

## Recognising bias in Common Era temperature reconstructions

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### ARTICLE INFO

#### Keywords:

Climate variation

Common Era

IPCC

Large-scale network

Multi-proxy reconstruction

Science communication

Tree rings

### ABSTRACT

A steep decline in the quality and quantity of available climate proxy records before medieval times challenges any comparison of reconstructed temperature and hydroclimate trends and extremes between the first and second half of the Common Era. Understanding of the physical causes, ecological responses and societal consequences of past climatic changes, however, demands highly-resolved, spatially-explicit, seasonally-defined and absolutely-dated archives over the entire period in question. Continuous efforts to improve existing proxy records and reconstruction methods and to develop new ones, as well as clear communication of all uncertainties (within and beyond academia) must be central tasks for the paleoclimate community.

Since its foundation in 1991 by the United States and Swiss National Science Foundations, PAGES (Past Global Changes) provides support for the gathering and synthesis of observations, reconstructions, and the modelling of past climate, ecosystem, environmental and societal

dynamics. Resulting collaborations, datasets and publications became valuable benchmarks in paleoclimatology and global climate change research. Among many other advantages, PAGES offers unique opportunities for early career researchers and interdisciplinary studies. One of

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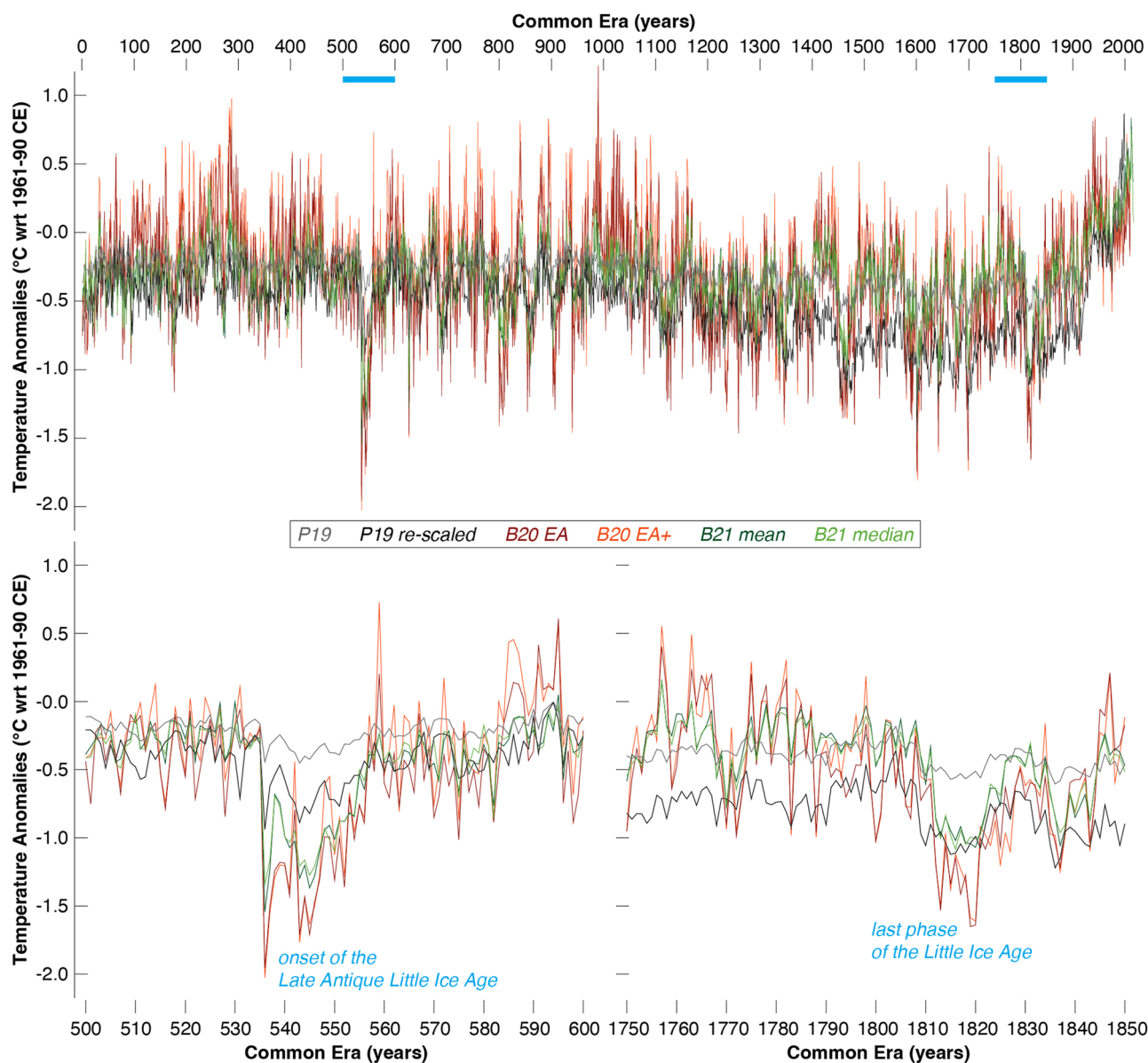
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<https://doi.org/10.1016/j.dendro.2022.125982>

