Environmental Reviews

The Medieval Climate Anomaly in Oceania

Journal:	<i>Environmental Reviews</i>
Manuscript ID	er-2019-0012.R1
Manuscript Type:	Review
Date Submitted by the Author:	13-May-2019
Complete List of Authors:	Lüning, Sebastian; Institute for Hydrography, Geoecology and Climate Sciences, Gałka, Mariusz; University of Lodz, Department of Geobotany and Plant Ecology, Faculty of Biology and Environmental Protection García-Rodríguez, Felipe; CURE-Rocha, Centro Universitario Regional Este Vahrenholt, Fritz; University of Hamburg, Department of Chemistry
Is this manuscript invited for consideration in a Special Issue?:	Not applicable (regular submission)
Keyword:	Late Holocene, Little Ice Age, Temperature reconstructions, Palaeoclimatology, El Niño-Southern Oscillation

SCHOLARONE™
Manuscripts

The Medieval Climate Anomaly in Oceania

Sebastian Lüning^{1*}, Mariusz Gałka², Felipe García-Rodríguez^{3,4}, Fritz Vahrenholt⁵

Abstract

Temperatures in Oceania have risen by 0.5-1°C over the past 100 years, resulting e.g. in significant retreat of New Zealand's glaciers. In order to better understand natural and anthropogenic contributions to this warming process, the observed climatic change has to be placed in a longer-term palaeotemperature context. Of particular interest is the Medieval Climate Anomaly (MCA, 1000-1200 AD), a recognized period of natural pre-industrial climate change, associated with marked temperature and hydroclimatic variability that is best known from the Northern Hemisphere. Temperature reconstructions for Oceania were traditionally based on two classical tree ring series. Here, we are enlarging the Oceania reference dataset with another 13 published temperature reconstructions from SE Australia, New Zealand and West Papua. These are based on a variety of proxy types, and help to geographically and methodologically augment the regional palaeoclimate database. The proxy series have been thoroughly compared and the MCA trends palaeoclimatologically mapped. Ten out of the 15 sites show a relatively warm MCA, compared to the last 1500 years, with warming generally occurring in the envelope period 900-1500 AD. In some sites of SE Australia and at the west coast of New Zealand's South Island, warming appears to be delayed by 200-300 years. The end of the medieval warming at around 1500 AD occurred about two centuries later than on most other continents, suggesting a possible interhemispheric climate lag mechanism possibly involving deepwater circulation. Likely drivers for the medieval warming in Oceania are atmospheric-ocean cycles such as the Southern Annular Mode (SAM) and El Niño-Southern Oscillation (ENSO), in combination

with solar activity changes. MCA palaeotemperature data are still lacking for large parts of Oceania, namely the arid and tropical parts of Australia, Micronesia, central and northern Polynesia, as well as central and eastern Melanesia, highlighting the need for future research.

Keywords: climate change; Late Holocene; Little Ice Age; temperature reconstructions; palaeoclimatology; El Niño-Southern Oscillation; Medieval Warm Period; Southern Hemisphere

¹Institute for Hydrography, Geoecology and Climate Sciences, Hauptstraße 47, 6315 Ägeri, Switzerland. E-mail: luening@ifhgk.org

²Mariusz Gałka, Department of Geobotany and Plant Ecology, Faculty of Biology and Environmental Protection, University of Lodz, 12/16 Banacha Str., Lodz, Poland. E-mail: gamarga@wp.pl

³Felipe García-Rodríguez, Centro Universitario Regional Este, CURE-Rocha, Ruta 9 y Ruta 15 s/n, Uruguay. E-mail: felipegr@fcien.edu.uy

⁴Felipe García-Rodríguez, Programa de Pós-Graduação em Oceanologia, Instituto de Oceanografia, Universidade Federal do Rio Grande, Av. Itália, km 8, Cx.P. 474, 96201-900, Rio Grande, RS, Brazil.

⁵Fritz Vahrenholt, Department of Chemistry, University of Hamburg, Martin-Luther-King-Platz 6, 20146 Hamburg, Germany. E-mail: fritz.vahrenholt@chemie.uni-hamburg.de

*Corresponding author

49 Introduction

50 Oceania is a geographic region that comprises Australasia, Melanesia, Micronesia, and
51 Polynesia. Like in most other parts of the world, average temperatures in Oceania have risen
52 by 0.5-1°C over the past 100 years (IPCC 2014) with an increase in warmer days and nights
53 (Donat et al. 2013). Significant warming has been reported from Australia (Commonwealth of
54 Australia 2016), New Zealand (Ministry for the Environment New Zealand and Stats NZ
55 2017; Mullan et al. 2018), and Hawaii (U.S. Global Change Research Program 2017).
56 Temperatures in Oceania appear to have risen generally more slowly than in large parts of
57 the Northern Hemisphere (IPCC 2014), but long-term warming in the tropical Pacific has
58 continued over the past few decades (Whan et al. 2014). A simple regional mean of a Pacific
59 island series shows a trend of +0.16°C per decade over 1961-2010 (Jones et al. 2013).
60 Nevertheless, natural temperature fluctuations associated with ocean cycles such as El Niño-
61 Southern Oscillation (ENSO), Southern Oscillation Index (SOI), Pacific Decadal Oscillation
62 (PDO), Interdecadal Pacific Oscillation (IPO), and Southern Annular Mode (SAM) have
63 repeatedly led to decadal-scale cooling phases in Oceania (Bordbar et al. 2017; Chinn et al.
64 2014; Saurral et al. 2018).

65 Global warming has also resulted in a remarkable retreat of glaciers in New Zealand. Franz
66 Josef Glacier in the Southern Alps has retreated about 3 km over the past 100 years
67 (Oerlemans 2005; Purdie et al. 2014). The glacier had already started shrinking shortly after
68 1600 AD during the middle of the Little Ice Age (LIA) when Franz Josef Glacier reached its
69 maximum extent (McKinze et al. 2004). Half or more of New Zealand's ice mass has been
70 lost since the LIA ice maximum (Chinn et al. 2014; Hoelzle et al. 2007). Long-term retreat
71 was repeatedly interrupted by re-advance phases, most recently 1946-1951, 1965-1967,
72 1983-1999 and 2004-2008 AD (Chinn et al. 2005; Fitzharris et al. 2007; Fitzharris et al. 1992;
73 Purdie et al. 2014). This superimposed modulation of glacier dynamics is most probably
74 linked to the ocean cycles and associated temperature variability (Mackintosh et al. 2017),
75 rather than changes in precipitation (Chinn et al. 2005). Glacier retreat commenced after the

76 peak of the Little Ice Age (LIA), which (besides the 8.2 ka event) represents the coldest
77 phase in the global climate evolution of the past 10,000 years (Chambers et al. 2014; Marcott
78 et al. 2013; PAGES 2k Consortium 2013; Solomina et al. 2016). Modern glacier retreat has
79 been also noted in New Guinea (Klein and Kincaid 2006).

80 In order to better understand and distinguish natural and anthropogenic contributions to the
81 warming and glacier retreat of the last 150 years, the observed climatic change has to be
82 placed in a longer-term palaeotemperature context. Of particular interest is the Medieval
83 Climate Anomaly (MCA), a recognized period of natural pre-industrial climate change
84 associated with marked temperature and hydroclimatic variability in many parts of the world
85 (e.g. Graham et al. 2011; Lüning et al. 2018a; Lüning et al. 2018b; Lüning et al. 2017; Mann
86 et al. 2009; Seager et al. 2007). The anomaly was first described by Lamb (1965) as 'Early
87 Medieval Warm Epoch', which subsequently changed in the literature to 'Medieval Warm
88 Period' (MWP), and later to MCA. It is generally agreed today that the core period of the
89 MCA encompasses ca. 1000-1200 AD, even though different time chronologies and
90 durations have historically been reported in the literature (e.g. Crowley and Lowery 2000;
91 Esper and Frank 2009; Mann et al. 2009; Nunn 2007). The MCA represents the most recent
92 natural warm phase and provides crucial context information for assessing our Current Warm
93 Period (CWP) and its warming process (e.g. Gergis et al. 2016; Ljungqvist et al. 2012;
94 Neukom et al. 2011).

