Ulf Büntgen and Lena Hellmann

The Little Ice Age in Scientific Perspective: Cold Spells and Caveats

In "The Waning of the Little Ice Age: Climate Change in Early Modern Europe," Kelly and Ó Gráda argue that European temperature estimates extending back into late medieval times contain no major breaks, cycles, or trends, that could be associated with a Little Ice Age (LIA). They use a selection of frost fairs and contracting glaciers, as well as disappearing British vineyards and Arctic colonies, to imply the irrelevance of climate forcing and sequential cooling. The first sentence of their abstract in this issue's table of contents, aptly, if skeptically, posits the existence of a cool LIA period and its putative consequences for economic, political, and cultural history, far beyond the realm of climatology: "The supposed ramifications of the Little Ice Age, a period of cooling temperatures straddling several centuries in northwestern Europe, reach far beyond meteorology into economic, political, and cultural history." Clearly, the issues surrounding the LIA are complex.[1]

This comment on their article points to several factors that challenge the hypothesis of a missing palaeoclimatic signal for the

Ulf Büntgen is Head of the Dendroecology Group at the Swiss Federal Research Institute WSL, as well as an Associated Research Fellow at the Oeschger Centre for Climate Change Research, University of Bern, and at the Global Change Research Centre AS CR, Brno. He is the lead author of "Filling the Eastern European Gap in Millennium-Long Temperature Reconstructions," *Proceedings of the National Academy of Science,* CX (2012), 1773–1778, and of "2500 Years of European Climate Variability and Human Susceptibility," *Science,* CCCI (2011), 578–582.

Lena Hellmann is a doctoral student, Oeschger Centre for Climate Change Research, University of Bern. She is the lead author of "Tracing the Origin of Arctic Driftwood," *Journal of Geophysical Research,* B, CXVIII (2013), 68–76.

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1   In addition to their article in this issue, see also Morgan Kelly and Cormac Ó Gráda, "Change Points and Temporal Dependence in Reconstructions of Annual Temperature: Did Europe Experience a Little Ice Age?" working paper 2012/10 (University College Dublin Centre for Economic Research, 2012), available at www.ucd.ie/economics/research.

LIA. Avoiding semantical digressions and quibbles about the quality and suitability of Kelly and Ó Gráda's evidence in support their argument, we instead provide independent evidence of several temperature depressions that occurred between c. 1350 and 1900 in different regions of the globe. Nevertheless, we are well aware of the various sources of uncertainty that can emerge from the decreasing quality and quantity of the proxy evidence in the passage of time, together with the methodological constraints involved in preserving the full-amplitude range and spatial extent of the high-to-low-frequency dynamics of climate in the past. Moreover, we are particularly sensitive to the complexity of linking climate variability with human history; any straightforward comparison that supposes simple causal determination and disregards other contributing factors, such as sociocultural and medical stressors, seriously risks exceeding the evidence.

A proper approach to these issues requires a brief review of the literature about the onset of LIA research, as well as a survey of the latest evidence of global-scale and Holocene-long temperature change along with a more regional assessment. This preliminary exposition lays the groundwork for a discussion about the evolution of climate across the European Alps during the last millennium, and the extent to which external forcings have exerted influence on it. Throughout, we cannot lose sight of the data-related and methodologically induced uncertainties associated with the spatiotemporal nature of the LIA.

THE ORIGINS OF THE LITTLE ICE AGE THEORY   At this juncture, the LIA is a well-established conception in glaciology and climatology, having been introduced almost eighty years ago by Matthes in 1939. This earliest mention, in relation to glacier dynamics in the Sierra Nevada, California, received more official notice in an article by Moss in 1951. Follow-up studies generally relied on observations of late-Holocene glacial advances in the United States and elsewhere. Lamb, however, concentrated on Europe, describing a relatively cool period with reduced harvests and abandoned villages.[2]

2   François E. Matthes, "Report of the Committee on Glaciers, April 1939," *Transactions of the American Geophysical Union,* XX (1939), 518–523; John H. Moss, *Early Man in the Eden Valley* (Philadelphia, 1951), 9–12; Jean M. Grove, "The Little Ice Age in the Massif of Mont Blanc," *Transactions of the Institute of British Geographers* (1966), 129–143; Hubert H. Lamb,

In 1967, Porter and Denton criticized the term *little ice age,* proposing that it be replaced with *neoglaciation* in light of a prolonged period of glacial expansion during the Holocene. Although Manley and Landsberg were to question the term and its temporal application again years later, the notion of an LIA applied to the period roughly between the sixteenth and the mid-nineteenth century, when many of the world's glaciers expanded, was relatively secure. Nevertheless, a clear link between the glacier-based LIA theory and cooler temperatures remained debatable. In fact, the complex relationship between climate and glacial change, including different response lags, evoked different orientations to the LIA in glaciology and climatology. Glaciology focused on a longer period of glacial advance from roughly 1300 to 1950 A.D., especially in the European Alps, depending mostly on winter precipitation, whereas climatology looked at summer temperatures, which were significantly lower from around 1570 to 1900 than they were to become later. Above and beyond these temporal issues are uncertainties related to the spatial dimension of the LIA. In the 1980s, Landsberg claimed that LIA cooling was not global, whereas Grove suggested a coherent large-scale temperature depression that justified a common name.[3]

