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Progress and uncertainties in global and hemispheric temperature reconstructions of the Common Era

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ABSTRACT

Global and hemispheric temperature reconstructions provide an important means of placing recent anthropogenic temperature trends in the context of preindustrial climate variations and evaluating their causes. As new reconstructions have been developed and estimates of past climate have been refined, results continue to show that by the late 20th century temperatures very likely exceeded those of any time in at least the last millennium. Despite progress over the last two decades, however, there remain persistent uncertainties with regard to, *inter alia*, first millennium temperatures at global and annual scales, the magnitude of multidecadal to millennial-scale changes and their causes, and the surface temperature response to volcanic eruptions. We review the strengths and limitations of existing global and hemispheric paleoclimate temperature reconstructions and highlight likely sources of extant uncertainties, all in the context of the recent Sixth Assessment Report from Working Group I of the Intergovernmental Panel on Climate Change. Based on our review of these factors, we provide recommendations for using, interpreting, and improving large-scale temperature reconstructions.

1. Introduction

Annual or seasonal paleoclimate reconstructions spanning the last 2000 years — the Common Era — provide a long-term and high-resolution perspective on the Earth's climate trajectory that is not otherwise available from the relatively short instrumental record (Mann and Jones, 2003; Jones et al., 2009; Frank et al., 2010; Christiansen and Ljungqvist, 2012, 2017; Smerdon and Pollack, 2016; Turney et al., 2019). Among the many types of reconstructions now available, here we focus specifically on global or hemispheric (henceforth ‘large-scale’) temperature reconstructions with annual to decadal resolution. These large-scale temperature reconstructions give a longer-term context to, and thus better characterization of, the global temperature changes that have been caused by anthropogenic greenhouse gas emissions since the beginning of the industrial era (Schurer et al., 2017; Hawkins et al., 2017). They also provide important information about the complete range of temperature extremes, improve the characterization of climate variability on interannual to millennial time scales, and quantify the response and sensitivity of the climate system to changes in radiative forcing (e.g. Hegerl et al., 1997, 2003, 2007; Jones et al., 2009; PAGES2k, 2013; Ault et al., 2013; Fernández-Donado et al., 2013; Stoffel et al., 2015; PAGES 2k-PMIP3 group, 2015; Abram et al., 2016; Turney et al., 2019; Parsons and Hakim, 2019). Large-scale temperature reconstructions are nevertheless created almost exclusively from proxy data — including tree-rings, corals, ice cores, speleothems, and marine and lake sediments — each of which contain various biases in how they record temperatures, are heterogeneously sampled through time and space, and need to be statistically calibrated against instrumental data to provide estimates of past climate. These factors infuse Common Era temperature reconstructions with uncertainties that are inherent to the indirect representation of past climate by imperfect biological, physical, and geochemical archives, as well as from specific seasonal biases in proxy sampling of past climate, the relatively sparse availability of proxies in both space and time, and the wide range of statistical methods and assumptions used to transform a diverse set of proxy data into quantitative estimates of past temperatures.

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Perhaps because of these uncertainties, there remains a perennial debate about the reliability of large-scale Common Era temperature reconstructions, about whether the range of uncertainties are appropriately quantified in existing estimates, and consequently about the evaluation of contemporary temperature trends against periods of warm and cold epochs during the Common Era. We use the occasion of the recent publication of Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) to revisit this debate. We provide an assessment of the current understanding of the uncertainties and challenges of large-scale temperature reconstructions over the Common Era and propose some basic guidelines for interpreting and enhancing their reliability and utility. We place this effort in the context of past IPCC reports and the most recent assessment provided in AR6, the latter of which focused on a single estimate of global mean annual temperatures during the Common Era (IPCC, (2021); their Figure SPM.1). Our motivation is to provide an overview of the state of the science that goes beyond the simple characterizations of the broad features of the large-scale temperature history over the last two thousand years.

2. History and progress

In 2001, the Summary for Policymakers for the Third Assessment Report (TAR) of the IPCC (Albritton et al., 2001) prominently highlighted the last millennium temperature reconstruction – the so-called ‘Hockey Stick’ – developed by Mann et al. (1999) (Fig. 1a). Although several earlier efforts to estimate large-scale past temperatures from proxy data had been made (e.g. Groveman and Landsberg, 1979; Jacoby and D'Arrigo, 1989; D'Arrigo and Jacoby, 1993), the spatiotemporal reconstruction by Mann et al. (1998) was the first attempt to reconstruct global temperatures over six centuries of Earth history using reduced-space empirical orthogonal function methods (Fritts et al., 1971; Cook et al., 1994). A year later, Mann et al. (1998) was extended to estimate the complete last millennium (Mann et al., 1999), although only the Northern Hemisphere mean was reconstructed. Mann et al. (1999) relied on a relatively sparse network of climate sensitive proxy records to estimate past temperatures prior to 1400, many of these directly sensitive to hydroclimate instead of temperature, and the uncertainties were therefore quite large between 1000 and 1400 CE (Fig. 1a). Beyond the Summary for Policymakers, other chapters of the TAR discussed additional large-scale temperature reconstructions and evidence for exceptional 20th century warmth (Folland et al., 2001), including those by Jones et al. (1998), Pollack et al. (1998), and Briffa (2000).

Over the next two decades, the paleoclimate community refined estimates of large-scale temperature variability, challenged existing efforts, and innovated new approaches to climate reconstruction, including the adoption and testing of new statistical methods (c.f. Schneider, 2001; Esper et al., 2002; Li et al., 2010; Tingley and Huybers, 2013; Hanhijärvi et al., 2013; Evans et al., 2013; Hakim et al., 2016; Gómez-Navarro et al., 2017; Christiansen and Ljungqvist, 2017), the development of new proxy records and the expansion of existing networks (McCarroll et al., 2002; Jones et al., 2009; Rydval et al., 2014; Emile-Geay et al., 2017; Christiansen and Ljungqvist, 2017; St. George and Esper, 2019; Wilson et al., 2019; Björklund et al., 2019; Pearl et al., 2020; Heeter et al., 2021), and a close examination of the sensitivity of reconstructions to assumptions and proxy biases (Frank et al., 2010; Smerdon and Pollack, 2016; Anchukaitis, 2017). Although this process was frequently public and occasionally acrimonious (e.g. Smerdon and Pollack, 2016; Zorita, 2019), both the Fourth (AR4) and the Fifth (AR5) Assessment Report of the IPCC (Jansen et al., 2007; Masson-Delmotte et al., 2013) considered over a dozen credible yet diverse estimates of past Northern Hemisphere and global mean temperatures. Comparative plots of these reconstructions were used to show their range of estimates and their overlap was used to illustrate periods of agreement as well as remaining uncertainties (Fig. 1b and c). There were indeed still substantial periods of disagreement even in 2013 (Masson-Delmotte et al., 2013), particularly in the magnitude of low-frequency variability, the trajectory and magnitude of Medieval temperature anomalies, and the response of the climate system to volcanic eruptions (D'Arrigo et al., 2013; Fernández-Donado et al., 2013; Smerdon and Pollack, 2016).