95 Previous millennium-long temperature reconstructions for Australasia, the Southern
96 Hemisphere and the world traditionally used only two Oceanian proxy series fully
97 encompassing the MCA (Gergis et al. 2016; Mann et al. 2008; Mann et al. 2009; Neukom
98 and Gergis 2012; Neukom et al. 2014; PAGES 2k Consortium 2013, 2017). Namely, these
99 are the tree ring series from Mt. Read in Tasmania (Cook et al. 1991; Cook et al. 2000) and
100 Oroko Swamp in New Zealand (Cook et al. 2002), both of which show a neutral first half of
101 the MCA and a relatively warm second half compared to the last 1000 years. Most of the
102 regional reconstructions (e.g. Emile-Geay et al. 2013; Gergis et al. 2016; PAGES 2k

Consortium 2013, 2017) also include a coral proxy series from the Pacific Palmyra Atoll (Cobb et al. 2003). However, coverage of this series is very patchy over the MCA interval and only provides information for the last 50 years of the Anomaly. Furthermore, it is unclear whether the oxygen isotopes reflect temperature or precipitation changes. This dataset must therefore be treated with caution. Overall, the low number of high quality proxies and the low proxy type diversity results in a potential bias for the MCA trends in this large ocean-dominated region. Ideally, proxy data from a larger number of sites with different palaeotemperature reconstruction methodologies would have to be combined in order to avoid local site and proxy-type-inherent issues. In this contribution we are attempting to shed further light on the MCA in Oceania by incorporating further sites to the regional database and by diversifying the proxy data types. The analysis is based on a total of 15 published records (Fig. 1, Table 1) that have been identified in a systematic regional screening process. For each site, proxy trends and their palaeotemperature significance are being discussed in detail (texts S1-S3 and Figures S1-S4 in Supporting Information), which form the basis of a regional integration.

Modern Climate Elements of Oceania

Climate zones

According to the Köppen-Geiger climate classification (e.g. Köppen 1918), Oceania can be grouped into tropical, arid and temperate climate zones. The northern part of the region (northern Australia, New Guinea, Melanesia, Polynesia, Micronesia) is generally tropical, whilst the southeastern part (eastern Australia, New Zealand) is dominated by a temperate climate. The majority of Australia is characterized by arid desert and steppe climate. High altitude climate conditions prevail in the Southern Alps in New Zealand, where large glaciers and snowfields exist. For a detailed overview of Australasian climate see e.g. Lorrey and Bostock (2014).

129

130 ***Currents and Upwelling zones***

131 Ocean currents in Oceania are dominated by the counterclockwise-flowing South Pacific
132 Gyre system. Key elements are the westward-flowing South Equatorial Current, the warm
133 southward-flowing East Australian Current (EAC) between Australia and New Zealand
134 (Wijeratne et al. 2018), and the eastward-flowing Antarctic Circumpolar Current (Rintoul
135 2009). The western side of Australia is characterized by the cold, northward-flowing West
136 Australian Current that forms part of the Indian Ocean Gyre. Closer to the coast of Western
137 Australia flows the warm Leeuwin Current southwards (Cresswell and Domingues 2009). The
138 coasts of Northwest Australia are affected by the Indonesian Throughflow which carries
139 warm water westwards from the Pacific Ocean to the Indian Ocean through the straits and
140 deep passages of the Indonesian Archipelago (Feng et al. 2018; Jones 2012). Seasonal
141 upwelling occurs in southern and northeast Australia as well as in parts of New Zealand (e.g.
142 Cresswell et al. 2017). The January ITCZ lies north of Australia.

143

144 **Material and Approach**

145 ***Literature review***

146 The mapping project is based on a literature screening process during which all accessible
147 published Oceania palaeotemperature case studies were evaluated with emphasis on their
148 temporal coverage, type of climate information and data resolution. Suitable papers including
149 the MCA core period 1000-1200 AD were selected for a thorough analysis. A recent
150 synthesis paper by Dixon et al. (2017) on Australasian palaeoclimate records of the past
151 2000 years facilitated the search for data. Palaeohydroclimatic changes are not part of our
152 study and will be evaluated in a future contribution.

153

Palaeoclimate archives and data types

MCA climate reconstructions of the high-graded publications comprised several natural and historical archives, namely (1) sediment cores from offshore marine, lakes, peatlands, (2) age dating of glacier moraines, (3) tree rings, (4) cave stalagmites, (5) deep sea black corals, and (6) historical and archaeological accounts on societal change. Data types include (a) palaeontology: pollen assemblages, tree ring width; (b) inorganic geochemistry: Mg/Ca planktonic foraminifera sea surface temperature (SST), $\delta^{18}\text{O}$ in foraminifera, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in stalagmites for temperature reconstructions; (c) organic geochemistry: chlorophyll, Uk'37 SST; and (d) geophysics: radiocarbon ^{14}C and ^{10}Be age dating of glacier moraines; sea surface radiocarbon reservoir ages of deep sea corals. Previous work on calcite stable isotope values from New Zealand speleothems showed that $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ are affected by both rainfall and temperature. Temperature usually has the more dominant effect on $\delta^{18}\text{O}$ values and is typically correlating positively. In the case of $\delta^{13}\text{C}$, rainfall was found to be more influential (Hendy et al. 2011; Lorrey et al. 2008; Williams et al. 2005; Williams et al. 2015). Nevertheless, some exceptions exist in which $\delta^{18}\text{O}$ values have a negative relationship to temperature, e.g. in Mt Arthur alpine records from NW Nelson in New Zealand (e.g. Hellstrom et al. 1998).

Data processing and visualisation

Qualitative. Key information of the identified publications were captured on a georeferenced online map which is open-access to all interested members of the palaeoclimate scientific community for research and reference purposes (<http://t1p.de/mwp>). The MCA palaeotemperature was visually assessed and compared to the phases preceding and following the anomaly. The MCA conditions were colour-coded with red dots marking a trend towards warmer conditions while blue dots represent cooling. The colour-coding provides much-needed initial orientation in the complex global MCA climate puzzle.

Quantitative. In order to robustly document, visualise and analyse MCA palaeoclimatic variability, all relevant climate curve data were collected in digital form for flexible plotting and curve comparison. The tabulated data were retrieved (a) from palaeoclimate online data repositories (mainly Pangaea, NOAA's National Climatic Data Center NCDC (now: National Centers for Environmental Information, NCEI), and data supplements of papers), (b) from authors by email request and (c) by digitizing and vectorising using WebPlotDigitizer (<https://automeris.io/WebPlotDigitizer/>). Data sources for each site are listed in Table S1. All curve data have been loaded into Lloyd's Register's software ICTM which serves as a common database and comparison tool in the MCA mapping project. ICTM was originally developed for 'geological well correlations' in the fields of water, minerals and petroleum exploration. The software reliably handles large amounts of fully customizable curve data types related to georeferenced wells. By way of technology transfer, we are introducing well correlation software to the field of the climate sciences which allows fast and flexible comparison of climate curves. Another advantage is the advanced visualisation and shading of peak and trough curve anomalies, a functionality which is not available in most standard spreadsheet software packages. See Lüning et al. (2017) for details on the workflow. The vectorized Oceania base maps in this paper were retrieved from <http://www.d-maps.com>.

Challenges

Like any other regional palaeoclimatic synthesis, the current Oceania palaeotemperature MCA mapping effort is subject to a number of challenges. Palaeoclimatology is not an exact mathematical science, nevertheless provides crucial proxy data for the palaeoclimatological context and model calibration. A probabilistic approach is needed whereby the most likely scenario is selected from the set of available proxies. Issues identified in the current synthesis include (1) low resolution palaeoclimatic data, (2) limited age control, (3) conflicting information from multiple proxies. See Lüning et al. (2017) for a more detailed discussion.

Findings

A total of 15 study sites have been identified in Oceania which are mostly concentrated in southeastern Australia and New Zealand, except for site 1 which lies south of West Papua (Fig. 1, Table 1). Detailed site descriptions and palaeotemperature panels are shown in the Supporting Information to this paper (texts S1-S3, figures S1-S4, Table S1). Two panels with eight representative sites and the Australasian warm season temperature composite by Gergis et al. (2016) are illustrated in Figures 2 and 3. Proxy plots start at 500 AD in order to also document the climatic trends preceding the MCA and place the anomaly in a multi-centennial context.

