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High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects

P.D. Jones,[1]* K.R. Briffa,[1] T.J. Osborn,[1] J.M. Lough,[2] T.D. van Ommen,[3] B.M. Vinther,[4] J. Luterbacher,[5] E.R. Wahl,[6] F.W. Zwiers,[7] M.E. Mann,[8] G.A. Schmidt,[9] C.M. Ammann,[10] B.M. Buckley,[11] K.M. Cobb,[12] J. Esper,[13] H. Goosse,[14] N. Graham,[15] E. Jansen,[16] T. Kiefer,[17] C. Kull,[18] M. Küttel,[5] E. Mosley-Thompson,[19] J.T. Overpeck,[20] N. Riedwyl,[5] M. Schulz,[21] A.W. Tudhope,[22] R. Villalba,[23] H. Wanner,[5] E. Wolff[24] and E. Xoplaki[5]

([1]Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK; [2]Australian Institute of Marine Science, Townsville MC, QLD 4810, Australia; [3]Australian Antarctic Division & ACE CRC, Private Bag 80, Hobart Tasmania 7001, Australia; [4]Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark; [5]Oeschger Centre for Climate Change Research (OCCR) and NCCR Climate and Institute of Geography, Climatology and Meteorology, University of Bern, Hallerstrasse 12, CH-3012 Bern, Switzerland; [6]Division of Environmental Studies and Geology, Alfred University, NOAA-Paleoclimatology, Boulder CO 80305, USA; [7]Climate Research Division, Environment Canada, 4905 Dufferin Street, Toronto Ont. M3H 5T4, Canada; [8]Earth System Science Center, Department of Meteorology, Pennsylvania State University, 523 Walker Building, University Park PA 16802, USA; [9]NASA Goddard Institute for Space Studies, 2880 Broadway, New York NY 10025, USA; [10]Climate & Global Dynamics Division, NCAR, Boulder CO 80307-3000, USA; [11]Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Palisades, New York NY 10964, USA; [12]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 311 Ferst Drive, Atlanta GA 30332-0340, USA; [13]Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland; [14]Institut dAstronomie et de Géophysique G. Lemaître, Université Catholique de Louvain, Chemin du cyclotron 2, 1348 Louvain-la-Neuve, Belgium; [15]Hydrologic Research Center, 12780 High Bluff Drive, ú, La Jolla CA 92130-3017, USA; [16]Department of Geology, University of Bergen, Bjerknes Centre for Climate Research, Allegaten 55, NO-5007 Bergen, Norway; [17]PAGES International Project Office, Sulgeneckstrasse 38, 3007 Bern, Switzerland; [18]Advisory Body on Climate Change (OcCC), Schwarztorstrasse 9, CH-3007 Bern, Switzerland; [19]Department of Geography and Byrd Polar Research Center, Ohio State University, 108 Scott Hall, 1090 Carmack Road, Columbus OH 43210, USA; [20]Institute for the Study of Planet Earth, University of Arizona, 715 N. Park Avenue, 2nd Floor, Tucson AZ 85721, USA; [21]MARUM – Center for Marine Environmental Sciences and Faculty of

