Introduction to the Special Issue on Climate of the Past 2000 Years: Global and Regional Syntheses

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

[1]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
[2]School of Earth and Environmental Sciences, Northfields Avenue, University of Wollongong, New South Wales 2522, Australia
[3]Institut National de la Recherche Scientifique, Centre Eau Terre Environnement, G1K 9A9, Québec, QC, Canada
[4]Research School of Earth Sciences and ARC Centre of Excellence for Climate System Science, Australian National University, Canberra ACT 2601, Australi
[5]Department of Geology, University of Maryland, College Park, Maryland 20742, USA
[6]Georges Lemaître Centre for Earth and Climate Research (TECLIM), Earth and Life Institute, Université catholique de Louvain (UCL), Leuven, Belgium
[7]PAGES International Project Office, Falkenplatz 16, 3012 Bern, Switzerland
[8]School of Earth Sciences & Environmental Sustainability, Northern Arizona University, Flagstaff, USA
[9]Regional Climate Group, Department of Earth Sciences, University of Gothenburg, 40530 Gothenburg, Sweden
[10]University of Bern, Oeschger Centre for Climate Change Research & Institute of Geography, 3012 Bern, Switzerland

Correspondence to: Chris Turney (c.turney@unsw.edu.au)

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".

1.1 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 (Bronselaer et al., 2018; Comyn-Platt et al., 2018; Friedlingstein et al., 2013; Randerson et al., 2015), 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 is limited in both space

and time (Rayner et al., 2003). There is increasing recognition that instrumental and satellite observations do not fully capture the amplitude 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 (Nelson et al., 2016; Huber and Knutti, 2011; Caseldine and Turney, 2010; Turney et al., 2006). 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, Arctic, Antarctic, South 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 scale, with a long-term global cooling trend prior to the 20th 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 behavior of phenomena, integrating projects addressing climate changes across regional boundaries (Abram et al., 2014; Abram et al., 2016; Neukom et al., 2014; McGregor et al., 2015; 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; Kaufmann and 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 (Thomas et al., 2017; Stenni 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; 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 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 this particular ice cap will soon disappear if current trends continue through this century.

To complete this Special Issue, Kaufman and 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.

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, Nature Climate Change, 4, 564-569, 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, 10.1038/nature19082, 2016.

Bronselaer, B., Zanna, L., Munday, D. R., and Lowe, J.: Southern Ocean carbon-wind stress feedback, Climate Dynamics, 51, 2743-2757, 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 Quatern 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, Nature Geosci, 11, 568-573, 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, 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, 10.5194/cp-13-1593-2017, 2017.

Freund, M., Henley, B.J., Karoly, D.J., Allen, K.J., Baker, P.J., 2017. Multi-century cool- and warm-season rainfall reconstructions for Australia's major climatic regions. Clim. Past 13, 1751-1770.

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, Journal of Climate, 27, 511-526, 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, 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 Oldenborgh, G.J.v. (2017) Estimating Changes in Global Temperature since the Preindustrial Period. 98(9), 1841-1856.

Huber, M., and Knutti, R.: Anthropogenic and natural warming inferred from changes in Earth's energy balance, Nature Geosci, advance online publication, 2011.

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, United Kingdom 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, 10.5194/cp-12-2181-2016, 2016.

Kaufman, D. S., and the PAGES 2k Special Issue Editors: Technical note: Open-paleo-data implementation pilot – the PAGES 2k special issue, Clim Past, 14, 593-600, 10.5194/cp-14-593-2018, 2018.

Lamb, H. H.: The early Medieval warm epoch and its sequel, Palaeogeography, Palaeoclimatology, Palaeoecology, 1, 13-37, 1965.

Lamb, H. H.: Climate: Past, Present and Future. Methuen and Co Ltd, London. 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., Massei, N., Seftigen, K., Thomas, E. K., Werner, J., Andersson, S., Berntsson, A., Luoto, T. P., Nevalainen, L., Saarni, S., and Väliranta, M.: Arctic hydroclimate variability during the last 2000 years: current understanding and research challenges, Clim Past, 14, 473-514, 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-Bliesner, 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, United Kingdom 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, Nature Geosci, 8, 671-677, 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.: Proceedings of the National Academy of Sciences, 113, 298-303, 10.1073/pnas.1506494113, 2016.

Neukom, R., Gergis, J., Karoly, D. J., Wanner, H., Curran, M., Elbert, J., Gonzalez-Rouco, F., Linsley, B. K., Moy, A. D., Mundo, I., Raible, C. C., Steig, E. J., van Ommen, T., Vance, T., Villalba, R., Zinke, J., and Frank, D.: Inter-hemispheric temperature variability over the past millennium, Nature Clim. Change, 4, 362-367, 10.1038/nclimate2174, 2014.

Nicolle, M., Debret, M., Massei, N., Colin, C., deVernal, 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, 10.5194/cp-14-101-2018, 2018.

PAGES2k Consortium: A global multiproxy database for temperature reconstructions of the Common Era, Scientific Data, 4, 170088, doi: 170010.171038/sdata.172017.170088, 2017.

PAGES 2k Consortium: Continental-scale temperature variability during the past two millennia, Nature Geosci, 6, 339-346, 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, 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.: Multicentury changes in ocean and land contributions to the climate-carbon feedback, Global Biogeochem Cycles, 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, Journal of Geophysical Research: Atmospheres, 108, 4407, doi:4410.1029/2002JD002670, 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. , 7, 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, 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, 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, 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), Journal of 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., Schellnhuber, H.J., 2018. Trajectories of the Earth System in the Anthropocene. Proceedings of the National Academy of Sciences, doi: 10.1073/pnas.1810141115.

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, 10.5194/cp-13-1609-2017, 2017.

Thomas, E. R., van Wessem, J. M., Roberts, J., Isaksson, E., Schlosser, E., Fudge, T. J., Vallelonga, 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, 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. (2015) Tropical sea surface temperatures for the past four centuries reconstructed from coral archives. 30(3), 226-252.

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., Mons, B., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data 3, 160018.

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, 10.1016/j.jas.2005.05.014, 2006.

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, 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, 45, 12,497-412,505, doi:10.1029/2018GL079447, 2018.