away from the calibration period mean casts doubt on the absolute amplitude of past temperature change.

WHERE WE STAND TODAY

The so-called 'Hockey Stick' debate[42,43] is/was centered on the not-only academically relevant task of

defining the true course of temperatures over the past millennium and trying to resolve discrepancies among reconstructions due to data and methodological details. Similar scientific debates occurred earlier. It was pointed out that the 1979 Groveman and Landsberg reconstruction received criticism for sparse data representation during the early reconstructed period and also for the warmth reconstructed during the late seventeenth and early eighteenth centuries.[9] The former criticism could be (and perhaps has been) invoked for nearly every reconstruction published to date. Without wishing to rehash all such details, in the following text we highlight where we broadly find that progress has been achieved and where more is necessary.

There is now broad recognition for the importance of preserving all possible climatic frequencies in proxy data and reconstructions. This is a step forward to simply using data that have likely not preserved low-frequency signals. Advances include the widespread use of Regional Curve Standardized tree-ring data to preserve the long-term signals,[44] and efforts to derive the highest possible resolution from records typically analyzed at decadal or lower resolution.[45] The most recent generation of reconstructions now typically employ only highly resolved data where the long-terms trends have been preserved (see, for example, Refs 22 and 28), and proxies where the low-frequency variability has not been preserved are increasingly recognized as having little room to contribute to understanding long-term change. It should be noted that the fact that a proxy record is annually resolved and thus allows high-frequency information to be discerned, should not automatically disqualify this record to contribute to the quantification of low-frequency variability.[26] Such selection would unnecessarily result in a significant reduction of predictors that have skill across all frequency domains and possibly overweight low-resolution series for estimating long-term trends.[26,46,47] More research is still needed to consider the frequency dependent characteristics of proxies' signals and achieve appropriate high versus low-frequency weighting.[47–50]

The climatic signal in proxy records is now routinely calibrated—and often verified—via comparisons with instrumental records allowing assessment of proxy trustworthiness in the recent period. Interdisciplinary advances have led and are leading to increases in the number of available high-quality proxy archives. This includes temporal extensions both toward present (allowing better calibration) and back in time (allowing longer term perspectives on natural climate variation). However, it is also recognized that reconstructed values are highly dependent upon the calibration models applied[51,52] and the instrumental data utilized.[53,54] Repetitive testing of proxy data against various meteorological seasons and parameters until acceptable correlations are found likely results in an optimistic view of proxy quality.[55] In addition, data overlap and data sparse regions in large-scale reconstructions, challenges independent and truly large-scale assessment of climate variation.[34] Very few temperature sensitive reconstructions are available for the mid-to-low latitudes, although on going activities are filling these gaps.[56,57] Even the most well-replicated large-scale reconstructions tend to have only a handful of proxies prior to ~1400.[28] Techniques that use co-variance information among proxy records and instrumental fields attempt to fill some of these gaps, but it often is not clear how individual proxies are weighted in the final reconstruction.[58] Although much recent literature is devoted to methodological disputes and improvements, sparse and noisy data are likely the underlying cause for the high methodological sensitivity in the first place.

The regional to large-scale amplitude remains poorly characterized. The wide range of reconstructed amplitudes presented in the 2007 IPCC report that results from variable preservation of low-frequency signals, calibration methodologies, and proxy and instrumental noise has not yet been fully reconciled.[53] New ensemble reconstruction estimates that consider and mitigate many of these uncertainties place the amplitude for annual NH land and sea-surface temperatures at ~0.7°C between the warmest (1971–2000) and coldest (1601–1630) climatological periods of the past millennium.[2] Potential biases of long-term instrumental temperature trends for both land[54,59] and sea-surface[60] temperatures affect the calibration of low-frequency signals and the temperature amplitude. Challenges in defining appropriate spatial and seasonal representativity also result in amplitude uncertainties. Apart from the amplitude differences, the various large-scale reconstructions still display large discrepancies in their time evolution, particularly at the interannual and centennial time-scales.

