



## Introduction to the special issue “Climate of the past 2000 years: regional and trans-regional syntheses”

Chris S. M. Turney<sup>1</sup>, Helen V. McGregor<sup>2</sup>, Pierre Francus<sup>3</sup>, Nerilie Abram<sup>4</sup>, Michael N. Evans<sup>5</sup>, Hugues Goosse<sup>6</sup>, Lucien von Gunten<sup>7</sup>, Darrell Kaufman<sup>8</sup>, Hans Linderholm<sup>9</sup>, Marie-France Loutre<sup>7</sup>, and Raphael Neukom<sup>10</sup>

<sup>1</sup>Palaeontology, Geobiology and Earth Archives Research Centre and ARC Centre of Excellence in Australian Biodiversity and Heritage (CABAH), School of Biological, Earth and Environmental Sciences, University of New South Wales, Australia

<sup>2</sup>School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW 2522, Australia

<sup>3</sup>Institut National de la Recherche Scientifique, Centre Eau Terre Environnement, G1K 9A9, Québec, QC, Canada

<sup>4</sup>Research School of Earth Sciences and ARC Centre of Excellence for Climate Extremes, Australian National University, Canberra ACT 2601, Australia

<sup>5</sup>Department of Geology, University of Maryland, College Park, Maryland 20742, USA

<sup>6</sup>Georges Lemaître Centre for Earth and Climate Research (TECLIM), Earth and Life Institute, Université catholique de Louvain (UCL), Leuven, Belgium

<sup>7</sup>PAGES International Project Office, Falkenplatz 16, 3012 Bern, Switzerland

<sup>8</sup>School of Earth Sciences & Environmental Sustainability, Northern Arizona University, Flagstaff, Arizona, USA

<sup>9</sup>Regional Climate Group, Department of Earth Sciences, University of Gothenburg, 40530 Gothenburg, Sweden

<sup>10</sup>University of Bern, Oeschger Centre for Climate Change Research & Institute of Geography, 3012 Bern, Switzerland

**Correspondence:** Chris S. M. Turney (c.turney@unsw.edu.au)

Received: 23 September 2018 – Discussion started: 17 October 2018

Accepted: 7 March 2019 – Published: 29 March 2019

**Abstract.** This PAGES (Past Global Changes) 2k (climate of the past 2000 years working group) special issue of *Climate of the Past* brings together the latest understanding of regional change and impacts from PAGES 2k groups across a range of proxies and regions. The special issue has emerged from a need to determine the magnitude and rate of change of regional and global climate beyond the timescales accessible within the observational record. This knowledge also plays an important role in attribution studies and is fundamental to understanding the mechanisms and environmental and societal impacts of recent climate change. The scientific studies in the special issue reflect the urgent need to better understand regional differences from a truly global view around the PAGES themes of “Climate Variability, Modes and Mechanisms”, “Methods and Uncertainties”, and “Proxy and Model Understanding”.

### 1 Introduction

Since the late twentieth century, scientific understanding of our global environment and climate has undergone a remarkable transformation (Lamb, 1965, 1977). Reconstructions of historic globally averaged temperatures indicate the second-half of the twentieth century experienced a rise of 1 °C (Hawkins et al., 2017), during which the planet has experienced unprecedented rates of environmental change (Steffen et al., 2018). Future climate extremes are projected to increase in amplitude and frequency compared to the historic period (IPCC, 2013), enhanced by climate–human–carbon feedbacks (Friedlingstein et al., 2013; Randerson et al., 2015; Bronselaer et al., 2018; Comyn-Platt et al., 2018), with potentially irreversible consequences (centennial to millennial in duration) for the environment. However, a major source of uncertainty in projections of future climate change and its impacts lies in the validation of models using observational climate data that are limited in both space and time (Rayner et al., 2003). There is increasing recognition that instrumental and satellite observations do not fully capture the ampli-

tude of changes and range of extremes we are projected to experience in the next century and beyond (Masson-Delmotte et al., 2013).

This PAGES (Past Global Changes) 2k (climate of the past 2000 years working group) special issue of *Climate of the Past* brings together the latest understanding of regional change and impacts from PAGES 2k groups across a range of proxies and regions. The special issue has emerged from a need to determine the magnitude and rate of change of regional and global climate beyond the timescales accessible within the observational record. This knowledge also plays an important role in attribution studies and is fundamental to understanding the mechanisms and environmental and societal impacts of recent climate change (Turney et al., 2006; Caseldine and Turney, 2010; Huber and Knutti, 2012; Nelson et al., 2016). With these considerations, an increasing number of reconstructions have been developed from proxies that preserve sub-annual (e.g. ice cores, tree rings, and corals) to multi-decadal (e.g. sediments, pollen, boreholes) changes; so-called “natural archives” (Masson-Delmotte et al., 2013). The rapid expansion of sites has come with unintended consequences, most notably the need for shared protocols and databases to fully exploit these archives (PAGES2k Consortium, 2017).

