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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. Critically, 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). It also includes a better integration of paleoclimate and projected future climate change (e.g., Figure TS.1 in Arias 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 global warming in a long-term context.

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

[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%.

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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, forcing 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 are indicative of long-term changes that are now underway. By looking both backward and forward, we can make a like-to-like, multi-century-scale comparison between the paleoclimate data and recent *plus* upcoming warming.

The upcoming warming includes committed climate change, which arises because slow-moving components of the climate system will continue to react to the greenhouse gasses already in the atmosphere for centuries to come (Fox-Kemper et al., 2021). For example, deep ocean warming lags changes in surface temperature by multiple millennia in simulations by climate models of intermediate complexity (Clark et al., 2016), and the deep Pacific is likely still adjusting to cooling that occurred during the Little Ice Age (Gebbie and Huybers, 2019).

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The upcoming warming will also be driven by the new emissions of greenhouse gases. 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] 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). Under a high emissions scenario (SSP3-7.0), 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, which likely occurred around 6500 years ago (Fig. 1). AR6 determined, with medium confidence, that global temperature then was between 0.2 and 1°C warmer than the late 1800s (Gulev et al., 2021). This temperature range was based on several published studies of proxy-based temperature reconstructions. Global temperature estimated from 16 climate models, which were programmed to simulate climate for the mid-Holocene, 6000 years ago, averages around –0.3 ± 0.1°C (±1σ) colder than pre-industrial control runs (Brierley et al., 2020). While the discrepancy between the observational 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 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.

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

[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 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.

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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 be warmer than the peak of the Last Interglacial, around 125,000 years ago.

Data availability: The timeseries data plotted in Figure 1 are available in their original publications.

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

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

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References

Arias, P. A., Bellouin, N., Coppola, E., Jones, R. G., Krinner, G., Marotzke, J., Naik, V., Palmer, M. D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P. W., Trewin, B., Achuta Rao, K., Adhikary, B., Allan, R. P., Armour, K., Bala, G., Barimalala, R., Berger, S., Canadell, J. G., Cassou, C., Cherchi, A., Collins, W., Collins, W. D., Connors, S. L., Corti, S., Cruz, F., Dentener, F. J., Dereczynski, C., Di Luca, A., Diongue Niang, A., Doblas-Reyes, F. J., Dosio, A., Douville, H., Engelbrecht, F., Eyring, V., Fischer, E., Forster, P., Fox-Kemper, B., Fuglestvedt, J. S., Fyfe, J. C., Gillett, N. P., Goldfarb, L., Gorodetskaya, I., Gutierrez, J. M., Hamdi, R., Hawkins, E., Hewitt, H. T., Hope, P., Islam, A. S., Jones, C., Kaufman, D. S., Kopp, R. E., Kosaka, Y., Kossin, J., Krakovska, S., Lee, J.-Y., Li, J., Mauritsen, T., Maycock, T. K., Meinshausen, M., Min, S.-K., Monteiro, P. M. S., Ngo-Duc, T., Otto, F., Pinto, I., Pirani, A., Raghavan, K., Ranasinghe, R., Ruane, A. C., Ruiz, L., Sallée, J.-B., Samset, B. H., Sathyendranath, S., Seneviratne, S. I., Sörensson, A. A., Szopa, S., Takayabu, I., Treguier, A.-M., van den Hurk, B., Vautard, R., von Schuckmann, K., Zaehle, S., Zhang, X., and Zickfeld, K.: Technical Summary, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf, 2021.

https://doi.org/10.5194/cp-2021-146
Preprint. Discussion started: 1 November 2021

Brierley, C. M., Zhao, A., Harrison, S. P., Braconnot, P., Williams, C. J. R., Thornalley, D. J. R., Shi, X., Peterschmitt, J.-Y., Ohgaito, R., Kaufman, D. S., Kageyama, M., Hargreaves, J. C., Erb, M. P., Emile-Geay, J., D'Agostino, R., Chandan, D., Carr'e, M., Bartlein, P., Zheng, W., Zhang, Z., Zhang, Q., Yang, H., Volodin, E.M., Tomas, R. A., Routson, C., Peltier, W. R., Otto-Bliesner, B., Morozova, P. A., McKay, N. P., Lohmann, G., Legrande, A. N., Guo, C., Cao, J., Brady, E., Annan, J. D., and Abe-Ouchi, A.: Large-scale features and evaluation of the PMIP4-CMIP6 mid-Holocene simulations. Climate of the Past, 16, 1847-1872, https://doi.org/10.5194/cp-16-1847-2020, 2020.