Discussion

Temperature trends

Ten out of the 15 sites show a relatively warm MCA, compared to the last 1500 years (Fig. 4). The marine core MD-98-2176 off West Papua (site 1) shows a major warm peak during the MCA, even though the SST data appear a bit noisy overall (Stott et al. 2004) (Fig. S1). Marine core MD03-2611 off southeast Australia (site 2) yielded a 900 year long warm phase whereby the highest temperatures were reached in the late MCA (Moros et al. 2009; Perner et al. 2018) (Fig. S1). A brief cold episode during the early MCA coincides with the solar Oort minimum. The two Tasmanian tree rings areas Cradle Mountain (site 4) and Mt Read (site 5) are characterized by a significant amount of temperature variability, yet the MCA in both locations is dominated by relatively warm conditions within the 1500 year context (Allen et al. 2017; Cook et al. 2000) (Figs. 3 and S2). The warm phase in Mt Read lasts from 900 to 1500 AD. A similarly long warm period occurs in Mt Honey on Campbell Island (site 8) where pollen-derived temperatures stayed high from 900 until 1650 AD (McGlone et al. 2010) (Fig. 2).

A warm MCA is also suggested by most cave studies in New Zealand. Oxygen isotopes from stalagmite suggest several hundred years of medieval elevated temperatures in Fiordland (site 9, 900-1400 AD), Hawkes Bay (site 13, 700-1200 AD) and Waitomo (site 14, 950-1500 AD) (Lorrey et al. 2008; Williams et al. 2004) (Fig. 2). Whilst Fiordland and Waitomo show a similar timing of the warm period, the Hawkes Bay warming appears to be shifted to older ages by 200 years. Both Waitomo and Hawkes Bay sites are located on North Island, likely sharing the same climate history. It cannot be ruled out that the discrepancy in timing is related to age model issues rather than local variability. A warm MCA is also indicated by Mt Cook glacier reconstructions because the MCA lies between two well-dated glacier advance phases that occurred 1000 AD and 1400 AD (Schaefer et al. 2009) (Fig. 2). An archaeological kauri tree rings from northern North Island (site 15) suggests warm-wet conditions during the majority of the MCA, as evidenced by a reduction in tree ring width (Boswijk et al. 2014) (Fig S4). Yet, the earliest part of the MCA, coinciding with the solar Oort Minimum, appears to have been cool and dry.

An alternation of well-defined multicentennial warm and cold phases has been reconstructed for Grotto of Oddities in SE Australia (site 3). Temperatures oscillated with an amplitude of more than 1°C during the past 1500 years (McGowan et al. 2018). A pronounced warm peak was reported for the period 1150-1450 AD (Fig. 3), largely post-dating the MCA warming documented in many of the other Oceania study sites. One possibility is that the warming could in fact have commenced 150 years earlier, which would still be well within the age model uncertainty of this speleothem study (see Supplement text S1 for details). A second possibility is that warming in some areas of the region was delayed by 200-300 years. The pattern of late MCA warming appears to be also developed in three other Oceania sites. Firstly, a cave study in the Nelson District in northern South Island (site 12) shows mild MCA warming, followed by abrupt warming at the end of the MCA (Williams et al. 2005) (Fig. S3). Temperatures stayed high until 1500 AD. Secondly, a very similar timing occurs in Oroko Swamp at the central west coast of South Island, a warm season dataset (Cook et al. 2002) (site 11). Here, the MCA is characterized by a cold first half and a warmer second half. Oroko

warming lasted until 1500 AD. Thirdly, late MCA warming is also suggested in a study of the East Australian Current (EAC) which reaches its greatest strength after the MCA (Komugabe-Dixon et al. 2016) (Fig. 3).

The temperature reconstructions of two sites are to be treated with caution. An organic productivity study in the southern Tasmanian Duckhole Lake (site 6) (Saunders et al. 2013) suggests a millennium-long warming trend (Fig. S2, text S2), which, however, is not supported by any other palaeotemperature reconstructions in the region. It may be worth considering, whether the real temperature signal is contained in the de-trended data set or whether the proxy is actually valid beyond the calibration interval (see Supplement text S2 for details).

Based on all available MCA studies, the overall warming appears to have occurred in the envelope period of 900-1500 AD. The 900 AD starting date can be found e.g. in Mt Read, Mt Honey, Fiordland and Waitomo (Figs. 2 and 3). The 1500 AD end date (± 100 years) is documented in Grotto of Oddities, Mt Read, South Tasman Sea, Mt Honey, Fiordland, Oroko Swamp, Nelson District and Waitomo (Figs. 2 and 3). The end of the medieval warming appears to be slightly later than for most other continents where this warm period typically ends around 1250-1350 AD (PAGES2k 2013). Goosse et al. (2004) proposed an interhemispheric climate lag mechanism, involving the long-term memory of deepwater masses, inducing a lagged response of about 150 years in the Southern Ocean compared to the Northern Hemisphere (see also Nunn 2007).

Australasian temperature composites

The medieval warming ending around 1500 AD is well represented in the Australasian temperature composite published by Gergis et al. (2016) (Fig. 3). Out of the 28 records used for their reconstruction, only two of them cover the full MCA, namely Mt Read (our site 5) and Oroko Swamp (our site 11). Data coverage of the also used classical Palmyra series (Cobb

et al. 2003) is patchy. The general trends in the Australasian composite of the past millennium are dominated by the Mt Read tree ring data set, especially for the initial 500 years (Fig. 3). Interestingly, the cooler early MCA interpreted in Oroko hardly influences the composite. The strong 20th century temperature uptick in the Australasia reconstruction is based on instrumental data (Gergis et al. 2016: Supplement text S3.1). The Mt Read tree ring reconstructions show somewhat lower temperatures for the late 20th century which were already occasionally reached during the past 1000 years (Cook et al. 1991; Cook et al. 2000). The Australasia temperature reconstruction of the PAGES 2k Consortium (2013) appears very similar to the composite of Gergis et al. (2016).

Climate Drivers

The documented MCA temperature change in Oceania occurred in pre-industrial times and therefore requires suitable climate drivers other than anthropogenic greenhouse gasses (Nunn 2007). A good starting point is the study of atmospheric-ocean cycles which are responsible for modern climate variability at interannual timescales. Modern climate variability in Oceania is heavily influenced by El Niño-Southern Oscillation, ENSO (e.g. McLean et al. 2009; Ning et al. 2018; Wang et al. 2017), Indian Ocean Dipole, IOD (e.g. Zhang et al. 2015), Southern Annular Mode, SAM (e.g. Gillett et al. 2006), and the Interdecadal Pacific Oscillation, IPO (e.g. Duncan et al. 2010; Salinger et al. 2014). Palaeoclimate reconstructions of the past centuries and millennia have identified such cycles as important climatic drivers (Cook et al. 2000; Cook et al. 2006; Gouramanis et al. 2013; Komugabe-Dixon et al. 2016; Lorrey et al. 2008; Perner et al. 2018).

The main MCA warming phase coincides with a higher SAM, more El Niño-dominated ENSO, more positive IPO and higher solar activity (Abram et al. 2014; Conroy et al. 2008; Steinhilber et al. 2012; Vance et al. 2015) (Fig. 5). Spectral analysis of the classical Mt Read tree rings series (site 5), yields characteristic cycle periods associated with the solar Gleissberg (80 years) and Suess-de Vries (210 years) cycles (Cook et al. 1995; Cook et al.

2000). The reconstructions of global volcanic forcing (Sigl et al. 2015) and global volcanic aerosol optical depth (Crowley and Unterman 2013) suggest low volcanic activity during the early part of the MCA (950-1100 AD), and increased volcanic activity in the second half (1100-1350 AD), followed by low volcanic activity (1350-1600 AD) (Fig. 5). Comparison with multi-decadal temperature proxy records from Oceania does not reveal a climate signal in either the MCA nor early LIA climate data that would correspond to this global volcanic activity pattern. At shorter time scales of up to four years, however, Blake et al. (2018) demonstrated that large eruptions may cause climatic effects in Australia. The exact driver of medieval warming in Oceania is still poorly understood and remains an essential subject for future research. Without this key information, climate models are still unable to reproduce the observed medieval climate patterns reconstructed for Oceania and the Pacific (Ault et al. 2013; Parsons et al. 2017). Nevertheless, parts of the mechanism are beginning to become clearer, involving changes in SAM and ENSO (Goodwin et al. 2014a). The Subtropical Ridge and the Westerly Storm Tracks shifted poleward during the MCA, followed by an equatorward move 1300-1350 AD (Goodwin et al. 2014a; Goodwin et al. 2014b).