Despite the attempts in AR4 and AR5 to reflect uncertainties across multiple reconstruction efforts and to represent time-dependent uncertainties as they expanded back in time, these efforts were surprisingly abandoned in the most recent AR6 Working Group I (WG1) report in favor of a single ensemble-based reconstruction of global temperature with relatively static uncertainty bounds over the Common Era (PAGES 2k Consortium, 2019; IPCC, 2021; Gulev et al., 2021; Eyring et al., 2021, see AR6 WG1 Figures SPM.1, 2.11a, and 3.2c). The most recent assessment (Fig. 1d) is thus a turn away from the attempts in previous reports to provide a full accounting of uncertainty in reconstruction efforts (Frank et al., 2010; Smerdon and Pollack, 2016), an incomplete representation of forward progress in both understanding and quantifying disagreement in temperature reconstructions of the Common Era, and is an unnecessary return to a singular representation of large-scale temperature estimates that span all or part of the last several millennia.

3. Strengths and limitations of Common Era reconstructions

The different types of proxy data and the range of statistical methods that are used to reconstruct past climate all have their advantages and disadvantages. The extent to which Common Era temperature estimates can be considered reliable depends both on the specific research question they are used to address and how the strength of any climatic inference is affected by the inherent uncertainties. Despite progress over the last two decades, many challenges remain. Of the many causes of uncertainty in Common Era temperature reconstructions, we consider the most important to be: the space and time availability (or lack therefore) of proxy data, the mix of different proxies and their individual biases, and the sensitivity to methodological choices in statistical approaches to reconstruction. While ensemble-based approaches such as PAGES 2k Consortium (2019) and Büntgen et al. (2021) do attempt to address some of these uncertainties, all of them continue to affect efforts to accurately and precisely estimate Common Era temperatures at local to global scales.

3.1. Spatial distribution and temporal extent

The paleoclimate proxies available for reconstruction of Common Era temperatures have important spatial and temporal biases in their availability, seasonality, and climate response. For the most recent six centuries, a well-replicated network of thousands of tree-ring time series provide information about past climates, particularly at mid- and high-latitudes in North America, Europe and Asia (St. George, 2014). The majority of these chronologies are moisture sensitive, but high elevation and high latitude tree-ring chronologies, particularly those using the latewood maximum density (MXD) proxy, are available for skillful temperature reconstructions (Esper et al., 2015, 2016, 2018; Stoffel et al., 2015; Schneider et al., 2015; Guillet et al., 2017; Anchukaitis et al., 2017). Fewer tree-ring chronologies are available in the tropics and in the Southern Hemisphere, although temperature sensitive sites have been

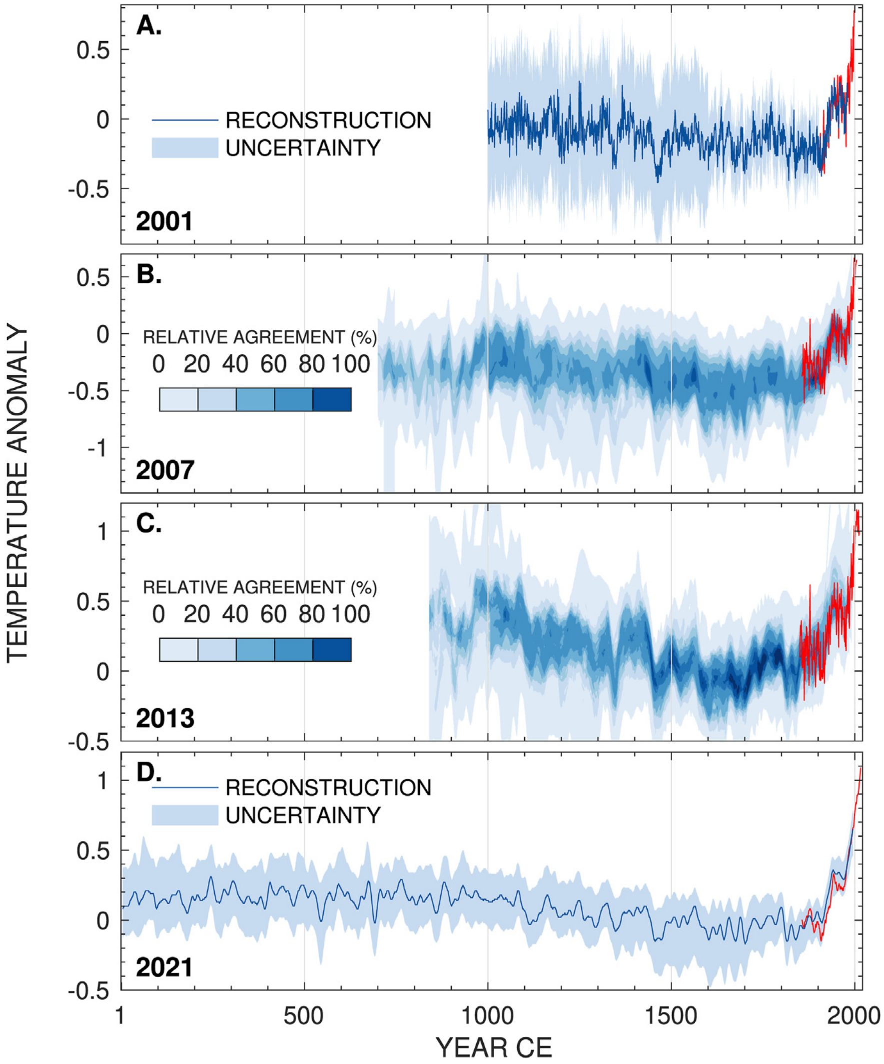

Fig. 1. Large-scale temperature reconstructions featured in IPCC reports since 2001. (A) Northern Hemisphere annual mean temperature reconstruction by Mann et al. (1999) as featured in the IPCC Third Assessment Report WG1 Summary for Policymakers (Fig. 1b; Albritton et al., 2001). Instrumental data in red are from Jones and Briffa (1992). (B) Overlapping range of agreement for 10 of the reconstructions assessed in the Fourth Assessment Report (AR4) (Figure 6.10c; Jansen et al., 2007) expressed as anomalies from their 1961 to 1990 mean. The corresponding instrumental data plotted in red are from HadCRUT v2 (Jones and Moberg, 2003). (C) Overlapping range of agreement for 15 of the reconstructions assessed in the Fifth Assessment Report (AR5) (Masson-Delmotte et al., 2013), expressed as anomalies from their 1500 to 1850 mean. The original AR5 figure (Figure 5.8a) did not include overlapping instrumental data, but for illustrative purposes we plot the contemporaneous instrumental HadCRUT v4 (Morice et al., 2012) for the Northern Hemisphere used elsewhere in the AR5 chapter and adjusted upward by 0.27C to match the overlapping paleoclimate data (Masson-Delmotte et al., 2013). (D) Global mean annual temperature reconstruction by PAGES 2k Consortium (2019) featured in the Summary for Policy Makers of the Sixth Assessment Report (AR6) Working Group 1 (Figure SPM.1; IPCC, 2021) including the overlapping and smoothed global mean surface temperature data from Gulev et al. (2021) in red.(For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

