Technical Note: Past and future warming – Direct comparison on multi-century timescales

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Abstract. In 2013, the Intergovernmental Panel on Climate Change concluded that Northern Hemisphere temperatures had reached levels unprecedented in at least 1400 years. The 2021 report now sees global mean temperatures rising to levels unprecedented in over 100,000 years. This Technical Note briefly explains the reasons behind this major change. Namely, the new assessment reflects additional global warming that occurred between two reports, and improved paleotemperature reconstructions that extend further back in time. In addition to past and recent warming, the conclusion also considers multi-century future warming, which thereby enables a direct comparison with paleotemperature reconstructions on multi-century time scales.

1 Global paleotemperature assessment in AR6

The recent climate assessment report (AR6) by the Intergovernmental Panel on Climate Change (IPCC, 2021) concluded that global temperature[1] is reaching a level unprecedented in more than 100,000 years. That is much further back than was reported previously by the IPCC. The 2013 IPCC report (AR5) concluded that the Northern Hemisphere had warmed to levels that were unprecedented in at least 1400 years (Masson-Delmotte et al., 2013). With climate change presently on course to exceeding conditions uncharted by humans, the new report takes a longer-term view, with greater attention to paleoclimate reference periods further back in time (e.g., Box TS.2 in Arias et al., 2021; Cross-Chapter Box 2.1 in Gulev et al., 2021). AR6 also includes a better integration of paleoclimate across the report, including a direct comparison of paleotemperature and projected future temperature change (Figure TS.1 in Arias et al., 2021; Cross-Chapter Box 2.1 Figure 1 in Gulev et al., 2021). This Technical Note gathers evidence from several chapters of the new IPCC-AR6-Working Group I report and provides additional details for paleoclimate scientists to explain the basis for the updated assessment of recent and future global warming in a long-term context.

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[1] The term "global temperature" is used to refer to both mean annual surface temperature and mean surface air temperature. AR6 determined that the two metrics differ by less than 10% (Cross-Chapter Box 2.3 in Gulev et al., 2021).

To assess the understanding of global temperature prior to industrialization, AR5 like its predecessors, relied heavily on annually resolved temperature records. The majority of these are tree-ring chronologies from the terrestrial Northern Hemisphere, characterized by precise estimates of past climate variability with annual resolution. AR5 (Masson-Delmotte et al., 2013) focused on whether temperatures had yet exceeded those of medieval times, a period of relative warmth that is well known from some regions (PAGES 2k Consortium, 2013). Less attention was given to the Earth's temperature history prior to the last two thousand years because few tree-ring records are that long. Furthermore, when AR5 was drafted, global decadal average temperature stood 0.8°C higher than the 1850-1900 pre-industrial reference period. In AR6, the last decade is estimated to have reached 1.1°C warmer than this reference period. Of the 0.3°C increase, 0.19°C is the actual additional warming since the 2013 report; the other 0.1°C is due to better methods and new data (Cross-Chapter Box 2.3 in Gulev et al., 2021). That is substantially higher, prompting us to look further back beyond the year-by-year reconstruction that is available over the past two millennia.

Since 2013, there has been a major effort to assemble information from other archives of paleoclimate information prior to 2000 years ago. The most common source are sediments that accumulate in lakes and in the ocean, and contain a variety of biogeochemical indicators of past temperature (e.g., Kaufman et al., 2020a). Since AR5, the global coverage of these proxy records has increased, and their temporal resolution and age control has also improved. In addition, major new global data compilations have benefited from internationally coordinated campaigns and from better practices for data reuse (Williams et al., 2018). The cyberinfrastructure that supports the archival, distribution, interoperability and reusability of these data has improved substantially. Notably, all of the site-level data and code used to reconstruct global temperature over the Holocene (Kaufman et al., 2020b) are now publicly available (Routson et al., 2020).