Conclusions

Temperatures in Oceania have risen by 0.5-1°C over the past 100 years, resulting e.g. in significant retreat of New Zealand's glaciers. In order to better understand natural and anthropogenic contributions to this warming, the observed climatic change has to be placed in a longer-term palaeotemperature context. Of particular interest is the Medieval Climate Anomaly (MCA, 1000-1200 AD), a recognized period of natural pre-industrial climate change, associated with marked temperature and hydroclimatic variability that is best known from the Northern Hemisphere. Temperature reconstructions for Oceania were traditionally based on two classical tree ring series. Here, we are enlarging the Oceania reference dataset with another 13 published temperature reconstructions from SE Australia, New Zealand and West

Papua. These are based on a variety of proxy types, and help to geographically and methodologically diversify the regional palaeoclimate database. The proxy series have been thoroughly compared and the MCA trends palaeoclimatologically mapped. Ten out of the 15 sites show a relatively warm MCA, compared to the last 1500 years, with warming generally occurring in the envelope period 900-1500 AD. In some sites of SE Australia and at the west coast of New Zealand's South Island, warming appears delayed by 200-300 years. The end of the medieval warming at around 1500 AD occurred about two centuries later than on most other continents, suggesting a possible interhemispheric climate lag mechanism possibly involving deepwater circulation. Likely drivers for the medieval warming in Oceania are atmospheric-ocean cycles such as the Southern Annular Mode (SAM) and El Niño-Southern Oscillation (ENSO), in combination with solar activity changes. MCA palaeotemperature data are still missing for large parts of Oceania, namely the arid and tropical parts of Australia, Micronesia, central and northern Polynesia, as well as central and eastern Melanesia, highlighting the need for future research. A better understanding of climate change in Oceania during the last millennium is not only important for global syntheses, but also in the context of impact on Pacific societies (Goodwin et al. 2014b; Nunn 2007; Nunn 2000; Nunn et al. 2007).

Acknowledgements

We wish to thank all scientists whose case studies form the basis of this palaeoclimate mapping synthesis. We are grateful for provision of tabulated data and valuable discussions to Julien Emile-Geay, Kathryn Allen, Matt McGlone, Kerstin Perner, Frank Bosse, Paul Williams, and Hamish McGowan. Part of the data were sourced through the PANGAEA online data base and the NOAA National Centers for Environmental Information (NCEI, formerly NCDC), invaluable services which are greatly acknowledged. We are indebted to Jurgis Klaudius and Lloyd's Register for providing the database and well correlation software

IC™ for this project. This review forms part of the Medieval Climate Anomaly Mapping Project which in its startup phase has been kindly supported by crowdfunding. We are particularly grateful to Jens Kröger for helping to jump-start the project. The authors have no competing interests. Note that this study is fully unrelated to the first author's employment in the hydrocarbon sector and was neither commissioned nor funded by the energy industry. SL undertook this study outside office hours as a private person, trained geoscientist, and former full-time academic. The project was greatly facilitated by Google My Maps which allows to effectively capture and share MCA map data with the climate science community. The vectorised Oceania base map in this paper was sourced from <http://www.d-maps.com>, a useful service for which we are thankful. We are grateful to two anonymous reviewers who greatly helped to improve this manuscript.

References

- Abram, N. J., Mulvaney, R., Vimeux, F., Phipps, S. J., Turner, J., and England, M. H., 2014, Evolution of the Southern Annular Mode during the past millennium: Nature Climate Change, v. 4, p. 564.
- Allen, K. J., Cook, E. R., Buckley, B. M., Larsen, S. H., Drew, D. M., Downes, G. M., Francey, R. J., Peterson, M. J., and Baker, P. J., 2014, Continuing upward trend in Mt Read Huon pine ring widths – Temperature or divergence?: Quaternary Science Reviews, v. 102, p. 39-53.
- Allen, K. J., Fenwick, P., Palmer, J. G., Nichols, S. C., Cook, E. R., Buckley, B. M., and Baker, P. J., 2017, A 1700-year Athrotaxis selaginoides tree-ring width chronology from southeastern Australia: Dendrochronologia, v. 45, p. 90-100.

- 389 Ault, T. R., Deser, C., Newman, M., and Emile-Geay, J., 2013, Characterizing decadal to
390 centennial variability in the equatorial Pacific during the last millennium: Geophysical
391 Research Letters, v. 40, no. 13, p. 3450-3456.
- 392 Blake, S. A. P., Lewis, S. C., LeGrande, A. N., and Miller, R. L., 2018, Assessing the impact
393 of large volcanic eruptions of the last millennium (850–1850 CE) on Australian rainfall
394 regimes: Clim. Past, v. 14, no. 6, p. 811-824.
- 395 Bordbar, M. H., Martin, T., Latif, M., and Park, W., 2017, Role of internal variability in recent
396 decadal to multidecadal tropical Pacific climate changes: Geophysical Research
397 Letters, v. 44, no. 9, p. 4246-4255.
- 398 Boswijk, G., Fowler, A. M., Palmer, J. G., Fenwick, P., Hogg, A., Lorrey, A., and Wunder, J.,
399 2014, The late Holocene kauri chronology: assessing the potential of a 4500-year
400 record for palaeoclimate reconstruction: Quaternary Science Reviews, v. 90, p. 128-
401 142.
- 402 Burrows, C. J., 1989, Aranuiian radiocarbon dates from moraines in the Mount Cook region,
403 New Zealand: New Zealand Journal of Geology and Geophysics, v. 32, no. 2, p. 205-
404 216.
- 405 Chambers, F. M., Brain, S. A., Mauquoy, D., McCarroll, J., and Daley, T., 2014, The 'Little
406 Ice Age' in the Southern Hemisphere in the context of the last 3000 years: Peat-
407 based proxy-climate data from Tierra del Fuego: The Holocene, v. 24, no. 12, p.
408 1649-1656.
- 409 Chinn, T., Winkler, S., Salinger, M. J., and Haakensen, N., 2005, Recent glacier advances in
410 Norway and New Zealand: A comparison of their glaciological and meteorological
411 causes: Geogr. Ann., v. 87A, no. 1, p. 141-157.
- 412 Chinn, T. J., Kargel, J. S., Leonard, G. J., Haritashya, U. K., and Pleasants, M., 2014, New
413 Zealand's Glaciers, *in* Kargel, J. S., Leonard, G. J., Bishop, M. P., Kaab, A., and
414 Raup, B. H., eds., Global Land Ice Measurements from Space, Springer, p. 675-715.

- 415 Cobb, K. M., Charles, C. D., Cheng, H., and Edwards, R. L., 2003, El Niño/Southern
 416 Oscillation and tropical Pacific climate during the last millennium: *Nature*, v. 424, p.
 417 271.
- 418 Commonwealth of Australia, 2016, State of the Climate 2016: [www.csiro.au/state-of-the-](http://www.csiro.au/state-of-the-climate)
 419 climate, p. 1-23.
- 420 Conroy, J. L., Overpeck, J. T., Cole, J. E., Shanahan, T. M., and Steinitz-Kannan, M., 2008,
 421 Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake
 422 sediment record: *Quaternary Science Reviews*, v. 27, no. 11, p. 1166-1180.
- 423 Cook, E., Bird, T., Peterson, M., Barbetti, M., Buckley, B., D'Arrigo, R., and Francey, R.,
 424 1992, Climatic change over the last millennium in Tasmania reconstructed from tree-
 425 rings: *The Holocene*, v. 2, no. 3, p. 205-217.
- 426 Cook, E., Bird, T., Peterson, M., Barbetti, M., Buckley, B., D'Arrigo, R., Francey, R., and
 427 Tans, P., 1991, Climatic Change in Tasmania Inferred from a 1089-Year Tree-Ring
 428 Chronology of Huon Pine: *Science*, v. 253, no. 5025, p. 1266-1268.
- 429 Cook, E. R., Buckley, B. M., and D'Arrigo, R. D., 1995, Decadal-scale oscillatory modes in a
 430 millennia-long temperature reconstruction from Tasmania, *in* D.G., M., Bryan, K., Ghil,
 431 M., Hall, M. M., Karl, T. R., Sarachik, E. S., Sorooshian, S., and Talley, L. D., eds.,
 432 Natural climate variability on decade-to-century time scales: Washington, D.C.,
 433 National Academy Press, p. 523-531.
- 434 Cook, E. R., Buckley, B. M., D'Arrigo, R. D., and Peterson, M. J., 2000, Warm-season
 435 temperatures since 1600 BC reconstructed from Tasmanian tree rings and their
 436 relationship to large-scale sea surface temperature anomalies: *Climate Dynamics*, v.
 437 16, no. 2, p. 79-91.
- 438 Cook, E. R., Buckley, B. M., Palmer, J. G., Fenwick, P., Peterson, M. J., Boswijk, G., and
 439 Fowler, A., 2006, Millennia-long tree-ring records from Tasmania and New Zealand: a
 440 basis for modelling climate variability and forcing, past, present and future: *Journal of*
 441 *Quaternary Science*, v. 21, no. 7, p. 689-699.