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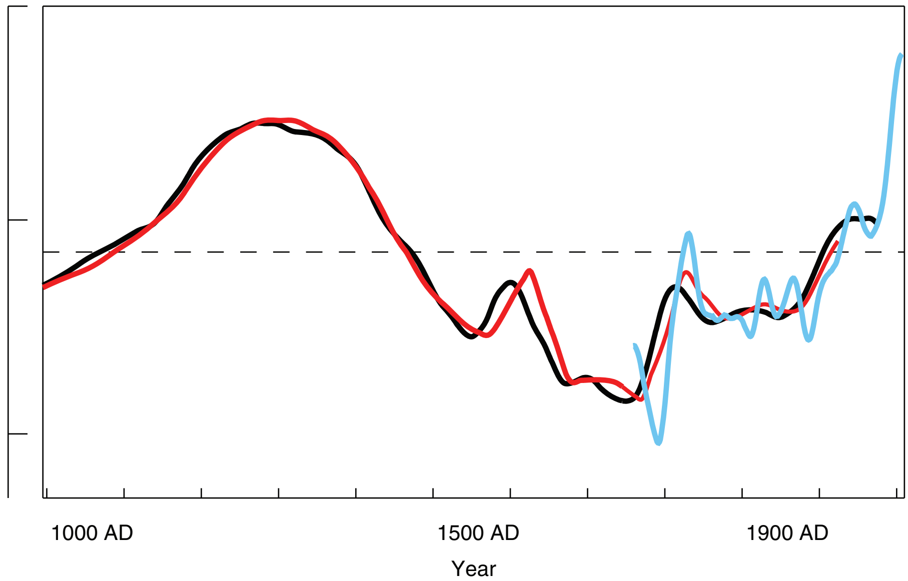

Figure 7 The black curve and the x- and y-axes are a redrawn version of figure 7.1c from the First Working Group of IPCC Report (Folland *et al.*, 1990). The y-axis originally had only unnumbered tick markings and was labelled 'temperature scale'. The red curve is from Lamb (1982: figure 30, the upper (annual) curve). The amplitude of this curve has been scaled to correspond to that of the black curve. The Lamb (1982) time series does have an explicit temperature scale, and the best-fit scaling between this curve and the IPCC curve indicates that one tick-mark interval on the IPCC figure corresponds almost exactly with 1°C. The degree of smoothing for both these curves is unknown, but Lamb (1982) states that the red curve is based on 50-yr means (supported by earlier publications). The blue curve is a smoothed version of the annual instrumental Central England Temperature record from Manley (1974, updated) including the last complete year of 2007. This has been smoothed with a 50-yr Gaussian weighted filter with padding (Mann, 2004). The blue curve is plotted with the same scaling as used for the red curve, further supporting the conclusions that the red curve is based on the same data after the start of the instrumental record in 1659. The red and blue curves illustrate the differences that can occur between a filtered curve and one composed of non-overlapping 50-yr averages, and also that recent measured warming may be comparable with presumed earlier warmth

experiments, because more complex interactions with atmospheric radiative transfer can be simulated, such as the stratospheric warming caused by absorption of both short- and long-wave radiation by the sulphate aerosol which might have dynamical responses in the atmosphere.

This particular example (Figure 6, from HadCM3) also highlights the potential importance of strong geographic variations in forcing. The short-term impact of volcanic eruptions is clear, influencing most latitudes, and there is a long-term trend towards positive forcing arising mostly from greenhouse gas forcing (with a small contribution from solar irradiance changes). The forcing from sulphate aerosol emissions into the mid-latitudes of the Northern Hemisphere, while rather uncertain in its magnitude, is strong enough in this implementation to dominate the greenhouse gas forcing throughout the simulation (even in the late-nineteenth century, as pointed out by Tett *et al.*, 2007), though the negative forcing begins to reduce in recent decades. The negative forcing from Antarctic stratospheric ozone depletion is also clear in the last decade of this simulation. Forcings may have important seasonal as well as geographic structure; Goosse *et al.* (2006b), for example, suggest that land-use changes (with a minor influence from orbital changes) might have contributed to warming during the Mediaeval period (relative to the present day) but only in summer and only for some regions in the mid- and high-latitudes of the Northern Hemisphere.

Conclusions

This article has reviewed the characteristics and current research status of documentary and high-resolution proxy climatic sources and addressed the various approaches by which they may be combined to provide field reconstructions or large-area averages. We have also extensively discussed the use of climate model simulations and how they can inform the debate and take forward research into the optimal combination and interpretation of the various data. Finally, we summarize our principal findings and recommendations for the continued exploitation of palaeoclimatological data for reconstructing large-scale averages and spatial patterns of climate variability over recent millennia. These recommendations are ordered according to the section order in the review:

(1) In the area of tree-ring research the number of available long chronologies is expanding but remains small, and although potential sites with known subfossil data are limited, the effort in developing these is fully justified: there remain large areas of the terrestrial world where chronology network development is in its infancy (much of the lower-latitudes and virtually all of the SH).