Contrary to Kelly and Ó Gráda, none of the studies cited above defines the LIA by temperature breaks, cycles, or trends; nor was the LIA's birthplace almost 100 years ago in Europe. Kelly and Ó Gráda claim to have screened all of the available millennium-

"The Early Medieval Warm Epoch and Its Sequel," *Palaeogeography, Palaeoclimatology, and Palaeoecology,* I (1965), 13–37.

3   S. C. Porter and George H. Denton, "Chronology of Neoglaciation in the North American Cordillera," *American Journal of Science,* CCLXV (1967), 177–210; Gordon Manley, "Central England Temperatures: Monthly Means 1659 to 1973," *Quarterly Journal of the Royal Meteorological Society,* C (1974), 389–405; Helmut Erich Landsberg, *Historical Weather Data and Early Meteorological Observations: Paleoclimate Analysis and Modelling* (New York, 1985), 27–70; Michael E. Mann, "Little Ice Age," in Michael C. MacCracken and John S. Perry (eds.), *Encyclopedia of Global Environmental Change. I. The Earth System: Physical and Chemical Dimensions of Global Environmental Change* (Chichester, 2002), 504–509; Christian Pfister, *Das Klima der Schweiz von 1525–1860 und seine Bedeutung in der Geschichte der Bevölkerung und Landwirtschaft* (Bern, 1985); Grove, "The Initiation of the 'Little Ice Age' in Regions Round the North Atlantic," *Climatic Change,* XLVIII (2001), 53–82; Raymond S. Bradley and Philip D. Jones, "'Little Ice Age' Summer Temperature Variations: Their Nature and Relevance to Recent Global Warming Trends," *The Holocene,* XXX (1993), 367–376; John A. Matthews and Keith R. Briffa, "The Little Ice Age: Re-evaluation of an Evolving Concept," *Geografiska Annaler,* LXXXVII A (2005), 17–36; Grove, *The Little Ice Age* (New York, 1988), 498.

long temperature reconstructions without finding any statistical evidence for breaks, trends, and cycles in European weather that would justify the LIA. Not only, however, do they fail to produce any of these records and analyses; they also fail to make an important distinction between climate and weather, the latter being unsuitable to account for much more than stochastic noise. Furthermore, they ignore a rich scientific foundation for the LIA when they question the value of anecdotal confirmation of cooler episodes between the fourteenth and nineteenth centuries.

More specifically, Kelly and Ó Gráda's reliance on continuous annual estimates of Central European winter and summer temperatures, based on abundant documentary sources from the past five centuries, probably overestimates the ability of such records to mirror the full range of low-frequency climate variability on timescales greater than decades. Dependence on the value and extent of existing sources, as well as on their methodological interpretation, for the structure of climate indices reveals a key weakness of documentary-based climate reconstructions, commonly known in tree-ring research as "segment length curse." This methodological restriction, a by-product of splicing various individual sources together, affects the preservation of long-term trends beyond the length of the discrete report. For example, personal accounts of weather extremes are generally constrained to a fraction of an individual's lifespan, thus serving as an inadequate signification of lower-frequency variability.[4]

Finally, Kelly and Ó Gráda wrongly declare that neither European nor Northern Hemispheric temperature reconstructions reveal a decline from around A.D. 1635 to 1665—a period roughly matching the Maunder Minimum of decreased solar activity and increased volcanic eruptions. Distinct temperature depressions during the seventeenth century are typical features in many re-

4 Petr Dobrovolná et al., "Monthly, Seasonal and Annual Temperature Reconstructions for Central Europe Derived from Documentary Evidence and Instrumental Records since AD 1500," *Climatic Change*, CI (2010), 69–107; Rudolf Brázdil et al., "Historical Climatology in Europe—State of the Art," *ibid.*, LXX (2005), 363–430; Philip D. Jones et al., "High-Resolution Palaeoclimatology of the Last Millennium: A Review of Current Status and Future Prospects," *The Holocene*, XIX (2009), 3–49; Giovanna Battipaglia et al., "Five Centuries of Central European Temperature Reconstructed from Tree-Ring Density and Documentary Evidence," *Global and Planetary Change*, LXXII (2010), 182–191; E. R. Cook, "The 'Segment Length Curse' in Long Tree-Ring Chronology Development for Palaeoclimatic Studies," *The Holocene*, V (1995), 229–237; Pfister, *Wetternachhersage: 500 Jahre Klimavariationen und Naturkatastrophen (1496–1995)* (Bern, 1999).