identified in the Andes, Tasmania, and New Zealand (Lara and Villalba, 1993; Cook et al., 2000; Mann and Jones, 2003; Jones et al., 2009; Neukom and Gergis, 2012; Esper et al., 2016; Allen et al., 2019). Corals provide critical and high signal-to-noise information about sea surface temperatures in the tropical oceans, but are comparatively short lived, providing robust information only over recent centuries (Tierney et al., 2015; Thompson, 2021), except in cases where fossil corals provide estimates over earlier time slices of the Common Era (e.g. Cobb et al., 2003; Dee et al., 2020). In the first millennium of the Common Era, a reduction in the number of available tree-ring chronologies leads to an increased importance for sediment records and ice cores in multiproxy temperature reconstructions (Fig. 2a; Emile-Geay et al., 2017). This shift through time results not only in a change in proxy type, but also a shift in the extent and geographic distribution of proxies (Fig. 2b).

Declining proxy availability, particularly during the first millennium of the Common Era, is the dominant control on the potential length of large-scale reconstructions. For instance, Cook et al. (2013) confined their tree-ring reconstruction of Asian summer temperatures from tree-ring chronologies to the period from 800 to 1989 CE due to the paucity of older data. Those authors further expressed reservations about the reliability of the reconstruction even prior to 1250 CE. Of the original PAGES2k continental-scale temperature reconstructions, only the Arctic and European domains covered the full Common Era (PAGES2k, 2013). Many recent reconstructions of temperature from the relatively proxy-rich Northern Hemisphere extratropics have only extended back to between the 6th to 8th centuries (Schneider et al., 2015; Stoffel et al., 2015; Wilson et al., 2016; Guillet et al., 2017; Anchukaitis et al., 2017), limited by the availability of tree-ring records. Indeed, relatively few temperature-sensitive tree-ring chronologies are available for the entire Common Era and of those,

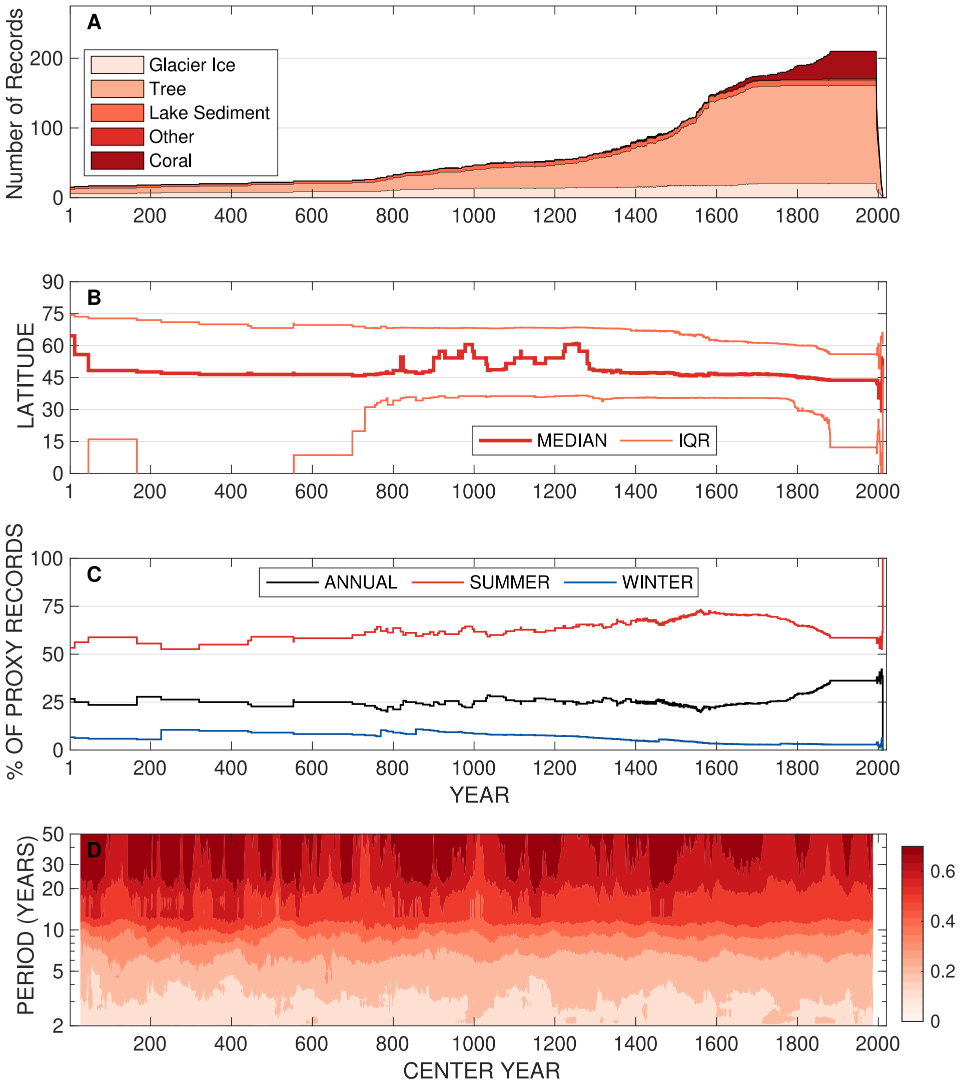

Fig. 2. Spatial and temporal characteristics of the 210 annual resolution proxies used in the global annual temperature reconstruction by PAGES 2k Consortium (2019) featured in the IPCC AR6 (IPCC, 2021; Eyring et al., 2021). (A) The types and sample depth of the nominally annual and temperature-sensitive proxies as selected by PAGES 2k Consortium (2019) from the full PAGES2k database (Emile-Geay et al., 2017). (B) The median latitude of the available annual proxies through time as well as the interquartile latitude range (IQR). (C) The percentages of annual proxies available in the PAGES 2k Consortium (2019) reconstruction in each year grouped by their seasonality as recorded in the PAGES2k database (Emile-Geay et al., 2017). The 'Annual' category includes records that span all or most of a 12-month period (including both calendar or tropical year) or have subannual resolution (largely corals) that can be averaged to obtain an annual signal (Tierney et al., 2015); 'summer' records are those with a boreal summer or Northern Hemisphere growing season sensitivity, and 'winter' are those records with a boreal winter or Southern Hemisphere growing season sensitivity. A small number of annual proxy records ($n = 3$) had seasonal climate responses in the database that did not clearly fall within these categories. (D) The mean proxy spectrum for those annual records available (in panel A) in overlapping consecutive 50-year periods using the multitaper method (Thomson, 1982). The individual records were normalized [0,1] prior to estimating their spectra.

only one comprises exclusively MXD data, the preferred proxy measurement for temperature reconstruction (Esper et al., 2016, 2018; Büntgen et al., 2021).

