Pollen-based quantitative climate reconstructions for Australia, Last Glacial Maximum to present

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Presented for the degree of

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August 15, 2017

Table of contents

List of figures

List of tables

Abstract

Studies of palaeoclimate records help us understand how the climate has changed and evolved over the millennia. Climate models can provide explanations for these changes because they allow us to examine the impact of changes in individual climate forcings, such as greenhouse gas concentrations or orbital changes. There are uncertainties in climate model parameterisations, which makes it important to use large-scale quantitative palaeoclimate reconstructions to evaluate the results. Such evaluations have been largely focused on the northern hemisphere; there have been next to no evaluations of simulated climate changes in Australia because of the lack of continent-wide quantitative palaeoclimate reconstructions for model evaluation. This lack partly reflects the need to evaluate the decisions and assumptions involved in making quantitative palaeoclimate reconstructions in the specific context of Australia, as these decisions and assumptions affect the quality of the reconstructions. The aim of my thesis is to provide quantitative climate reconstructions over the past 22,000 years for Australia. In chapter 2, I make a thorough evaluation of the techniques and decisions involved in performing quantitative palaeoclimate reconstructions using the modern analogue technique on modern pollen samples from Australia. The methodology resulting from this chapter is used in chapter 3 to perform reconstructions of regional climates from the Last Glacial Maximum to the present day. Chapter 4 uses these reconstructions to evaluate state-of-the-art climate model simulations of Australia.

Candidate declaration

I certify that the work in this thesis entitled "Pollen-based quantitative climate reconstructions for Australia, Last Glacial Maximum to present" has not previously been submitted for a degree not has it been submitted as part of requirements for a degree to any other university or institution other than Macquarie University.

I also certify that the thesis is an original piece of research and it has been written by me. Any help and assistance that I have received in my research work and the preparation of the thesis itself have been appropriately acknowledged.

In addition, I certify that all information sources and literature used are indicated in the thesis.

Annika Herbert (43065465)

15th August, 2017

Acknowledgements

First of all I would like to thank my supervisor, Professor Sandy P. Harrison. Thank you for all the support and advice you have given me during my candidature. It has been a privilege to work so closely with a researcher of such experience and generosity as you. Thank you for taking a chance on a poor Masters student and bringing me to the other side of the world, it has been the most remarkable experience of my life. Thank you for providing me with so many useful contacts and introducing me to the rest of the BCD research group, together we were one big family, and we are now friends for life, thanks to you and Colin. Special thanks to Dr Ines Hessler, not only for all the invaluable help you provided for this thesis project by your tireless work on the database, but also for your friendship and letting me look after your lovely cats on occasion. Thank you also to Dr Kevin Willis, for your work on the climate data, and for providing a sounding board for ideas, and all those much needed evenings in the pub. Thank you Dr Doug Kelley, the nicest guy in the world, for being you and for providing support and lodging in Reading. For this, and for throwing the best parties in Sydney, I must also thank the wonderful Lauren. Thank you to Dr Guanqi Li for providing a much needed sounding board as I was trying to get my head around modelling. Big thanks also to Dr Anna Ukkola, for your friendship and support, and for providing a dash of Nordic spirit on the other side of the world.

I would also like to thank my co-supervisor Dr Paul Hesse for providing an extra level of support, valuable feedback and valued conversations regarding quaternary science.

I want to thank all the collaborators who contributed their hard-earned data to this project, especially those who were gracious enough to welcome me into their labs. Thank you to everyone at ANU, especially Professor Geoff Hope, for providing all those large scrolls (!) of data you inherited from Dr Michael Macphail. They were very well worth the hours spent digitising. Thank you to Zhang for doing so much of that work for me! Thank you to Dr Jon Luly for letting me digitise all your old records and for driving me to and from the university for the duration of my wonderful stay in Townsville. Thank you to everyone at the University of Queensland in Brisbane, especially Dr Lydia Mackenzie for being my guide and Professors James Shulmeister and Patrick Moss for sparing me some of your valuable time and, of course, your precious data. Thank you to Professor Scott Mooney for providing support and to Professor Lesley Head for those priceless arid interior records. Special thanks also to Professor John Dodson for your valuable time and access to countless records, and to Dr Pia

Atahan for being a guide to ANSTO and for helping with the scanning of the records and digitising suggestions.

I would also like to thank all the wonderful European researchers I met on two trips, for their help, support and conversation. Special thanks to Dr Basil Davis for suggesting the use of a much more computer efficient software package, vastly speeding up the reconstruction process. Thank you to everyone at the LSCE outside Paris, especially Drs Pascale Braconnot and Masa Kageyama for being my guides and helping me find my way through the French countryside.

Thank you also to my review panel for providing useful ideas and for being an extra layer of support, and to Macquarie University for giving me the scholarship and making all this possible.

I would also like to thank everyone in the Mosman Symphony Orchestra for providing much needed distraction and diversion and for listening to me prattle on about my research, even if you didn't understand what I was on about.

Last, but certainly not least I would like to thank my wonderful family, my parents for being just one skype call away. Knowing I had your undying support really helped me through the tough times. My sister Ingrid, for coming to see my world, however brief your stay was, it brightened up a rainy winter. My aunt Alison, for your support and, of course, for helping your stranded, jetlagged, disorganised niece when she needed you most. My boyfriend Dean, for putting up with me through it all and letting me vent my frustrations and talk through my ideas. Particularly over the last couple of months, with me turning your flat into my personal thesis writing den, I will never be able to thank you enough for just letting me.

List of publications

Publications for thesis:

Three journal articles constitute Chapters 2-4 of my thesis. One of these papers have been published, the other two are in preparation for submission.

Chapter 2: **Herbert, A.V.** and Harrison, S.P., 2016. Evaluation of a modern-analogue methodology for reconstructing Australian palaeoclimate from pollen. Review of Palaeobotany and Palynology 226, 65-77.

Chapter 3: **Herbert, A.V.,** Harrison, S.P., Witt, B., Dodson, J., Moss, P., Mooney, S., Hope, G., Stevenson, J., Haberle, S., Luly, J., Shulmeister, J., Head, L., (in prep.) Quantitative reconstruction of Australian climate change since the Last Glacial Maximum using pollen.

Chapter 4: **Herbert, A.V.** and Harrison, S.P., (in prep.) Comparing model outputs with statistical temperature reconstructions derived from a comprehensive pollen database for Australia.

Other publications obtained during candidature

Harrison, S.P., Kelley, D.I., Wang, H., **Herbert, A.,** Li, G., Bradstock, R., Fontaine, J., Enright, N., Murphy, B.P., Pekin, B.K., Penman, T., Russell-Smith, J., Wittkuhn, R.S., (subm.) Patterns in the abundance of post-fire resprouting in Australia based on plot-level measurements. Global Ecology and Biography.

Harrison, S.P., Willis, K., Wang, H., **Herbert, A.,** Prentice, I.C., 2013. Glacial and Holocene climates of Australia reconstructed by vegetation-model inversion. AGU Fall Meeting Abstracts 1, 03.

Conference presentations:

2014: "Evaluation of a modern-analogue methodology for reconstructing Australian palaeoclimate from pollen." At second PMIP3 general meeting: Namur, Belgium. 25-30th May 2014 (poster).

2013: "Testing the potential of modern Australian pollen samples to reconstruct bioclimatic variables." At International Union for Quaternary Research (INQUA) Early Career Researchers conference: Wollongong University, Australia. 2nd-6th December 2013 (oral).

Seminar presentations

2014: "Evaluation of a modern-analogue methodology for reconstructing Australian palaeoclimate from pollen." Invited presentation, Laboratoire des Sciences du Climat et de l'Environnement, Orme des Merisiers, Gif sur Yvette Cedex, France.

2014: "Testing the potential of modern Australian pollen samples to reconstruct bioclimatic variables." At Postgraduate Research Conference (HDR Annual Report): Macquarie University, Sydney, Australia. 1st-2nd December 2014 (oral).

2013: "Testing the potential of modern Australian pollen samples to reconstruct bioclimatic variables." At Postgraduate Research Conference (HDR Annual Report): Macquarie University, Sydney, Australia. 18th November 2013 (oral).

2013: "Pollen-based climate reconstructions using statistical techniques – thesis plan." At Brown Bag seminars, Macquarie University, Sydney, Australia. 22nd February 2013 (oral).

Chapter 1

Introduction

Chapter 1: Introduction

Understanding past changes in climate is key to understanding the climate system overall, as the recent changes documented in observational records represent a very small portion of the Earth's history and thus the capacity of the climate system. Only when these changes and the forces that drive them are fully understood can we accurately predict possible future changes and their impact on human life. As these predictions are performed by climate models, evaluating these models using large-scale statistical palaeoclimate reconstructions is a research priority (e.g. Braconnot *et al.,* 2012). This thesis includes a first continental-scale quantitative palaeoclimate reconstruction for Australia going back to the Last Glacial Maximum (LGM) and uses this to evaluate regional climate model output.

The aims of this thesis are:

a) To examine the impact of statistical decisions and assumptions on the quality of quantitative climate reconstructions.
b) To perform the first continental scale quantitative palaeoclimate reconstruction for Australia going back to the Last Glacial Maximum.
c) To evaluate regional climate model output using this reconstruction.

This introduction will describe the physical geography of Australia and its climatic influence (section 1.1) before describing the various controls on modern Australian climate, so that changes in the past can be understood in their proper context (section 1.2). It will then describe how these climatic controls has influenced the development of the unique Australian flora (Section 1.3), followed by a description of the controls that work on longer timescales, by examining how the climate system has evolved, both worldwide and in the Australian context (section 1.4). Section 1.5 then addresses how past changes in climate can be quantitatively reconstructed, and the issues involved in performing these reconstructions. Following this, details on climate models will be given, both in terms of methodology and design, but also their use (section 1.6). Lastly, section 1.7 will give an overview of the whole thesis and how the various issues raised in the introduction will be addressed.

1.1 Physical geography of Australia

Australia is a relatively flat continent completely surrounded by ocean. This combination means that changes in ocean temperature have a significant impact on the climate, not just in coastal areas, but also, to a lesser degree, the interior, due to the lack of major mountain ranges blocking the way. The Great Dividing Range is the only significantly elevated area, but even so has few peaks over 1700 metres above sea level, with Mount Kosciuszko the highest at 2228 metres above sea level (Bridgman *et al.,* 2008). This mountain range is also the source of most rivers along the east coast as well as the important Murray-Darling Rivers. The Murray-Darling Basin extends over approximately 1 million km^2 of partly arid land. Due to its vast size it can take weeks for rainfall in the headwaters to reach places further downstream (Bridgman *et al.,* 2008). For many rivers flowing in the arid regions of Australia, large quantities of water never reaches the sea, due to evaporation or termination in interior basins, for instance. Some quite large rivers like the Finke are not connected to the sea at all, but rather drain into the interior salt lakes, such as Lake Eyre, Lake Frome and Lake Tyrrell. These are ephemeral lakes that get encrusted with salt during dry periods (Luly, 1993). Due to the arid nature of large parts of Australia, depositional aeolian landforms such as sand dune systems form an important part of the landscape and provides vital clues regarding past changes in aridity and wind patterns (e.g. Hesse *et al.,* 2004).

1.2 Modern climate of Australia

Australia as a continent spans some 30° in latitude (and has a similar longitudinal span, see figure 1.1), in a position that lends itself to great variation of climate, from tropical in the north to cool temperate in the south (Figure 1.1b). There is also considerable variability in precipitation, with tropical areas receiving more than 1000 mm yr^{-1} and the interior of the continent receiving less than 200 mm yr^{-1} (Figure 1.1a). The aridity in much of the interior is also exacerbated by high evaporation rates.

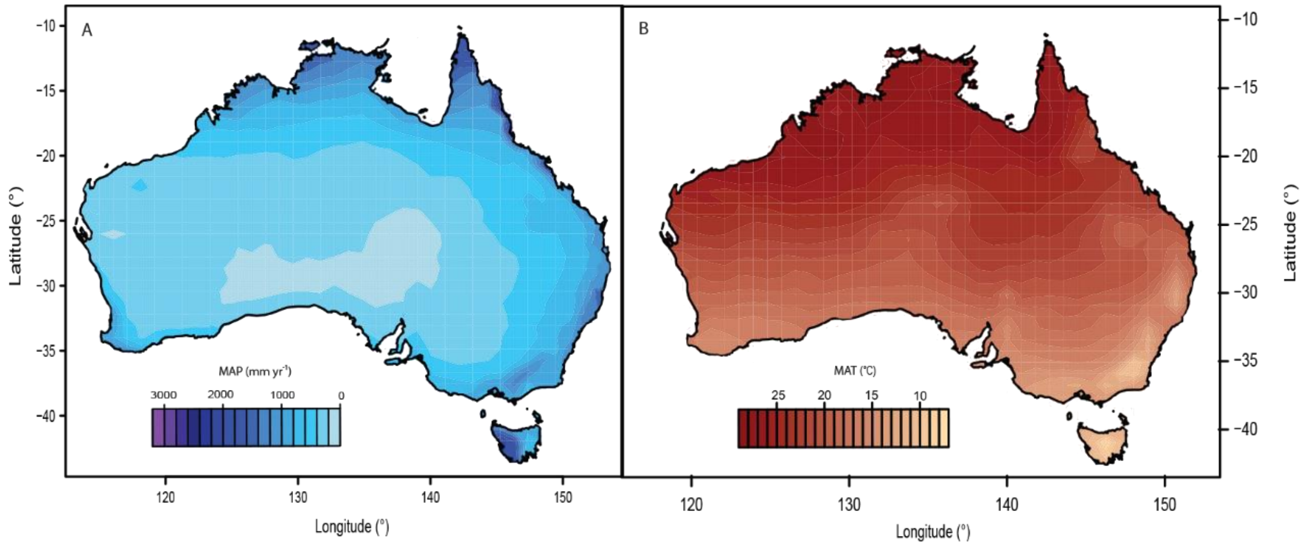

Figure 1.1, Australian climate patterns, (a) Mean Annual Precipitation (MAP), showing the extent of the arid interior, (b) Mean Annual Temperature (MAT), highlighting the high temperatures across much of the continent. Climate data from ANUCLIM (Xu and Hutchinson, 2011), averaged to a 0.5° grid cell resolution.