2 Temperature comparison on multi-century timescales

Sediment-based proxy records have a fundamental limitation, however; most are inherently smoothed so that the full extent of their fluctuations are attenuated relative to the decadal-scale climate fluctuations that actually occurred. The smoothing is caused by the physical mixing of sediment by burrowing organisms and by currents at the bottom of lakes and the ocean. It also arises because the age control for the records has greater uncertainty than annually resolved records. When averaged together, finer-scale fluctuations are cancelled out, on average. As such, the reconstructions attest to temperature changes averaged over multiple centuries, which is a minimum estimate of changes that occurred on a decadal timescale.

Smoothing of the paleoclimate record makes it difficult to compare the long-term past temperature against the rapid changes of recent decades. However, these recent changes herald a long-term period of global warming that is unlikely to be reversed anytime soon, even under optimistically low emissions scenarios. By looking both backward and forward, we can make informed estimates of long-term average temperature, thereby enabling a like-to-like, multi-century-scale comparison between the paleoclimate data and recent *plus* upcoming warming.

Deleted: forcing

Deleted: are indicative of long-term changes that are now underway. …

65   The upcoming global warming will be driven by continued emissions of greenhouse gases, and will be exacerbated regionally as slow-moving components of the climate system continue to react to the greenhouse gasses already in the atmosphere for centuries to come (Fox-Kemper et al., 2021). In AR6, climate model projections out to 2300 use new emissions scenario extensions (Meinshausen et al., 2020) and an updated emissions-driven emulator, which is calibrated to the extensively modelled 21st century climate (Lee et al., 2021). These projections show that, even under a low emissions scenario[2]

70 global temperature of at least 1°C warmer than the late 1800s is nearly certain to persist for centuries (Fig. 1). Even for the low emissions scenario (SSP1-2.6), the average temperature over the 400-year-long period from 1900 to 2300, a temporal resolution that is on par with proxy records, is estimated at 1.2°C [0.9, 1.7°C] warmer than 1850-1900 (mean [5%, 95% range]) (Lee et al., 2021). Assuming CO_2 emissions reach net zero, climate models indicate that global warming might still further increase or decrease during subsequent centuries (MacDougall et al., 2020). In contrast, under a high emissions scenario (SSP3-

75 7.0), the 400-year average temperature is estimated at 4.1°C [2.1, 4.7°C] relative to 1850-1900.

    This multi-century, approximately 1.2 to 4.1°C level of global warming can be reasonably compared with global temperature over a similar time horizon, that is, the warmest multi-century interval of the Holocene (Fig. 1). AR6 determined, with medium confidence, that peak Holocene global temperature was between 0.2 and 1°C warmer than the late 1800s (Gulev et al., 2021). This assessed temperature range was based on several published studies of proxy-based temperature

80 reconstructions. These include a global compilation of quality-controlled marine and terrestrial multi-proxy records (Temp12k, Kaufman et al., 2020a), which was used to generate a multi-method ensemble global temperature reconstruction (Kaufman et al., 2020b). The median reconstruction shows that the warmest 200-year-long interval prior to industrialization took place around 6500 years ago, when global temperature is estimated to have been 0.7 °C [0.3, 1.8] warmer than the 19th century. The Temp12k reconstruction is similar to the only other available Holocene global temperature reconstruction based on both

85 terrestrial and marine proxy data (Marcott et al., 2013). That study used a much smaller dataset and different procedures to estimate maximum warmth of 0.8°C ± 0.3°C (2σ) relative to 1850-1900 at around 7 ka (adjusted by adding 0.3°C to account for different reference periods). In contrast, reconstructions based on selected proxy types indicate that mid-Holocene land and ocean surface temperatures were indistinguishable from pre-industrial climate (Harrison et al., 2015). This and other evidence for relatively low mid-Holocene global temperatures led to the AR6 assessed value that favours the lower estimates within the