gional- and global-scale studies, whether or not they include time-series smoothing to which Kelly and Ó Gráda object.[5]
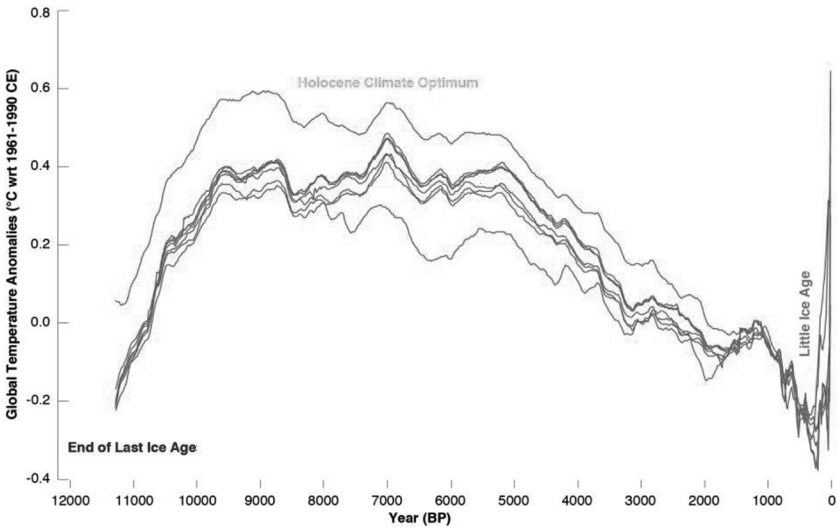
NEW LINES OF EVIDENCE   Glaciologically and/or climatologically defined intervals require a broad spatial and temporal context for their evaluation. A recent multi-proxy compilation suggests that global temperatures reached their Holocene minimum in the eighteenth century. Evidence from seventy-three regional records indicates a relatively warm early Holocene from around 10,000 to 5,000 years ago, followed by a cooling trend through the middle to late Holocene, culminating in temperatures reaching their coolest point around 200 years ago—the LIA (see Figure 1). Kelly and Ó Gráda argue that their global temperature reconstruction for the past 1,500 years is indistinguishable, within uncertainty bands, from the Common Era large-scale approach of Mann et al. in 2009, relating the LIA temperature depression to a roughly 2 °C change in the North Atlantic.[6]

A closer look at continent-wide and millennium-long temperature variability discovers a wide range of interannual to multi-decadal disagreement in past variability. Nevertheless, the grand average global mean reveals cold conditions in the nineteenth century, well synchronized across all of the continents. A clear picture of relatively warm temperatures between medieval and recent times, separated by prolonged cooling in between, derives from the Arctic, Asia, and Australasia (see Figure 2). A more complicated picture originates from South America, where strong multidecadal to centennial temperature changes distinguished the entire past millennium. In summary, pre-LIA temperatures from 1000 to 1349 were warmer than LIA temperatures from 1350 to 1899 on all six continents (Figure 2). Post-LIA conditions from 1900 to the present were warmer throughout the world, with the exception of Ant-

5   Jürg Luterbacher et al., "The Late Maunder Minimum (1675–1715)—"A Key Period for Studying Decadal Scale Climate Change in Europe," *Climate Change,* XLIX (2001), 441–462; Büntgen et al., "Summer Temperature Variations in the European Alps, AD 755–2004," *Journal of Climate,* XIX (2006), 5606–5623; David C. Frank, Büntgen, et al., "Ensemble Reconstruction Constraints of the Global Carbon Cycle Sensitivity to Climate," *Nature,* CDLXIII (2010), 527–530.
6   Shaun A. Marcott, "A Reconstruction of Regional and Global Temperature for the Past 11,300 Years," *Science,* CCCXXXIX (2013), 1198–1201; Michael E. Mann et al., "Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly," *ibid.,* CCCXXVI (2009), 1256–1260.