The Australian climate is controlled by a complicated atmospheric circulation regime (Figure 1.2), in the south dominated by mid-latitude westerly winds, whose strength and position are dependent on the meridional pressure gradient, which varies seasonally. In the north the dominating controls are the winter-time South East Trade winds and the summer monsoon. These are influenced by the Southern Hemisphere Hadley Cell circulation, driven by the equatorial trough, an area of low pressure where the trade winds from both hemispheres meet (Colls and Whitaker, 2012). The descending part of this circulation consists of dry air descending over the Australian interior (Sturman and Tapper, 2006). Some of this descending air then travels back to the equator along the surface, creating the south easterly trade winds. These trade winds in turn bring about the Walker Circulation over the tropics, resulting in heavy summer rainfall over the northeast coast of Australia. In addition, the seasonal movement of the Inter-Tropical Convergence Zone (ITCZ), with its strong atmospheric convection, and the subtropical high pressure belt (STA, Sub-Tropical Anti-cyclone) controls the movement of the monsoonal system, moving with the monsoon southward into northern Australia in austral summer (e.g., Beaufort *et al.,* 2010; Reeves *et al.,* 2013). In winter the ITCZ and the monsoon moves northward, leading to northern Australia experiencing a dry winter, with increased wind intensity (Beaufort *et al.,* 2010). All of these controls will be described in further detail in the following sections of this introduction.

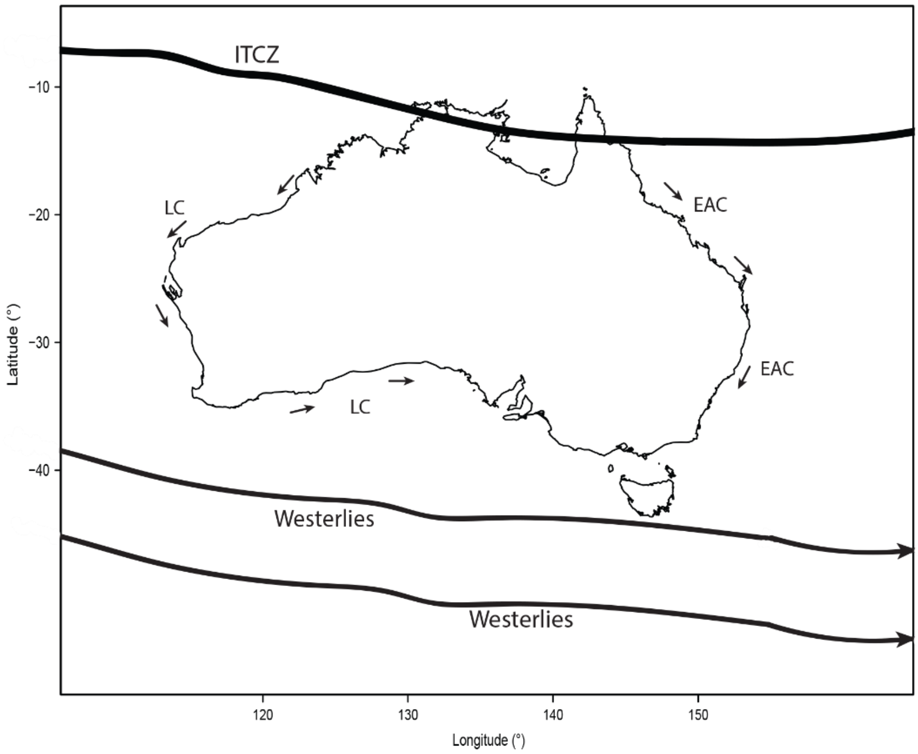

Figure 1.2, Location of key atmospheric and ocean circulation systems influencing Australia during the summer months. ITCZ: Intertropical Convergence Zone; EAC: East Australian Current; LC: Leeuwin Current; Westerlies: Southern Hemisphere Westerly Winds. Adapted from Turney *et al.* (2006).

1.2.1 Australian monsoon system

The aforementioned patterns incorporate mechanisms involved in the Australian monsoon system, which is, just like other monsoon systems, driven by hemispheric temperature gradients. It moves south along with the ITCZ during austral summer, when the temperature contrast between the hemispheres is reduced (Muller *et al.,* 2008). This causes increased rainfall in monsoonal areas, with areas north of 20°S receiving most of their yearly rainfall during the monsoon season, usually 3-4 months long (December to March). In northern Australia, the monsoon season is determined by the position of the equatorial trough, with equatorial westerly winds advecting moisture into the region. It is constrained by sea surface temperature differences between the east and west Pacific, increasing the intensity of ocean-atmosphere circulation in the Pacific Ocean and strengthening the Walker Circulation, limiting the penetration of the summer monsoon over Australasia by increasing the amount of descending dry air over central Australia (Shulmeister, 1999). Over the northern part of the continent, the “monsoon shear line” separates areas of high summer rainfall in the north from areas with a drier, easterly wind dominated climate regime (McBride and Keenan, 1982, Figure 1.3). The position of this shear line is directly related to the semi-permanent summer heat low over the Pilbara region, whose relatively high latitude results in the most southern position of the shear line being over northwestern Australia during February, retreating to about 10°S by March, when the summer monsoon ceases over Australia. The monsoon shear line and the heat low over Pilbara both fade by May (Suppiah, 1992).

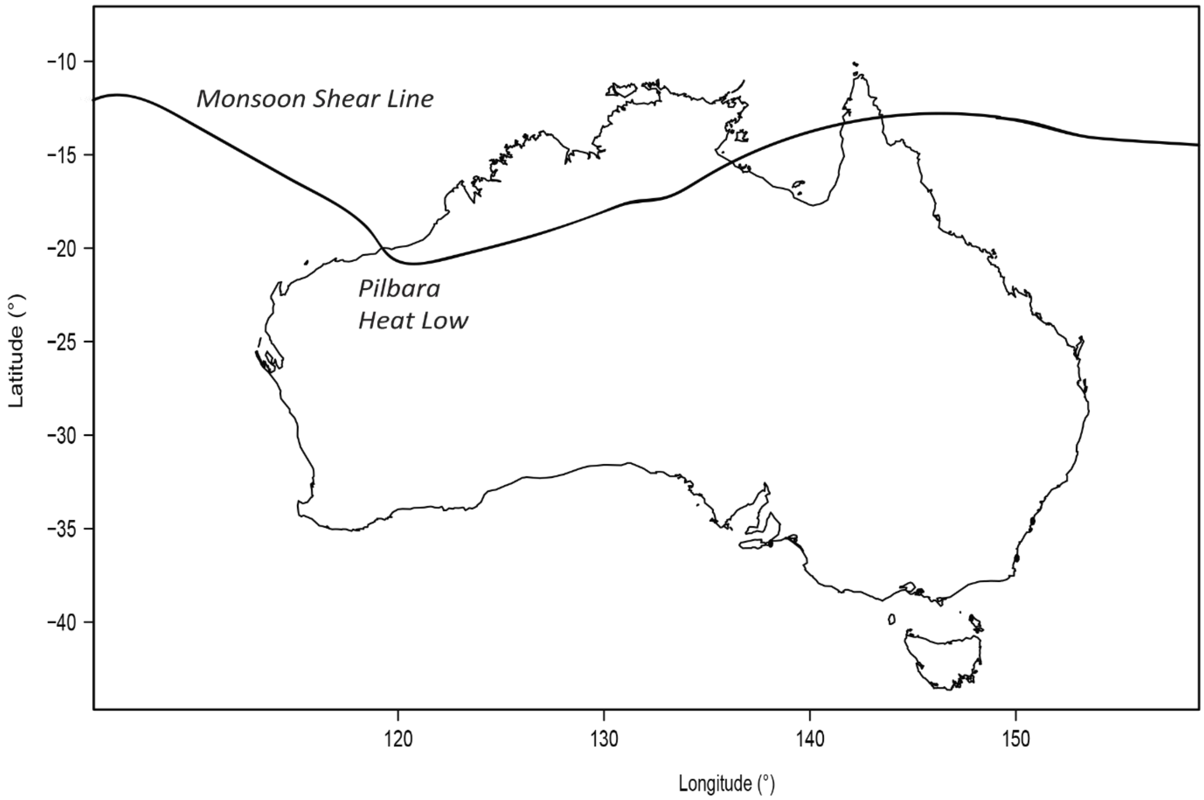

Figure 1.3, Location of Monsoon Shear Line and Pilbara Heat Low during the summer months, adapted from Croke *et al.* (1999).

The Australian monsoon is an integral part of the larger monsoon system, incorporating the East Asian monsoon and the Indian monsoon. The East Asian monsoon is focused over Northern Hemisphere landmasses, but still influences, and is influenced by, the Australian monsoon through the cross-equatorial flow of airmasses. A stronger East Asian summer monsoon coincides with a weaker cross-equatorial flow and a diminished Australian monsoon (Denniston *et al.,* 2013a; Xia *et al.,* 2014), whereas dry south-easterly winds from Australia are important to the East Asian summer monsoon.

1.2.2 El Niño Southern Oscillation

The Australian monsoon varies from year to year in terms of onset and cessation. Onset of the monsoon has been linked to sea surface temperatures (SSTs) and may thus be influenced by the El Niño Southern Oscillation (ENSO, Sturman and Tapper, 2006). ENSO is a coupled ocean-atmosphere phenomenon driven by the inverse relationship of sea-level pressure between the Indonesian-Australian region and the west coast of South America, the pressure being below average in the former region when it is above average in the latter, and vice versa. This relationship is due to these regions being connected by the Walker Circulation, rising air in the Indonesian-Australian region and sinking air near the west coast of South America (Colls and Whitaker, 2012). At the surface level, the pressure difference between these two regions drives the trade winds blowing east to west across the Pacific Ocean, bringing warm surface water west and causing upwelling of cold deep water in the east, resulting in a slanted thermocline, deeper in the west than in the east. This is known as the neutral or Walker Circulation phase of the three phases of ENSO, the other two being El Niño and La Niña. La Niña phases are enhanced Walker Circulation phases, characterised by stronger trade winds, increased upwelling in the eastern Pacific and an increased thermocline slope. El Niño phases have the reversed pattern, with weakened or even reversed trade winds and weaker upwelling in the eastern Pacific, resulting in warmer than normal ocean waters in the eastern and central Pacific, colder than normal in the west, and hence a significant decline in the slope of the cross-Pacific thermocline.

For Australia, La Niña phases cause a strengthening of the monsoon through strengthening the Walker Circulation which increases rainfall in northern and eastern Australia and increases temperatures north of Australia. During El Niño events the opposite pattern occurs, with lower rainfall over Australia, especially over inland eastern Australia, and varying effects in the south-eastern and –western parts of the country (e.g., Allan, 1985; An and Jin, 2004; Kiem and Franks, 2004). These phases are significantly correlated with negative rainfall anomalies in western Tasmania, for example (Fletcher and Thomas, 2010a). ENSO is measured using several indices, such as the difference in normalised sea-level pressure between Tahiti and Darwin, negative representing years with an El Niño-event (Suppiah, 1992). During periods with a persistently positive index, the Australian summer monsoon is more likely to penetrate further south (Pittock, 1975, 1980).

1.2.3 Southern Hemisphere mid-latitude westerly winds

Mid-latitude westerly winds are zonal winds, lying between the subtropical high pressure belt and the sub-Antarctic trough. They are primarily driven by equator-to-pole thermal and pressure gradients (Fletcher and Moreno, 2011; Chavaillaz *et al.,* 2013) and are the strongest time-averaged oceanic winds in the world (Russell *et al.,* 2006; Hodgson and Sime, 2010), having a strong influence on the circulation of the Southern Ocean. The southern westerlies drive the Antarctic Circumpolar Current (ACC; Russell *et al.,* 2006) and determine the location of the Subtropical Front, which in turn influences the location of the Leeuwin Current, carrying warm water along the west coast of Australia, occasionally extending to Tasmania (Figure 1.2; De Deckker *et al.,* 2012). Due to the influence of thermal gradients, the westerly winds migrate northwards during the winter, similar to the Intertropical Convergence Zone (ITCZ), and brings winter rainfall to southern Australia. Mid-latitude westerly winds are therefore important components of the Australian climate system, as well as being vital for ocean circulation. The southern westerly winds are responsible for heat fluxes at the ocean-atmosphere interface and drive the wind-driven circulation, controlling the release of heat and moisture from the ocean. As mentioned previously, they are particularly important for the Antarctic Circumpolar Current, causing uniquely strong upwelling, which brings water from 2-3 km depth to the surface, along with its nutrients (Russell *et al.,* 2006; Chavaillaz *et al.,* 2013). One of the patterns the strength of the westerly winds has been linked to in Australia is precipitation over Tasmania (Rees and Cwynar, 2010). As the moisture laden winds are advected over the central ranges of Tasmania, they cause orographic uplift and the distinct west and east climatic and biogeographic zonation (Fletcher and Thomas, 2010b). The strength of the westerlies is dependent on the polar-equator pressure gradient, a stronger gradient causing increased westerlies, in turn strengthening the sub-tropical high-pressure belt. This blocks the regular penetration of monsoonal systems into higher latitude areas of Australia and causes the northern margin of the westerly wind belt and the desert areas under the southeast trade winds to become more arid, as summer rainfall declines (Shulmeister, 1999).