Lower-resolution and time-uncertain proxy records are therefore critical for temperature reconstructions prior to the last millennium. In the Arctic, a mix of tree-ring chronologies over recent centuries and longer records from sediments and ice cores provide a 2000 year perspective (McKay and Kaufman, 2014). Across Antarctica, several ice-core stable isotope records cover the complete span of the Common Era (Stenni et al., 2017). Marine sediment records provide typically centennial-scale resolution over the last 2000 years (McGregor et al., 2015), and both marine and lake sediments add important proxy data in the tropics (e.g. Nicholson et al., 2013; Dixon et al., 2017). These lower-resolution and time-uncertain records nevertheless have their own limitations on late-Holocene timescales. Many cannot be directly calibrated against instrumental records and both resolution and age uncertainties confound uncertainty estimation and spatial reconstructions. The lack of annual resolution also limits their utility for studying interannual variability, seasonal or annual extremes, and the climate response to volcanic eruptions.

More than two decades after the 'hockey stick' reconstruction was published (Mann et al., 1999; Albritton et al., 2001), many of the proxy-specific spatial and temporal sampling limitations faced by earlier investigators persist. While community efforts like PAGES2k (Emile-Geay et al., 2017) have yielded public databases of temperature-sensitive proxy data covering the last 2000 years, the number of records in the tropics and Southern Hemisphere and during the first millennium still remain quite limited. Furthermore, the change through time in not only the number of proxies but also the spatial coverage and proxy network composition imply there should be temporally dependent biases, with increased uncertainties in large-scale temperature estimates earlier in the Common Era as the network of available proxies declines in number and geographic coverage.

In the IPCC (2021), the global temperature reconstruction by PAGES 2k Consortium (2019) applies multiple methods to a 210 record subset of nominally annual resolution and temperature-sensitive proxy data collated by the PAGES2k consortium (Emile-Geay et al., 2017; Neukom et al., 2019) (Fig. 3). An additional 47 lower resolution or discontinuous records were identified as temperature sensitive, but could only be used by some of the reconstruction methods applied by PAGES 2k Consortium (2019). Fig. 2b shows the median and interquartile range (the 25th and 75th percentile) of the latitudes of the annual resolution records used over the Common Era. Throughout the last 2000 years, these proxy records are dominated by those in the Northern Hemisphere (Fig. 3). Coral records available over the most recent centuries (Fig. 2a) briefly pull the median toward the equator in the 19th and 20th centuries, and rapidly changing proxy number and type during the Medieval epoch (*sensu lato*, ca. 800 to 1300 CE) cause fluctuations in the median latitude of the remaining sites. Prior to 800 CE, as fewer than 30 annual records are used in the reconstruction, the interquartile range of latitudes widens, as the mix of records becomes split between lake sediments and glacial ice (including Antarctica ice cores) and the remaining tree ring records, the latter of which are still biased toward Northern Hemisphere sites (Fig. 3). The median latitude over the Common Era is 47°N (range, 29.35°N to 64.60°N) indicating that this global reconstruction is dominated throughout by Northern Hemisphere records.

3.2. Seasonality, spectral proprieties, and climate response

Although it is desirable from the perspective of understanding changes in planetary radiative balance and fundamental properties of the Earth system like equilibrium climate sensitivity (e.g. Hegerl et al., 2006), resolving global annual mean temperature remains a challenge. As described in the preceding section, there are important temporal dependencies in proxy availability, leaving some regions without sufficient paleoclimate data for robust reconstruction skill. But even where extension of temperature reconstructions is possible over the full Common Era, there are uncertainties related to the changing mix of available proxies and their seasonal climate response.

To what extent are differences in seasonality important in Common Era temperature reconstructions? McKay and Kaufman (2014) suggested that the mix of proxy seasonalities within Arctic