(2) It was widely believed 20 years ago that cross-dating trees in tropical regions was not possible. Recent work has led to a growing number of cross-dated chronologies being developed, principally in southeast Asia in regions of marked seasonality in rainfall. It is important this work continues.

(3) There have been recent and continuing improvements in statistical methods for producing long chronologies, which can be shown to retain low-frequency climatic variability more realistically than was previously the norm. Work is needed to further assess the applicability of these methods in a wider range of situations than have been explored to date.

(4) Significant continued effort is required to provide the high degree of intrasite and importantly intersite (ie, regional scale) sample replication needed to demonstrate reliable long-timescale chronology expression. Local and regional-average chronologies and regression-based estimates of climate variability should be routinely presented with explicit indications of their separate timescale and time-dependent confidence limits.

(5) There is pressing need for further study of the likely precedence and causes of the apparent 'divergence' between instrumentally recorded and some dendroclimatically estimated temperature trends (typically some high-latitude NH regions) in

recent decades. This emphasizes the priority requirement for systematic updating of many existing tree-ring data, to continue in parallel with efforts to expand the representation of data into new areas.

(6) In coral proxy climate research, replication of important single coral $\delta^{18}O$ and Sr/Ca records would allow quantification of signal *versus* noise in coral reconstructions. Owing to the rarity of long coral cores, however, this may only be possible over the late-twentieth century.

(7) There should be greater effort to increase the number of long coral climate reconstructions using both modern and subfossil corals, taking full advantage of existing resources and by collecting new materials.

(8) *In situ* monitoring of environmental variables (eg, SST, salinity, seawater $\delta^{18}O$ etc.) is required to improve the interpretation of coral $\delta^{18}O$ and Sr/Ca records with respect to regional climate patterns.

(9) Standard calibration and verification procedures (as commonly used in dendroclimatology) should be developed for coral records, with a focus on the interannual-to-decadal timescale, rather than seasonal, calibrations.

(10) Coral Sr/Ca ratios should be routinely measured with $\delta^{18}O$ to improve the climatic interpretation of both geochemical tracers.

(11) All corals used for climate reconstruction should be carefully screened for diagenesis, and this information, along with metadata related to the sampling location, methods and environment should be made available through an established data centre.

(12) Cross-dating of the many Greenland ice cores is reducing dating uncertainties and improving understanding of the factors that cause variations at interannual timescales. Volcanic horizons are particularly important in this regard, especially known events in the historic past such as Icelandic eruptions and Vesuvius in AD 79. This cross-dating of ice cores in Greenland needs to extend to the Antarctic, even though it will be much harder to achieve.

(13) Both analyses of time series of ice-core isotope data and modelling approaches have shown that the traditional spatial calibration of the isotopic thermometer may be unsuitable in many cases. It needs to be supplemented by an improved, quantitative understanding of processes.

(14) Calibration of ice-core isotopic series and of coral records should be undertaken at the appropriate timescale for the problem being studied whenever possible. Attempts to reconstruct the annual cycle may give a false sense of calibration skill.

(15) Further intercomparison and process studies using model and meteorological data are required to improve understanding of the calibration of the ice-core thermometer, its seasonal biases, temporal stability and geographical applicability. The processes controlling isotopic content in non-polar ice cores require particular attention.

(16) Changes in ice sheet elevation and changes in climatic conditions upstream of an ice-core drill site can introduce non-climatic biases in isotopic series. Hence such effects should be considered when interpreting isotopic records from ice cores.

(17) The full range of proxy information available from ice cores has not been exploited. Approaches which use a wider range should be pursued.