To varying degrees, all three IPCC icons conform to the broad notion of the MWP, LIA, and recent warmth. The horizontal lines provided in the two most recent IPCC reports (see Figure 1) readily allow comparison and conclusions for the unprecedented nature of current (1961–1990) warmth. Doubt is rather most strongly cast upon the magnitude of LIA cold. The prominent MWP of Lamb (1965) appears to have fueled debate on the spatial extent of this era.[28,39,61–63] For example, in the 2007 IPCC report eight regional

proxy series were purported to illustrate 'the heterogeneous nature of climate during the "MWP"'. However, a recent analysis showed that based upon these data the IPCC conclusions were nontenable and that the MWP was no more heterogeneous than the LIA or even the present.[63] Rather, it was suggested that too few (and noisy) proxy series currently exist to assess possible heterogeneity. A recent reconstruction of the North Atlantic Oscillation (NAO; see Ref 64) showed a persistently positive low-frequency state between about 1050 and 1400 and thus helped provide a dynamical explanation for European Warmth during Medieval times.[41,65] However, globally distributed proxy data suggest widespread reorganization of the oceanic and atmospheric circulation during the MWP-LIA transition,[64,66–68] leaving the question open of the climate state, forcing, and teleconnections during Medieval times. The origin of this reorganization, possibly resulting from random internal variations or externally driven forcing[69,70] or a combination thereof, requires further exploration, but will ultimately contribute to a dynamical understanding of paleoclimatic variability and its forcing.

With an ultimate goal of understanding the climate system well enough to make predictions, comparisons of reconstructed and modeled climate variations are necessary. To provide a true test of skill, these two sources of information should ideally be kept independent until they are both reasonably accomplished. Intermingling at an earlier stage may lead to overfitting and thus overly confident assessments of predictive capability. It is not clear to us if it is 'too early', but the fact is that such comparisons have been made and show that post-1200 A.D. climate models and reconstructions provide roughly compatible pictures of past temperature variations. This agreement suggests that either (1) to the first order the climate of the past ~800 years is understood at the hemispheric scale (2) climate models (or reconstructions) have been tweaked until they fit, or, but not necessarily unrelated to the above, (3) a good fit is obtained for the wrong reasons (e.g., an underestimate of the natural forcing and an unrealistically large climate sensitivity of the models, or vice versa, may compensate for each other), or (4) some combination these factors. Resolution of this predicament may require a bottom-up and community wide re-evaluation of the basic data, assumptions, and algorithms.

WHERE NEXT?

With respect to the reconstruction of large-scale temperature variation, increases in the amount and quality of proxy data and improved understanding of how to best combine these data have led to significant progress being made in the past 30 years; however, by far, not all is solved. Here, we outline a couple of additional research strategies that may contribute to reducing uncertainties in future reconstructions and contribute to improved predictions.

Expert Assessment

The diverse nature of proxy climate archives, ranging from tree-ring isotopes to documentary data to marine sediment particle sizes, means that a wide variety of physical, biological, and chemical processes and their assessment are responsible for the encoding and decoding of the climate signal. A detailed familiarity, and ideally a mechanistic understanding, of these processes and the characteristics (e.g., seasonal response, nonlinearities, anthropogenic disturbances, frequency biases) of different archives in general and individual records, in particular, is likely advantageous if not invaluable for developing climate reconstructions. Every reconstruction—ranging from the very simple normalization and averaging of all available records to those so complicated that GCM models need to be invoked to even get an idea if they may work with real world data[71]—depend fundamentally upon the individual data archives. While climate reconstruction may be more complicated than problems that could be posed to the first mechanical computer by its inventor, a quote from the 1864 autobiography of Charles Babbage,[72] may still be apt:

> *On two occasions I have been asked,—"Pray, Mr. Babbage, if you put into the machine wrong figures, will the right answers come out?" In one case a member of the Upper, and in the other a member of the Lower, House put this question. I am not able rightly to apprehend the kind of confusion of ideas that could provoke such a question.*