Fig. 1 Different Methods and Reconstructions of Global–Scale and Holocene-Long Temperature Anomalies
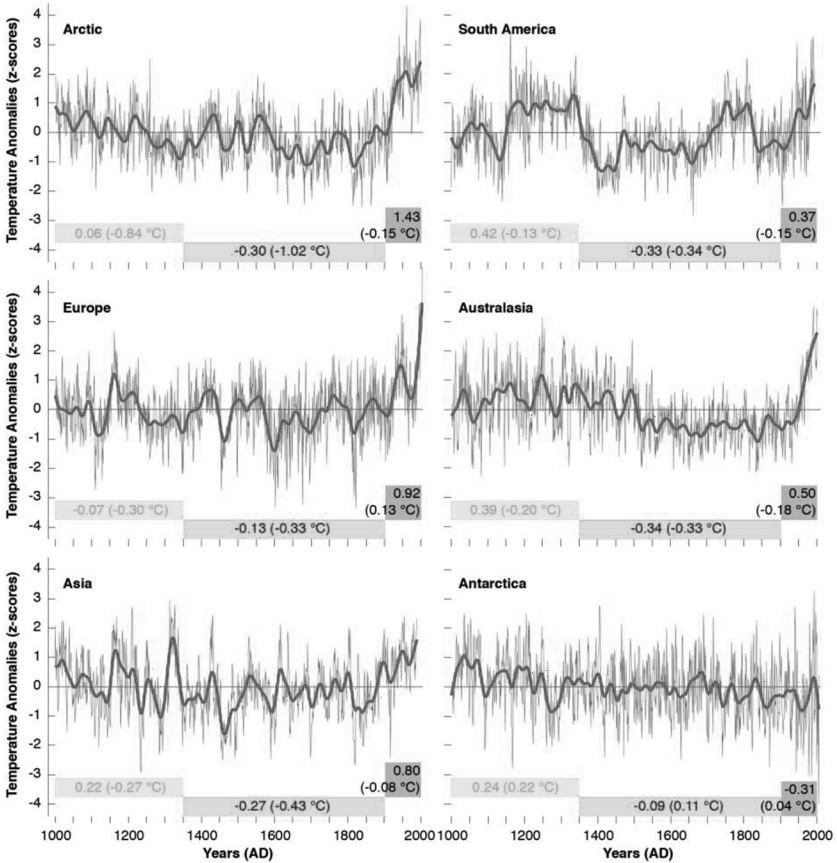
arctica where recent temperatures are still fluctuating below earlier levels, possibly reflecting effects of climate inertia from the surrounding oceans, although the causal mechanism is still uncertain.[7]

Focusing on the European Alps, at least two independent proxy archives—glaciers and tree rings—exhibit a clear picture of relatively warm medieval and recent temperatures interrupted by a period of cooling (see Figure 3). Numerous recent and relict tree-ring-width measurements from the Austrian Alps allow interannual to multicentennial variations in summer temperature to be reconstructed for the past 2,500 years. This record indicates considerable natural variability during the past millennium (see Figure 3B), but

7   PAGES 2k Consortium, "Continental-Scale Temperature Variability During the Past Two Millennia," *Nature Geoscience,* VI (2013), 503, doi:10.1038/ngeo1834; David H. Bromwich et al., "Central West Antarctica among the Most Rapidly Warming Regions on Earth," *Nature ibid.,* VI (2013), 139–145; Tas Van Ommen, "Antarctic Response," *ibid.,* 334–335; Büntgen et al., "Causes and Consequences of Past and Projected Scandinavian Summer Temperatures, 500–2100 AD," *PLoS ONE,* 6(9) (2011), e25133. doi:10.1371/journal.pone .0025133.

it also reflects relatively warm conditions before c. 1250 and after c. 1850.[8]

An independent line of evidence derives from an exclusive collection of maximum latewood-density measurements from nearly 200 individual core samples of high-elevation larch trees (*Larix decidua* Mill.), including various living treeline stands and historical buildings in the western Swiss Alps. These data show high temperatures in the tenth and thirteenth centuries that resemble twentieth-century conditions (Figure 3B). These warm periods were divided by relatively cooler conditions from c.1350 to 1700. Six of the ten warmest decades between 755 and 2004 occurred in the twentieth century. The maximum temperature amplitude for the past 1,250 years is estimated to be 3.1 °C between the warmest (1940s) and coldest (1810s) decades. The reconstruction captures the coldest and warmest single years—1816 and 2003, respectively. Comparison with large-scale reconstructions confirms decadal to longer-term agreement. Furthermore, warm (cold) summers generally matched episodes of high (low) solar activity.[9]

Fossil chironomids—non-biting midges from varved sedimentary layers in Lake Silvaplana, Swiss Alps—enabled an estimation of mean temperatures in July back to 1032 A.D. This record, indicating roughly 1 °C warmer conditions during medieval times in contrast to the modern reference period from 1961 to 1990 (see Figure 3C), divides the LIA into three fairly cold phases—roughly, 1260 to 1480, 1510 to 1720, and 1730 to 1780. These fluctuations coincide to some extent with independently reconstructed tem-