The community-driven PAGES 2k Network was established in 2008 to provide global leadership in this endeavour. The first phase of the network (2008–2013) focussed on generating and analysing a global array of regional climate reconstructions (representing Australasia, the Arctic, the Antarctic, South America and Central America, North America, Europe, Asia, and the oceans) for the last two millennia. Notably, in 2013, the regional PAGES 2k reconstructions demonstrated clear regional expressions of temperature variability at the multi-decadal to century scales, with a long-term global cooling trend prior to the twentieth century (PAGES 2k Consortium, 2013). During the second phase (2014–2016), and with the support of the CMIP5/PMIP3 project (Taylor et al., 2012), the focus shifted towards the identification of processes and the behaviour of phenomena, integrating projects addressing climate changes across regional boundaries (Abram et al., 2014; Neukom et al., 2014; McGregor et al., 2015; Abram et al., 2016; Tierney et al., 2017; Zhong et al., 2018). A major community effort consisted of creating a global database of temperature data for the Common Era using well-defined selection criteria and applying a clear open-data policy (PAGES 2k Consortium, 2017; Kaufman and PAGES 2k special-issue editorial team, 2018). Since 2017, a network of projects identified and led by 2k community members has been addressing questions articulated around the PAGES themes of “Climate Variability, Modes and Mechanisms”, “Methods and Uncertainties” and “Proxy and Model Understanding”.

The scientific studies in the special issue reflect the urgent need to better understand regional differences from a truly global view. They report annually resolved reconstructions

of precipitation and temperature derived from ice, marine, and terrestrial archives for Antarctica (Stenni et al., 2017; Thomas et al., 2017), Australia (Freund et al., 2017), China (Shi et al., 2017), and India (Xu et al., 2018), placing hydroclimate extremes in the context of historic trends, and providing new insights into variability and their regional forcing(s). The work of Guevara-Murua et al. (2018) exploits historic archives to report 300 years of hydroclimate change in Central America and finds major societal impacts associated with extremes; this is an area of research that we anticipate will become increasingly important with future attempts to both recover historic climate archives and adapt to the impacts of climate change.

Alongside these efforts, lower-resolution (interannual to multi-decadal resolution) archives offer the opportunity to develop longer records of past climate and environmental change. In this special issue, several new reconstructions are presented that highlight the complementary value of lower-resolution records for deriving millennial-length reconstructions from Australia (Dixon et al., 2017), the North Atlantic (Franke et al., 2017), North America (Shuman et al., 2018), the sub-Arctic (Nicolle et al., 2018), and the Arctic (Linderholm et al., 2018). These studies provide insights into multi-decadal to centennial forcing mechanisms, and provide a long-term context for late twentieth century regional change. At the same time, they also highlight where future work should be focussed, including the importance of comprehensive dating strategies for reducing chronological uncertainties, and identifying geographic areas where there remains a paucity of paleoclimate data. The latest compilation of borehole temperature profiles from North America reported by Jaume-Santero et al. (2016) is a demonstration of the value of an extensive network of sites. Here, the reconstructions show that North America has experienced relatively greater warming than the global historic mean, with evidence for amplified temperature changes at high latitude.

This PAGES 2k special issue also illustrates the importance of integrating climate model-proxy studies to better understand the mechanisms and future impacts of high-latitude change. Seftigen et al. (2017), for instance, explore the drivers of hydroclimate change in Scandinavia over the past two millennia and identify important differences between model simulations and proxy data, demonstrating the critical importance of having a dense network of records for such studies. Pendleton et al. (2017) model the radiocarbon-dated extent of an ice cap on Arctic Baffin Island and find that only twentieth century warming can explain its retreat. Worryingly, this study projects that this particular ice cap will soon disappear if current trends continue through this century.

To complete this special issue, Kaufman and PAGES 2k special-issue editorial team (2018) report the challenges and benefits of data stewardship to facilitate further use of published data. Although there is strong support for making data more findable, accessible, interoperable, and reusable (FAIR;

Wilkinson et al., 2016), the vigorous discussion that accompanies this note illustrates some of the questions that may arise. Further work to identify, attribute, and make accessible the climate of the past 2000 years will support efforts to place the climate of the past two centuries in context, and provide a basis for assessment of the emergent effects of continued anthropogenic forcing of the climate over the forthcoming century and beyond.