Expert assessment to evaluate the signal of a particular record from a particular proxy archive (e.g., the low-frequency skill of a new speleothem record) will be invaluable in trying to minimize 'wrong figures' being put into a large-scale reconstruction. It seems advisable at this point to use fewer, but expert-assessed proxy records, rather than hundreds of proxy series, and hope that reconstruction algorithms will overcome the often huge noise components typical for many of the available time series. This seems particularly to be the case for the lowest frequency variations and the lower resolution proxies that cannot even be calibrated (and verified) against the short instrumental data. Specific considerations from experts acquainted with the proxy archives will likely

vary considerably from field to field and also as advances are made in quantifying and understanding proxy signals, and as new proxy types, parameters, and processing methods are developed.

Ensemble Reconstructions

Although high-quality data are keys, new methods that explicitly recognize and incorporate uncertainties inherent to the reconstruction process could lead to the development and implementation of ensemble/probabilistic assessments of past climatic variation[2] (But see also Refs 20,73,74). It is unlikely that structural uncertainties, such as the use of a single reconstruction methodology, a particular calibration model, a preferred approach to preserve low-frequency variations in tree-ring data, and selection of some truncation parameter in multivariate regularization approaches, will be eliminated. Intuition for the characteristics of the underlying problem may limit this range of choices to a reasonable, but not unique set of possibilities. Systematic exploration and acceptance of these ensemble members as viable alternatives may minimize any subconscious selection of outcomes that fit with preconceived notions[75] for how the climate has varied. A simple example is for users to simultaneously consider the suite of reconstructions shown in Figure 1, rather than selecting and only reporting results based upon agreement with a particular reconstruction. In practice, more comprehensive schemes can be developed that consider uncertainty and decisions at numerous levels (e.g., data uncertainties, pre-processing steps, data selection, method definition). However, the ensemble range should avoid useless outcomes and thus be small enough to convey discriminant power. This is one reason why a mechanistic understanding and expert assessment of the available proxies is invaluable.

Forcing Time-series

When linking reconstructed and modeled past temperatures to estimate a value for the climate sensitivity or the efficacy of the more poorly quantified past forcings (namely, volcanic,[76] solar,[77] and land-use/land-cover changes[78]) more than accurate temperature reconstructions are necessary.[79] This is readily apparent when it is considered that the multidecadal surface temperature change averaged over the NH in even the most complex GCMs can largely be boiled down to a linear transformation of the input forcing. Climatic effects of individual volcanic eruptions are usually short-lived, but clustering of eruptions, as (inconveniently for forcing discrimination) occurred during the Late Maunder and Dalton solar minima, can also induce apparent low-frequency climatic variations.[80] Land-use shifts may elicit strong climate changes, but this response is itself unclear, and climate models simulations driven by the same land-use history display a large range of responses.[81] In a similar vein, state of the art simulations[82] driven by current best estimates (reduced by a factor of 2 from the 2001–2007 IPCC reports) of solar forcing fail to reproduce the MWP-LIA sequence prominent in most proxy records,[2] and therefore may require explanation from internal random unforced variations, attribution to volcanic activity, or other poorly parameterized factors. Control simulations with constant external forcing produce multidecadal variations of the NH temperature of just 0.2°C,[83] seemingly ruling out sole effects of internal random climate variations. Given the defined relationships between forcing series and modeled output, refined forcing series[69,76–78,84] may be crucial to resolve such questions. Constraining the large-scale amplitude and efficacy of forcing agents appears to be the highest priority, although as models are increasingly being used for regional studies, parallel increases in spatial and temporal resolution of forcing time-series will also be necessary.

CONCLUSION

The geological principle of uniformitarianism, often summarized as 'the present is the key to the past', was invoked by early natural scientists to comprehend long time-scale processes that occurred so slowly or in the far distant past, that only traces remaining could be used to infer what occurred. Significant natural variability and the long response time of the oceanic and terrestrial systems to climate change, make it exceedingly difficult to understand and therefore predict climate based upon short present observational data. Current anthropogenic activities have led to unprecedented trajectories and states in the earth's coupled climate system, but characterization of the natural climate variability will at least allow a better understanding of the basic operating rules and patterns of climate change. In the context of trying to understand the consequences of new anthropogenic regimes, this uniformitarianism paradigm must be flipped and the past used to grasp hints for what the future may hold.