8   Büntgen et al., "2500 Years of European Climate Variability and Human Susceptibility," *Science,* CCCI (2011), 578–582.
9   Büntgen et al., "Summer Temperature Variations"; Jan Esper, Cook, and Fritz H. Schweingruber, "Low-Frequency Signals in Long Tree-Ring Chronologies for Reconstructing Past Temperature Variability," *Science,* CCXCV (2002), 2250–2252; Anders Moberg et al., "Highly Variable Northern Hemisphere Temperatures Reconstructed from Low- and High-Resolution Proxy Data," *Nature,* CDXXXIII (2005), 613–617; Rosanne D'Arrigo, Robert J. S. Wilson, and G. Jacoby, "On the Long-Term Context for Late 20th Century Warming," *Journal of Geophysical Research,* CXI (2006), D03103; Minze Stuiver and Thomas F. Braziunas, "Atmospheric C-14 and Century-Scale Solar Oscillations," *Nature,* CCCXXXVIII (1989), 405–408; Edouard Bard et al., "Solar Irradiance during the Last 1200 Years Based on Cosmogenic Nuclides," *Tellus* B, LII (2000), 985–992; Thomas J. Crowley, "Causes of Climate Change over the Past 1000 Years," *Science,* CCXCV (2000), 270–277; Jürg Beer, W. Mende, and R. Stellmacher, "The Role of the Sun in Climate Forcing," *Quaternary Science Reviews,* XIX (2000), 403–415.

perature changes in Switzerland, Europe, and even the Northern Hemisphere.[10]

Superimposed on the sun, which is generally considered an important driving force of the earth's climate system, are volcanic eruptions (see Figure 3D). Although the regional character of both climate reconstructions and forcing agents does not always permit the inference of systematic relationships, detailed analyses generally suggest a cooling of several years following primarily tropical events. The most prominent example is the "Year without Summer" (1816), after the Tambora eruption in Indonesia. Hence, the reconstructed long-term variations in Alpine summer temperature mimic solar activity; higher-frequency fluctuations often coincide with the timing of volcanic eruptions, which may even mask the sun/climate relationship.[11]
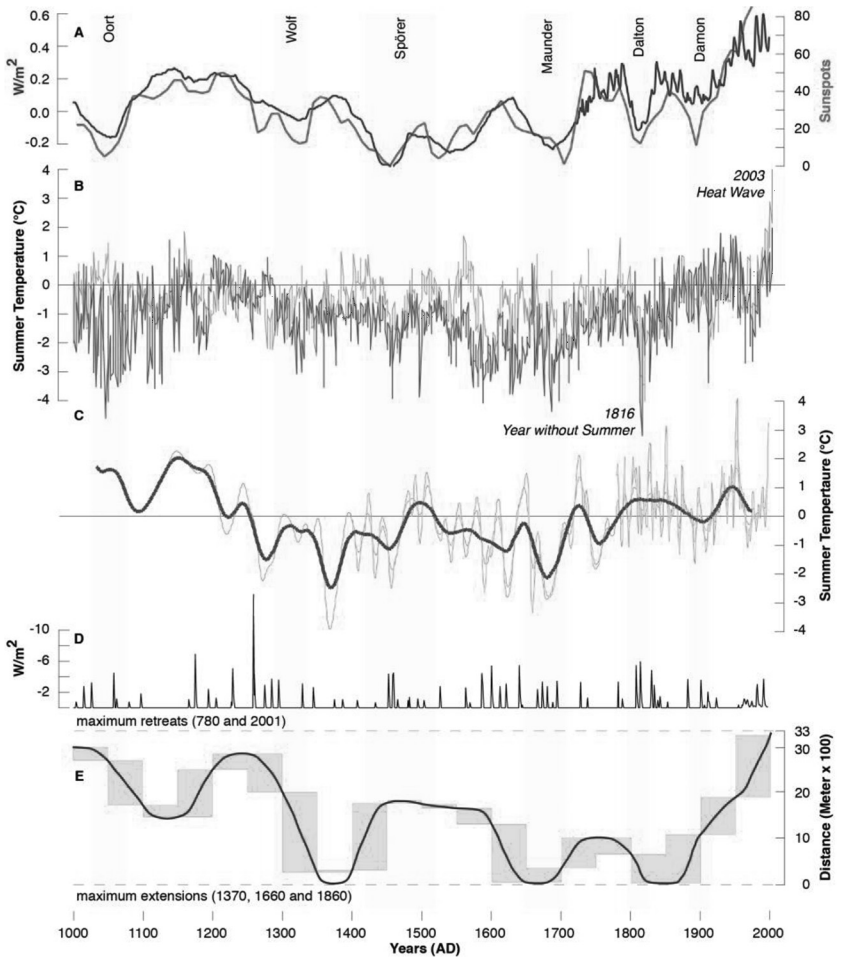
Linking dendro-examples with regional length and mass-balance approximations of the Great-Aletsch glacier exhibits a high level of long-term coherency (see Figure 3E). Fluctuations on multidecadal to centennial timescales describe a first extension in the fourteenth century, followed by a retreat from c. 1450 to 1600 and two more advances in the seventeenth and nineteenth centuries. These ups and downs during the LIA likely refer to modifications in atmospheric circulation patterns during the Wolf, Maunder, and Dalton solar minima, the last of which probably expressed the most extended Alpine glacier advance of the Holocene.[12]