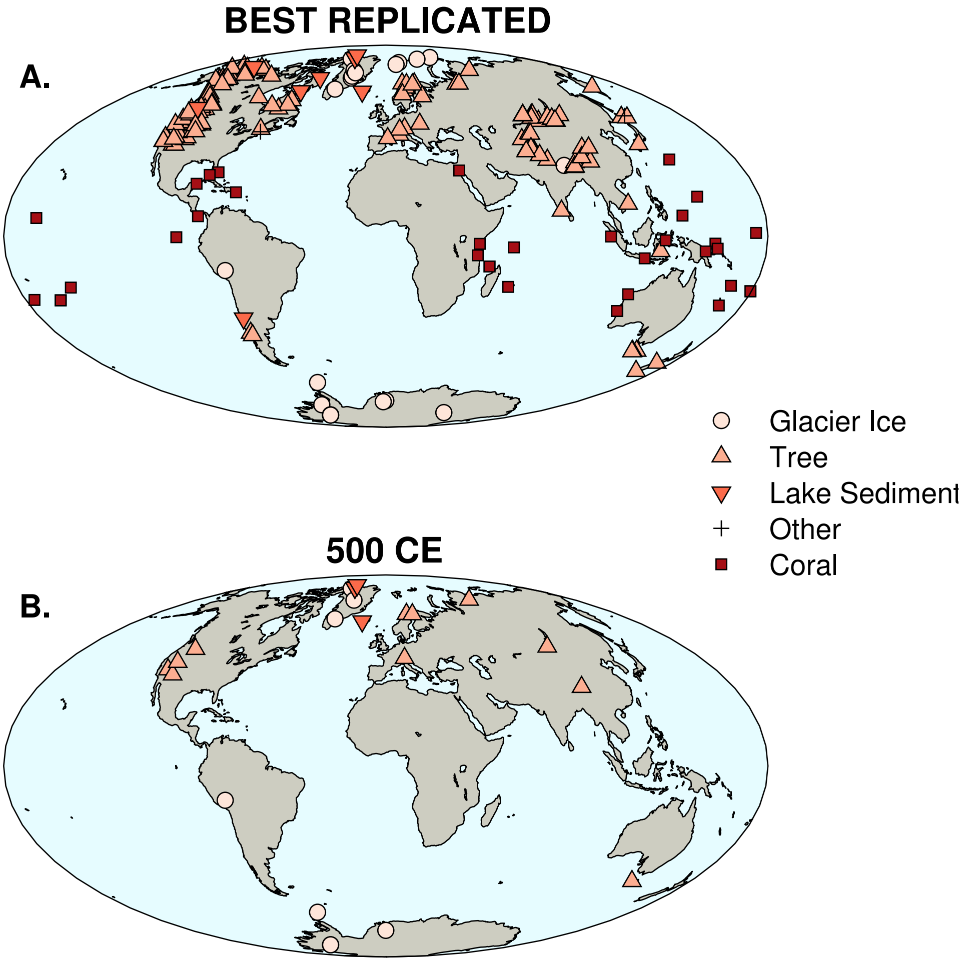

Fig. 3. Annual resolution proxy data available for all the global mean annual temperature reconstructions by PAGES 2k Consortium (2019) featured in the IPCC AR6 (IPCC, 2021; Eyring et al., 2021), which uses a subset of the temperature-sensitive database compiled by the PAGES2k consortium (Emile-Geay et al., 2017). (A) The proxy locations during the 20th century when the greatest number of proxies ($n = 210$) are available, and (B) the remaining annual proxies ($n = 22$) available in the year 500 CE. See also Fig. 2.

paleoclimate data resulted in an annual target as the optimal common signal, but there are reasons to be cautious in assuming that multiproxy data with a mix of seasonalities provides an accurate estimate of mean annual temperatures. While in the tropics there is a strong correlation between boreal summer (June through August temperature) and annual temperatures, over Northern Hemisphere land regions – where the majority of available Common Era proxy data are found – mean annual temperatures and summer temperatures are relatively weakly correlated ($r < 0.50$, Emile-Geay et al., 2017, their Figure S6). Summer-dominated proxies therefore may not reflect the range of variability or trends in annual temperatures. As Briffa and Jones (1993) warned the paleoclimate community nearly three decades ago, “Inferring annual temperature change on the basis of summer-responsive data is highly questionable.” This warning extends to inference about specific climate phenomena. For instance, at interannual timescales the signal of post-volcanic cooling is predominantly observed in the summer season, whereas winters may even warm over continents after eruptions (Robock, 2000), although this effect has also recently been questioned (Polvani et al., 2019; Polvani and Camargo, 2020). At longer timescales, orbitally-forced temperature signals have a different trend magnitude depending on season. Lücke et al. (2021) showed that temperature reconstructions dominated by proxy records sensitive to early summer temperatures would show different millennial-scale orbital trends compared to those reconstructions using proxies with primarily a late summer signal, which often includes the valuable tree-ring MXD proxy.

Kaufman et al. (2009) identified long-term millennial cooling trends in the Arctic over the Common Era that they linked to orbital forcing. McGregor et al. (2015) also found long-term cooling trends in low-resolution marine data, but attributed these trends to volcanic forcing using climate models. However, long-term cooling trends are muted or missing in many large-scale tree-ring and multiproxy reconstructions that extend into the first millennium (e.g. Mann et al., 2008; Kaufman et al., 2009; Esper et al., 2012; PAGES 2k Consortium, 2019). While this could in part be due to well-known detrending and standardization challenges associated with retaining the lowest frequency trends in tree-ring chronologies (Cook et al., 1995; Büntgen et al., 2021), it is possible to preserve millennial and orbital trends even in tree-ring data (Esper et al., 2002, 2012). Differences in the magnitude of cooling over the Common Era could therefore reflect a mix of causes, including declining proxy availability and a changing composition of proxy types in space and time, each with their own biases (e.g. Klippel et al., 2020; Lücke et al., 2021). Whatever the cause, the inconsistency in reconstructions and between proxy types in millennial-scale trends over the Common Era motivates caution when interpreting the magnitude of those pre-industrial temperature trends and inferences about the exact temperatures of the first millennium. Mixing proxies with different seasonalities has the potential to confound the reconstruction of climate variability at a range of timescales, from interannual to millennial (Briffa and Jones, 1993; Lücke et al., 2021).

The subset of PAGES2k (Emile-Geay et al., 2017) annual resolution proxies used in PAGES 2k Consortium (2019) are dominated by boreal summer and growing season signals throughout the Common Era (between 53% and 73% of records, Fig. 2b), in part reflecting the dominance of Northern Hemisphere tree-ring data in the second millennium. Proxies interpreted by Emile-Geay et al. (2017) as reflecting annual conditions account for between 19% and 42% of records. Boreal winter and austral summer records are a minority of the proxies available. The changing proxy mix also leads to a shift in the spectral properties of the available proxies over time (Fig. 2d). As a greater percentage of the proxy mix is represented by glacial ice, lake sediments, and tree-ring width records in the first millennium, the mean spectrum of the database shifts toward more low-frequency and reduced interannual variability. Note that this occurs even without considering the lower frequency records used in only some of the methods employed by PAGES 2k Consortium (2019), which would likely exacerbate this pattern. The dominance of Northern Hemisphere summer-sensitive proxies (Fig. 2b and c) reflects the overall greater availability of high-resolution records – particularly tree rings – at those latitudes. This spatial, temporal, spectral, and seasonal bias in available proxy data remains a persistent challenge for truly global annual temperature reconstructions (Esper and Frank, 2009).

One important topic where proxy-specific climate response and spectral properties have been shown to affect interpretations is in studies of temperature anomalies following large volcanic eruptions (Lücke et al., 2019). More than 30 years ago and using the tree-ring MXD proxy, Jones et al. (1995) and Briffa et al. (1998) showed rapid cooling in the Northern Hemisphere summer temperature sensitive tree-ring MXD network (Fig. 4a). Later reconstructions that used multiproxy and tree-ring width data, however, failed to show this abrupt cooling (Mann et al., 1999; D'Arrigo et al., 2006; Mann et al., 2008) (Fig. 4a and b). Mann et al. (2012) suggested this discrepancy was caused by universally missing rings induced by volcanic cooling, a theory that was subsequently shown to be unsupported (Anchukaitis et al., 2012; D'Arrigo et al., 2013; Esper et al., 2013b,a; St. George et al., 2013; Büntgen et al., 2014; Sigl et al., 2015; Büntgen et al., 2018). In contrast to the original Mann et al. (2012) conjecture, there is now strong evidence that the tree-ring width proxy reflects a muted and lagged volcanic cooling signal, while MXD from the same trees record the abrupt temperature decrease following eruptions (Frank et al., 2007; D'Arrigo et al., 2013; Esper et al., 2015; Schneider et al., 2015; Stoffel et al., 2015; Anchukaitis et al., 2017; Guillet et al., 2017; Lücke et al., 2019; Zhu et al., 2020) (Fig. 4b). While there are additional challenges when using tree-ring chronology networks to estimate past volcanic cooling (Anchukaitis et al., 2012; D'Arrigo et al., 2013; Neukom et al., 2018), a primary factor appears to be the availability of tree-ring MXD chronologies (Zhu et al., 2020). Even within a single archive like tree rings, different metrics can reflect different seasons. For instance, tree-ring width displays a range of seasonal temperature sensitivities depending on species and location, while MXD typically reveals a more confined sensitivity to summer or even late summer temperature (Briffa et al., 2002; Zhu et al., 2020). Reconstructions that include low-resolution or time-uncertain records can also show a damped response (Lücke et al., 2019, c.f. Fig. 4a), although some recent multiproxy reconstructions do show good agreement with tree-ring based estimates (Tejedor et al., 2021). Direct comparisons between proxy reconstructions and model simulations are also confounded by uncertainties in the timing and location of past volcanic eruptions, the exact radiative forcing associated with each eruption, the role of internal climate variability, and the accuracy of climate models in simulating important related atmospheric processes (Timmreck et al., 2009; LeGrande et al., 2016; Stevenson et al., 2017; Zambri et al., 2019; Toohey and Sigl, 2017; Zanchettin et al., 2019; Marshall et al., 2020, 2021).