- 442 Cook, E. R., Palmer, J. G., and D'Arrigo, R. D., 2002, Evidence for a 'Medieval Warm Period'
 443 in a 1,100 year tree-ring reconstruction of past austral summer temperatures in New
 444 Zealand: *Geophysical Research Letters*, v. 29, no. 14, p. 12-11-12-14.
- 445 Cresswell, G., and Domingues, C. M., 2009, Leeuwin Current, *in* Steele, J. H., ed.,
 446 *Encyclopedia of Ocean Sciences (Second Edition)*: Oxford, Academic Press, p. 444-
 447 454.
- 448 Cresswell, G. R., Peterson, J. L., and Pender, L. F., 2017, The East Australian Current,
 449 upwellings and downwellings off eastern-most Australia in summer: *Marine and*
 450 *Freshwater Research*, v. 68, no. 7, p. 1208-1223.
- 451 Crowley, T. J., and Lowery, T. S., 2000, How Warm Was the Medieval Warm Period?:
 452 *AMBIO: A Journal of the Human Environment*, v. 29, no. 1, p. 51-54.
- 453 Crowley, T. J., and Unterman, M. B., 2013, Technical details concerning development of a
 454 1200 yr proxy index for global volcanism: *Earth Syst. Sci. Data*, v. 5, no. 1, p. 187-
 455 197.
- 456 Dixon, B. C., Tyler, J. J., Lorrey, A. M., Goodwin, I. D., Gergis, J., and Drysdale, R. N., 2017,
 457 Low-resolution Australasian palaeoclimate records of the last 2000 years: *Clim. Past*,
 458 v. 13, no. 10, p. 1403-1433.
- 459 Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R. J. H., Willett, K. M.,
 460 Aguilar, E., Brunet, M., Caesar, J., B., H., Jack, C., Klein Tank, A. M. G., Kruger, A.
 461 C., Marengo, J., Peterson, T. C., Renom, M., Oria Rojas, C., Rusticucci, M., Salinger,
 462 J., Elayah, A. S., Sekele, S. S., Srivastava, A. K., Trewin, B., Villarroel, C., Vincent,
 463 L. A., Zhai, P., Zhang, X., and Kitching, S., 2013, Updated analyses of temperature
 464 and precipitation extreme indices since the beginning of the twentieth century: The
 465 HadEX2 dataset: *Journal of Geophysical Research: Atmospheres*, v. 118, no. 5, p.
 466 2098-2118.
- 467 Duncan, R. P., Fenwick, P., Palmer, J. G., McGlone, M. S., and Turney, C. S. M., 2010, Non-
 468 uniform interhemispheric temperature trends over the past 550 years: *Climate*
 469 *Dynamics*, v. 35, no. 7, p. 1429-1438.

- 470 Emile-Geay, J., Cobb, K. M., Mann, M. E., and Wittenberg, A. T., 2013, Estimating Central
471 Equatorial Pacific SST Variability over the Past Millennium. Part I: Methodology and
472 Validation: *Journal of Climate*, v. 26, no. 7, p. 2302-2328.
- 473 Esper, J., and Frank, D., 2009, The IPCC on a heterogeneous Medieval Warm Period:
474 *Climatic Change*, v. 94, no. 3, p. 267-273.
- 475 Feng, M., Zhang, N., Liu, Q., and Wijffels, S., 2018, The Indonesian throughflow, its
476 variability and centennial change: *Geoscience Letters*, v. 5, no. 1, p. 3.
- 477 Fitzharris, B. B., Clare, G. R., and Renwick, J., 2007, Teleconnections between Andean and
478 New Zealand glaciers: *Global and Planetary Change*, v. 59, no. 1, p. 159-174.
- 479 Fitzharris, B. B., Hay, J. E., and Jones, P. D., 1992, Behaviour of New Zealand Glaciers and
480 Atmospheric Circulation Changes over the Past 130 years: *The Holocene*, v. 2, no. 2,
481 p. 97-106.
- 482 Gergis, J., Neukom, R., Gallant, A. J. E., and Karoly, D. J., 2016, Australasian Temperature
483 Reconstructions Spanning the Last Millennium: *Journal of Climate*, v. 29, no. 15, p.
484 5365-5392.
- 485 Gillett, N. P., Kell, T. D., and Jones, P. D., 2006, Regional climate impacts of the Southern
486 Annular Mode: *Geophysical Research Letters*, v. 33, no. 23, p. n/a-n/a.
- 487 Goodwin, I. D., Browning, S., Lorrey, A. M., Mayewski, P. A., Phipps, S. J., Bertler, N. A. N.,
488 Edwards, R. P., Cohen, T. J., van Ommen, T., Curran, M., Barr, C., and Stager, J. C.,
489 2014a, A reconstruction of extratropical Indo-Pacific sea-level pressure patterns
490 during the Medieval Climate Anomaly: *Climate Dynamics*, v. 43, no. 5, p. 1197-1219.
- 491 Goodwin, I. D., Browning, S. A., and Anderson, A. J., 2014b, Climate windows for Polynesian
492 voyaging to New Zealand and Easter Island: *Proceedings of the National Academy of*
493 *Sciences*, v. 111, no. 41, p. 14716-14721.
- 494 Goosse, H., Masson-Delmotte, V., Renssen, H., Delmotte, M., Fichet, T., Morgan, V., van
495 Ommen, T., Khim, B. K., and Stenni, B., 2004, A late medieval warm period in the
496 Southern Ocean as a delayed response to external forcing?: *Geophysical Research*
497 *Letters*, v. 31, no. 6, p. n/a-n/a.

- 498 Gouramanis, C., De Deckker, P., Switzer, A. D., and Wilkins, D., 2013, Cross-continent
499 comparison of high-resolution Holocene climate records from southern Australia —
500 Deciphering the impacts of far-field teleconnections: *Earth-Science Reviews*, v. 121,
501 p. 55-72.
- 502 Graham, N. E., Ammann, C. M., Fleitmann, D., Cobb, K. M., and Luterbacher, J., 2011,
503 Support for global climate reorganization during the “Medieval Climate Anomaly”:
504 *Climate Dynamics*, v. 37, no. 5, p. 1217-1245.
- 505 Hellstrom, J., McCulloch, M., and Stone, J., 1998, A Detailed 31,000-Year Record of Climate
506 and Vegetation Change, from the Isotope Geochemistry of Two New Zealand
507 Speleothems: *Quaternary Research*, v. 50, no. 2, p. 167-178.
- 508 Hendy, C. H., Whittaker, T. E., and Hellstrom, J. C., 2011, Abrupt millennial-scale changes in
509 intensity of Southern Hemisphere westerly winds during marine isotope stages 2–4:
510 *Geology*, v. 39, no. 5, p. 455-458.
- 511 Hoelzle, M., Chinn, T., Stumm, D., Paul, F., Zemp, M., and Haeberli, W., 2007, The
512 application of glacier inventory data for estimating past climate change effects on
513 mountain glaciers: A comparison between the European Alps and the Southern Alps
514 of New Zealand: *Global and Planetary Change*, v. 56, no. 1, p. 69-82.
- 515 IPCC, 2014, *Climate Change 2014; Synthesis Report of the IPCC Fifth Assessment Report*
516 (AR5): [https://www.ipcc.ch/pdf/assessment-](https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf)
517 [report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf](https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf).
- 518 Jones, D. A., Collins, D. A., McGree, S., Trewin, B., Skilling, E., Diamond, H., Fa’anunu, O.,
519 Hiriassia, D., Hugony, S., Hutchinson, R., Inape, K., Jacklick, L., Malsale, P., Moniz, T.,
520 Ngemaes, M., Porteous, A., Seuseu, S., Tahani, L., Teimitsi, F., Toorua, U.,
521 Vaiimene, M., Vuniyayawa, V., and Vavae, H., 2013, An updated analysis of
522 homogeneous temperature data at Pacific Island stations: *Australian Meteorological*
523 *and Oceanographic Journal*, v. 63, p. 285-302.