We have herein reviewed the changing icons in high-resolution paleoclimateology and discussed the current (post-2007 IPCC) understanding of large-scale temperature variation over the past 1000 or so years. We suggest that expert knowledge of the proxy archives will be critical to reduce uncertainties

and large-scale reconstructions. At the same time, recognition and acceptance of structural uncertainties will allow a more accurate assessment of reconstruction errors. Improved forcing time series will allow refined hindcasts and ultimately better predictions. For at least the next several hundred years, observed climate variations will be a superposition of natural and anthropogenic forcing.

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REFERENCES

1. Knutti R, Hegerl GC. The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nature Geosci*, 2008, 1:735–743.
2. Frank DC, Esper J, Raible CC, Büntgen U, Trouet V, et al. Ensemble reconstruction constraints on the climate sensitivity of the global carbon cycle. *Nature* 2010, 463:527–530.
3. Osborn TJ, Briffa KR. The real color of climate change? *Science* 2004, 306:621–622.
4. Ammann CM, Joos F, Schimel DS, Otto-Bliesner BL, Tomas RA. Solar influence on climate during the past millennium: results from transient simulations with the NCAR Climate System Model. *Proc Nat Acad Sci U S A* 2007, 104:3713–3718.
5. Esper J, Wilson RJS, Frank DC, Moberg A, Wanner H, et al. Climate: past ranges and future changes. *Quat Sci Rev* 2005, 24:2164–2166.
6. Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 2000, 408:184–187.
7. Groveman B, Landsberg H. Simulated northern hemisphere temperature departures 1579–1880. *Geophys Res Lett* 1979, 6:767–769.
8. Landsberg H, Groveman B, Hakkarinen I. A simple method for approximating the annual temperature of the Northern Hemisphere. *Geophys Res Lett* 1978, 5:505–506.
9. Jacoby G, D'Arrigo R. Reconstructed Northern Hemisphere annual temperature since 1671 based on high-latitude tree-ring data from North America. *Clim Change* 1989, 14:39–59.
10. Fritts H. *Tree Rings and Climate*. Caldwell: Blackburn Press; 1976, 567.
11. D'Arrigo RD, Jacoby GC. Secular trends in high northern latitude temperature reconstructions based on tree rings. *Clim Change* 1993, 25:163–177.
12. Bradley R, Jones P. Little Ice Age summer temperature variations: their nature and relevance to recent global warming trends. *The Holocene* 1993, 3:367–376.
13. Jones P, Briffa K, Barnett T, Tett S. High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. *The Holocene* 1998, 8:455–471.
14. Mann ME, Bradley RS, Hughes MK. Global-scale temperature patterns and climate forcing over the past six centuries. *Nature* 1998, 392:779–787.
15. Pollack HN, Huang SP, Shen PY. Climate change record in subsurface temperatures: a global perspective. *Science* 1998, 282:279–281.
16. Mann ME, Bradley RS, Hughes MK. Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophys Res Lett* 1999, 26:759–762.
17. Huang SP, Pollack HN, Shen PY. Temperature trends over the past five centuries reconstructed from borehole temperatures. *Nature* 2000, 403:756–758.
18. Briffa K. Annual climate variability in the Holocene: interpreting the message of ancient trees. *Quat Sci Rev* 2000, 19:87–105.
19. Crowley T, Lowery T. How warm was the medieval warm period? *Ambio* 2000, 29:51–54.
20. Briffa K, Osborn T, Schweingruber F, Harris I, Jones P, et al. Low-frequency temperature variations from a northern tree ring density network. *J Geophys Res: Atmospheres* 2001, 106:2929–2941.
21. Briffa K, Osborn T, Schweingruber F, Jones P, Shiyatov S, et al. Tree-ring width and density data around the Northern Hemisphere: part 2, spatio-temporal variability and associated climate patterns. *The Holocene* 2002, 12:759–789.
22. Esper J, Cook E, Schweingruber F. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* 2002, 295:2250–2253.