3.3. *Methodological sensitivity*

The potential consequences of methodological choices made in the development of proxy records and their application in temperature reconstructions have long been recognized (c.f. Fritts et al., 1979; Kutzbach and Guetter, 1980). Following the publication of Mann et al. (1999), Esper et al. (2002) and Esper et al. (2004) showed that different approaches to tree-ring detrending and standardization strongly influenced the magnitude of cooling

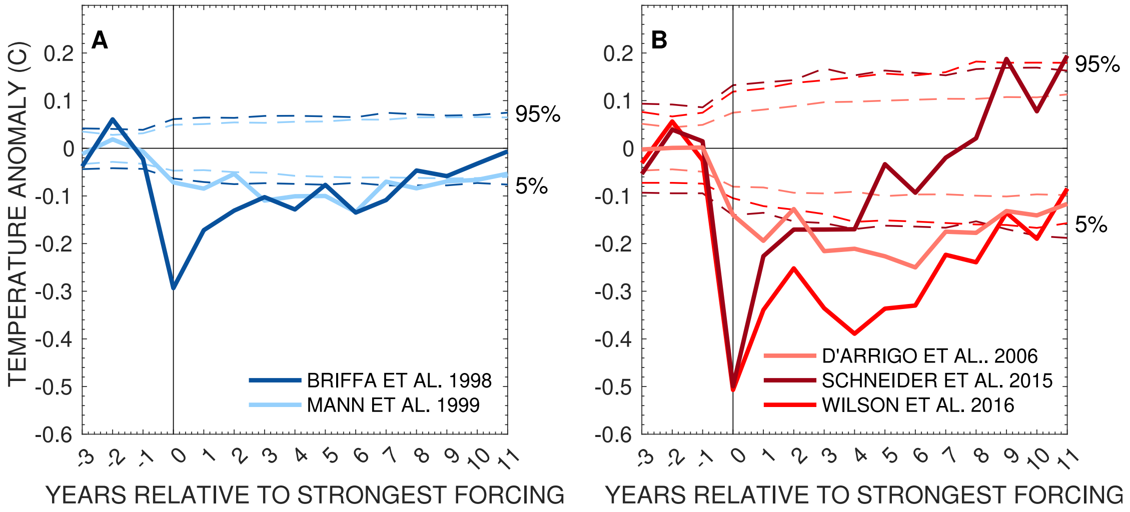

Fig. 4. Superposed Epoch Analysis (SEA) showing the composite mean temperature anomaly associated with the 12 largest volcanic eruptions since 1400 CE (in terms of global radiative forcing estimates from Sigl et al. (2015): 1458, 1815, 1809, 1641, 1601, 1695, 1836, 1832, 1453, 1595, 1884, and 1783 CE) for five large-scale Northern Hemisphere temperature reconstructions for the last millennium. We selected only eruptions since 1400 CE so that all the events were captured by all five of the reconstructions. The event year (Year 0) is set to the year of the maximum estimated negative forcing anomaly associated with the eruption. The reconstructions include (A) the MXD reconstruction extending back to 1400 CE from Briffa et al. (1998) and the last millennium multiproxy reconstruction from Mann et al. (1999), and (B) the tree-ring reconstruction by D'Arrigo et al. (2006) that uses predominantly tree-ring width, the summer Northern Hemishere reconstruction using the NTREND network by Wilson et al. (2016), which is a mix of tree-ring latewood density (MXD), blue intensity (BI), and ring width, and the reconstruction from Schneider et al. (2015) which uses entirely MXD data. For all reconstructions shown here the response to volcanic eruptions is calculated by first removing the mean temperature of the 3 years prior to each event year (Year 0) and then averaging across all events. No additional rescaling has been applied to the reconstructions, so the magnitude of the composite response reflects the variance of the original reconstruction. Uncertainty bounds (5th and 95th percentile, dashed lines) are based on a 1000 member Monte Carlo simulation drawing random event year lists with replacement and are plotted in the same color as the composite responses for each reconstruction. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

during the Little Ice Age and the range of reconstructed temperature changes over the last millennium. A number of authors also explored the consequences of statistical methods on the magnitude of past temperature variability (von Storch et al., 2004; Esper et al., 2005b,a; Bürger and Cubasch, 2005; Smerdon et al., 2008; Christiansen and Ljungqvist, 2017). Esper et al. (2005b) called disagreement about the magnitude of last millennium temperature variability “amplitude desideratum”, suggesting the inability to constrain this essential feature was of the utmost importance but a significant challenge.

Precisely resolving low-frequency temperature variability still remains an ambition (Esper et al., 2004) nearly two decades later. At issue are both the treatment and biases of individual proxies like tree rings, but also differences between the low-frequency behavior of different proxies (Emile-Geay et al., 2017; Klippel et al., 2020), and the sensitivity of reconstruction variability to methodological choices. Büntgen et al. (2021) conducted a double-blind experiment in which they asked 15 different research groups to develop a large-scale temperature reconstruction using a limited number of tree-ring proxies covering the last 2000 years. Each group had to decide how to combine the raw tree-ring data to create chronologies, which chronologies to include as predictors, what season, spatial domain, and data product to target for their reconstruction, and what statistical methods to use. The outcome revealed that choices made by individual investigators can result in large differences in various critical features of reconstructions, including their overall variance and mean values, the magnitude of the response following volcanic eruptions, their year-to-year persistence structure and spectra, and 20th-century trends. Different combinations of a range of valid and reasonable methodological choices can thus lead to different conclusions about important features of the climate of the Common Era.