90 Temp12k ensemble reconstruction (Fig. 1b).

    Climate models generally simulate Holocene global temperature that correlate with greenhouse gas concentrations. More specifically, global temperature estimated from 16 climate models programmed to simulate climate for the mid-

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[2] Based on information in Lee et al. (2021), in the low-emissions scenario (SSP1-2.6), emissions peak this decade then decrease to net negative emissions by 2080; in the intermediate scenario (SSP2-4.5), emissions remain at about the current levels until the middle of the century, then decrease; and in the high-emissions scenario (SSP3-7.0), emissions approximately double between 2015 and 2100. Following 2100, all scenarios reduce emissions such that CO_2 emissions from land use are reduced to zero by 2150; any net negative fossil CO_2 emissions are reduced to zero by 2200, and positive fossil CO_2 emissions are reduced to zero by 2250. Non-CO_2 fossil fuel emissions are also reduced to zero by 2250 while land-use-related non-CO_2 emissions are held constant at 2100 levels.

Holocene, 6000 years ago, averages around –0.3 ± 0.1°C (±1σ) colder than pre-industrial control runs (Brierley et al., 2020). A recent global temperature reconstruction based on data assimilation, which was published after AR6, blends climate model simulations with sea-surface temperatures proxies, and shows essentially no multi-millennial change in global temperature following 8000 years ago and prior to industrialization (Osman et al., 2021). While the discrepancy between the observational

115 and model results is the subject of ongoing research, the lower temperatures simulated by models are consistent with the conclusion that a global warming level of at least 1°C is unprecedented during the pre-industrial Holocene.

We need to look much further back for a time when temperature might have exceeded the 1°C global warming level (Fig. 1). There is no evidence that global temperature higher than Holocene occurred during the last major ice age (marine isotope stages (MIS) 4-2). For the Last Interglacial (MIS 5), around 125,000 years ago, AR6 (Gulev et al., 2021) has medium

120 confidence that global temperature averaged over multiple centuries was between 0.5 and 1.5°C higher than the late 1800s, which overlaps with the 1°C warming level. This led to the AR6 statement that the last decade was more likely than not warmer than any multi-century period after the Last Interglacial (Gulev et al., 2021). The statement was simplified in Figure SPM.1 of the Summary for Policy Makers (IPCC, 2021), which stated that global temperature during mid-Holocene was the warmest in at least the last 100,000 years, and that the Last Interglacial, around 125,000 years ago, is the next most recent candidate for a

125 period of higher temperature. No attempt was made in AR6 to assess temperatures of other warm substages of MIS 5.

3 Conclusion

Global warming has reached 1°C relative to the late 1800s and, in the absence of strong reduction in greenhouse gas emissions, is on track to remain at least as warm and possibly much warmer for multiple centuries. The duration of this ongoing and upcoming global warming is on par with that of the resolution of paleotemperature reconstructions. Human caused global

130 warming is now exceeding the warmest multi-century period of the Holocene, and thereby the envelope of temperatures under which agriculturally based society has flourished (Steffen et al., 2018). Without rapid and sustained reductions in greenhouse gas emissions, the average temperature of coming centuries will exceed 1.5°C above preindustrial temperature, and therefore will be warmer than the peak of the Last Interglacial, around 125,000 years ago.

135 **Data and code availability:** The timeseries data plotted in Figure 1 are available through publicly accessible sources. Temperatures were adjusted to a common baseline and the values were compiled into a single table for convenience of future use (Supplement). The data and code used to draft the figure are available at https://doi.org/10.5281/zenodo.5842209.

Author contribution: DSK wrote the manuscript with input from NPM. NPM drafted the figure.

140

Competing interests: The authors declare that they have no conflict of interest.

Acknowledgments: We thank Dan Lunt and an anonymous reviewer for their helpful comments.

Financial Support: DSK and NPM are supported by NSF grant 1929460.