10   Isabelle Larocque-Tobler et al., "Thousand Years of Climate Change Reconstructed from Chironomid Subfossils Preserved in Varved Lake Silvaplana, Engadine, Switzerland," *Quaternary Science Review,* XXIX (2010), 1940–1949.
11   Bard et al., "Solar Irradiance"; Beer, Mende, and Stellmacher, "Role of the Sun"; John A. Eddy, "The Maunder Minimum," *Science,* CXCII (1976), 1189–1202; Judith Lean and David Rind, "Climate Forcing by Changing Solar Radiation," *Journal of Climate,* XI (1998), 3069–3093; Haraldur Sigurdsson and Sean Carey, "Plinian and Co-Ignimbrite Tephra Fall from the 1815 Eruption of Tambora Volcano," *Bulletin of Vocanology,* LI (1989), 243–270; Clive Oppenheimer, "Climatic, Environmental and Human Consequences of the Largest Known Historic Eruption: Tambora Volcano (Indonesia) 1815," *Progress in Physical Geography,* 27 (2003), 230–259; John Donarummo, Michael Ram, and Michael R. Stolz, "Sun/Dust Correlations and Volcanic Interference," *Geophysical Research Letters,* XXIX (2002), doi:10.1029/2004GL014858.
12   Wilfried Haeberli and Hanpeter Holzhauser, "Alpine Glacier Mass Changes during the Past Two Millennia," *Pages News,* I (2003), 13–15; Martin Hoelzle et al., "Secular Glacier Mass Balances Derived from Cumulative Glacier Length Changes," *Global Planetary Change,* XXXVI (2003), 77–89; Luterbacher et al., "Late Maunder Minimum (1675–1715)"; Grove, *Little Ice Age.*

Fig. 3A, 3B, 3C, 3D, 3E. (Continued)

Unusually Active Sun since the 1940s," *Physical Review Letters,* XCI (2003), 211101.1–2111.01.4. Vertical shadings denote the timing of great solar minima (see Minze Stuiver and Thomas F. Braziunas, "Atmospheric C-14 and Century-Scale Solar Oscillations," *Nature,* CCCXXXVIII [1989], 405–408). The sunspot–number reconstruction (eleven–year–smoothed) is not independent of the spliced solar–activity reconstruction, since both are based on ice–core measurements of ^{10}Be cosmogenic isotopes (see Edouard Bard et al., "Solar Irradiance during the Last 1200 Years Based on Cosmogenic Nuclides," *Tellus* B [2000], LII, 985–992; Jürg Beer, W. Mende, and R. Stellmacher, "The Role of the Sun in Climate Forcing," *Quaternary Science Reviews,* XIX [2000], 403–415).

Figure 3B Tree-ring width from Büntgen et al., "2500 Years of European Climate Variability and Human Susceptibility," *Science,* CCCI (2011), 578–582; maximum lakewood density from Büntgen et al., "Summer Temperature Variations in the European Alps, AD 755–2004," *Journal of Climate* XIX (2006), 5606–5623.

Figure 3C See Isabelle Larocque-Tobler et al., "Thousand Years of Climate Change Reconstructed From Chironomid Subfossils Preserved in Varved Lake Silvaplana, Engadine, Switzerland," *Quaternary Science Review,* XXIX (2010), 1940–1949.

Figure 3D See Crowley, "Causes of Climate Change over the Past 1000 Years."

Figure 3E See Wilfried Haeberli and Hanspeter Holzhauser, "Alpine Glacier Mass Changes during the Past Two Millennia," *Pages News,* I (2003), 13–15.

Glacial retreats comparable to the most recent one have been reconstructed for medieval times. However, cumulative tongue-length fluctuations of the Great-Aletsch, and several other Alpine glaciers, resembling low-frequency temperature variations and thus contributing to our understanding of past amplitude ranges, are attended with a high level of causal uncertainty. Nevertheless, the Great-Aletsch glacier, the largest and best-documented glacier in the world, possesses a long history of advances and retreats recorded by radiocarbon and tree-ring dating, moraine investigations, and annual measurements since 1892, has subsequently allowed a unique mass-balance model to be developed. Even more fascinating is the sampling of (ideally *in-situ*) stumps that attest to formerly overridden forests, artifacts of recently retreating glacial tongues across the Alpine arc (see Figure 4).[13]

13 Holzhauser, "Dendrochronologische Auswertung fossiler Hölzer zur Rekonstruktion der nacheiszeitlichen Gletschergeschichte," *Schweiz Z Forstwes,* CVIII (2002), 17–28; Kurt Nicolussi et al., "Holocene Tree-Line Variability in the Kauner Valley, Central Eastern Alps, Indicated By Dendrochronological Analysis of Living Trees and Subfossil Logs," *Vegetation History and Archaeobotany,* XVI (2005), 221–234; Johannes Oerlemans, "Extracting a Climate Signal from 169 Glacier Records," *Science,* CCCVIII (2005), 675–677; Haeberli and Holzhauser, "Alpine Glacier Mass Changes"; Hoelzle et al., "Secular Glacier Mass Balances"; Holzhauser, Michel Magny, and Heinz J. Zumbühl, "Glacier and Lake-Level Variations in West-Central Europe over the Last 3500 Years," *The Holocene,* XV (2005), 789–801.