Clark, P. U., Shakun, J., Marcott, S., Mix, A., Eby, M., Kulp, S., Levermann, A., Milne, G., Pfister, P., Santer, B., Schrag, D., Solomon, S., Stocker, T., Strauss, B., Weaver, A., Winelmann, R., Archer, D., Bard, E., Goldner, A., Lambeck, K., Pierrehumbert, R., and Plattner, G.-K.: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. Nature Climate Change, 6, 360–369, https://doi.org/10.1038/nclimate2923, 2016.

Fox-Kemper, B., H. T. Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A., and Yu, Y.: Ocean, Cryosphere and Sea Level Change, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, https://www.ipcc.ch/report/ar6/wg1/downloads/report/ IPCC_AR6_WGI_ Chapter_09.pdf, 2021.

Gebbie, G., and Huybers, P.: The Little Ice Age and 20th-century deep Pacific cooling. Science, 363, 70-74, https://doi.org/10.1126/science.aar8413, 2019.

Gulev, S. K., Thorne, P. W., Ahn, J., Dentener, F. J., Domingues, C. M., Gerland, S., Gong, D., Kaufman, D. S., Nnamchi, H. C., Quaas, J., Rivera, J. A., Sathyendranath, S., Smith, S. L., Trewin, B., von Shuckmann, K., and Vose, R. S.: Changing State of the Climate System, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_02.pdf, 2021.

Hansen J., Sato, M., Russell, G., Kharecha, P.: Climate sensitivity, sea level and atmospheric carbon dioxide. Phil. Trans. R. Soc. A 371, 20120294, https://doi.org/10.1098/rsta.2012.0294. 2013.

IPCC, Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B.: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf, 2021.

Kaufman, D., McKay, N., Routson, C., Erb, M., Davis, B., Heiri, O., Jaccard, S., Tierney, J., Dätwyler, C., Axford, Y., Brussel, T., Cartapanis, O., Chase, B., Dawson, A., de Vernal, A., Engels, S., Jonkers, L., Marsicek, J., Moffa-Sánchez, P., Morrill, C., Orsi, A., Rehfeld, K., Saunders, K., Sommer, P., Thomas, E., Tonello, M., Tóth, M., Vachula, R., Andreev, A., Bertrand, S., Biskaborn, B., Bringué, M., Brooks, S., Caniupán, M., Chevalier, M., Cwynar, L., Emile-Geay, J., Fegyveresi, J., Feurdean, A., Finsinger, W., Fortin, M., Foster, L., Fox, M., Gajewski, K., Grosjean, M., Hausmann, S., Heinrichs, M., Holmes, N., Ilyashuk, B., Ilyashuk, E., Juggins, S., Khider, D., Koinig, K., Langdon, P., Larocque-Tobler, I., Li, J., Lotter, A., Luoto, T., Mackay, A., Magyari, E., Malevich, S., Mark, B., Massaferro, J., Montade, V., Nazarova, L., Novenko, E., Pařil, P., Pearson, E., Peros, M., Pienitz, R., Płóciennik, M., Porinchu, D., Potito, A., Rees, A., Reinemann, S., Roberts, S., Rolland, N., Salonen, S., Self, A., Seppä, H., Shala, S., St-Jacques, J., Stenni, B., Syrykh, L., Tarrats, P., Taylor, K., van den Bos, V., Velle, G., Wahl, E., Walker, I., Wilmshurst, J., Zhang, E., and Zhilich, S.: A global database of Holocene paleo-temperature. Scientific Data 7, 115, https://doi.org/10.1038/s41597-020-0445-3, 2020a.

Kaufman, D., McKay, N., Routson, C., Erb, M., Dätwyler, C., Sommer, P., Heiri, O., and Davis, B.: Holocene global surface temperature: A multi-method reconstruction approach. Scientific Data, 7, 201, https://doi.org/10.1038/s41597-020-0530-7, 2020b.

Lee, J. Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J. P., Engelbrecht, F., Fischer, E., Fyfe, J. C., Jones, C., Maycock, A., Mutemi, J., Ndiaye, O., Panickal, S., and Zhou, T.: Future Global Climate: Scenario-Based Projections and Near-Term Information, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_04.pdf, 2021.

Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, A., González Rouco, J. F., Jansen, E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramesh, R., Rojas, M., Shao, S., Timmermann, A.: Information from Paleoclimate Archives, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T.F., Qin, D.,

https://doi.org/10.5194/cp-2021-146
Preprint. Discussion started: 1 November 2021

Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter05_FINAL.pdf, 2013.

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., Smith, S. J., van den Berg, M., Velders, G. J. M., Vollmer, M. K., and Wang, R. H. J.: The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. Geosci. Model Dev., 13, 3571–3605, https://doi.org/10.5194/gmd-13-3571-2020, 2020.

PAGES 2k Consortium: Continental-scale temperature variability during the last two millennia. Nature Geosci. 6, 339-346, https://doi.org/10.1038/NGEO1797, 2013.