- 524 Jones, D. S., 2012, Australian Barnacles (Cirripedia: Thoracica), Distributions and
 525 Biogeographical Affinities: Integrative and Comparative Biology, v. 52, no. 3, p. 366-
 526 387.
- 527 Klein, A. G., and Kincaid, J. L., 2006, Retreat of glaciers on Puncak Jaya, Irian Jaya,
 528 determined from 2000 and 2002 IKONOS satellite images: Journal of Glaciology, v.
 529 52, no. 176, p. 65-79.
- 530 Komugabe-Dixson, A. F., Fallon, S. J., Eggins, S. M., and Thresher, R. E., 2016,
 531 Radiocarbon evidence for mid-late Holocene changes in southwest Pacific Ocean
 532 circulation: Paleoceanography, v. 31, no. 7, p. 971-985.
- 533 Köppen, W., 1918, Klassifikation der Klimate nach Temperatur, Niederschlag and Jahreslauf:
 534 Petermanns Geographische Mitteilungen, p. 64. pp.
- 535 Lamb, H. H., 1965, The early medieval warm epoch and its sequel: Palaeogeogr.
 536 Palaeoclim. Palaeoecol., v. 1, p. 13-37.
- 537 Ljungqvist, F. C., Krusic, P. J., Brattström, G., and Sundqvist, H. S., 2012, Northern
 538 Hemisphere temperature patterns in the last 12 centuries: Clim. Past, v. 8, p. 227-
 539 249.
- 540 Lorrey, A., Williams, P., Salinger, J., Martin, T., Palmer, J., Fowler, A., Zhao, J.-x., and Neil,
 541 H., 2008, Speleothem stable isotope records interpreted within a multi-proxy
 542 framework and implications for New Zealand palaeoclimate reconstruction:
 543 Quaternary International, v. 187, no. 1, p. 52-75.
- 544 Lorrey, A. M., and Bostock, H. C., 2014, Australasia: An Overview of Modern Climate and
 545 Paleoclimate during the Last Glacial Maximum, *in* Beattie, J., O'Gorman, E., and
 546 Henry, M., eds., Climate, Science, and Colonization: Histories from Australia and New
 547 Zealand: New York, Palgrave Macmillan US, p. 19-42.
- 548 Lüning, S., Galka, M., Bamonte, F. P., Rodríguez, F. G., and Vahrenholt, F., 2018a, The
 549 Medieval Climate Anomaly in South America: Quaternary International.

- 550 Lüning, S., Galka, M., Danladi, I. B., Adagunodo, T. A., and Vahrenholt, F., 2018b,
551 Hydroclimate in Africa during the Medieval Climate Anomaly: Palaeogeography,
552 Palaeoclimatology, Palaeoecology, v. 495, p. 309-322.
- 553 Lüning, S., Galka, M., and Vahrenholt, F., 2017, Warming and Cooling: The Medieval
554 Climate Anomaly in Africa and Arabia: Paleoceanography, v. 32, no. 11, p. 1219-
555 1235.
- 556 Mackintosh, A. N., Anderson, B. M., Lorrey, A. M., Renwick, J. A., Frei, P., and Dean, S. M.,
557 2017, Regional cooling caused recent New Zealand glacier advances in a period of
558 global warming: Nature Communications, v. 8, p. 14202.
- 559 Mann, M. E., Zhang, Z., Hughes, M. K., Bradley, R. S., Miller, S. K., Rutherford, S., and Ni,
560 F., 2008, Proxy-based reconstructions of hemispheric and global surface temperature
561 variations over the past two millennia: PNAS, v. 105, no. 36, p. 13252-13257.
- 562 Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann,
563 C., Faluvegi, G., and Ni, F., 2009, Global Signatures and Dynamical Origins of the
564 Little Ice Age and Medieval Climate Anomaly: Science, v. 326, no. 5957, p. 1256-
565 1260.
- 566 Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C., 2013, A Reconstruction of
567 Regional and Global Temperature for the Past 11,300 Years: Science, v. 339, no.
568 6124, p. 1198-1201.
- 569 McGlone, M. S., Turney, C. S. M., Wilmshurst, J. M., Renwick, J., and Pahnke, K., 2010,
570 Divergent trends in land and ocean temperature in the Southern Ocean over the past
571 18,000 years: Nature Geoscience, v. 3, p. 622.
- 572 McGowan, H., Callow, J. N., Soderholm, J., McGrath, G., Campbell, M., and Zhao, J.-x.,
573 2018, Global warming in the context of 2000 years of Australian alpine temperature
574 and snow cover: Scientific Reports, v. 8, no. 1, p. 4394.
- 575 McKinzey, K. M., Lawson, W., Kelly, D., and Hubbard, A., 2004, A revised Little Ice Age
576 chronology of the Franz Josef Glacier, Westland, New Zealand: Journal of the Royal
577 Society of New Zealand, v. 34, no. 4, p. 381-394.

- 578 McLean, J. D., de Freitas, C. R., and Carter, R. M., 2009, Influence of the Southern
579 Oscillation on tropospheric temperature: *Journal of Geophysical Research*, v. 114, p.
580 1-8.
- 581 Ministry for the Environment New Zealand, and Stats NZ, 2017, Our atmosphere and climate
582 2017: [http://www.mfe.govt.nz/publications/environmental-reporting/our-atmosphere-](http://www.mfe.govt.nz/publications/environmental-reporting/our-atmosphere-and-climate-2017)
583 [and-climate-2017](http://www.mfe.govt.nz/publications/environmental-reporting/our-atmosphere-and-climate-2017).
- 584 Moros, M., De Deckker, P., Jansen, E., Perner, K., and Telford, R. J., 2009, Holocene
585 climate variability in the Southern Ocean recorded in a deep-sea sediment core off
586 South Australia: *Quaternary Science Reviews*, v. 28, no. 19–20, p. 1932-1940.
- 587 Mullan, B., Salinger, J., Renwick, J., and Wratt, D., 2018, Comment on “A Reanalysis of
588 Long-Term Surface Air Temperature Trends in New Zealand”: *Environmental*
589 *Modeling & Assessment*, v. 23, no. 3, p. 249-262.
- 590 Neukom, R., and Gergis, J., 2012, Southern Hemisphere high-resolution palaeoclimate
591 records of the last 2000 years: *The Holocene*, v. 22, no. 5, p. 501-524.
- 592 Neukom, R., Gergis, J., Karoly, D. J., Wanner, H., Curran, M., Elbert, J., Gonzalez-Rouco, F.,
593 Linsley, B. K., Moy, A. D., Mundo, I., Raible, C. C., Steig, E. J., van Ommen, T.,
594 Vance, T., Villalba, R., Zinke, J., and Frank, D., 2014, Inter-hemispheric temperature
595 variability over the past millennium: *Nature Clim. Change*, v. 4, no. 5, p. 362-367.
- 596 Neukom, R., Luterbacher, J., Villalba, R., Küttel, M., Frank, D., Jones, P. D., Grosjean, M.,
597 Wanner, H., Aravena, J.-C., Black, D. E., Christie, D. A., D'Arrigo, R., Lara, A.,
598 Morales, M., Soliz-Gamboa, C., Srur, A., Urrutia, R., and von Gunten, L., 2011,
599 Multiproxy summer and winter surface air temperature field reconstructions for
600 southern South America covering the past centuries: *Climate Dynamics*, v. 37, no. 1-
601 2, p. 35-51.
- 602 Ning, L., Liu, J., Wang, Z., and Bradley, R. S., 2018, Different influences on the tropical
603 Pacific SST gradient from natural and anthropogenic forcing: *International Journal of*
604 *Climatology*, v. 38, no. 4, p. 2015-2028.