1.3 Australian vegetation

The Australian flora has evolved independently from the influence of flora from other significant landmasses for millions of years, and as such has developed many unique species. The unique character of this flora has been further aided by the stress the lack of fertile soil has provided (Bridgman *et al.,* 2008; Jones *et al.,* 2016), which has meant that the emerging flora had to adapt. This lead to the evolution of sclerophylly some 60 million years ago, according to plant fossils (Hill, 2004), though it is also a perfect adaptation to arid conditions that have gradually developed in Australia over the past 20 million years (Fujioka and Chappell, 2010). This aridification has intensified over the past 2.5 million years, a period characterised by glacial-interglacial cycles of cool, arid and warm, less arid periods. These climatic oscillations favoured adaptable taxa and caused the extinction of less adaptable taxa (Martin, 2006). These climatic fluctuations also caused dramatic fluctuations in sea levels, due to water being periodically tied up in ice sheets. These drops in sea level caused a land bridge to form between Australia, Tasmania and Papua New Guinea during glacial periods (figure 1.4), facilitating the migration of humans ca 40 000 years ago (e.g. Allen, 1989; Hiscock, 1990) as well as flora. The prevalence of bushfires has also aided the development of Australia's unique flora, with *Eucalyptus* only becoming common due to an increase in fire frequency over the last few 10's of thousands of years (Hill, 2004). Whether or not this increase in fire frequency is due to human interference is a much debated issue (e.g. Butler *et al.,* 2014; Sakaguchi *et al.,* 2013).

1.4 Evolution of climate since the Last Glacial Maximum

1.4.1 Drivers of climate change

There are several drivers of climate that work on a global scale, both external to the climate system (i.e. orbital configurations) and internal (i.e. greenhouse gas concentrations). These drivers regulate the global climate on all timescales, from interannual (e.g. ENSO) to multi-millennial, in terms of glaciation cycles. On this latter scale, so-called Milankovitch cycles of orbital configuration are dominant. These cycles have largely dictated the frequency of glaciations over the past 800,000 years and consist of 3 cycles: (a) eccentricity of orbit, going from almost elliptical to almost circular over ca. 96,000 years, (b) obliquity/tilt of Earth's axis (at a periodicity of ca. 42,000 years), and (c) precession, the "wobble" of the tilt (dictating the timing of the equinoxes, at a periodicity of ca. 21,000 years; Milankovitch, 1941).

Over the past 800,000 years the Milankovitch cycles have led to regular glaciations at ca. 100,000 year intervals, with short interglacials (ca. 10,000 years) and long glacial periods (ca. 90,000 years, Bell and Walker, 2005). The last glaciation reached its peak about 18-24 thousand years ago, with the exact timing being a source of continued debate (Hughes and Gibbard, 2015). Here we use the same definition of the Last Glacial Maximum as used by modelling studies, 21 $\pm$ 1 thousand years ago (Braconnot *et al.,* 2012). The precessional cycle has influenced the climate since the last glacial period, with minimum Southern Hemisphere seasonality occurring during the mid-Holocene, ca. 6000 years ago, caused by a minima in summer insolation.

There are inherently large changes in ice sheet configurations between interglacial and glacial periods, and this has a profound effect on sea level, as large portions of the world's water is locked up in ice sheets during glacial periods. During the height of the last glacial period sea levels are believed to have been around 120 metres lower than they are today (Yokoyama *et al.,* 2001), though recent studies suggest the sea level drop may have been 134 meters (Lambeck *et al.,* 2014). Whatever the real figure was, the decrease in sea level was significant and had an intense impact on atmospheric circulation and global precipitation patterns, such as changing the meridional temperature gradient (Justino *et al.,* 2005).

Concentrations of greenhouse gases such as CO_2, CH_4, N_2O and water vapour vary naturally as a response to changes in atmospheric circulation or vegetation patterns. During a glaciation the concentrations are at their lowest, due to decreased photosynthetic rate, large landmasses being sealed off by ice and increased absorption from a cooler ocean. The reverse occurs during deglaciations, increasing the concentrations. Especially CO_2 has a strong impact on vegetation, with some reconstructed Australasian boundary shifts during glacial times possibly being caused by changing CO_2 levels, not a clear reaction to temperature or precipitation changes (e.g., Hope *et al.,* 2004). Plants are directly affected by CO_2 levels in the atmosphere, and when the levels increase this allows plants using the standard photosynthetic pathway C_3 to take up more carbon while losing less water (Prentice *et al.,* 2017). The reverse therefore occurs during glacial periods, when CO_2 levels are at a minimum, thereby restricting the distribution of C_3 plants in favour of the C_4 pathway which is better adapted to low CO_2 levels (e.g. Prentice and Harrison, 2009). Including CO_2 levels in reconstructions of glacial climates when using plant-based data sources such as pollen may therefore be of vital importance (Prentice *et al.,* 2017).

In addition to all the processes mentioned above, there have also been climatic changes at shorter timescales, for example Bond cycles, Heinrich events and Dansgaard-Oeschger cycles. Dansgaard-Oeschger (D-O) cycles are signified by rapid warmings followed by coolings and occur with 1000-, 1450-, and 3000-year cyclicity during glacial periods (Dansgaard *et al.,* 1993; Harrison and Sanchez Goni, 2010), while Heinrich events are large iceberg-calving events evident from ice-rafted debris and occurring during the cold stages after D-O events (Heinrich, 1988). Bond cycles are the combination of these two, so that one Bond cycle consists of a major D-O warm period followed by a series of smaller warm periods, then a long cold period, terminated by a Heinrich event (Bond *et al.,* 1997; Muller *et al.,* 2008). All these events are centred in the North Atlantic region, but research suggests that changes in the strength of ocean circulation (especially the Atlantic Meridional Overturning Circulation, AMOC) causes temperature oppositions between the hemispheres, as a temporary shutdown of AMOC, such as during Heinrich events, might lead to an increase in deep-sea ventilation in the Southern Ocean, essentially replacing the ventilation in the North Atlantic (Broecker, 1998). This would lead to the Southern Hemisphere experiencing warm events when the Northern Hemisphere experiences cold events, but it is debated at which scale this occurs, whether it works the same for all climatic events, and which areas are affected in which way. In addition, some researchers have found evidence for changes in precipitation as well as temperature in the Southern Hemisphere in response to climatic events in the Northern Hemisphere, as changes in the intensity of AMOC would also lead to changes in the hemispheric temperature gradient and thus to a change in the position of the ITCZ (Wang *et al.,* 2006; Muller *et al.,* 2008; Denniston *et al.,* 2013a). But with climatic events on such relatively short time scales as Heinrich events, it is not clear whether the reported wet events are linked to the North Atlantic events or not, due to dating uncertainties and low resolution of the records. There has been some suggestion that Heinrich events may have been triggered by changes in SSTs in the tropical Pacific (Clement *et al.,* 2001). In this case North Atlantic events would slightly lag behind climatic events nearer the tropical Pacific, rather than the other way around.

Feedbacks are important features of the climate system, for example changes in reflectivity, or albedo. Albedo is the measure of how much solar radiation is reflected by the surface of the Earth, with ice and snow reflecting more efficiently than water and vegetation, thus having a higher albedo. Therefore, initial melting of ice sheets during deglacial periods decreases the reflectivity of the surface by exposing darker surfaces under the ice and snow, causing the Earth to absorb more heat from the Sun, leading to more melting, and creating a positive feedback loop. This process also works in reverse, with initial growth of ice caps causing more radiation to be reflected, and thus less heat to be absorbed, leading to further cooling and further growth of the ice caps (Hall, 2004).

Clouds are another important feedback mechanism, but they can be both positive and negative at the same time, in that they reflect solar radiation, thus having a cooling effect, but also emit long-wave radiation, warming the surface (Sturman and Tapper, 2006). This has led to clouds being a large source of uncertainty in climate models, despite efforts being made to minimise this uncertainty (Webb *et al.,* 2013), with cloud response to changing CO_2 concentrations (Taylor *et al.,* 2009) and tropical low cloud feedback (Kamae *et al.,* 2016) particular issues to be addressed.

1.4.2 Impact of global forcings on Australian climates

The Australian landmass did not support a major ice sheet during the last ice age, with minor ice caps present in Tasmania and the Snowy Mountains (Petherick *et al.,* 2011), but changes in the Northern Hemisphere ice sheets still impacted Australia by changing the sea levels. Global sea-levels were about 120-134 m lower at the LGM than they are today, leading to the Australian landmass being at least some 43% larger (as calculated from figures in Gautney and Holliday, 2015; Figure 1.4, based on the 120 m estimate of sea level reduction), incorporating Tasmania and Papua New Guinea. The Gulf of Carpentaria was not part of the sea, but a large lake, at times containing freshwater (De Deckker *et al.,* 1988). As a result of the low sea-level during the last glacial period, the Australian monsoon is likely to have been weakened, due to large areas of its moisture sources in the Gulf of Carpentaria and the Arafura Sea being dry at this time (McGlone *et al.,* 1992; Shulmeister and Lees, 1995).

Figure 1.4, Australian LGM coastline, with current landmasses in grey. Adapted from Field and Wroe, 2012.

The westerly winds are theoretically expected to move south during glacial times, driven by the same forces that drives them south in the winter, the decreased temperature gradient (section 1.2.3). However, there is considerable debate regarding the nature and position of the LGM westerly winds (section 1.4.3), with multiple reconstruction and modelling studies failing to reach a consensus (e.g. Kohfeld *et al.,* 2013; Rojas, 2013).

Changes in ocean circulation is another important forcing influencing the Australian climate system. The Leeuwin current, for instance, is a warm current moving southwards along the coast of Western Australia (Figure 1.2), but may travel as far as Tasmania in winter during La Niña phases, bringing warm and humid conditions (De Deckker *et al.,* 2012). A similar warm current operates on the east coast, the East Australia Current (EAC, Figure 1.2), bringing warm air all the way to the north of New Zealand (Bostock *et al.,* 2006).

1.4.3 Australian palaeoclimate reconstructions

The Last Glacial Maximum in Australia was not only a cold period, but also fairly dry, though in some areas quite wet, evidenced for example by higher lake levels in the interior (Harrison, 1993; Cohen *et al.,* 2012) and a suggestion of multiple flood events in the Flinders Ranges, based on analysis of silt deposits (Haberlah *et al.,* 2010). As well as these regionally wet areas, increased aridity may have been prevalent for large parts of Australia and is evident from increased dune activity and lower lake levels in southeastern Australia during the LGM (Harrison and Dodson, 1993; Hesse *et al.,* 2003; Black, 2006). By the early Holocene, the SST difference between the eastern and western Pacific had reportedly decreased (Philander, 1990 in Shulmeister, 1999), leading to a weaker Walker Circulation and an extended summer monsoon over Northern Australia (Shulmeister, 1999). Based on evidence from Tasmanian pollen records, the height of Southern Hemisphere temperatures is also believed to have occurred during the early to mid-Holocene, around 7.5 ka BP (Fletcher and Thomas, 2010b; Shakun and Carlson, 2010).

According to peat deposits from the Snowy Mountains, a speleothem record from eastern Victoria and charcoal records from across Australia, there was a peak in Australian precipitation during the mid-Holocene (approx. 6 ka BP), followed by a period of slightly cooler and drier climate ca. 4-2 ka BP (Costin, 1972; Goede *et al.,* 1996; Kershaw *et al.,* 2002). This is supported by evidence from pollen and lake level records from northern Australia which indicate that the climate was wetter and warmer in this area from around 5.5 ka BP to around 3.7 ka BP (Kershaw, 1983; Kershaw and Nix, 1988, 1989). Shulmeister (1999) suggests that this was due to a stronger, but more confined, summer monsoon caused by declining SSTs in the eastern Pacific, which strengthened the Hadley Circulation and increased flow into the west Pacific warm pool. Based on pollen records from salt lake basins in the arid interior, climate has become warmer in southeastern Australia over the past millennium, but with greater variation in moisture availability (Luly, 1993; Cupper *et al.,* 2000).

A review by Shulmeister (1999) found a 1000 year discrepancy between maximum Holocene precipitation in northern Australia versus southern Australia. He interpreted this as evidence for a decrease in summer monsoon rainfall, with a simultaneous increase in westerly wind intensity and decreased effective precipitation in southern Australia. This conclusion is mainly supported by pollen records presented by Shulmeister and Lees (1995). However, the other study cited in support of this conclusion, Williams (1994), only tentatively speculate that the apparent discrepancy in timing of maximum precipitation between western Victoria and northeast Queensland is due to an asynchronous response of the monsoon system and the winter westerlies system to postglacial warming. In addition, the difference in timing in this paper is 2000 years, which implies that dating uncertainties may at least partially explain the apparent discrepancy.