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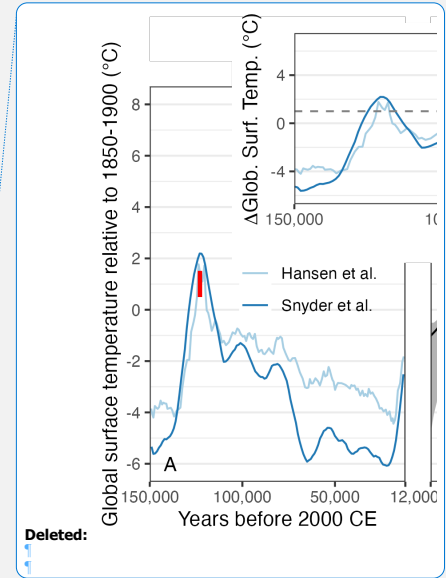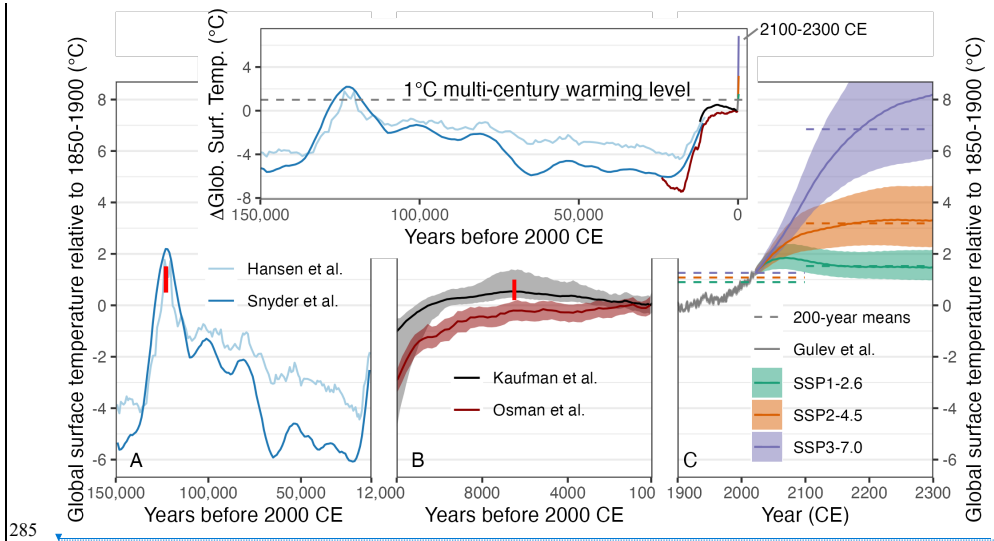
Figure 1: Global surface temperature (GST) over 150,000 years relative to 1850-1900. Three timescales are shown according to their published resolutions: (A) 150 to 12 ka based on marine oxygen isotopes in foraminifera (Hansen et al., 2013; Snyder, 2016). (B) 12 ka to 1900 CE based on the Temp12k multi-method, multi-proxy ensemble reconstruction (Kaufman et al., 2020b), and a post-AR6 reconstruction that blends marine proxy evidence with a climate model simulation (Osmann et al., 2021); and (C) 1900 to 2300 based on instrumental observations (gray line) (Gulev et al., 2021), and projections using three emissions scenarios (low, intermediate, and high) as assessed in AR6 (Lee et al., 2021). Horizontal dashed lines are 200-year averages (1900-2100, 2100-2300). Lines in (A) and (B) show the mean and shading in (B) shows the 5-95% range. Red vertical lines are the IPCC assessed (medium confidence; Gulev et al., 2021) temperature ranges from proxy evidence for the warmest intervals of the Last Interglacial (around 125,000 years ago, 0.5-1.5°C) and Holocene (around 6500 years ago, 0.2-1°C). These values are based on multiple studies, including the time series displayed here. Inset shows all three panels on the same time scale with 200-year resolution so that past, present and future are directly comparable.