**Data availability.** All papers in this special issue were reviewed by a data stewardship team to ensure they followed data availability practices consistent with the recommendations of Climate of the Past and of PAGES. For further details please see Kaufman et al. (2018).

**Author contributions.** CSMT wrote the paper with assistance from all other others. All authors were editors for the special issue.

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

**Special issue statement.** This article is part of the special issue “Climate of the past 2000 years: regional and trans-regional syntheses”. It is not associated with a conference.

**Acknowledgements.** We thank Keely Mills and Graciela Gil Romera for their helpful and considered advice.

**Review statement.** This paper was edited by Keely Mills and reviewed by Graciela Gil Romera.

## References

- Abram, N. J., Mulvaney, R., Vimeux, F., Phipps, S. J., Turner, J., and England, M. H.: Evolution of the Southern Annular Mode during the past millennium, *Nat. Clim. Change*, 4, 564–569, <https://doi.org/10.1038/nclimate2235>, 2014.
- Abram, N. J., McGregor, H. V., Tierney, J. E., Evans, M. N., McKay, N. P., Kaufman, D. S., and the PAGES 2k Consortium: Early onset of industrial-era warming across the oceans and continents, *Nature*, 536, 411–418, <https://doi.org/10.1038/nature19082>, 2016.
- Bronselaer, B., Zanna, L., Munday, D. R., and Lowe, J.: Southern Ocean carbon-wind stress feedback, *Clim. Dynam.*, 51, 2743–2757, <https://doi.org/10.1007/s00382-017-4041-y>, 2018.
- Caseldine, C. J., and Turney, C.: The bigger picture: towards integrating palaeoclimate and environmental data with a history of societal change, *J. Quaternary Sci.*, 25, 88–93, 2010.
- Comyn-Platt, E., Hayman, G., Huntingford, C., Chadburn, S. E., Burke, E. J., Harper, A. B., Collins, W. J., Webber, C. P., Powell, T., Cox, P. M., Gedney, N., and Sitch, S.: Carbon budgets for 1.5 and 2°C targets lowered by natural wetland and permafrost feedbacks, *Nat. Geosci.*, 11, 568–573, <https://doi.org/10.1038/s41561-018-0174-9>, 2018.
- Dixon, B. C., Tyler, J. J., Lorrey, A. M., Goodwin, I. D., Gergis, J., and Drysdale, R. N.: Low-resolution Australasian palaeoclimate records of the last 2000 years, *Clim. Past*, 13, 1403–1433, <https://doi.org/10.5194/cp-13-1403-2017>, 2017.
- Franke, J. G., Werner, J. P., and Donner, R. V.: Reconstructing Late Holocene North Atlantic atmospheric circulation changes using functional paleoclimate networks, *Clim. Past*, 13, 1593–1608, <https://doi.org/10.5194/cp-13-1593-2017>, 2017.
- Freund, M., Henley, B. J., Karoly, D. J., Allen, K. J., and Baker, P. J.: Multi-century cool- and warm-season rainfall reconstructions for Australia’s major climatic regions, *Clim. Past*, 13, 1751–1770, <https://doi.org/10.5194/cp-13-1751-2017>, 2017.
- Friedlingstein, P., Meinshausen, M., Arora, V. K., Jones, C. D., Anav, A., Liddicoat, S. K., and Knutti, R.: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks, *J. Climate*, 27, 511–526, <https://doi.org/10.1175/JCLI-D-12-00579.1>, 2013.
- Guevara-Murua, A., Williams, C. A., Hendy, E. J., and Imbach, P.: 300 years of hydrological records and societal responses to droughts and floods on the Pacific coast of Central America, *Clim. Past*, 14, 175–191, <https://doi.org/10.5194/cp-14-175-2018>, 2018.
- Hawkins, E., Ortega, P., Suckling, E., Schurer, A., Hegerl, G., Jones, P., Joshi, M., Osborn, T. J., Masson-Delmotte, V., Mignot, J., Thorne, P., and van Oldenborgh, G. J.: Estimating Changes in Global Temperature since the Preindustrial Period, *B. Am. Meteorol. Soc.*, 98, 1841–1856, 2017.
- Huber, M. and Knutti, R.: Anthropogenic and natural warming inferred from changes in Earth’s energy balance, *Nat. Geosci.*, 5, 31–36, 2012.
- IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 1535 pp., 2013.
- Jaume-Santero, F., Pickler, C., Beltrami, H., and Mareschal, J.-C.: North American regional climate reconstruction from ground surface temperature histories, *Clim. Past*, 12, 2181–2194, <https://doi.org/10.5194/cp-12-2181-2016>, 2016.
- Kaufman, D. S. and PAGES 2k special-issue editorial team: Technical note: Open-paleo-data implementation pilot – the PAGES 2k special issue, *Clim. Past*, 14, 593–600, <https://doi.org/10.5194/cp-14-593-2018>, 2018.
- Lamb, H. H.: The early Medieval warm epoch and its sequel, *Palaeogeogr. Palaeoclimatol.*, 1, 13–37, 1965.
- Lamb, H. H.: *Climate: Past, Present and Future*, Methuen and Co Ltd, London, UK, 1977.
- Linderholm, H. W., Nicolle, M., Francus, P., Gajewski, K., Helama, S., Korhola, A., Solomina, O., Yu, Z., Zhang, P., D’Andrea, W. J., Debret, M., Divine, D. V., Gunnarson, B. E., Loader, N. J., Masei, N., Seftigen, K., Thomas, E. K., Werner, J., Andersson, S., Berntsson, A., Luoto, T. P., Nevalainen, L., Saarni, S., and Väli-ranta, M.: Arctic hydroclimate variability during the last 2000 years: current understanding and research challenges, *Clim. Past*, 14, 473–514, <https://doi.org/10.5194/cp-14-473-2018>, 2018.