Snyder, C. W.: Evolution of global temperature over the past two million years. Nature, 538, 226-228, https://doi.org/10.1038/nature19798, 2016.

Rouston, C., McKay, N., Sommer, P. S.: Dätwyler, C., and Erb, M.: nickmckay/Temperature12k: Analysis and plotting code for Temp12k Analysis Paper (1.2.0). Zenodo, https://doi.org/10.5281/zenodo.3888590, 2020.

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., and Donges, J. F.: Trajectories of the Earth System in the Anthropocene. Proc. National Acad. Sci., 115, 8252-8259, https://doi.org/10.1073/pnas.1810141115, 2018.

Williams, J. W., Kaufman, D. S., Newton, A., and von Gunten, L.: Building and Harnessing Open Paleodata, in: Building and Harnessing Open Paleodata, edited by: Williams, J. W., Kaufman, D. S., Newton, A., and von Gunten, L., Past Global Changes Magazine 26(2), 49, https://doi.org/10.22498/pages.26.2.49, 2018.

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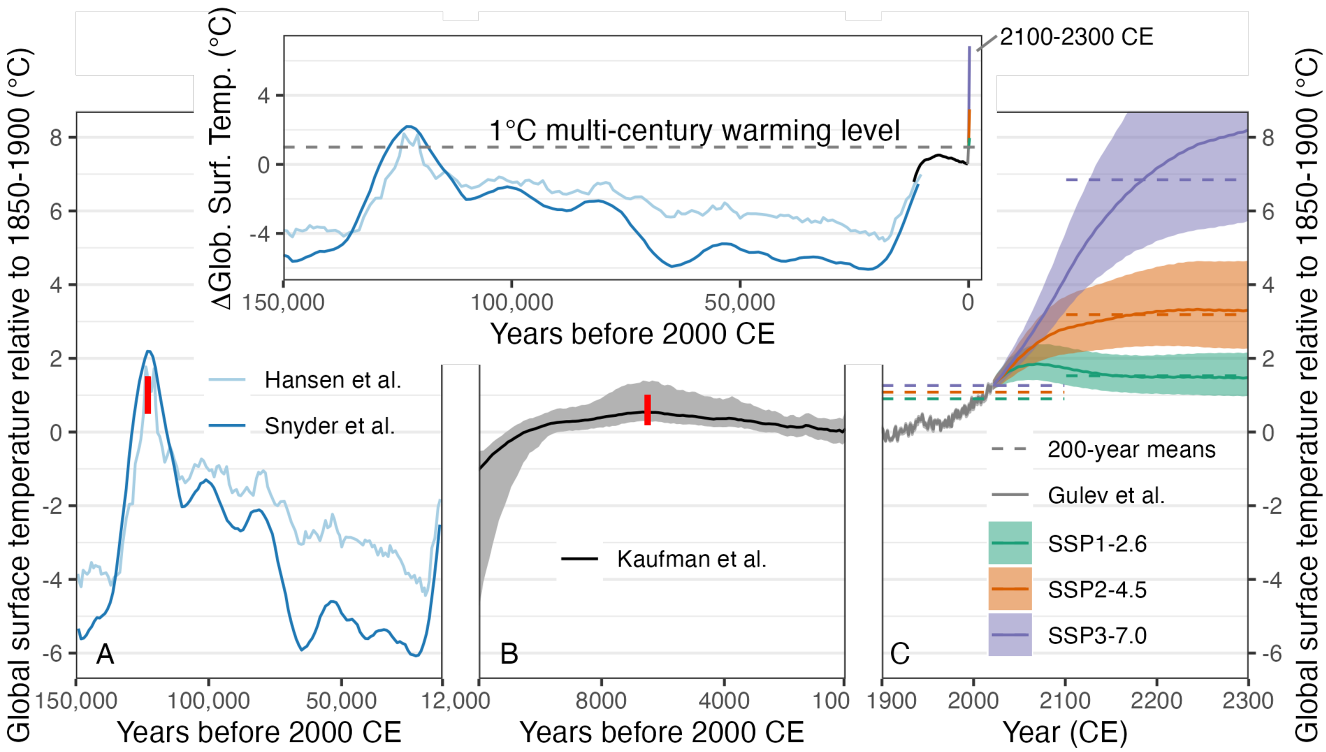

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215 **Figure 1: Global surface temperature (GST) over 150,000 years relative to 1850-1900.** Three timescales are shown according to their published resolutions: (A) 150 to 12 ka based on marine oxygen isotopes in foraminifera (Hansen et al., 2013; Snyder, 2016). (B) 12 ka to 1900 CE based on the Temperature12k multi-method, multi-proxy ensemble reconstruction (Kaufman et al., 2020b); 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) used 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.