- 605 Nunn, P., 2007, *Climate, Environment, and Society in the Pacific during the Last Millennium*,
606 Amsterdam, Elsevier, *Developments in Earth and Environmental Sciences*, vol. 6.
- 607 Nunn, P. D., 2000, *Environmental catastrophe in the Pacific Islands around A.D. 1300*:
608 *Geoarchaeology*, v. 15, no. 7, p. 715-740.
- 609 Nunn, P. D., Hunter-Anderson, R., Carson, M. T., Thomas, F., Ulm, S., and Rowland, M. J.,
610 2007, *Times of Plenty, Times of Less: Last-Millennium Societal Disruption in the*
611 *Pacific Basin: Human Ecology*, v. 35, no. 4, p. 385-401.
- 612 Oerlemans, J., 2005, *Extracting a Climate Signal from 169 Glacier Records*: *Science*, v. 308,
613 p. 675-677.
- 614 PAGES 2k Consortium, 2013, *Continental-scale temperature variability during the past two*
615 *millennia*: *Nature Geosci*, v. 6, no. 5, p. 339-346.
- 616 -, 2017, *A global multiproxy database for temperature reconstructions of the Common Era*:
617 *Scientific Data*, <https://www.ncdc.noaa.gov/paleo-search/study/21171>, v. 4.
- 618 Parsons, L. A., Loope, G. R., Overpeck, J. T., Ault, T. R., Stouffer, R., and Cole, J. E., 2017,
619 *Temperature and Precipitation Variance in CMIP5 Simulations and Paleoclimate*
620 *Records of the Last Millennium*: *Journal of Climate*, v. 30, no. 22, p. 8885-8912.
- 621 Perner, K., Moros, M., De Deckker, P., Blanz, T., Wacker, L., Telford, R., Siegel, H.,
622 Schneider, R., and Jansen, E., 2018, *Heat export from the tropics drives mid to late*
623 *Holocene palaeoceanographic changes offshore southern Australia*: *Quaternary*
624 *Science Reviews*, v. 180, p. 96-110.
- 625 Purdie, H., Anderson, B., Chinn, T., Owens, I., Mackintosh, A., and Lawson, W., 2014, *Franz*
626 *Josef and Fox Glaciers, New Zealand: Historic length records*: *Global and Planetary*
627 *Change*, v. 121, p. 41-52.
- 628 Rintoul, S. R., 2009, *Antarctic Circumpolar Current*, in Steele, J. H., ed., *Encyclopedia of*
629 *Ocean Sciences (Second Edition)*: Oxford, Academic Press, p. 178-190.
- 630 Salinger, M. J., McGree, S., Beucher, F., Power, S. B., and Delage, F., 2014, *A new index for*
631 *variations in the position of the South Pacific convergence zone 1910/11–2011/2012*:
632 *Climate Dynamics*, v. 43, no. 3, p. 881-892.

- 633 Saunders, K., Grosjean, M., and Hodgson, D., 2013, A 950 yr temperature reconstruction
634 from Duckhole Lake, southern Tasmania, Australia: *The Holocene*, v. 23, no. 6, p.
635 771-783.
- 636 Saurral, R. I., Doblas-Reyes, F. J., and García-Serrano, J., 2018, Observed modes of sea
637 surface temperature variability in the South Pacific region: *Climate Dynamics*, v. 50,
638 no. 3, p. 1129-1143.
- 639 Schaefer, J. M., Denton, G. H., Kaplan, M., Putnam, A., Finkel, R. C., Barrell, D. J. A.,
640 Andersen, B. G., Schwartz, R., Mackintosh, A., Chinn, T., and Schlüchter, C., 2009,
641 High-Frequency Holocene Glacier Fluctuations in New Zealand Differ from the
642 Northern Signature: *Science*, v. 324, no. 5927, p. 622-625.
- 643 Seager, R., Graham, N., Herweijer, C., Gordon, A. L., Kushnir, Y., and Cook, E., 2007,
644 Blueprints for Medieval hydroclimate: *Quaternary Science Reviews*, v. 26, no. 19, p.
645 2322-2336.
- 646 Sigl, M., Winstrup, M., McConnell, J. R., Welten, K. C., Plunkett, G., Ludlow, F., Buntgen, U.,
647 Caffee, M., Chellman, N., Dahl-Jensen, D., Fischer, H., Kipfstuhl, S., Kostick, C.,
648 Maselli, O. J., Mekhaldi, F., Mulvaney, R., Muscheler, R., Pasteris, D. R., Pilcher, J.
649 R., Salzer, M., Schupbach, S., Steffensen, J. P., Vinther, B. M., and Woodruff, T. E.,
650 2015, Timing and climate forcing of volcanic eruptions for the past 2,500 years:
651 *Nature*, v. 523, no. 7562, p. 543-549.
- 652 Solomina, O. N., Bradley, R. S., Jomelli, V., Geirsdottir, A., Kaufman, D. S., Koch, J., McKay,
653 N. P., Masiokas, M., Miller, G., Nesje, A., Nicolussi, K., Owen, L. A., Putnam, A. E.,
654 Wanner, H., Wiles, G., and Yang, B., 2016, Glacier fluctuations during the past 2000
655 years: *Quaternary Science Reviews*, v. 149, p. 61-90.
- 656 Steinhilber, F., Abreu, J. A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkilä, U., Kubik,
657 P. W., Mann, M., McCracken, K. G., Miller, H., Miyahara, H., Oerter, H., and
658 Wilhelms, F., 2012, 9,400 years of cosmic radiation and solar activity from ice cores
659 and tree rings: *Proceedings of the National Academy of Sciences*, v. 109, no. 16, p.
660 5967-5971.

- 661 Stott, L., Cannariato, K., Thunell, R., Haug, G. H., Koutavas, A., and Lund, S., 2004, Decline
662 of surface temperature and salinity in the western tropical Pacific Ocean in the
663 Holocene epoch: *Nature*, v. 431, no. 7004, p. 56-59.
- 664 Stott, L., Timmermann, A., and Thunell, R., 2007, Southern Hemisphere and Deep-Sea
665 Warming Led Deglacial Atmospheric CO₂ Rise and Tropical Warming:
666 *Science*, v. 318, no. 5849, p. 435-438.
- 667 U.S. Global Change Research Program, 2017, Fourth National Climate Assessment (NCA4):
668 Hawaii in Table 6.1, <https://science2017.globalchange.gov/>.
- 669 Vance, T. R., Roberts, J. L., Plummer, C. T., Kiem, A. S., and van Ommen, T. D., 2015,
670 Interdecadal Pacific variability and eastern Australian megadroughts over the last
671 millennium: *Geophysical Research Letters*, v. 42, no. 1, p. 129-137.
- 672 Wang, C., Deser, C., Yu, J.-Y., DiNezio, P., and Clement, A., 2017, El Niño and Southern
673 Oscillation (ENSO): A Review, *in* Glynn, P. W., Manzello, D. P., and Enochs, I. C.,
674 eds., *Coral Reefs of the Eastern Tropical Pacific: Persistence and Loss in a Dynamic*
675 *Environment*: Dordrecht, Springer Netherlands, p. 85-106.
- 676 Whan, K., Alexander, L. V., Imielska, A., McGree, S., Jones, D., Ene, E., Finaulahi, S., Inape,
677 K., Jacklick, L., Kumar, R., Laurent, V., Malala, H., Malsale, P., Pulehetoa-Mitiepo, R.,
678 Ngemaes, M., Peltier, A., Porteous, A., Seuseu, S., Skilling, E., Tahani, L., Toorua,
679 U., and Vaiimene, M., 2014, Trends and variability of temperature extremes in the
680 tropical Western Pacific: *International Journal of Climatology*, v. 34, no. 8, p. 2585-
681 2603.
- 682 Wijeratne, S., Pattiaratchi, C., and Proctor, R., 2018, Estimates of Surface and Subsurface
683 Boundary Current Transport Around Australia: *Journal of Geophysical Research:*
684 *Oceans*, v. 123, no. 5, p. 3444-3466.
- 685 Williams, P. W., King, D. N. T., Zhao, J.-X., and Collerson, K. D., 2004, Speleothem master
686 chronologies: combined Holocene 18O and 13C records from the North Island of New
687 Zealand and their palaeoenvironmental interpretation: *The Holocene*, v. 14, no. 2, p.
688 194-208.