23. Mann ME, Jones PD. Global surface temperatures over the past two millennia. *Geophys Res Lett* 2003, 30:1820. DOI:10.1029/2003GL017814

24. Huang S. Merging information from different resources for new insights into climate change in the past and future. *Geophys Res Lett* 2004, 31:L13205. DOI: 10.1029/2004gl019781

25. Oerlemans J. Extracting a climate signal from 169 glacier records. *Science* 2005, 308:675–677.

26. Moberg A, Sonechkin D, Holmgren K, Datsenko N, Karlén W. Highly variable Northern Hemisphere temperatures reconstructed from low-and high-resolution proxy data. *Nature* 2005, 433:613–617.

27. Rutherford S, Mann ME, Osborn TJ, Bradley RS, Briffa KR, et al. Proxy-based Northern Hemisphere surface temperature reconstructions: sensitivity to method, predictor network, target season, and target domain. *J Clim* 2005, 18:2308–2329.

28. D'Arrigo R, Wilson R, Jacoby G. On the long-term context for late twentieth century warming. *J Geophys Res* 2006, 111:D03103.

29. Smith CL, Baker A, Fairchild IJ, Frisia S, Borsato A. Reconstructing hemispheric-scale climates from multiple stalagmite records. *Int J Clim* 2006, 26:1417–1424.

30. Ammann CM, Wahl ER. The importance of the geophysical context in statistical evaluations of climate reconstruction procedures. *Clim Change* 2007, 85:71–88.

31. Hegerl GC, Crowley TJ, Allen M, Hyde WT, Pollack HN, et al. Detection of human influence on a new, validated 1500-year temperature reconstruction. *J Clim* 2007, 20:650–666.

32. Juckes MN, Allen MR, Briffa KR, Esper J, Hegerl GC, et al. Millennial temperature reconstruction intercomparison and evaluation. *Clim Past* 2007, 3: 591–609.

33. Frank D, Esper J, Cook ER. Adjustment for proxy number and coherence in a large-scale temperature reconstruction Geophys. *Res Lett* 2007, 34:L16709. DOI:10.1029/2007gl030571

34. Wilson R, D'Arrigo R, Buckley B, Büntgen U, Esper J, et al. A matter of divergence: tracking recent warming at hemispheric scales using tree ring data. *J Geophys Res: Atmospheres* 2007, 112:D17103. DOI:10.1029/2006JD008318

35. Loehle C. A 2000-Year global temperature reconstruction based on non-treering proxies. *Energy Environ* 2007, 18:1049–1058.

36. Mann ME, Zhang ZH, Hughes MK, Bradley RS, Miller SK, et al. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proc Natl Acad Sci U S A* 2008, 105:13252–13257.

37. Houghton J, Jenkins G, Ephraums J *Climate change: The IPCC Scientific Assessment*. World Meteorological Organization, United Nations Environmental Programme. Cambridge, England: Cambridge University Press; 1990, 406.

38. Houghton J, Ding Y, Griggs D, Noguer M, Van der Linden P, et al. *Climate Change 2001: The Scientific Basis*. Cambridge: Cambridge University Press; 2001, 881.

39. IPCC Climate Change. *The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2007.

40. Jones PD, Briffa KR, Osborn TJ, Lough JM, van Ommen TD, et al. High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. *The Holocene* 2009, 19:3–49.

41. Lamb H. The early medieval warm epoch and its sequel. *Palaeogeogr Palaeoclimatol Palaeoecol* 1965, 1: 13–37.

42. Regalado A, Climate Debate, The 'Hockey Stick'*Leads to a Face-Off*. *The Wall Street Journal*, February 14. 2005, A1.