There have been multiple studies of the position and strength of the southern westerly winds during the LGM. In theory, the reduced interhemispheric temperature gradient during this time would have caused a southwards shift of the ITCZ, and with it the westerly wind system, as occurs in boreal winter. Some evidence has also been found for this in pollen and lake-level reconstructions from eastern Australia suggesting drier conditions compared to today (Harrison and Dodson, 1993). However, De Deckker *et al.* (2012) links the increased aridity to a northwards shift of the oceanic Subantarctic Front (SAF)/Polar Front (PF), the movement of which is determined by the location of the westerly wind belt, positioned north of the SAF/PF. They found support for this in the foraminiferal record of an oceanic core just off the coast of South Australia. Extensive sea surface temperature (SST) reconstructions by Barrows and Juggins (2005) also support the northward displacement of the westerly winds during the LGM, as does palaeoshoreline reconstructions from Lake Frome and speleothem records from the Flinders Ranges (Cohen *et al.,* 2011), but not speleothem records from Kangaroo Island presented in the same study, something that was supposedly caused by undersampling. An extensive review based on multiple records from Australia and New Zealand concluded that the latitudinal movement of the westerly wind belt over a glacial cycle may not have been much larger than the modern seasonal movement, and could not draw a conclusion as to its position during the LGM, only that the winds were probably stronger than today (Shulmeister *et al.,* 2004). Hodgson and Sime (2010) also struggled to draw a conclusion from their review of studies of a subantarctic pollen record, a glacial moraine record from New Zealand and records from lakes and peat bogs in central Chile, but suggested that the westerly wind belt may not have so much shifted as expanded. Multiple modelling studies have attempted to simulate the westerly wind belt during the LGM, with similarly conflicting results. Some papers suggest that they shifted towards the equator (e.g., Kim *et al.,* 2003; Chavaillaz *et al.,* 2013), some suggest a poleward shift (e.g., Valdes, 2000; Wyrwoll *et al.,* 2000; Kitoh *et al.,* 2001; Shin *et al.,* 2003; Rojas, 2013), or a marginal shift (Otto-Bliesner *et al.,* 2006; Rojas *et al.,* 2009), and others suggest a change in strength (Rojas *et al.,* 2009; Rojas, 2013). A review by Kohfeld *et al.* (2013) concluded that only by combining data reconstructions and model simulations will it be possible to establish how the southern westerly wind belt actually behaved during the LGM.

1.5 Quantitative climate reconstructions

There have been relatively few attempts to make large-scale quantitative climate reconstructions for Australia, and the only continent-wide reconstruction to date forms part of the PAGES 2k synthesis (Neukom *et al.,* 2013, 2014). However, the Australian component of this synthesis only spans the last millennium. D'Costa and Kershaw (1997) documented the climate ranges of key plant taxa in the South-East Australian Pollen Database (SEAPD), and Pickett *et al.* (2004) reconstructed continent-wide palaeovegetation patterns, but neither made quantitative reconstructions. Cook and van der Kaars (2006) used the SEAPD in addition to their own compilation of northern Australian pollen samples to test the validity of a transfer function approach on Australian pollen samples. The methodology was later used by van der Kaars *et al.* (2006) on a marine core from off the coast of northwestern Australia. Prentice *et al.* (2017) used the same continental pollen database used in this thesis to reconstruct moisture, focusing on the Last Glacial Maximum. Chapter 3 in this thesis thus represents of the first continuous continent-wide quantitative reconstruction of Australian palaeoclimate extending further than the last millennium to date. Large-scale quantitative reconstructions are needed to evaluate climate model performance (Braconnot *et al.,* 2012, section 1.4.3), and the lack of such reconstructions for Australia may therefore hamper these efforts, an issue that this thesis is a step towards resolving.

1.5.1 Available data sources

Data sources used in quantitative palaeoclimate reconstructions are available from almost every environment on earth, from ocean cores (with foraminifera, ostracods, diatoms, dinoflagellates and pollen) and ice cores (containing ancient air pockets and stable isotopes) to rat middens in deserts (containing pollen and beetles), lakes and bogs (with pollen, diatoms, ostracods, chironomids and beetles), caves (speleothems), tree rings and corals. Depending on study area and data source, preservational issues may severely limit the temporal range of the study. As this thesis has an Australian focus, ice cores can be discarded as potential data sources, but all the others have been utilised, though some have only been used on a limited number of sites so far. In addition to the aforementioned data sources for quantitative reconstructions, dust records, glacial landform studies and lake level data can supply an estimate of aridity fluctuations, ice cap or glacier movements as well as fluctuations in vegetation cover, which may be important as independent verification of reconstructions from other sources (e.g., Harrison, 1993; Barrows *et al.,* 2002; Hesse *et al.,* 2003, 2004).

In Australia the use of beetles for quantitative palaeoclimate reconstructions is still in development, due in part to the fragmented nature of the records and the large amounts of organic material that is needed (Porch and Elias, 2000). However, they have proved useful in other parts of the world when combined with a higher resolution record utilising for instance pollen or diatoms, and have the potential to be a useful addition to similar studies in Australia (Porch, 2007; Porch, 2010).

Tree rings were the major source of data for the PAGES2k synthesis (Neukom *et al.,* 2013) because of the high-resolution, accurately dated records they provide. Unfortunately the longest record only goes back 4000 years (Cook *et al.,* 2000), with most studies limited to the last millennium. This is due to the lack of long living trees, an issue encountered by tree ring studies worldwide (e.g. Cook *et al.,* 1991, 2006), though fossil wood can also be used to examine time windows in the past, such as the last glacial period based on wood found in the La Brea tar pits (Li *et al.,* 2017).

There are too few Australian palaeorecords containing diatoms or chironomids to justify a study of the scale I am conducting, but they do show future potential (Gell *et al.,* 1994; Tibby *et al.,* 2006; Tibby and Haberle, 2007, Chang *et al.,* 2015). The use of stable carbon isotopes or amino acid racemization rate-based temperatures from emu eggshells is an underutilised technique, mainly useful as an additional data source from the arid interior, where there are few sources of information available (Johnson *et al.,* 1999, Miller *et al.,* 1997, 2016). In addition, Woltering *et al.* (2014) successfully reconstructed mean annual air temperature using branched glycerol diakyl glycerol tetraether (GDGT) distributions in a lake sediment core from Fraser Island in southern Queensland.

A widely used source of data in Australia are speleothems, which can be well-dated using ^{230}Th dating and can supply valuable high-resolution temperature and precipitation records, and have done so, particularly providing important palaeoclimatic information for tropical Western Australia (Denniston *et al.,* 2013a,b,c), South Australia (Blyth *et al.,* 2010) and the southwest (Treble *et al.,* 2005). As speleothems are only found in caves this limits the spatial extent of these records, and the topography in which they are found, but they are still invaluable resources for increasing the area of Australia covered by palaeoclimatic records.

Pollen records are the most spatially extensive and widely used source of data for quantitative reconstructions of terrestrial climates worldwide and for Australia (e.g. D'Costa and Kershaw, 1997; Whitmore *et al.,* 2005; Bartlein *et al.,* 2011). This is due to climate exerting a strong control on vegetation distribution (Harrison *et al.,* 2010) and to the fact that the records can be well dated using radiocarbon techniques (Prentice, 1988; Whitmore *et al.,* 2005). However, there are some issues regarding preservation of pollen grains, especially in dry sediments, a potentially large issue in such a dry continent as Australia. Sites containing extensive records are confined to limited areas, mainly around the coast and in the southeast. But there are records from less typical environments available, such as estuaries (Moss *et al.,* 2005), river sediments (van der Kaars *et al.,* 2006), artesian spring outflows (Boyd, 1990, 1994) and stick-nest rat middens (Head, 1993). These environments have successfully been used previously for similar studies elsewhere in the world (e.g. artesian spring outflows in North America: Martin, 1963).

Pollen records are used in this thesis to reconstruct past climate across Australia because they provide the best spatial and temporal cover of terrestrial climates available for this region. Some of the other sources may be useful as independent verification of pollen-based reconstructions, but this verification will be limited by the constraints outlined above. Marine data, e.g. foraminifera and ostracods from ocean cores, and stable isotopes from corals, can be used as an additional source of information, and for examining land-sea temperature contrasts (e.g. as part of a monsoon system study; De Deckker *et al.,* 1988, 2014; Dunbar *et al.,* 1994), but are not the main focus here.

1.5.2 Methodological approaches for quantitative reconstructions

There are many techniques available to reconstruct palaeoclimate quantitatively, such as inverse regression (Webb, 1980; Bartlein *et al.,* 1984; Huntley and Prentice, 1988), transfer functions (Webb and Bryson, 1972; Klemm *et al.,* 2013), modern analogues (Howe and Webb, 1983; Overpeck *et al.,* 1985; Jackson and Williams, 2004; Jiang *et al.,* 2010), response surfaces (Bartlein *et al.,* 1986; Gonzales *et al.,* 2009), probability density function (Kühl *et al.,* 2002; Chevalier *et al.,* 2014), boosted regression trees (De'ath, 2007; Salonen *et al.,* 2014), Bayesian modelling (Vasko *et al.,* 2000; Haslett *et al.,* 2006; Ilvonen *et al.,* 2016), the coexistence approach (Mosbrugger and Utescher, 1997; Zhang *et al.,* 2015) and even inverse-vegetation modelling (Guiot *et al.,* 2000; Garreta *et al.,* 2010). Only some of these techniques will be described in detail, but most use some form of modern-analogue technique, which applies modern relationships between assemblages and climate variables to palaeo-assemblages to infer past climate states. One such technique is response surfaces, which describes the way the abundances of taxa depend on the joint effects of two or more environmental variables (Bartlein *et al.,* 1986). This is done by remapping a sequence of taxon abundance patterns from geographic space into climate space and then using these response surfaces collectively to infer a sequence of climatic changes. However, the response surfaces have limited geographical and temporal applicability, as pollen types may have response surfaces with multiple optima, especially if one taxon represents multiple species with differing ecological needs. Gonzales *et al.* (2009) have expanded on this technique to minimise the issue of a lack of modern analogues by "mirroring pollen abundances for each taxon around a four-dimensional climate axis".

Transfer functions is the name given to a set of equations used to transform pollen data into climatic information (Webb and Bryson, 1972). These equations may be in the shape of correlation analysis of rank order (Ogden, 1969) or multivariate statistics such as canonical correlation analysis (CCA, Webb and Bryson, 1972; ter Braak and Verdonschot, 1995). The latter works by finding an ordered set of mutually orthogonal patterns among the climatic data and a set among the pollen data. These patterns are referred to as canonical variates and the correlations between pairs of variates (one from each set) are canonical correlations. Significantly correlated pairs are then used to calculate a set of canonical regression-coefficients that work as transfer functions, transforming pollen data into estimates of climatic variables.

The Modern Analogue Technique (MAT) measures the difference between the assemblages using for example the Square Chord Distance (SCD) coefficient (Overpeck *et al.,* 1985), with modern analogues that pass a predefined threshold being used to infer the climate of the palaeo-assemblage. One of the issues with this technique is that it needs a comprehensive modern calibration dataset to enable it to accurately reconstruct a wide range of palaeoclimates. Even with a comprehensive modern dataset, there will have been assemblages in the past that have no modern analogues (Overpeck *et al.,* 1992). One way to get around the non-analogue problem is to group the plant taxa into their Plant Functional Types (PFT) before performing the reconstructions (Nakagawa *et al.,* 2002). Another issue arising from a limited modern dataset is the edge effect. This is when the modern dataset is at the edge of the climatic space for a certain variable, e.g. temperature. Any change in temperature beyond this edge would not be captured by this edge dataset. Velle *et al.* (2011) managed to improve their reconstructions by being more selective with their site selection, but this will only work with studies similar to theirs, which was performing reconstructions based on chironomids from a lake on Spitsbergen in the far north of Norway. They started with a modern dataset covering the whole of Norway, and improved their reconstructions by excluding lakes at the warm end of the temperature gradient. However, if the study relates to a site or group of sites in a warm area with no cold temperature sites in the modern dataset and the aim is to reconstruct glacial temperatures, trimming the dataset will not help. This is a significant problem in Australia because of its geographical isolation, meaning that the glacial floral assemblages present in Australia during the LGM and that do not exist anywhere on this continent today, will therefore not exist anywhere else either. Just as with the non-analogue problem mentioned previously, grouping taxa into their PFTs might minimise the edge effect.

Despite these issues MAT has previously been used successfully on large pollen datasets worldwide (e.g., Gajewski *et al.,* 2000; Davis *et al.,* 2003; Peyron *et al.,* 2006; Connor and Kvavadze, 2008; Guiot *et al.,* 2008; Bartlein *et al.,* 2011), and so this technique could have been selected for comparison reasons alone. However, it is also a very computer efficient and statistically robust technique, which is why it has been so successful in similar studies.

No matter which technique is used, the nature of the pollen samples may affect the reconstructions, for example whether they are core top samples or another type of surface sample. Samples from cores taken in moderately sized lakes or peatbogs should in theory provide a good record of the regional pollen rain (Sugita *et al.,* 2010; Wang *et al.,* 2014) and thus of regional vegetation and climate. However, it is not always possible to sample such sites exclusively and additional surface samples from other sites within a basin or from other environments need to be used. Both the representation and preservation of pollen may vary with surface sample type, i.e. samples from closed-canopy vegetation are more likely to reflect very local vegetation than samples from open vegetation (Tauber, 1967). Dry sediments preserve pollen grains poorly, as do surface soils, when compared to wet sediment samples (Wilmshurst and McGlone, 2005).