A great deal of effort has gone into testing the statistical methods used to estimate past temperatures from networks of proxy data (e.g. Zorita et al., 2003; von Storch et al., 2004; Mann et al., 2005; Rutherford et al., 2005; Bürger and Cubasch, 2005; Bürger et al., 2006; Wahl and Ammann, 2007; Smerdon et al., 2008; Riedwyl et al., 2009; Smerdon et al., 2011; Smerdon, 2012; Steiger et al., 2014; Smerdon et al., 2016; Dee et al., 2016; King et al., 2021; Yun et al., 2021). Despite the knowledge gained from these statistical experiments on both real and simulated paleoclimate data, many of the methodological decisions made in the process of developing a reconstruction remain only weakly constrained (c.f. Bürger and Cubasch, 2005; Bürger et al., 2006; Tingley et al., 2012; Christiansen and Ljungqvist, 2017). Recent studies confirm that even for identical or similar networks of proxy data the differences resulting from statistical and methodological choices and assumptions make both reconstructions and non-trivial climate inferences drawn from them ‘fragile’ (Wang et al., 2015; Degroot et al., 2021; King et al., 2021). To address this, the PAGES 2k Consortium (2019) median reconstruction highlighted in AR6 (Fig. 1d) incorporates the result of seven different reconstruction methods applied to a subset of the multiproxy PAGES2k dataset (Emile-Geay et al., 2017). While they found a wide range of variability at centennial and longer timescales, at multidecadal timescales all the methods suggested similar patterns of variability, presumably driven by the influence of the common set of proxy records, particularly in the sparsely sampled first millennium. But the estimated uncertainties for this reconstruction used in AR6 only reflect the methodological differences as applied to the PAGES2k dataset at decadal and longer time scales. Much larger latent uncertainties are almost certainly present due to the change through time in proxy availability, sensitivity, and spatial distribution (Figs. 2 and 3). Because the consequences of these uncertainties are poorly represented in AR6, which is intended to reflect an assessment of the current state of the science, the report fell short in its representation of what we know and what we have learned about Common Era temperatures over the last two decades.

4. A contemporary assessment of temperature reconstructions of the Common Era

The utility of Common Era temperature reconstructions depends on the questions that are asked of them and how the strength of inference is affected by a complete accounting of uncertainty. While there remain substantial uncertainties in the magnitude of Medieval warmth even 20 years after the publication of the TAR (Figs. 1c and 5; Albritton et al., 2001; Folland et al., 2001), nearly all reconstructions continue to confirm that temperatures over the late 20th century and into the early 21st are now warmer than any other period over the last millennium. But substantial progress has indeed been made since the publication of the TAR: new methods, new proxy records, and a better understanding of their strengths and limitations, show a larger range of variability at timescales from interannual to multicentennial, confirm a cooling response to volcanic eruptions, and extend further into the past (Figs. 4 and 5). While the PAGES 2k Consortium (2019) reconstruction incorporates many of these advances and also displays the general trajectory of previous large-scale reconstructions, even when it is scaled to Northern Hemisphere summer temperatures it shows a reduced amplitude of decadal and multidecadal variability and a flat trajectory over the first millennium (Fig. 5). The magnitude of preindustrial decadal-to-centennial variability, rather than the observed and indisputable anthropogenic temperature 'blade' alone, influences the degree to which reconstructed Common Era temperature trajectories resemble the original hockey stick.

Given the challenges, biases, and limitations discussed above, it is safe to conclude that substantial uncertainties remain in reconstructing large-scale temperatures, which in turn give rise to meaningful differences in the character of reconstructed Common Era temperatures. This important reality of the current state of the science should be confronted and accurately addressed (Figs. 4 and 5), in contrast to both the AR6 presentation and to incorrect claims that there is little meaningful difference between some early and more recent large-scale temperature reconstructions (Mann, 2021). Thus, to truly move "beyond the hockey stick" (Mann, 2021) requires continued and considered accounting of the range of uncertainties from proxy and methodological sensitivities, the progress and advances that have been made, and the work still to be done. This is true in general but even more so for community (PAGES2k, 2013; PAGES 2k Consortium, 2019; Turney et al., 2019) and consensus efforts like the IPCC (2021) that are intended to represent a full assessment of the current state of climate science. Recognizing and quantifying these differences is furthermore important when conducting comparisons between model simulations and climate reconstructions over the Common Era (Fernández-Donado et al., 2013; PAGES 2k-PMIP3 group, 2015; Jungclaus et al., 2017), as they affect estimates of the magnitude and relative contribution of forced and unforced climate variability, the spatiotemporal and spectral characteristics of temperature anomalies, and confidence in our assessments of model fidelity (Schurer et al., 2013; Hartl-Meier et al., 2017; Zhu et al., 2019; PAGES 2k Consortium, 2019; Zhu et al., 2020; Eyring et al., 2021).

With the above in mind, we recommend the following:

1. **Use and evaluate multiple reconstructions** – Relying on a single reconstruction of Common Era temperatures cannot currently provide a complete characterization of the possible range and magnitude of uncertainties in past temperature variability and trends. While recent Northern Hemisphere summer temperature reconstructions have to a certain extent converged for the last millennium (Schneider et al., 2015; Stoffel et al., 2015; Wilson et al., 2016; Anchukaitis, 2017; Guillet et al., 2017; Esper et al., 2018; Degroot et al., 2021) uncertainties and disagreements still exist in space and at various frequencies (Esper et al., 2018; Eyring et al., 2021). Even various large-scale reconstructions all using the PAGES2k database (Emile-Geay et al., 2017) as their starting point disagree with one another about the magnitude and patterns of past changes (PAGES 2k Consortium, 2019; Tardif et al., 2019; Degroot et al., 2021; King et al., 2021). A complete assessment of Common Era temperature therefore must take into account and quantify these differences between research groups, across proxy datasets, and arising from different reconstruction methodologies. While ensemble reconstructions can partially address methodological sensitivity, compositing across these differences can unintentionally obscure them.