Fig. 4 Collecting Disc Samples from Subfossil Wood Recently Released by the Morteratsch Glacier in the Southeastern Swiss Alps, Canton Grison


NOTE   Photograph kindly provided by M. Schmidhalter, Dendrolab-Valais, Brig, Switzerland. Location of the 1850s side moraine and the glacier tongue indicates the massive ice loss during the last 160 years. For more information about Alpine glacial dynamics, see Frank Paul, Holger Frey, and Raymond Le Bris, "A New Glacier Inventory for the European Alps from Landsat TM Scenes of 2003: Challenges and Results," *Annals of Glaciology,* LII (2011), 144–152.

REMAINING UNCERTAINTIES   The examples presented herein, despite their signfcance, are not comprehensive enough to draw anything close to a complete picture of past temperature variability, neither for the globe and the Holocene nor for Europe and the last millennium. Yet, these data easily demonstrate the difficulty of defining a single universal corset that suits the LIA, not only for different continents but also for the various regional proxy records with their seasonal offsets. Uncertainty about the different archives and their methodological treatment further complicates our understanding of the LIA.[14]

14   Bradley and Jones, "'Little Ice Age' Summer Temperature Variations"; Matthews and Briffa, "Little Ice Age"; Jones et al., "High-Resolution Palaeoclimatology of the Last Millennium"; Mann, "Little Ice Age."

Fig. 5 Current Limitations Affecting The Improvement Of Millennium-Long Temperature Reconstructions
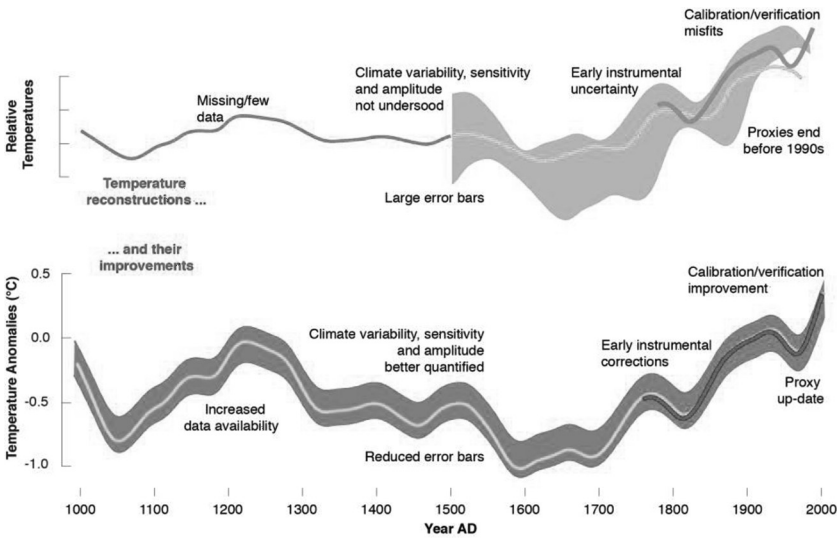
A wide range of palaeoclimatic proxy bias usually results from the data used and the methods applied, or from a combination thereof (see Figure 5). In disentangling natural and anthropogenically induced climate variability during the last millennium, the main task is to improve the existing multi-proxy reconstructions and to build new ones. This approach, the advantages of which compensate for the disadvantages inherent in the individual archives, is, in our opinion, highly valuable, promising a deeper insight into the nature of the LIA and its climatological surroundings during medieval and recent times.

The association between proxy records and their instrumental targets can have a significant effect on a reconstructed climate history. In this regard, Frank et al.'s discussion of a systematic tree-ring underestimation of early instrumental temperatures challenged our general understanding of the relationship between dendro-proxy and instrumental-target data. Moreover, Frank et al. introduced meaningful corollaries to the interpretation of climate variability

during both instrumental and pre-instrumental times: First, removing the biological age trend while simultaneously retaining the relevant climatic information is challenging, especially the long-term cooling trends, since cooling conditions and age trends both result in narrower ring widths in temperature-sensitive tree-ring data. The Regional Curve Standardization (RCS) method overcomes the low-frequency limitations inherent in age-trend estimations derived for each individual tree-ring series, but it could introduce other biases. Second, annual-growth variations, particularly evident in radial increments, often reflect a previous year's conditions. Related feedback or physiological non-linearity may shift the spectral properties of the inferred climatic variable from a "whiter" to a "redder" process (see note). Third, the choice of proper target season, climatic variable, and instabilities is crucial, given that it is the relative mixture of separate environmental variables that drives tree-growth over time.[15]