Consideration should also be given to the question of temporal averaging. When using palaeoclimate reconstructions as part of a large-scale synthesis, for example in order to evaluate palaeoclimate models, it may be necessary to average or pool results within a selected time window to minimise the impact of dating uncertainties. The length of time varies depending on the period in question. Due to dating and calibration uncertainties increasing with time, as well as records getting more and more scarce the further back in time a study goes, time windows increase with time, a 1000-year window being commonly used for the mid-Holocene (centred at 6 ka BP) and up to 2000 years for glacial periods (i.e. LGM, centred at 21 ka BP). This approach ensures that the researcher still achieves good coverage for each time period (e.g., Gajewski *et al.,* 2000; Bartlein *et al.,* 2011). Averaging can either be performed on individual sample reconstructions or on a single composite sample created by averaging or pooling the counts of the individual pollen samples. The advantage of creating a composite sample is that it reduces intersample variability that may be introduced due to natural interannual variability of pollen production between plants, or due to differences in approaches to grain counting between individual researchers.

Most researchers will not count all grains present in a sample, unless it is a poor sample. Instead they will count a predetermined number of grains (e.g. a minimum of 2-300, Fletcher and Thomas, 2007; Hashimoto *et al.,* 2006) and extrapolate the total number based on the measured proportions. Whereas this method does save time it may lead to the exclusion of rare species and thus lead to artificial intersample variation, as generally a larger count means a more reliable estimate (Hill, 1996). When creating a composite sample these differences are averaged out, leaving one sample for the desired time period. However, in doing this, natural fluctuations may also be averaged out. Similarly, when averaging samples spatially, in order to build a composite modern sample from multiple samples in a valley surrounding a cored lake, for instance, these samples should only be taken from similar locations, to minimise natural variation. On the other hand, averaging reconstructions from individual samples, whilst still being subject to the issue of intersample variation, does offer an additional measure of uncertainty, as each sample will be represented by its own reconstruction.

The spatial resolution of the modern climate data used may also have an impact on the final reconstructions. The climate data can be obtained by interpolation between meteorological stations or from a gridded climatology, the most widely available data sets gridded at a resolution of 0.5°, with finer resolution data sets now available for some regions, including Australia. Using an interpolated dataset may introduce error when interpolating over a large area with complicated topography. Using a coarse grid may lead to the exclusion of extreme values that may be present at a finer resolution. However, pollen samples from a reasonably sized basin represent vegetation for a larger area than immediately surrounding the sample site. It may even represent vegetation for a larger area than the selected climatic grid size. This is likely to be the case for some sites in central Australia, such as Lake Eyre, but the vast majority of sites are likely to be of a size similar to a finer grid.

All of these methodological issues, as well as the analytical decisions involved in MAT, are addressed and tested in Chapter 2.

1.6 Modelling palaeoclimates

One drawback associated with any means of inferring climate from data is that the causes of the reconstructed climatic variations are not always clear, and any reconstruction will inherently only provide part of the picture, as any given climate may have been formed in a number of ways, and any given climate may influence the data sources in multiple ways. Using multiple data sources and/or a large database will help to complete this picture, but it is very hard be certain, especially for a continent with the scarcity of long records like Australia. With palaeoclimate modelling the boundary conditions can be changed in order to test the likelihood of different scenarios. This is done by making specific changes to certain boundary conditions, e.g. CO_2 concentration or insolation. Therefore if the results change significantly the altered boundary conditions can be assumed to be the cause. This type of work is important as it enhances our knowledge of the climate system. Miller *et al.* (2006), for example, performed such a study to successfully evaluate the importance of including the thinning of the Antarctic ozone layer when simulating recent changes in the Southern Hemisphere westerly winds. Quantitative palaeoclimatic reconstructions are vital as independent assessors of the accuracy of these palaeoclimatic model simulations (e.g. Schmidt, 2010; Braconnot *et al.,* 2012; Hargreaves *et al.,* 2013; Chevalier *et al.,* 2017). Even when using different models from those used to simulate past climatic changes, the increased knowledge of the climate system may aid in the improvement of simulations of future climates, which is why sections on palaeoclimate modelling and reconstructions are included in the assessment reports for the Intergovernmental Panel on Climate Change (Stocker *et al.,* 2013). Model evaluation will be described in detail in section 1.6.3 below.

1.6.1 Methodology and theory

Climate models are numerical representations of the physics controlling the climate system, the first ones being an extension of meteorological models and focusing on atmospheric circulation. These models used varying numbers of atmospheric layers, divided by air pressure, and with ocean temperature prescribed either from observations or calculations based on other model input, such as solar radiation and hydrology (Manabe *et al.,* 1965; Bourke, 1974). The reflectivity of different surface types as well as estimated cloud cover at two different atmospheric heights were incorporated from the beginning of palaeoclimate modelling (Williams *et al.,* 1974).

Early atmospheric models used specified ocean temperatures (e.g. Williams *et al.,* 1974), later being coupled with ocean models for a more responsive ocean, as well as incorporating terrestrial input such as vegetation and topography, developing into Earth System Models (ESMs). ESMs are Atmosphere-Ocean Global Climate Models (AOGCMs) coupled to biogeochemical components and have been used in the latest three phases of the Coupled Modelling Intercomparison Project (CMIP; Taylor *et al.,* 2012).

As models have grown more complex, so has the number of equations they use increased, along with their incorporated boundary conditions, which limit the output from each equation depending on which time period is being examined. An important condition to take into account when studying palaeoclimates is that of orbital configuration (section 1.4.1). This is most commonly defined by using the orbital parameters from Berger (1978), in which he calculates the long-term variations of eccentricity, obliquity and the longitude of the perihelion measured from the moving vernal equinox. As other boundary conditions vary slightly between models, the standardised procedures of CMIP and PMIP (Palaeoclimate Modelling Intercomparison Project) will be outlined in section 1.6.2 below.

Due to differences in, for instance, radiation transfer code and underlying climate, the forcing imposed on different models may vary by more than 10% (Schmidt, 2010). For computer efficiency reasons models operate with fairly coarse grid resolutions, which also varies between models. For instance, the atmospheric resolution of IPSL-CM5 is 2.5° x 1.25°. This model is used in PMIP3 and CMIP5 and the resolution is finer than in the previous version of the model (Dufresne *et al.,* 2013). However, it is coarser than for instance an individual cloud, and cloud parameterisation must be used. Finer resolution models are more detailed spatially, and they have been found to also improve the model performance in most cases (Reichler and Kim, 2008). Overall, there is still disagreement regarding the magnitude and pattern of temperature anomalies both between model simulations and statistical reconstructions and within an ensemble of model runs (Hargreaves and Annan, 2014). One source of inter-model uncertainty is known to be cloud response to changing CO_2 concentrations (Taylor *et al.,* 2009). The techniques for evaluating the quality of climate models are described in section 1.6.3 below, and will be used in chapter 4.

1.6.2 PMIP and CMIP modelling

The Palaeoclimate Modelling Intercomparison Project (PMIP) started in 1991 after a NATO Advanced Workshop, with the aim to “evaluate models under palaeoclimate conditions and improve our understanding of past climates” (Joussaume and Taylor, 2000). This project is currently in its fourth phase and includes multiple working groups with modellers from all over the world. The Coupled Modelling Intercomparison Project (CMIP) started in 1995 with the aim to provide climate scientists with a database of coupled GCM simulations under standardised boundary conditions (Meehl *et al.,* 2000). This project is currently in its sixth phase and incorporates modelling of future scenarios, thus having a great influence on the work of IPCC (Eyring *et al.,* 2016; Kageyama *et al.,* 2016). To aid comparison and model evaluation, CMIP and PMIP follow the same protocol and have divided their experiments into categories. Within each category there are a number of core experiments that each modelling group has to perform, such as a pre-industrial control run (using 1850 CE level forcings, e.g. CO_2 concentration of 280 ppm), before proceeding to more specific, but also clearly defined, experiments (Taylor *et al.,* 2009).

The pre-industrial control run uses either computed or prescribed vegetation distribution and land use parameters, pre-industrial levels of greenhouse gases (i.e. ca 280 ppm CO_2) and natural aerosols, with the runs being set for 500 model years, after initial spin-up to reach equilibrium. The control run acts as a calibration of the model's internal variability (Taylor *et al.,* 2012). Each new phase of PMIP and CMIP uses updated boundary conditions, here we will focus on those used by PMIP3 and CMIP5.

The mid-Holocene was chosen as an important reference period for model experiments due to the likelihood of regional climates being significantly different from today (Braconnot *et al.,* 2012), the availability of numerous data syntheses (e.g., Bartlein *et al.,* 2011) and the external forcing being well known. The large differences in regional climate come from the fact that seasonality was different during this period, due to a difference in orbital configuration (the main difference was in obliquity, but precession also had an impact, according to calculations in Berger, 1978). The Northern Hemisphere experienced an increase in temperature seasonality on land by about 5%, the Southern Hemisphere experiencing a decrease of the same magnitude (Joussaume *et al.,* 1999). The mid-Holocene PMIP3/CMIP5 runs use specified orbital parameters and greenhouse gas concentrations (e.g., CO_2=280 ppm, CH_4=650 ppb and N_2O=270 ppb) and reconstructed or computed vegetation distributions, the runs set for at least 100 model years after spin-up (https://wiki.lsce.ipsl.fr/pmip3/doku.php/pmip3:design:6k:final).

The LGM has been chosen as a key period for palaeoclimate model simulations as the climate at this time was radically different compared to today, and compared to the mid-Holocene. Just like the mid-Holocene the large natural forcings controlling the climate during the LGM are relatively well known (Braconnot *et al.,* 2012). The PMIP3/CMIP5 model runs use specified orbital parameters and greenhouse gas concentrations (e.g., CO_2=185 ppm, CH_4=350 ppb and N_2O=200 pb), specified ice sheet distribution and topography (blended from ICE6G [Peltier *et al.,* 2015], GLAC-1 [Tarasov *et al.,* 2012] and ANU [Lambeck *et al.,* 2006]), defined land-sea distribution (e.g., closed Bering Strait), lowered sea level by ca 116 m, with associated change in ocean bathymetry, computed vegetation distribution, computed or pre-industrial aerosol distribution and slightly elevated salinity (+1 PSU), with runs set for at least 100 model years after spin-up (https://wiki.lsce.ipsl.fr/pmip3/doku.php/pmip3:design:21k:final). The importance of using palaeoclimate simulations to evaluate future simulations using the same models becomes clear when considering that the radiative forcing for the LGM and the RCP4.5 future scenario are roughly opposite (Chavaillaz *et al.,* 2013). For a full list of CMIP5 and PMIP3 models that have been used to simulate mid Holocene and LGM climate, see table 1.1.

Despite all the specified parameters, there are still fairly large inter-model differences due to differences in model construction. For instance, differences have been noted in modelled modern surface albedo and cloud feedbacks, despite having a common starting point (Joussaume *et al.,* 1999; Braconnot *et al.,* 2012). In addition, the improvements that have been made to models between phases 3 and 5 of CMIP have not significantly improved their general ability to capture observed patterns of north Australian sea surface temperature evolution, with only 2 out of the 6 best performing CMIP5 models capturing the right patterns (NorESM1-M and CNRM-CM5, Catto *et al.,* 2012).

Table 1.1, PMIP3 and CMIP5 models used to simulate Mid-Holocene (6 ka BP) and LGM climates (21 ka BP), information from Harrison *et al.* (2014) and Schmidt *et al.* (2014), resolution from https://portal.enes.org/data/enes-model-data/cmip5/resolution.

	Model	Institution	Experiments	Resolution	Model type (coupled components)
1	BCC-CSM1.1	Beijing Climate Centre, China Meteorological Administration, China.	Mid-Holocene	2.79° x 2.81°	Climate System Model; Ocean, Atmosphere, Carbon-cycle.
2	CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique, France.	Mid-Holocene, LGM	1.4° x 1.41°	Ocean, Atmosphere.
3	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence, Australia.	Mid-Holocene	1.87° x 1.88°	Ocean, Atmosphere.

4	FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Science; and CESS, Tsinghua University, China.	Mid-Holocene, LGM	2.79° x 2.81°	Ocean, Atmosphere.
5	GISS-E2-R	NASA Goddard Institute for Space Studies, USA.	Mid-Holocene, LGM	2° x 2.5°	Ocean, Atmosphere.
6	HadGEM2-CC	Hadley Centre, UK Met Office, UK.	Mid-Holocene	1.25° x 1.88°	Ocean, Atmosphere, Carbon-cycle.
7	HadGEM2-ES	Hadley Centre, UK Met Office, UK.	Mid-Holocene	1.25° x 1.88°	Earth System Model; Ocean, Atmosphere, Carbon-cycle.
8	IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France.	Mid-Holocene, LGM	1.89° x 3.75°	Ocean, Atmosphere, Carbon-cycle.
9	IPSL-CM5A-MR	Institut Pierre-Simon Laplace, France.	Mid-Holocene	1.27° x 2.5°	Ocean, Atmosphere.
10	MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan.	Mid-Holocene, LGM	2.79° x 2.81°	Earth System Model; Ocean, Atmosphere, Carbon-cycle.
11	MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan.	Mid-Holocene	1.4° x 1.41°	Ocean, Atmosphere.
12	MPI-ESM-P	Max Planck Institute for Meteorology, Hamburg, Germany.	Mid-Holocene, LGM	1.87° x 1.88°	Earth System Model; Ocean, Atmosphere.
13	MRI-CGCM3	Meteorological Research Institute, Tsukuba, Japan.	Mid-Holocene, LGM	1.12° x 1.13°	Coupled Global Climate Model; Ocean, Atmosphere.
14	NCAR-CCSM4	National Centre for Atmospheric Research, US/Department of Energy/NSF, USA.	Mid-Holocene, LGM	0.94° x 1.25°	Ocean, Atmosphere.
15	NorESM1-M	Norwegian Climate Centre, Norway.	Mid-Holocene	1.89° x 2.5°	Earth System Model; Ocean, Atmosphere.