Received 20 May 2022; Received in revised form 22 June 2022; Accepted 24 June 2022

Available online 27 June 2022

1125-7865/© 2022 Published by Elsevier GmbH.



**Fig. 1.** The Common Era: a paleoclimate game of two halves. Comparison of six Common Era temperature reconstructions, with foci on the onset of the Late Antique Little Ice Age (LALIA) in the 530 s and the last phase of the Little Ice Age (LIA) in the early 19th century that were both triggered by large volcanic eruptions. The figure further emphasises that annual resolution of a proxy is not a reliable criterion for its ability to capture climate information for a given year because of possible age biases outside the stated age uncertainties, which in the case of ice cores from Greenland and Antarctica, as included in P19, may range in the order of a decade or even several centuries (Sigl et al., 2014, 2015; Baggenstos et al., 2018), respectively. P19 = full ensemble median by PAGES 2k Consortium (2019), P19 re-scaled = full ensemble median by PAGES 2k Consortium (2019) scaled against mean 30–70°N landmass June–August temperatures, B20 = Eurasian mean by Büntgen et al. (2020), B20 EA+ = Eurasian and North American mean by Büntgen et al. (2020), B21 mean = ensemble mean by Büntgen et al. (2021), B21 median = ensemble median by Büntgen et al. (2021).

the flagship products is undoubtedly the latest PAGES 2k reconstruction of global mean surface temperature for the past 2000 years (PAGES2k Consortium, 2019; hereinafter P19), which applied seven different statistical reconstruction methods on the same proxy and calibration datasets (Cowtan and Way, 2014; PAGES2k Consortium, 2017).

Despite community-wide agreement that multi-proxy compilations are the most appropriate methodology to climate reconstructions, consensus around the limitations of the data used and methods applied has yet to be reached (e.g., Büntgen et al., 2021; Esper and Büntgen, 2021; Anchukaitis and Smerdon, 2022; Esper et al., 2022). This is of particular concern for P19 that has been exclusively selected by and prominently featured in the current Sixth Assessment Report from Working Group I of the Intergovernmental Panel on Climate Change and its most relevant Summary for Policy Makers (IPCC, 2021a, 2021b).

While we acknowledge the enlightening reassessment of reconstruction intercomparison by Neukom et al. (2022, hereinafter N22) and admit previous scaling issues (i.e., Büntgen et al., 2020), we must emphasise three points that are directly related to both N22 and P19 (on which N22 is primarily based). Firstly, a large-scale network composed predominantly of biological proxies located between 45° and 60° northern latitude favours an extra-tropical Northern Hemisphere warm season temperature reconstruction rather than the global annual mean. Secondly, a decline in the quality (archive resolution and dating precision) and quantity (sample replication and spatial distribution) of proxy records back in time not only affects the reconstructed temperature variance but also increases the associated uncertainty range. Thirdly, simply re-scaling proxy timeseries against different meteorological target datasets over different spatiotemporal domains may change their

**Table 1**

Common Era temperature extremes. Comparison of the ten warmest and coldest annual extremes in six Common Era temperature reconstructions (see Fig. 1 for details). The reconstructed values show that re-scaling alone does not change the data structure (i.e., the order of P19 and P19 re-scaled is almost identical), and that the multi-proxy reconstructions do not capture the extremes in the first half of the Common Era, such as the late Roman and early medieval warm periods and the Late Antique Little Ice Age (i.e., the warmest years of P19 and P19 re-scaled occurred since 1989 and their coldest years fall between 1455 and 1836 CE).