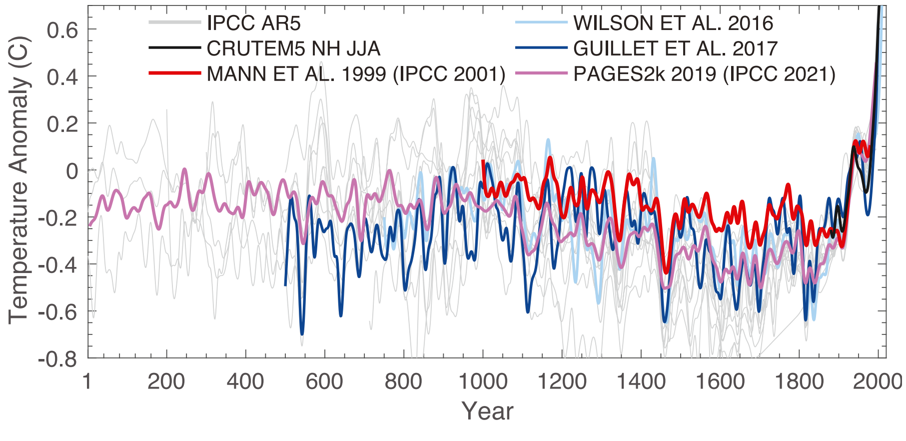

Fig. 5. Past and contemporary large-scale temperature reconstructions. The original "Hockey Stick" (Mann et al., 1999) featured in the TAR (Albritton et al., 2001) and the PAGES 2k Consortium (2019) reconstruction featured in AR6 (IPCC, 2021) are compared with the various Northern Hemisphere reconstructions included in the AR5 Paleoclimate chapter (Masson-Delmotte et al., 2013), and two recent Northern Hemisphere summer temperature tree-ring reconstructions from Wilson et al. (2016) and Guillet et al. (2017). For this comparison all the reconstructions have been re-scaled to match the mean and variance of the 1880 through 1990 instrumental mean summer (June through August) CRUTEM5 Northern Hemisphere temperature (shown in black, anomalies from the period 1961 to 1990; Osborn et al. (2021)). The plot excludes the 'LM08ave' reconstruction from the AR5 series as it has an unrealistically large amplitude, particularly once scaled to the overlapping period of observed Northern Hemisphere temperatures (see Christiansen and Ljungqvist, 2017). All series have been smoothed with a 20-year Gaussian filter. Conclusions based on this figure are not sensitive to the choice of the instrumental series used for scaling.

2. **Clearly define intended uses** – The reliability and utility of reconstructions should always be defined in terms of what purpose and what questions they are being used to address. The numerous reconstructions created over the last two decades largely continue to show that late 20th-century temperatures exceeded those of any time in the prior millennium, at least for the Northern Hemisphere summer. But beyond this superficial shape, various uncertainties discussed above influence our confidence in quantifying or making inferences about past temperatures or the behavior of the climate system at different temporal and spatial scales. For instance, it is clear that multi-centennial and millennial-scale trends in large-scale reconstructions remain uncertain and that conclusions about the climate impacts of explosive volcanism are sensitive to the type of proxy used, the observational dataset, and the statistical methods. Even in recent tree-ring reconstructions, the magnitude of decadal-scale variability varies across reconstructions, again likely due to differences in statistical methodology and instrumental target (Degroot et al., 2021; Büntgen et al., 2021). Despite progress over the last several decades, temperatures during the first millennium of the Common Era remain highly uncertain due to a lack of high resolution proxy data, a feature of large-scale reconstructions that should be adequately reflected in uncertainty bounds and incorporated into analyses of this earlier period.
3. **Evolve beyond the use of large-scale means** – We advocate not only for quantification of the full range of uncertainties across multiple reconstructions of Common Era mean temperature, but also for continued focus on spatial reconstructions of past temperature (Fritts et al., 1971; Cook et al., 1994; Mann et al., 1998; Evans et al., 2001; Anchukaitis and McKay, 2014; Tingley and Huybers, 2013; Hakim et al., 2016; Anchukaitis, 2017; Anchukaitis et al., 2017; Guillet et al., 2017; Esper et al., 2018; Steiger et al., 2018; Neukom et al., 2019; Tardif et al., 2019). Evaluation of reconstructions in both space and time consistently show that the best skill is in the vicinity of highly sensitive (high signal-to-noise) proxies (Smerdon et al., 2011, 2016; Wang et al., 2015; Anchukaitis et al., 2017; King et al., 2021; Yun et al., 2021). In order to continue to develop spatial reconstructions, we call for the ongoing development of new temperature-sensitive proxy records spanning the Common Era, the continued refinement and use of proxy systems models (Evans et al., 2013; Dee et al., 2015), and formal methodological comparison experiments to better identify the cause of differences in reconstructions. Specifically, the continued challenge imposed by sparse temperature-sensitive high-resolution proxy networks in both tropical and Southern Hemisphere regions spanning the complete Common Era (Fig. 3) strongly limit what conclusions can be drawn about the climate of those latitudes and, as a consequence, call into question whether existing large-scale reconstructions can truly be considered global.

Based on the uncertainties described herein, we conclude that large-scale Common Era temperature reconstructions are most reliable during the last millennium for the terrestrial Northern Hemisphere boreal summer and in the tropical Indo-Pacific Oceans for the most recent centuries where corals provide skillful reconstruction of tropical sea surface temperature. Prior to that time, in regions with sparse or time-uncertain proxy data for annual temperatures, the limitations of the data themselves and the sensitivity to reconstruction methods suggest the need for caution. Moreover, the full range of uncertainties must be considered across different time scales, as well as how these uncertainties affect our confidence in specific inferences about the climate system. While we understand the instinct to use the longest and latest temperature reconstruction, particularly for the purpose of placing rapid modern anthropogenic warming in context, we must move beyond simple observations of the general centennial-scale shape of large-scale temperature estimates. If this is to be truly achieved, we will need to continue to be cognisant of how proxy and methodological biases and uncertainties influence our assessment of the reliability of Common Era temperature reconstructions and the conclusions that we draw from them.

Data availability

Data in Fig. 1 are from Mann et al. (1999) (https://www.ncdc.noaa.gov/paleo/study/6276), Jansen et al. (2007) (https://www.ncdc.noaa.gov/paleo/study/6318), Masson-Delmotte et al. (2013) (https://doi.pangaea.de/10.1594/PANGAEA.828636) and IPCC (2021) (https://doi.org/10.5285/76cad0b4f6f141ada1c44a4ce9e7d4bd).

Data in Figs. 2 and 3 are from PAGES 2k Consortium (2019) (https://doi.org/10.6084/m9.figshare.c.4507043, Neukom et al. (2019) (https://doi.org/10.6084/m9.figshare.8097503) and Emile-Geay et al. (2017) (https://doi.org/10.6084/m9.figshare.c.3285353).

Data in Fig. 4 are from Mann et al. (1999) (https://www.ncdc.noaa.gov/paleo/study/6276), Briffa et al. (1998) (https://www.ncdc.noaa.gov/paleo/study/6224), Wilson et al. (2016) (https://www.ncei.noaa.gov/paleo/study/19743), D'Arrigo et al. (2006) (https://www.ncdc.noaa.gov/paleo/study/6358), and Schneider et al. (2015) (https://www.ncdc.noaa.gov/paleo/study/18875).

Data in Fig. 5 are from Masson-Delmotte et al. (2013) (https://doi.pangaea.de/10.1594/PANGAEA.828636), Mann et al. (1999), (https://www.ncdc.noaa.gov/paleo/study/6276), Wilson et al. (2016) (https://www.ncdc.noaa.gov/paleo/study/19743), Guillet et al. (2017) (https://www.ncdc.noaa.gov/paleo/study/21090), and Osborn et al. (2021) (https://www.metoffice.gov.uk/hadobs/crutem5/.

Author contribution

KJA and JES developed the ideas and concepts in the paper, analyzed the data, and wrote the paper KJA created the figures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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