1.6.3 Model evaluation

Quantitative palaeoclimate reconstructions provide valuable records from which to evaluate climate models. They can be used to evaluate the model's ability to simulate specific aspects of known climate events, such as the timing of events leading up to the Younger Dryas, ca 12 ka BP (Mikolajewicz *et al.,* 1997). It is important to use different scenarios for these evaluations, with the present day displaying near insolation maxima for December-January-February (DJF) in both hemispheres and 10 ka BP presenting DJF insolation minima in both hemispheres (e.g., Miller *et al.,* 2005). As certain models may capture changes in some regions better than in others, evaluating these models by comparing them to palaeoclimate reconstructions may not only aid model development, but also model selection for specific regions (Braconnot *et al.,* 2012).

A common measure of the difference between climate models is how they simulate climate sensitivity, defined as the "global mean surface temperature response to a doubling of CO_2 atmospheric concentration once the system has reached an equilibrium state" (Crucifix, 2006). This measure can be estimated from palaeo-reconstructions of the Last Glacial Maximum (LGM), as this was a time when the climate system was in near-equilibrium for thousands of years (Annan and Hargreaves, 2015). Thus climate sensitivity as measured from palaeorecords can be compared to those estimated from models simulating the LGM to provide an additional measure of climate model accuracy. Schneider von Deimling *et al.* (2006) used an estimate of climate sensitivity derived from reconstructed SSTs to constrain the large range of sensitivity estimates provided by their large model ensemble.

There are several statistical methods for model evaluation, including Hotelling's T^2 statistic (Wilks, 2011), medians and interquartile range (IQR), Kendall's rank correlation coefficient (Kendall, 1938), fuzzy distance (i.e. approximate rather than precise dissimilarities; Guiot *et al.,* 1999), global metrics ("multi-model ensemble median bias"; Gleckler *et al.,* 2008), the M statistic, or skill score (Watterson, 1996), normalised median error, and map-based statistics such as ΔW (Harrison and Prentice, 2003) and Kappa (Monserud and Leemans, 1992; Prentice *et al.,* 1992). Hotelling's T^2 is a multivariate generalisation of the common t-statistic (Wilks, 2011; Harrison *et al.,* 2014) and the IQR is a measure of spatial variability that is useful to assess agreement in the amplitude of potential anomalies. Map-based statistics are commonly used for qualitative comparisons of pairs of simulations, observations and/or reconstructions (Bartlein *et al.,* 1998; Kohfeld and Harrison, 2000), but quantitative assessment techniques such as Kappa statistics (Monserud and Leemans, 1992) and ΔW (Harrison and Prentice, 2003) are also available. The statistic ΔW is a modification of the ΔV statistic, an area-weighted dissimilarity measure (Sykes *et al.,* 1999). Kappa is a pixel-by-pixel similarity measure that was upgraded by Prentice *et al.* (1992) to include adjacent pixels and a measure of the proportion of agreement. Most of these measures may still come with some degree of "false discovery rate" (FDR), or expected proportion of falsely rejected null hypotheses (Wilks, 2006). The FDR test enforces a minimum value of probability which has to be exceeded by the minimum probability value for all associated null hypotheses to be accepted.

Many modelling studies do not use statistical measures when performing model-data comparison studies, simply stating that there are large or small differences, or how large the differences are. This is, at least in part, because climate modellers use so many different approaches to answer widely different research questions that it is not possible to use one single common measure of statistical agreement between simulations and reconstructions. Instead, each model study needs to properly, and individually, assess the appropriate method of quantitative verification suitable for their study (Gleckler *et al.,* 2008).

The simplest method for statistically comparing model output to palaeoclimate reconstructions is through point-by-point comparison. This approach may lead to misleadingly large error estimates, as slight spatial differences in climatological features will be counted as complete errors instead of presenting partial agreement. Regional or zonal averages have been used in an attempt to minimise this issue, but may introduce new issues when determining regional boundaries or when there are data patterns present that traverse several regions (Kohfeld and Harrison, 2000). These issues are dealt with when using fuzzy distance measures, as these assign degrees of agreement for each point, not just the usual "hit or miss" assignment (Guiot *et al.,* 1999). Another way to deal with this issue is to measure the skill of the models, the level of agreement between the simulated and observed climatological values over a certain region (Watterson, 1996).

Model evaluation of the types described above have been used to identify biases in climate models, such as overestimating the extent of monsoon influence in Africa (Perez-Sanz *et al.,* 2014), failing to reproduce spatial patterns of climate change (Harrison *et al.,* 2014), or the magnitude of regional changes (Braconnot *et al.,* 2012; Harrison *et al.,* 2015). As these biases were found to be present in all or most of the models examined in these studies, it suggests that the models may not be perfectly simulating all the climatic controls in the study areas, or at least not taking all of them fully into account. When some models present less of a bias than others, identifying the missed control may be a simple matter of examining the differences between these models and adjusting the appropriate boundary conditions. However, when all models show significant bias in, for example, simulations of tropical low cloud feedback, the issue might be a bit more complicated (Kamae *et al.,* 2016). That is why special working groups have been tasked with resolving such issues, which also includes the importance of wild fire simulations (Hantson *et al.,* 2016). Past evaluation studies which examined the impact of using prescribed changes in vegetation or asynchronous climate-vegetation model coupling (e.g. Braconnot *et al.,* 1999; Sitch *et al.,* 2003) on model-data discrepancies led to the incorporation of models with dynamic vegetation (ocean-atmosphere-vegetation general circulation models) in PMIP2 (Braconnot *et al.,* 2012), and a significant improvement to the models.

An evaluation of the climate models used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change showed that only 3 out of 14 climate models simulated regional precipitation over Australia very well, based on probability density functions (these three models being BCCR, ECHO-G and ECHAM; Perkins *et al.,* 2007). The aim of this thesis is to provide the large-scale quantitative palaeoclimate reconstructions needed in order to evaluate the updated versions of most of the models used in this study, to not only see if their performance has improved, but also identify areas of possible future improvement. Hopefully this will lead to more realistic simulations of future changes in regional climate across Australia.

1.7 Thesis overview

This thesis will examine the impact of the various methodological decisions involved in performing quantitative climate reconstructions discussed in section 1.5.2, with particular focus on how they impact on Australian palaeoclimate reconstructions from pollen. The lessons from this detailed examination will then be used in performing the much needed continental-scale continuous quantitative palaeoclimate reconstructions for Australia, in order to evaluate output from PMIP models according to the methodologies discussed in section 1.6.3. By performing this first continuous continental-scale quantitative reconstruction for Australia going back further than the last millennium, some of the issues raised in section 1.4.3 may also be addressed.

The chapters of this thesis are presented as either published manuscripts or manuscripts in preparation for publication. These manuscripts have co-authors, namely my supervisor, Professor Sandy Harrison and various data contributors. Professor Sandy Harrison provided a conceptual framework for the project and has therefore been included as a co-author on all papers. The thesis is outlined as follows:

Chapter 2 presents a detailed examination of the methodological decisions and assumptions associated with performing quantitative climate reconstructions for Australia using a continent-wide pollen dataset and the Modern Analogue Technique. This chapter has been published as:

- Herbert, A.V. and Harrison, S.P., 2016. Evaluation of a modern-analogue methodology for reconstructing Australian palaeoclimate from pollen. Review of Palaeobotany and Palynology 226, 65-77.

Chapter 3 presents quantitative palaeoclimate reconstructions for Australia going back to the LGM, following the methodology from chapter 2. This chapter is currently in preparation for publication:

- Herbert, A.V., Harrison, S.P., Witt, B., Dodson, J., Moss, P., Mooney, S., Hope, G., Stevenson, J., Haberle, S., Luly, J., Shulmeister, J., Head, L., (in prep.) Quantitative reconstruction of Australian climate since the Last Glacial Maximum using pollen.

Chapter 4 uses the reconstructions from chapter 3 to evaluate palaeoclimate output for Australia. This chapter is currently in preparation for publication:

- Herbert, A.V. and Harrison, S.P., (in prep.) Comparing model outputs with statistical climate reconstructions derived from a comprehensive pollen database for Australia.

The key findings of this study are then summarised in **Chapter 5.**

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Methods

As can be seen in table M1, chapters 2 and 3 employ similar methodologies and the same data. In fact, the methodology used in chapter 3 is the one established in chapter 2 as optimal for the data used. The reconstructions resulting from chapter 3 are then used in chapter 4 to evaluate palaeoclimate model output.

Specifically, in chapter 2 a number of tests are performed to determine the impact of various statistical decisions and assumptions on the quality of climate reconstructions. These tests were performed by splitting the modern dataset into sub-datasets, e.g. core top samples and surface samples, reconstructing the modern climate from these data using the Modern Analogue Technique (MAT). The statistical significance of any differences between the reconstructions was then determined using Kolmogorov-Smirnov tests, after testing for normality (using Shapiro-Wilk tests) and homogeneity of variance (using Fligner-Killeen tests).

After establishing the best approach to use for reconstructing climate from the Australian dataset, this methodology was put to use in chapter 3 to reconstruct Australian climate going back to the Last Glacial Maximum (LGM). The results were mapped according to the approach used in Bartlein *et al.* (2011), as it is a similar study with similar aims of being used for model evaluation. This model evaluation is the basis for chapter 4, comparing the reconstructions from chapter 3 with model output from PMIP3, focusing on the output for Australia for the mid-Holocene and LGM. The model output was mapped and the statistical significance of any differences to the reconstructions determined using the same tests as in chapter 2, split by models, but also testing ensemble means.

Table M1, Methods and data used in the thesis chapters.

Chapter	Analysis	Data
2	Quantitative modern climate reconstructions and significance analysis.	Modern pollen samples collected from collaborators across Australia. Climate data from ANUCLIM.
3	Quantitative palaeoclimate reconstructions.	Modern and fossil samples collected from collaborators across Australia. Climate data from ANUCLIM.
4	Significance analysis.	Reconstructed palaeoclimate from chapter 3. Model output from PMIP3.

Chapter 2

Evaluation of a modern-analogue methodology for reconstructing Australian palaeoclimate from pollen

Chapter 2: Evaluation of a modern-analogue methodology for reconstructing Australian palaeoclimate from pollen.

This chapter is based on detailed analyses of the inherent assumptions and decisions involved in performing quantitative palaeoclimate reconstructions using the Modern Analogue Technique on a large pollen dataset from Australia. Some of these decisions are specific to Australia, such as the impact of European settlement, but most are inherent assumptions associated with performing quantitative palaeoclimate reconstructions from pollen using the Modern Analogue Technique.

Contribution of co-authors: A.V.H was responsible for data analysis, figure and table generation, with guidance from S.P.H.; A.V.H. and S.P.H jointly wrote the text.

Review of Palaeobotany and Palynology 226 (2016) 65–77

Contents lists available at ScienceDirect

Review of Palaeobotany and Palynology

journal homepage: www.elsevier.com/locate/revpalbo

Evaluation of a modern-analogue methodology for reconstructing Australian palaeoclimate from pollen

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A R T I C L E I N F O

Article history:
Received 11 October 2014
Received in revised form 9 December 2015
Accepted 12 December 2015
Available online 30 December 2015

Keywords:
Climate reconstructions
Modern analogue technique
Pollen surface samples
Bioclimatic variables
Human impact
Palaeoclimate benchmarking

A B S T R A C T

Quantitative palaeoclimate reconstructions are widely used to evaluate climate model performance. Here, as part of an effort to provide such a data set for Australia, we examine the impact of analytical decisions and sampling assumptions on modern-analogue reconstructions using a continent-wide pollen data set. There is a high degree of correlation between temperature variables in the modern climate of Australia, but there is sufficient orthogonality in the variations of precipitation, summer and winter temperature and plant–available moisture to allow independent reconstructions of these four variables to be made. The method of analogue selection does not affect the reconstructions, although bootstrap resampling provides a more reliable technique for obtaining robust measures of uncertainty. The number of analogues used affects the quality of the reconstructions: the most robust reconstructions are obtained using 5 analogues. The quality of reconstructions based on post-1850 CE pollen samples differ little from those using samples from between 1450 and 1849 CE, showing that European post-settlement modification of vegetation has no impact on the fidelity of the reconstructions although it substantially increases the availability of potential analogues. Reconstructions based on core top samples are more realistic than those using surface samples, but only using core top samples would substantially reduce the number of available analogues and therefore increases the uncertainty of the reconstructions. Spatial and/or temporal averaging of pollen assemblages prior to analysis negatively affects the subsequent reconstructions for some variables and increases the associated uncertainties. In addition, the quality of the reconstructions is affected by the degree of spatial smoothing of the original climate data, with the best reconstructions obtained using climate data from a 0.5° resolution grid, which corresponds to the typical size of the pollen catchment. This study provides a methodology that can be used to provide reliable palaeoclimate reconstructions for Australia, which will fill in a major gap in the data sets used to evaluate climate models.