- 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-Bliessner, B., Quinn, T., Ramesh, R., Rojas, M., Shao, X., and 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., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 383–464, 2013.
- McGregor, H. V., Evans, M. N., Goosse, H., Leduc, G., Martrat, B., Addison, J. A., Mortyn, P. G., Oppo, D. W., Seidenkrantz, M.-S., Sicre, M.-A., Phipps, S. J., Selvaraj, K., Thirumalai, K., Filipsson, H. L., and Ersek, V.: Robust global ocean cooling trend for the pre-industrial Common Era, *Nat. Geosci.*, 8, 671–677, <https://doi.org/10.1038/ngeo2510>, 2015.
- Nelson, M. C., Ingram, S. E., Dugmore, A. J., Streeter, R., Peeples, M. A., McGovern, T. H., Hegmon, M., Arneborg, J., Kintigh, K. W., Brewington, S., Spielmann, K. A., Simpson, I. A., Strawhacker, C., Comeau, L. E. L., Torvinen, A., Madsen, C. K., Hambrecht, G., and Smiarowski, K.: *P. Natl. Acad. Sci. USA*, 113, 298–303, <https://doi.org/10.1073/pnas.1506494113>, 2016.
- Neukom, R., Gergis, J., Karoly, D. J., Wanner, H., Curran, M., Elbert, J., González-Rouco, F., Linsley, B. K., Moy, A. D., Mundo, I., Raible, C. C., Steig, E. J., van Ommen, T., Vance, T., Viallalba, R., Zinke, J., and Frank, D.: Inter-hemispheric temperature variability over the past millennium, *Nature Clim. Change*, 4, 362–367, <https://doi.org/10.1038/nclimate2174>, 2014.
- Nicolle, M., Debret, M., Massei, N., Colin, C., de Vernal, A., Divine, D., Werner, J. P., Hormes, A., Korhola, A., and Linderholm, H. W.: Climate variability in the subarctic area for the last 2 millennia, *Clim. Past*, 14, 101–116, <https://doi.org/10.5194/cp-14-101-2018>, 2018.
- PAGES2k Consortium: A global multiproxy database for temperature reconstructions of the Common Era, *Scientific Data*, 4, 170088, <https://doi.org/10.1038/sdata.2017.88>, 2017.
- PAGES 2k Consortium: Continental-scale temperature variability during the past two millennia, *Nat. Geosci.*, 6, 339–346, <https://doi.org/10.1038/ngeo1797>, 2013.
- Pendleton, S. L., Miller, G. H., Anderson, R. A., Crump, S. E., Zhong, Y., Jahn, A., and Geirsdottir, Á.: Episodic Neoglacial expansion and rapid 20th century retreat of a small ice cap on Baffin Island, Arctic Canada, and modeled temperature change, *Clim. Past*, 13, 1527–1537, <https://doi.org/10.5194/cp-13-1527-2017>, 2017.
- Randerson, J. T., Lindsay, K., Munoz, E., Fu, W., Moore, J. K., Hoffman, F. M., Mahowald, N. M., and Doney, S. C.: Multi-century changes in ocean and land contributions to the climate-carbon feedback, *Global Biogeochem. Cy.*, 29, 744–759, 2015.
- Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., and Kaplan, A.: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.-Atmos.*, 108, 4407, <https://doi.org/10.1029/2002JD002670>, 2003.
- Rohde, R., Muller, R., Jacobsen, R., Muller, E., and Perlmutter, S.: A New Estimate of the Average Earth Surface Land Temperature Spanning 1753 to 2011, *Geoinfor Geostat: An Overview 1: 1*, <https://doi.org/10.4172/2327-4581.1000101>, 2013.
- Seftigen, K., Goosse, H., Klein, F., and Chen, D.: Hydroclimate variability in Scandinavia over the last millennium – insights from a climate model–proxy data comparison, *Clim. Past*, 13, 1831–1850, <https://doi.org/10.5194/cp-13-1831-2017>, 2017.