(18) Documentary data are limited to regions with long-written histories, but archives from Turkey, Venice, the Vatican and the Middle East have barely been exploited.

(19) In Europe, documentary information decreases significantly once instrumental records commence. This is a severe impediment to their use in CFR and CPS reconstructions, as the use of degraded instrumental data to extend the series to the present may give a false sense of their reliability.

(20) Extending early instrumental data is vital, particularly for the calibration and verification of variability on decadal and longer timescales. Longer instrumental records (than those readily available in climatic data bases) can be found in many regions, with some extending for more than 100 years before the founding of NMSs.

(21) In Europe, there is a potential warm bias in pre-1860 summer temperatures (related to thermometer exposure), particularly in central Europe and Scandinavia.

(22) Wind information from ship logbooks is a reliable source for the reconstruction of past large-scale atmospheric circulation, but has hardly been exploited. There are also numerous (particularly British) logbooks yet to be digitized, which have the potential to improve and extend re-analyses of air or sea temperature as well as sea-level pressure further back in time.

(23) Varved sediments and speleothem records are finding increased palaeoclimatic utility, but a greater focus on quantitative documentation of chronological accuracy and climate sensitivity of both types of records is needed.

(24) Externally forced GCM simulations of the last millennium provide useful test beds for assessing the characteristics of the range of CPS and CFR techniques now available. A range of standard experiments should be developed to test these techniques, perhaps using common sets of pseudo-proxy networks, which could be made widely available for extensive testing of current and new methods.

(25) CPS-based reconstructions of NH temperature averages at the decadal timescale are relatively independent of the reconstruction approach. CFR-based reconstructions of internally consistent climate fields can offer key additional insights into spatial climate processes, but their reliability must be carefully tested (eg, the individual reliability of specific patterns and regions) and linked to the underlying proxy records. Issues regarding the potential underestimation of long-term variability in both CPS and CFR reconstructions have not yet been fully resolved: however, initial work in examining field fidelity for CFRs suggests that pattern reproduction may be robustly resolvable even in the face of significant amplitude loss.

(26) More realistic assessments of reconstruction uncertainty are needed that consider all sources of error and which can powerfully assess field fidelity. Methods need to be developed that incorporate uncertainties in individual proxies, the effect of proxy selection and uncertainties in the regression/scaling models. The ability of simple residuals between reconstructions and observations during calibration or verification to represent the total error needs to be further assessed.

(27) Further simulations with a hierarchy of climate models (GCMs, EMICs and EBMs) are needed to quantify the uncertainties associated with past forcings (eg, using a range of possible past forcings, perhaps with separate simulations for some individual forcings), with internal variability (eg, using ensembles) and varying climate processes (eg, using multiple models and by perturbing physical parameters with a model).

(28) Comparisons between simulations and climate reconstructions must take these forcing/model-related uncertainties into consideration, in addition to errors in the climate reconstructions. Only then can robust conclusions be drawn from such model–data comparisons.

We noted in the Introduction the dramatic improvements in late-Holocene palaeoclimatology made since the early 1990s. Interest in the subject and the large-scale reconstructions has multiplied over the same period. This development has, however, not kept pace with the needs for a more reliable picture for the late-Holocene climates. The questions that are now being asked are also different and can only be adequately addressed with realistic consideration of reconstruction uncertainty ranges. More realistic climate models are providing multiple simulations at higher-spatial resolution for assessing reconstructions and combination (CPS and CFR) approaches, but improvements in reconstructions and reductions in uncertainties in our understanding of late-Holocene climate change will only come with better and more widespread proxy climatic information from more diverse sources.