Moreover, the quantity of instrumental data does not remain stable over time. Generally, datasets become more and more sparse and less spatially representative the further back into the past that they go. Changes in data quantities directly affect the signal quality of any mean and its local variance, reducing possibilities for independent comparisons and verification. Last but not least, observational data can contain much nonclimatic noise caused by changes in station locations, instruments, viewing screens, recording times, observers, algorithms for the calculation of means, and other conditions at the site of measurement. Errors from these sources generally are not randomly distributed either in time or in direction.

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15   Jan Esper et al., "Effect of Scaling and Regression on Reconstructed Temperature Amplitude for the Past Millennium," *Geophysical Research Letters,* XXXI (2005), doi:10.1029/2004GL021236; *idem* et al., "Climate: Past Ranges and Future Changes," *Quaternary Science Reviews,* XXIV (2005), 2164–2166; Büntgen et al., "Summer Temperature Variations"; Frank, Büntgen, et al., "Warmer Early Instrumental Measurements versus Colder Reconstructed Temperatures: Shooting at a Moving Target," *Quaternary Science Reviews,* XXVI (2007a), 3298–3310. Regarding the matter of a "white" vs. a "red" process, a variance spectrum expresses the amount of variance in a time series that occurs at different frequencies or in different time scales. A white spectrum has equal variance in all time scales, whereas a red spectrum has greater variance in longer time scales than in shorter time-scales. A typical temperature record has a red variance spectrum, whereas a typical precipitation record should have a more white spectrum. The variance spectrum of a drought record, however, likely represents something in the middle; it combines signals from temperature as well as precipitation.

Long-term variance changes may cause additional amplitude shifts and spurious extremes.[16]

These cases exacerbate the difficulty of properly calibrating annually resolved and decisively dated archives to a dense and widespread set of reliable instrumental measurements. The situation, however, further weakens when the proxy records are of low resolution or the quality and quantity of the target network become less reliable, causing an often low level of explained variance, and the degree of freedom, to decrease even further. The upshot is that the long-term amplitude range of past changes in temperature remains poorly understood, and even greater uncertainties haunt changes in precipitation. The individual spatial domains of the different proxy records are vaguely defined, and the data are far too scanty to reflect large-scale dynamics in climate realistically, particularly for the Southern Hemisphere.[17]

Particularly worrisome is a simple assessment procedure that would define the quality of a "new" palaeoclimatic record by its ability to deliver higher temperatures for the medieval and recent periods than for the intervening period. Such an unscientific selection process would result in circular reasoning, greatly hampering our understanding of the earth's climate history. Any novel study that provides unique proxy and target data and thus independently helps to reduce the large body of uncertainty in climate reconstructions is a welcome contribution, even if it does not exactly fit a previous model.

The discussion of methodologies and findings herein strongly militates against the notion that palaeoclimatic evidence for the LIA is

16   Frank, Esper, and Cook, "Adjustment for Proxy Number and Coherence in a Large-Scale Temperature Reconstruction," *Geophysical Research Letters,* XXXIV (2007), doi: 10.1029/2007GL030571.
17   Esper, "Climate: Past Ranges and Future Changes"; Yemane Asmerom et al, "Multi-decadal to Multicentury Scale Collapses of Northern Hemisphere Monsoons over the Past Millennium," *Proceedings of the National Academy of Science,* CX (2013), 9651–9656; Armin Bunde, Büntgen, et al., "Is There Memory in Precipitation?" *Nature Climate Change,* III (2013), 174–175; Jörg Franke et al., "Spectral Biases in Tree-Ring Climate Proxies," *Nature Climate Change* (2013), doi: 10.1038/NCLIMATE1816; Cook et al., "North American Drought: Reconstructions, Causes, and Consequences," *Earth-Science Reviews,* LXXXI (2007), 93–134; Nicholas E. Graham et al., "Support for Global Climate Reorganization during the 'Medieval Climate Anomaly,'" *Climate Dynamics,* XXXVII (2007), 1217–1245; PAGES 2k Consortium, "Continental-Scale Temperature Variability."

lacking. By reviewing a rich body of regional- to large-scale temperature reconstructions that span from the last millennium to almost the entire Holocene, we confirm the existence of several temperature depressions that occurred at different intensities and spatial ranges between c. 1350 and 1900, thus supporting the conception of an LIA. Nonetheless, by stressing the genuine uncertainties that continue to surround paleoclimatic study, this comment is intended to suggest priorities for further research about the LIA and refinement of the state of the art.