- Shi, F., Zhao, S., Guo, Z., Goosse, H., and Yin, Q.: Multi-proxy reconstructions of May–September precipitation field in China over the past 500 years, *Clim. Past*, 13, 1919–1938, <https://doi.org/10.5194/cp-13-1919-2017>, 2017.
- Shuman, B. N., Routson, C., McKay, N., Fritz, S., Kaufman, D., Kirby, M. E., Nolan, C., Pederson, G. T., and St-Jacques, J.-M.: Placing the Common Era in a Holocene context: millennial to centennial patterns and trends in the hydroclimate of North America over the past 2000 years, *Clim. Past*, 14, 665–686, <https://doi.org/10.5194/cp-14-665-2018>, 2018.
- Smith, T. M. and Reynolds, R. W.: A global merged land-air-sea surface temperature reconstruction based on historical observations (1880–1997), *J. Climate*, 18, 2021–2036, 2005.
- Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., and Schellnhuber, H. J.: Trajectories of the Earth System in the Anthropocene, *P. Natl. Acad. Sci. USA*, 115, 8252–8259, <https://doi.org/10.1073/pnas.1810141115>, 2018.
- Stenni, B., Curran, M. A. J., Abram, N. J., Orsi, A., Goursaud, S., Masson-Delmotte, V., Neukom, R., Goosse, H., Divine, D., van Ommen, T., Steig, E. J., Dixon, D. A., Thomas, E. R., Bertler, N. A. N., Isaksson, E., Ekaykin, A., Werner, M., and Frezzotti, M.: Antarctic climate variability on regional and continental scales over the last 2000 years, *Clim. Past*, 13, 1609–1634, <https://doi.org/10.5194/cp-13-1609-2017>, 2017.
- Thomas, E. R., van Wessel, J. M., Roberts, J., Isaksson, E., Schlosser, E., Fudge, T. J., Vallenga, P., Medley, B., Lenaerts, J., Bertler, N., van den Broeke, M. R., Dixon, D. A., Frezzotti, M., Stenni, B., Curran, M., and Ekaykin, A. A.: Regional Antarctic snow accumulation over the past 1000 years, *Clim. Past*, 13, 1491–1513, <https://doi.org/10.5194/cp-13-1491-2017>, 2017.
- Tierney, J. E., Abram, N. J., Anchukaitis, K. J., Evans, M. N., Giry, C., Kilbourne, K. H., Saenger, C. P., Wu, H. C., and Zinke, J.: Tropical sea surface temperatures for the past four centuries reconstructed from coral archives, *Paleoceanography and Paleoclimatology*, 30, 226–252, 2015.
- Turney, C. S. M., Baillie, M., Palmer, J., and Brown, D.: Holocene climatic change and past Irish societal response, *J. Archaeol. Sci.*, 33, 34–38, <https://doi.org/10.1016/j.jas.2005.05.014>, 2006.
- Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., Gonzalez-Beltran, A., Gray, A. J. G., Groth, P., Goble, C., Grethe, J. S., Heringa, J., 't Hoen, P. A. C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S. J., Martone, M. E., Mons, A., Packer, A. L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M. A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., and Mons, B.: The FAIR Guiding Prin-

- principles for scientific data management and stewardship. *Scientific Data*, 3, 160018, <https://doi.org/10.1038/sdata.2016.18>, 2016.
- Xu, C., Sano, M., Dimri, A. P., Ramesh, R., Nakatsuka, T., Shi, F., and Guo, Z.: Decreasing Indian summer monsoon on the northern Indian sub-continent during the last 180 years: evidence from five tree-ring cellulose oxygen isotope chronologies, *Clim. Past*, 14, 653–664, <https://doi.org/10.5194/cp-14-653-2018>, 2018.
- Zhong, Y., Jahn, A., Miller, G. H., and Geirsdottir, A.: Asymmetric cooling of the Atlantic and Pacific Arctic during the past two millennia: A dual observation-modeling study, *Geophys. Res. Lett.*, 45, 12497–12505, <https://doi.org/10.1029/2018GL079447>, 2018.