1. Introduction

Quantitative palaeoclimate reconstructions are widely used to evaluate climate model performance because meteorological records only extend back for about 250 years and encompass a relatively modest range of climate variability (Braconnot et al., 2012; Harrison et al., 2013; Schmidt et al., 2014). The palaeo-record provides opportunities to examine model performance in intervals when the forcing and the climate response were large and comparable to the changes expected during the 21st century (Braconnot et al., 2012).

Pollen records are the most spatially extensive and widely accessible sources of data for quantitative reconstructions of past climates (Whitmore et al., 2005; Bartlein et al., 2011). Their usefulness reflects the fact that climate exerts a strong control on vegetation distribution (Harrison et al., 2010) and because the records can be dated using radiocarbon techniques (Prentice, 1988; Whitmore et al., 2005). There is a long history of reconstructing palaeoclimate from pollen using techniques such as inverse regression (Webb, 1980; Bartlein et al., 1984; Huntley and Prentice, 1988), transfer functions (Webb and Bryson, 1972), modern analogues (Howe and Webb, 1983; Overpeck et al., 1985; Jackson and Williams, 2004) and response surfaces (Bartlein et al., 1986; Gonzales et al., 2009). Large-scale reconstructions have been made for many regions, including North America (Gajewski et al., 2000; Williams et al., 2000; Viau and Gajewski, 2009), Europe (Cheddadi et al., 1997; Davis et al., 2003; Jost et al., 2005), Georgia (Connor and Kvavadze, 2008), Eurasia (Tarasov et al., 1999; Wu et al., 2007), Africa (Peyron et al., 2000; Peyron et al., 2006; Wu et al., 2007), China (Guiot et al., 2008) and New Zealand (Wilmshurst et al., 2007).

Many pollen-based reconstructions are based on some form of modern-analogue technique, in which modern relationships between pollen assemblages and climate variables are applied to palaeo-assemblages to infer past climate states. Similarity between assemblages is measured using the squared chord distance (SCD) (Overpeck

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http://dx.doi.org/10.1016/j.revpalbo.2015.12.006
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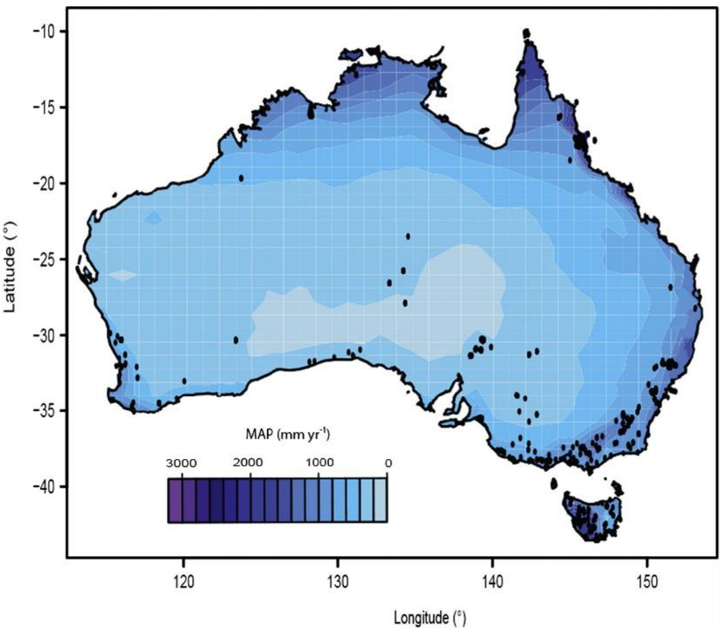

Fig. 1. Distribution of sites with pollen samples with ages < 500 yr. BP (1450 to 2014 CE), used in the analyses. The sites are plotted on a map showing mean annual precipitation (MAP), to emphasise the relative paucity of sites from the arid interior of the continent.

et al., 1985), with modern analogues that pass a defined threshold being used to infer the climate of the palaeo-assemblage. However, there are a number of other analytical decisions that also need to be made to make modern-analogue reconstructions (for a review, see e.g. Simpson, 2012). The first is the choice of technique for selecting the appropriate analogues through cross-validation: jackknife leave-one-out (Efron and Efron, 1982) or bootstrapping (Freedman, 1981). The jackknife leave-one-out technique takes one assemblage at a time and compares it to all the others to see which matches most closely. Bootstrapping compares an assemblage to a subset of randomly selected assemblages and repeats the comparisons a predetermined number of times. The second decision is the optimal number of analogues to minimise the

Table 1
Performance statistics for reconstructions performed using two different analogue selection techniques, jackknife leave-one-out (leave-one-out) and bootstrapping (bootstrap), where the number of analogues was selected automatically to produce the lowest possible root mean square error of prediction (RMSEP). The climate variables are mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual temperature (MAT, °C), growing degree days above a baseline of 5 °C (GDD5), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant–available moisture index (α). The reconstructions made using the two different selection techniques are not significantly different from one another (95% confidence limit) nor are they significantly different (95% confidence limit) from the appropriate observed values.

Variable	Mean		RMSEP			r^2		Analogues	
	Observed	Leave-one-out	Bootstrap	Leave-one-out	Bootstrap	Leave-one-out	Bootstrap	Leave-one-out	Bootstrap
MTCO	10.2	10.1	10.1	1.7	2.0	0.93	0.94	2	1
MTWA	21.3	21.3	21.3	1.4	1.7	0.94	0.94	2	1
MAT	15.9	15.8	15.8	1.5	1.8	0.94	0.94	2	1
GDD5	4002	3987	3980	532	642	0.94	0.94	2	1
MAP	1122	1120	1120	209	240	0.92	0.93	2	2
α	0.71	0.72	0.72	0.07	0.08	0.94	0.95	2	2

Table 2
Performance statistics for reconstructions performed using a different pre-selected number of analogues, using the bootstrapping technique of analogue selection. The climate variables are mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual temperature (MAT, °C), growing degree days above a baseline of 5 °C (GDD5), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant–available moisture index (α). Results where the reconstructions made using the different numbers of analogues are significantly different from one another (95% confidence limit) are shown in italics; results where the reconstructions differ significantly (95% confidence limit) from the appropriate observed values are shown in bold; results where the reconstructions made using either 5 or 10 analogues different from the results obtained by automatic selection of the number of analogues, as shown in Table 1, are marked with an asterisk (*).

Variable	Mean			RMSEP		r^2	
	Observed	10 analogues	5 analogues	10 analogues	5 analogues	10 analogues	5 analogues
MTCO	10.2	**9.9***	**10.1**	2.5	2.3	0.88	0.91
MTWA	21.3	21.1	21.3	2.1	1.9	0.88	0.91
MAT	15.9	**15.6***	15.8	2.3	2.0	0.88	0.91
GDD5	4002	**3916***	3978	791	706	0.88	0.92
MAP	1122	**1120**	1122	269	248	0.88	0.91
α	0.71	***0.72***	*0.72*	0.10	0.09	0.90	0.93

Table 3
Correlations between climate variables. The climate variables are mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual temperature (MAT, °C), growing degree days above a baseline of 5 °C (GDD5), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α).

	MTCO	MTWA	MAT	GDD5	MAP	α
MTCO		0.69	0.93	0.93	0.31	−0.10
MTWA	0.69		0.91	0.90	−0.30	−0.64
MAT	0.93	0.91		1.00	0.11	−0.37
GDD5	0.93	0.90	1.00		0.03	−0.37
MAP	0.31	−0.30	0.11	0.03		0.84
α	−0.10	−0.64	−0.37	−0.37	0.84	

chances of either falsely determining two samples to be analogues (type 1 errors) or considering two analogous samples not to be analogues (type 2 errors). The normal practise is to use between 5 and 10 analogues (Luo et al., 2010), with the exact number determined using the lowest root-mean-square error of prediction (RMSEP).

The nature of the pollen samples themselves can also affect the reconstructions. Samples from cores taken in moderately sized lakes or peatbogs should provide a good record of the regional pollen rain (Prentice, 1985, 1988) and thus of regional vegetation and climate. However, practical considerations mean that it is not always possible to sample such sites, and thus surface samples from other sites within a basin or from other environments are frequently used either as a check on the representativeness of core samples or to extend the range of climate space sampled. However, both the representation and the preservation of pollen vary with the type of surface sample. Samples from wet sediments are less subject to preservation issues, for example, than surface soils (Wilmshurst and McGlone, 2005). Samples from closed-canopy vegetation are more likely to reflect the very local vegetation than samples from open vegetation (Tauber, 1967). Although several studies have highlighted the sampling differences between common surface sample types (e.g. Cundill, 1991; Vermoere et al., 2000), there has been limited research on the implications of sample selection on quantitative climatic reconstructions. One noticeable exception is the study by Goring et al. (2010) which examines the impact of using samples from different depositional environments in western North America on climate reconstructions obtained using several statistical techniques. They showed that the impact of sample type varied depending on the statistical technique used but could have a non-negligible influence on the reconstructions. Goring et al. (2010) point out that the impact may vary between different regions and floras; no such study has been conducted in Australia. Thus, our underlying question is how different can two pollen assemblages be before it makes a difference to the reconstruction of Australian climate?

This question also underlies decisions about temporal averaging. It is common practise in presenting palaeoclimate reconstructions to average or pool results within a selected time window, usually a 1000-year window for the Holocene and sometimes up to 2000 years during glacial periods (e.g. Gajewski et al., 2000; Bartlein et al., 2011). These fairly large time windows are designed to minimise dating and calibration uncertainties. They also ensure that, despite the tendency for the number of samples to decrease with time because of sediment compression, there are sufficient samples available across sites to reconstruct geographic patterns. Temporal averaging can either be performed on individual sample reconstructions or on a single composite sample created by averaging or pooling the counts of the individual pollen samples, but there has been no systematic evaluation of which technique is more appropriate.

A final consideration is the impact of the spatial resolution of the modern climate used. Analogue climate can be obtained by interpolation between meteorological stations or from a gridded climatology. The most widely available data sets are gridded at a resolution of 0.5° resolution (e.g. CRUTS3.1: Harris et al., 2014; HadCRUT4: Morice et al., 2012; GHCN: Peterson and Vose, 1997), but finer resolution data sets are now available for some regions (e.g. CRU CL2: New et al., 2002). Although the failure of interpolated or gridded climates to capture analogues for a specific site or sample has been raised in the literature (see e.g. discussion in Bartlein et al., 2011), the impact of changing the size of the climatic grid of the baseline climate data on analogue reconstructions has not been systematically evaluated.

There have been relatively few attempts to make quantitative climate reconstructions for Australia. The only continent-wide reconstruction to date is part of the PAGES 2k synthesis (Neukom et al., 2013; Neukom et al., 2014) and the Australian component of this synthesis is based on coral, tree ring and documentary records rather than pollen, and only spans the last millennium. However, there have been pollen compilations at a sub-continental (D'Costa and Kershaw, 1997; Cook and van der Kaars, 2006) and continental scale (Pickett et al., 2004). D'Costa and Kershaw (1997) document the climate ranges of key taxa using the South-East Australian Pollen Database (SEAPD) but do not make quantitative reconstructions. The goal of Pickett et al. (2004) was to reconstruct palaeovegetation patterns, although they do make qualitative inferences about past climates based on these patterns. Cook and van der Kaars (2006) used the SEAPD and a compilation of northern Australian pollen samples to test whether a transfer-function approach could be used to make quantitative climate reconstructions. Van der Kaars et al. (2006) subsequently applied this methodology to a single marine core from northwestern Australia and made reconstructions of several climate variables going back 100,000 years.

One of the difficulties in reconstructing palaeoclimate from pollen in Australia is the arid nature of much of the continent, which leads to serious preservation issues. Palaeo-sites are confined to limited areas and thus sample a limited range of climate space. This has led to extensive sampling of less typical environments, such as estuaries (Moss et al., 2005), river sediments (Van der Kaars et al., 2006) and artesian spring outflows (Boyd, 1990), to extend the sampled climate space. Another concern is the degree to which the introduction of exotic taxa, such as *Pinus* and *Plantago lanceolata*, during European settlement of Australia in the mid-19th century affects the reliability of modern samples as analogues. Several studies have found European settlement had significant impacts on the Australian environment, through introduction of new

Table 4
Performance statistics for reconstructions performed using samples dated to between 1450 and 1849 CE (i.e. 500 to 101 yr. B.P; pre-1850) and samples between 1850 and 2014 CE (i.e. 100 yr. BP to present; post-1850). The climate space sampled by the pre-1850 and post-1850 samples is slightly different, and so the observed mean values for each period are given for comparison. The climate variables are mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α). Results where the reconstructions made using the two different data sets are significantly different from one another (95% confidence limit) are shown in italics; none of the results are significantly different from observed values.