43. North G, Biondi F, Bloomfield P, Christy J, Cuffey K, et al. *Surface Temperature Reconstructions for the Last 2,000 Years*. Washington, D.C.: The National Academies Press; 2006.

44. Esper J, Cook E, Krusic P, Peters K, Schweingruber F. Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. *Tree-Ring Res* 2003, 59:81–98.

45. Ojala AEK, Alenius T. 10,000 years of interannual sedimentation recorded in the Lake Nautajärvi (Finland) clastic-organic varves. *Palaeogeogr Palaeoclimatol Palaeoecol* 2005, 219:285–302.

46. Mann M, Rutherford S, Wahl E, Ammann C. Testing the fidelity of methods used in proxy-based reconstructions of past climate. *J Clim* 2005, 18:4097–4107.

47. Moberg A, Mohammad R, Mauritsen T Analysis of the Moberg et al. (2005) hemispheric temperature reconstruction. *Clim Dyn* 2008, 31:957–971.

48. Osborn T, Briffa K. Revisiting timescale-dependent reconstruction of climate from tree-ring chronologies. *Dendrochronologia* 2000, 18:9–25.

49. von Storch H, Zorita E, Gonzàlez-Rouco F. Assessment of three temperature reconstruction methods in the virtual reality of a climate simulation. *Int J Earth Sci* 2009, 98:67–82.

50. Christiansen B, Schmith T, Thejll P. A surrogate ensemble study of climate reconstruction methods: stochasticity and robustness. *J Clim* 2009, 22:951–976.

51. Lee T, Zwiers F, Tsao M. Evaluation of proxy-based millennial reconstruction methods. *Clim Dyn* 2008, 31:263–281.

52. Thejll P, Schmith T. Limitations on regression analysis due to serially correlated residuals: application to climate reconstruction from proxies. *J Geophys Res: Atmospheres* 2005, 110:D18103. DOI:10.1029/2005jd005895

53. Esper J, Frank DC, Wilson RJS, Briffa KR. Effect of scaling and regression on reconstructed temperature amplitude for the past millennium Geophys. *Res Lett* 2005: 32:L07711. DOI:10.1029/2004GL021236

54. Frank D, Büntgen U, Bohm R, Maugeri M, Esper J. Warmer early instrumental measurements versus colder reconstructed temperatures: shooting at a moving target. *Quat Sci Rev* 2007, 26:3298–3310.

55. Cook ER, Pederson N. Uncertainty, emergence, and statistics in dendrochronology. In: Hughes MK, Diaz H, Swetnam TW, eds. *Dendroclimatology: Progress and Prospects*. New York: Springer; 2009.

56. Wilson R, Tudhope A, Brohan P, Briffa K, Osborn T, et al. Two-hundred-fifty years of reconstructed and modeled tropical temperatures. *J Geophys Res: Oceans* 2006, 111:13.

57. Büntgen U, Frank D, Grudd H, Esper J. Long-term summer temperature variations in the Pyrenees. *Clim Dyn* 2008, 31:615–631.

58. Frank D, Esper J. Temperature reconstructions and comparisons with instrumental data from a tree-ring network for the European Alps. *Int J Climatol* 2005, 25:1437–1454.

59. Böhm R, Jones PD, Hiebl J, Frank D, Brunetti M, et al. The early instrumental warm-bias: a solution for long central European temperature series 1760–2007. *Clim Change* DOI:10.1007/s10584-009-9649-4.

60. Thompson D, Kennedy J, Wallace J, Jones P. A large discontinuity in the mid-twentieth century in observed global-mean surface temperature. *Nature* 2008, 453:646–649.

61. Hughes M, Diaz H. Was there a "Medieval Warm Period", and if so, where and when? *Clim Change* 1994, 26:109–142.

62. Bradley R, Hughes M, Diaz H. Climate change: climate in medieval time. *Science* 2003, 302:404.

63. Esper J, Frank D. The IPCC on a heterogeneous *Medieval Warm Period*. *Clim Change* 2009, 94:267–273.

64. Trouet V, Esper J, Graham NE, Baker A, Scourse JD, et al. Persistent positive north Atlantic oscillation mode dominated the medieval climate anomaly. *Science* 2009, 324:78–80.