- 689 Williams, P. W., King, D. N. T., Zhao, J. X., and Collerson, K. D., 2005, Late Pleistocene to
690 Holocene composite speleothem ^{18}O and ^{13}C chronologies from South Island, New
691 Zealand—did a global Younger Dryas really exist?: *Earth and Planetary Science*
692 *Letters*, v. 230, no. 3, p. 301-317.
- 693 Williams, P. W., Marshall, A., Ford, D. C., and Jenkinson, A. V., 1999, Palaeoclimatic
694 interpretation of stable isotope data from Holocene speleothems of the Waitomo
695 district, North Island, New Zealand: *The Holocene*, v. 9, no. 6, p. 649-657.
- 696 Williams, P. W., McGlone, M., Neil, H., and Zhao, J.-X., 2015, A review of New Zealand
697 palaeoclimate from the Last Interglacial to the global Last Glacial Maximum:
698 *Quaternary Science Reviews*, v. 110, p. 92-106.
- 699 Wilson, A. T., Hendy, C. H., and Reynolds, C. P., 1979, Short-term climate change and New
700 Zealand temperatures during the last millennium: *Nature*, v. 279, p. 315-317.
- 701 Zhang, W., Wang, Y., Jin, F.-F., Stuecker, M. F., and Turner, A. G., 2015, Impact of different
702 El Niño types on the El Niño/IOD relationship: *Geophysical Research Letters*, v. 42,
703 no. 20, p. 8570-8576.

704

705

Captions of Table and Figures

Table 1. MCA study sites in Oceania.

Fig. 1. Location map of studied sites. Key to site numbers in Table 1. Red lines mark proxy series panels illustrated in Supplement Figures S1-S4. Oceania base map sourced from D-Maps.com.

Fig. 2. Temperature development in Oceania during the past 1500 years based on palaeoclimate proxies of selected study sites showing the classical timing of Northern Hemisphere MCA warming (site number stated on top). 8: Mt Honey (McGlone et al. 2010); 9: Fiordland (Lorrey et al. 2008); 10: Mt Cook glaciers (Schaefer et al. 2009); 13: Hawkes Bay (Lorrey et al. 2008); 14: Waitomo (Williams et al. 2004). Location map in Fig. 1.

Fig. 3. Temperature development in Oceania during the past 1500 years based on palaeoclimate proxies of selected study sites showing a slightly delayed MCA warming compared to the Northern Hemisphere (site number stated on top). 3: Grotto of Oddities (McGowan et al. 2018); 7: South Tasman Sea (Komugabe-Dixson et al. 2016); 11: Oroko Swamp, 50 year LOESS smoothing (Cook et al. 2002); 12: Cave in NW Nelson District (Williams et al. 2005); 5. Mt Read, 50 year LOESS smoothing (Cook et al. 2000); Australasian temperature anomaly reconstruction of Gergis et al. (2016), 30 year LOESS smoothing. EAC=East Australia Current. Location map in Fig. 1.

Fig. 4. *Palaeotemperature trends during the MCA with color-coded study sites showing changes to warmer (red) climate. Yellow dots with red outside circle represent sites where peak warming occurred shortly after the MCA. Plain yellow dots mark locations with mixed MCA climate signals, conflicting proxies, suspected age model shifts, low data resolution or lack of information. Numbers refer to study sites as shown in Table 1. Winds are illustrated by purple and ocean currents by black arrows. Subtropical Ridge is marked by thick grey line. Oceania base map sourced from D-Maps.com.*

Figure 5. *Reconstructions of key drivers of natural climate variability. Southern Annular Mode, SAM, 70 year loess filter (Abram et al. 2014); El Niño-Southern Oscillation, ENSO (Conroy et al. 2008); Interdecadal Pacific Oscillation, IPO, piece-wise linear fit (Vance et al. 2015); solar activity changes (Steinhilber et al. 2012); volcanic eruptions (Sigl et al. 2015).*

Table 1. MCA study sites in Oceania.

No.	Locality	Region	Country	Archive	Proxies	Studies
1	MD98-2176	off West Papua	Indonesia	Marine core	Mg/Ca, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ of <i>Globigerinoides ruber</i>	Stott et al. 2004, Stott et al. 2007
2	MD03-2611	Murray Canyon	Australia	Maine core	UK'37 SST, $\delta^{18}\text{O}$ <i>G. bulloides</i>	Moros et al. 2009, Perner et al. 2018
3	Grotto of Oddities	Yarrangobilly Caves	Australia	Cave stalagmite	$\delta^{13}\text{C}$	McGowan et al. 2018
4	Cradle Mountain	Tasmania	Australia	Tree rings	Tree ring width	Allen et al. 2017
5	Mt. Read	Tasmania	Australia	Tree rings	Tree ring width	Cook et al. 1991, Cook et al. 1992, Cook et al. 2000, Allen et al. 2014
6	Duckhole Lake	Tasmania	Australia	Lake core	chlorophyll	Saunders et al. 2013
7	South Tasman Sea	Tasmanian	Australia	Deep sea black corals	sea surface radiocarbon reservoir ages	Komugabe-Dixon et al. 2016
8	Mount Honey	Campbell Island	New Zealand	Peat core	pollen	McGlone et al. 2010
9	Fiordland	South Island	New Zealand	Cave stalagmites	$\delta^{18}\text{O}$	Lorrey et al. 2008
10	Mount Cook Glaciers	South Island	New Zealand	Moraines	^{10}Be boulder and radiocarbon kill ages	Burrows 1989, Schaefer et al. 2009
11	Oroko Swamp	South Island	New Zealand	Tree rings	Tree ring width	Cook et al. 2002
12	Cave in NW Nelson District	South Island	New Zealand	Cave stalagmites	$\delta^{18}\text{O}$	Wilson et al. 1979, Williams et al. 2005
13	Hawkes Bay	North Island	New Zealand	Cave stalagmites	$\delta^{18}\text{O}$	Lorrey et al. 2008
14	Caves in Waitomo district	North Island	New Zealand	Cave stalagmites	$\delta^{18}\text{O}$, $\delta^{13}\text{C}$	Williams et al. 1999, Williams et al. 2004
15	kauri tree rings northern North Island	North Island	New Zealand	Tree rings	Tree ring width	Boswijk et al. 2014

Fig. 1. Location map of studied sites. Key to site numbers in Table 1. Red lines mark proxy series panels illustrated in Supplement Figures S1-S4.

Fig. 2. Temperature development in Oceania during the past 1500 years based on palaeoclimate proxies of selected study sites showing the classical timing of Northern Hemisphere MCA warming (site number stated on top). 8: Mt Honey (McGlone et al., 2010); 9: Fiordland (Lorrey et al., 2008); 10: Mt Cook glaciers (Schaefer et al., 2009); 13: Hawkes Bay (Lorrey et al., 2008); 14: Waitomo (Williams et al., 2004). Location map in Fig. 1.

Fig. 3. Temperature development in Oceania during the past 1500 years based on palaeoclimate proxies of selected study sites showing a slightly delayed MCA warming compared to the Northern Hemisphere (site number stated on top). 3: Grotto of Oddities (McGowan et al., 2018); 7: South Tasman Sea (Komugabe-Dixon et al., 2016); 11: Oroko Swamp, 50 year LOESS smoothing (Cook et al., 2002); 12: Cave in NW Nelson District (Williams et al., 2005); 5: Mt Read, 50 year LOESS smoothing (Cook et al., 2000); Australasian temperature anomaly reconstruction of Gergis et al. (2016), 30 year LOESS smoothing. EAC=East Australia Current. Location map in Fig. 1.

Figure 5. Reconstructions of key drivers of natural climate variability. Southern Annular Mode, SAM, 70 year loess filter (Abram et al., 2014); El Niño-Southern Oscillation, ENSO (Conroy et al., 2008); Interdecadal Pacific Oscillation, IPO, piece-wise linear fit (Vance et al., 2015); solar activity changes (Steinhilber et al., 2012); volcanic eruptions (Sigl et al., 2015).