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Appendix A

Figure 7.1c of IPCC (1990)

In the first report of the Intergovernmental Panel on Climate Change (IPCC, 1990) a 'schematic' diagram representing temperature variations over the last millennium was used (Folland *et al*., 1990: figure 7.1c, p. 202). The caption of part (c) of the figure reads: 'Schematic diagram of global temperature variations for the last thousand years. The dotted line represents conditions near the beginning of the twentieth century'. In the Supplementary IPCC Report in 1992 (Folland *et al*., 1992), the diagram had been dropped and the need for more data that would allow for the spatial aspects of past changes acknowledged. Subsequent IPCC reports included some of the first hemispheric reconstructions based on the burgeoning proxy archives (Bradley and Jones, 1993, in Nicholls *et al*., 1996 (Second IPCC Assessment Report, SAR) and MBH98, 1999; Jones *et al*., 1998; Briffa, 2000 and Crowley and Lowery, 2000 in Folland *et al*., 2001 (Third IPCC Assessment Report, TAR)). Hence the original 'schematic' 1990 diagram appeared to have been confined to history by subsequent IPCC reports, although this was never specifically stated. It has continued to reappear in a number of guises – web pages, reports (eg, Wegman *et al*., 2006), school teaching literature, sometimes with phrases evoking reminders of warmer/colder periods in the past (eg, vineyards in southern Britain, Vikings in Greenland in Mediaeval times, Frost Fairs on the Thames and icebergs off Norway in later centuries) – but as far as palaeoclimatologists were concerned the diagram was nothing more than how it was originally described in the caption: a schematic.

So where did the schematic diagram come from and who drew it? It can be traced back to a UK Department of the Environment publication entitled *Global climate change* published in 1989 (UKDoE, 1989), but no source for the record was given. Using various published diagrams from the 1970s and 1980s, the source can be isolated to a series used by H.H. Lamb, representative of central England, last published (as figure 30 on p. 84) by Lamb (1982). Figure 7 shows the IPCC diagram with the Lamb curve superimposed – clearly they are the same curve. The 'Central England' curve also appeared in Lamb (1965: figure 3 and 1977: figure 13.4), on both occasions shown as an 'annual' curve together with the extreme seasons: winter (December to February) and high summer (July and August). The IPCC diagram comes from the 1982 publication as the vertical resolution of the annual plot is greater. The data behind the 1977 version are given in table app. V.3 in Lamb (1977), but these are essentially the same as previously given in Lamb (1965). All three versions of the plot have error ranges (which are clearest in the 1982 version and indicate the range of apparent uncertainty of derived versions). The 1982 version dispenses with the three possible curves evident in Lamb (1965, 1977) and instead uses a version which accounts for the 'probable under-reporting of mild winters in Medieval times' and increased summer temperatures to meet 'certain botanical considerations'. Lamb (1965) discusses the latter point at length and raised summer temperatures in his Mediaeval reconstructions to take account of the documentary evidence of vineyards in southern and eastern England. The amount of extra warmth added during 1100–1350 was 0.3–0.4°C, or about 30% of the range in the black curve in Figure 7. At no place in any of the Lamb publications is there any discussion of an explicit calibration against instrumental data, just Lamb's qualitative judgement and interpretation of what he refers to as the 'evidence'. Variants of the curves also appear in other Lamb publications (see, eg, Lamb, 1969).

Many in the palaeoclimatic community have known that the IPCC (1990) graph was not representative of global conditions (even when it first appeared) and hence the reference to it as a schematic. Lamb's (1965, 1977, 1982) series has been used as one of the series comprising the NH composite developed by Crowley and Lowery (2000), representative of Central England. Various authors (eg, Farmer and Wigley, 1984; Wigley *et al*., 1986; Ogilvie and Farmer, 1997) have shown that such representativeness is only really the case for the instrumental part of the record from 1659 which is based on the well-known Manley (1974) series. Greater amounts of documentary data (than available to Lamb in the early 1970s) were collected and used in the Climatic Research Unit in the 1980s. These studies suggest that the sources used and the techniques employed by Lamb were not very robust (see, eg, Ogilvie and Farmer, 1997).

In summary, we show that the curve used by IPCC (1990) was locally representative (nominally of Central England) and not global, and was referred to at the time with the word 'schematic'.

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