65. Büntgen U, Frank DC, Nievergelt D, Esper J. Summer temperature variations in the European Alps, AD 755–2004. *J Clim* 2006, 19:5606–5623.

66. Cook ER, Woodhouse CA, Eakin CM, Meko DM, Stahle DW. Long-term aridity changes in the western US Science. 2004, 306:1015–1018.

67. Graham NE, Hughes MK, Ammann CM, Cobb KM, Hoerling MP, et al.Tropical Pacific – mid-latitude teleconnections in medieval times. *Clim Change* 2007, 83:241–285.

68. Seager R, Graham N, Herweijer C, Gordon AL, Kushnir Y, et al. Blueprints for medieval hydroclimate. *Quat Sci Rev* 2007, 26:2322–2336.

69. Mann ME, Cane MA, Zebiak SE, Clement A. Volcanic and solar forcing of the tropical Pacific over the past 1000 years. *J Clim* 2005, 18:447–456.

70. Emile-Geay J, Cane M, Seager R, Kaplan A, Almasi P. El Nino as a mediator of the solar influence on climate. *Paleoceanography* 2007, 22:16.

71. Von Storch H, Zorita E, Jones J, Dimitriev Y, Gonzalez-Rouco F, et al. Reconstructing past climate from noisy data. *Science* 2004, 306:679–682.

72. Babbage C. *Passages from the Life of a Philosopher*: London: Longman, Roberts, & Green, 1864.

73. van der Schrier G, Osborn TJ, Briffa KR, Cook ER. Exploring an ensemble approach to estimating skill in multiproxy palaeoclimate reconstructions. *The Holocene* 2007, 17:119–129.

74. Esper J, Frank D, Buntgen U, Verstege A, Luterbacher J. Long-term drought severity variations in Morocco. *Geophys Res Lett* 2007, 34:L17702. DOI:10.1029/2007gl030844

75. Klein JR, Roodman A. Blind analysis in nuclear and particle physics. *Ann Rev Nuclear Particle Sci* 2005, 55:141–163.

76. Gao CC, Robock A, Ammann C. Volcanic forcing of climate over the past 1500 years: an improved ice core-based index for climate models. *J Geophys Res: Oceans* 2008, 113: D23111. DOI:10.1029/2008jd010239

77. Steinhilber F, Beer J, Frohlich C. Total solar irradiance during the Holocene. *Geophys Res Lett* 2009, 36:5.

78. Pongratz J, Reick C, Raddatz T, Claussen M. A reconstruction of global agricultural areas and land cover for the last millennium. *Global Biogeochem Cycles* 2008, 22. DOI: 10.1029/2007 gb003153

79. Wanner H, Beer J, Butikofer J, Crowley TJ, Cubasch U, et al. Mid- to Late Holocene climate change: an overview. *Quat Sci Rev* 2008, 27:1791–1828.

80. Wagner S, Zorita E. The influence of volcanic, solar and the Dalton Minimum (1790–1830): CO_2 forcing on the temperatures in a model study. *Clim Dyn* 2005, 25:205–218.

81. Pitman AJ, de Noblet-Ducoudre N, Cruz FT, Davin EL, Bonan GB, et al. Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study. *Geophys Res Lett* 2009, 36:L14814. DOI: 10.1029/2009gl039076

82. Jungclaus J, et al. Ensemble simulations of the Last Millennium using an Earth System Model including

an interactive carbon cycle. *Geophysical Res* 2009, 11:EGU2009–EGU4043.

83. Zorita E, Gonzalez-Rouco F, Legutke S. Testing the Mann et al. (1998) approach to paleoclimate reconstructions in the context of a 1000-yr control simulation with the ECHO-G coupled climate model. *J Clim* 2003, 16:1378–1390.

84. Crowley TJ. Causes of climate change over the past 1000 years. *Science* 2000, 289:270–277.