Warmest Reconstructed Years/Summers of the CE (°C)						Coldest Reconstructed Years/Summers of the CE (°C)					
P19	P19 re-scaled	B20 EA	B20 EA+	B21 mean	B21 median	P19	P19 re-scaled	B20 EA	B20 EA+	B21 mean	B21 median
1998 0.44	1998 0.87	990 1.21	990 1.22	2012 0.84	2012 0.75	1474 -0.59	1474 -1.18	537 -1.50	537 -1.55	1642 -1.12	1642 -1.11
1994 0.35	1994 0.68	1942 0.82	287 0.98	2013 0.67	2013 0.67	1643 -0.59	1466 -1.18	1813 -1.53	1819 -1.59	544 -1.20	627 -1.13
1997 0.31	1997 0.62	1938 0.81	282 0.91	2003 0.66	2005 0.57	1701 -0.60	1701 -1.19	1642 -1.56	1642 -1.60	1601 -1.21	537 -1.16
1999 0.30	1999 0.56	284 0.77	284 0.89	2006 0.62	2003 0.56	1456 -0.60	1456 -1.19	1820 -1.64	1601 -1.60	1602 -1.22	544 -1.16
1991 0.28	1991 0.54	1020 0.75	1942 0.84	2005 0.58	2014 0.55	1705 -0.60	1602 -1.19	1819 -1.65	1820 -1.61	537 -1.23	1602 -1.19
2000 0.28	2000 0.52	287 0.75	894 0.83	2007 0.53	2006 0.54	1455 -0.60	1455 -1.21	1699 -1.66	545 -1.63	627 -1.28	1601 -1.20
1996 0.24	1996 0.48	1027 0.72	840 0.81	2008 0.51	2010 0.52	1836 -0.61	1836 -1.22	545 -1.71	1699 -1.73	546 -1.28	543 -1.21
1990 0.24	1990 0.45	895 0.71	759 0.81	1998 0.50	2007 0.44	1641 -0.61	1641 -1.24	543 -1.71	543 -1.77	543 -1.30	546 -1.21
1995 0.23	1995 0.44	1061 0.70	895 0.78	2001 0.49	2008 0.44	1699 -0.67	1699 -1.30	1601 -1.75	1602 -1.81	545 -1.37	545 -1.27
1989 0.20	1989 0.37	1964 0.70	705 0.78	2014 0.48	246 0.40	1601 -0.71	1601 -1.46	536 -1.95	536 -2.02	536 -1.54	536 -1.34

overall amplitude but not their internal structure of trends and extremes (Fig. 1; Table 1).

All these issues of spatial coverage and seasonal response, archive resolution and dating uncertainty, as well as proxy scaling and climate sensitivity have been raised previously by Hughes and Diaz (1994), Bürger and Cubasch (2005), Frank et al. (2010), Sigl et al. (2015) and Klippel et al. (2020), and most recently again by Büntgen et al. (2021), Esper and Büntgen (2021) and Plunkett et al. (2022); none of them cited in N22. Furthermore, we argue that it is not enough to evaluate past temperature changes on decadal time-scales when aiming to better understand the *i*) relative roles of external climate forcing factors, including volcanic eruptions, changes in solar radiation and greenhouse gases, *ii*) importance of internal climate dynamics, and *iii*) direct and indirect effects of the full range of climate variability on ecological, agricultural and societal systems, for which precisely-dated and fully-preserved year-to-year variation is critical (Sigl et al., 2015; Büntgen and Oppenheimer, 2020; Büntgen et al., 2022; Plunkett et al., 2022).

Given agreement that no climate reconstruction is perfect and effective communication of the remaining uncertainties must continue, we propose that the IPCC considers for future reports inclusion of a dedicated chapter on paleoclimate, as well as representation of a variety of independent temperature histories rather than selection of a single product.

**Declaration of Competing Interest**

The Authors declare no conflict of interest.

**Acknowledgements**

U.B. and J.E. received funding from SustES (CZ.02.1.01/0.0/0.0/16.019/0000797) and ERC (AdG 882727), and U.B., F.C.L., C.O., M.S. and J.E. discussed issues of this article at the second workshop of the Cooperation Group ‘Volcanoes, Climate and History’ at ZiF Bielefeld (9–13 May 2022). Two anonymous referees commented on a previous version of this manuscript.

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