Variable	Mean				RMSEP		r^2	
	Pre-1850		Post-1850		Pre-1850	Post-1850	Pre-1850	Post-1850
	Observed	Reconstructed	Observed	Reconstructed				
MTCO	9.2	*8.7*	10.1	*10.3*	2.5	2.6	0.91	0.91
MTWA	20.9	*20.8*	21.6	*22.0*	1.9	1.9	0.90	0.91
MAP	1091	1092	1076	1061	191	185	0.95	0.94
α	0.76	*0.77*	0.72	*0.71*	0.09	0.08	0.93	0.95

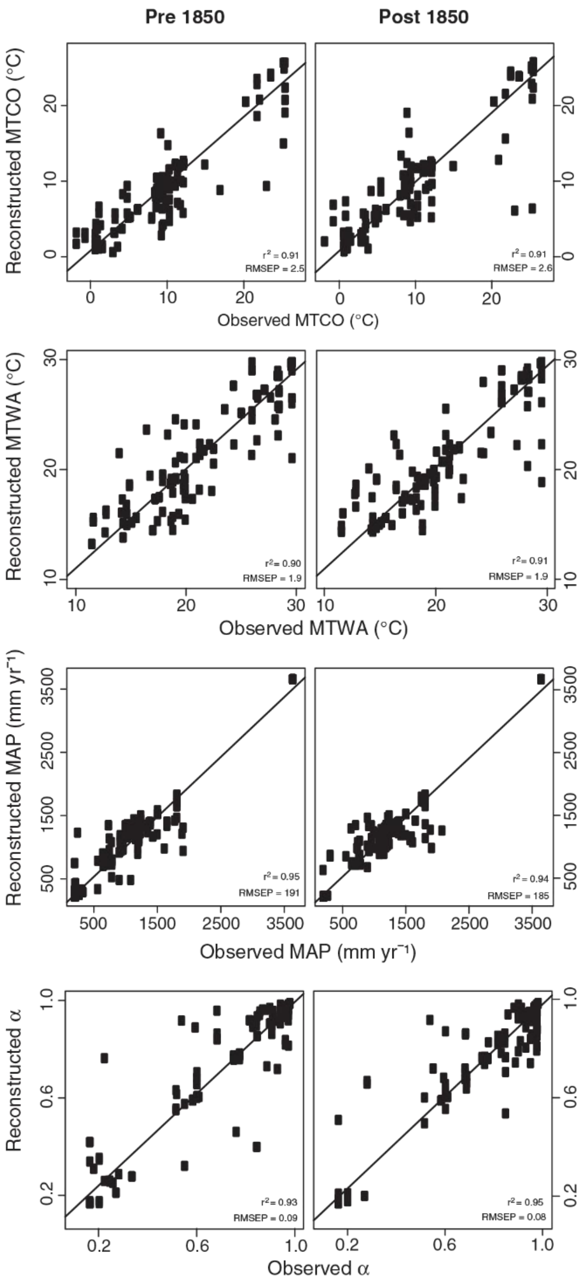

Fig. 2. Reconstructed versus observed values for mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α) for samples with ages dated to between 1450 and 1849 CE (i.e. 500 to 101 yr. B.P; pre-1850) and samples between 1850 and 2014 CE (i.e. 100 yr. BP to present; post-1850). The line represents the r^2 value shown. The associated RMSEP values are also shown.

species (exotic pollen), fire (charcoal) and erosion (magnetic susceptibility) (e.g. Gell et al., 1993; Mooney and Dodson, 2001; Dodson and Mooney, 2002; Fletcher and Thomas, 2010). Kershaw et al. (1994)

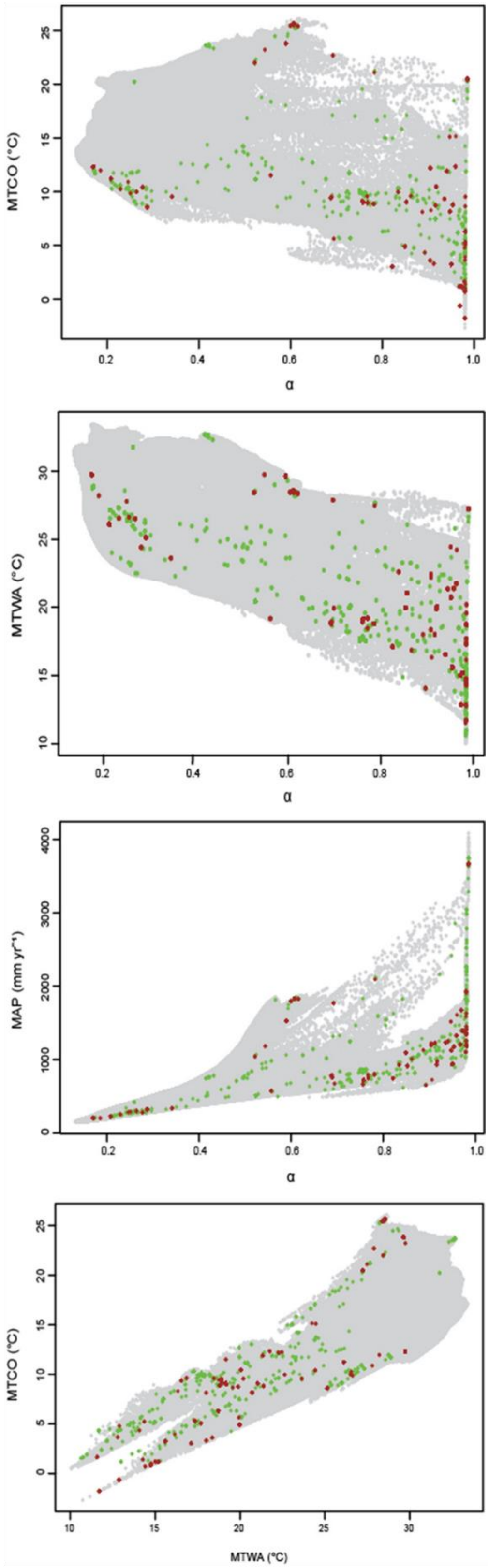

Fig. 3. The location of core top (brown points) and surface (green points) samples in climatic space, overlain on the total Australian climate space (grey dots), represented by (a) mean temperature of the coldest month (MTCO, °C) versus the Cramer–Prentice plant-available moisture index (α), (b) mean temperature of the warmest month (MTWA, °C) versus α, (c) MTCO versus MTWA and (d) mean annual precipitation (MAP) versus α.

Table 5
Performance statistics for reconstructions performed using samples only from cores (core top) and only from surface samples (surface) dated to post-1850 CE. The climate space sampled by core top and surface samples is slightly different and so the observed mean values for each period are given for comparison. The climate variables are mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α). Results where the reconstructions made using the two different data sets are significantly different from one another (95% confidence limit) are shown in italics; results where the reconstructions are significantly different (95% confidence limit) from the appropriate observations in bold.

Variable	Mean				RMSEP		r^2	
	Core top		Surface		Core top	Surface	Core top	Surface
	Observed	Reconstructed	Observed	Reconstructed				
MTCO	9.6	*9.6*	10.8	***10.6***	1.8	2.7	0.95	0.87
MTWA	21.3	*21.3*	21.2	*21.1*	1.5	2.1	0.95	0.89
MAP	1084	*1087*	1182	***1164***	133	316	0.97	0.86
α	0.74	*0.74*	0.71	*0.71*	0.06	0.10	0.97	0.90

thought the impact of European settlement on pollen assemblages sufficient to warrant only using averaged pre-European samples from the SEAPD as the modern samples for reconstructions, although they never tested the impact of using post-European samples. However, modern samples are used routinely and successfully for quantitative palaeoclimate reconstructions in other parts of the world, despite the presence of introduced species. So the question remains as to whether European settlement had sufficient impact to affect the ability of modern Australian pollen samples to provide reliable reconstructions of present-day climate and hence to provide suitable analogues for palaeo-reconstructions.

The purpose of this study is to test the impact of methodological decisions on the reliability of climate reconstructions for Australia using modern pollen samples in order to design an approach that can be applied to reconstruct past climates from pollen. Specifically, the study tests the methodological decisions, the basic assumptions and the impact of temporal and spatial averaging.

2. Methods

We used the pollen data set developed by Pickett et al. (2004), which was subsequently updated by the QUAVIDA working group (quest.bris.ac.uk/research/wkg-gps/QUAVIDA.html). Additional pollen samples, obtained directly from palynologists working in Australia, have been added to extend the range of sampled climate. The final data set (Fig. 1) comprises 1444 samples in the 0–500 yr. BP time window from 325 sites (for the full list of sites with coordinates and data sources, see supplementary information).

Climate data were obtained from the ANUCLIM software package (Xu and Hutchinson, 2011), which uses the ANUSPLIN thin-plate spline fitting package (Hutchinson, 2004) to interpolate meteorological data from the period 1970–1999 to a 0.05° grid cell resolution climatology. This is the climatology used by van der Kaars et al. (2006). These data were used to calculate a number of climatic and bioclimatic variables, including mean temperature of the coldest and warmest months (MTCO and MTWA, respectively), mean annual temperature (MAT), mean annual precipitation (MAP), growing degree days above 5 °C (GDD5) and the Cramer–Prentice plant-available moisture index (α, Cramer and Prentice, 1988). The bioclimatic variables, GDD5 and α, are considered to be more closely related to the controls on vegetation growth than standard meteorological variables (Harrison et al., 2010). GDD5 is calculated by linearly interpolating the monthly mean temperature to daily temperature then summing this for days where the mean temperature exceeds 5 °C. α is the ratio of actual to equilibrium evapotranspiration (Cramer and Prentice, 1988) and was calculated from monthly temperature, precipitation and percentage of sunshine hours using a simple soil water-balance model (Wang et al., 2013) with soil field water-holding capacity based on a single soil type for the continent. We choose these six variables because they are the variables included in the Bartlein et al. (2011) global benchmarking data set. However, as shown in Bartlein et al. (2011), it is not possible to reconstruct every variable at every site because of differential vegetation sensitivity to climate, e.g. tropical vegetation is unlikely to be sensitive to seasonal temperature and arid vegetation is more likely to be sensitive to drought. Thus, part of the purpose of this study is to test which variables can be reconstructed robustly from the Australian flora.

Taxa likely to represent local conditions (i.e. aquatic taxa, mangroves, parasitic plants, mosses, agricultural crops, obligate halophytes and ferns) were removed from the pollen data set, prior to analysis. Some taxa could be classified as belonging to one of these groups but also occur in other plant functional types (e.g. Chenopodiaceae can be halophytes but are also represented as succulents, forbs and shrubs), and these taxa have been retained in the data set because they represent non-excluded types. The sample counts were standardised to percentages, based on the sum of all remaining taxa. Reconstructions were performed using the Rioja package in R (Juggins, 2012), only using analogues with SCD-values lower than 0.9, the 2.5th percentile of the distribution of SCD values for this data set. In addition, no analogues were selected with SCD-values lower than 0.001, to reduce the risk of analogues being selected from the same site or the same core.

We ran number of separate tests to answer the following questions:

1. Does the choice of analogue selection method affect the reconstruction? Separate reconstructions were performed using jackknife

Table 6
Performance statistics for reconstructions performed using individual surface samples (individual) and after averaging or pooling all the surface samples (average and pooled) from a site dated to post-1850 CE. The mean climate of the two data sets is slightly different because of differences in the size of the populations, and so the observed mean values for each period are given for comparison. The climate variables are mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α). Results where the reconstructions made with the averaged samples differ from the individual samples, or where the pooled samples differ from the individual samples are shown in italics; results where the reconstructions are significantly different (95% confidence limit) from the appropriate observations in bold.

Variable	Mean						RMSEP			r^2		
	Individual		Averaged		Pooled		Individual	Averaged	Pooled	Individual	Averaged	Pooled
	Observed	Reconstructed	Observed	Reconstructed	Observed	Reconstructed						
MTCO	11.2	10.9	11.3	***10.5***	11.3	**10.6**	2.5	4.6	4.6	0.90	0.70	0.70
MTWA	21.5	21.3	21.7	21.4	21.7	21.4	1.8	3.7	3.7	0.93	0.70	0.71
MAP	1181	1195	1210	**1229**	1210	**1233**	243	486	483	0.93	0.67	0.68
α	0.69	0.70	0.70	0.68	0.70	0.68	0.08	0.18	0.18	0.94	0.67	0.67

leave-one-out and bootstrapping selection approaches. The number of selected analogues was chosen automatically to yield the lowest RMSEP.
2. Does the number of analogues selected affect the reconstruction? Separate reconstructions were made using 10 and 5 analogues. These reconstructions are also compared to the automatically selected number of analogues.
3. Are all climate variables equally well reconstructed using the Australian data set? In addition to evaluating the quality of the reconstructions performed in Step 1 and 2, we examined the cross-correlation between climate variables.
4. Do modern samples adequately reconstruct modern climate even though they may include exotic pollen? Separate reconstructions were performed based on samples dated to between 1450 and 1849 CE (500 to 101 yr. BP) and samples between 1850 and 2014 CE (i.e. 100 yr. BP to present). The date of 1850 CE is used by Mooney and Dodson (2001) as broadly corresponding to the time of European settlement and introduction of exotic pine in southeastern Australia.
5. Do surface samples adequately represent regional climate? Separate reconstructions were performed based on core top samples and surface samples. In addition, the proportion of climate space only represented by one of these groups was calculated by dividing the individual observations into sections of climate space and counting each section which is only represented by one of the two groups. In a separate test, we also examined whether averaging or pooling surface samples by site provided more robust reconstructions than the individual surface samples. Sites with only one surface sample were not used in this second test.
6. Does averaging or pooling samples within a specific time window produce similar reconstructions to those produced using individual samples? We separately averaged and pooled the pollen counts for all samples dated to post-1850 CE from each core and used these new assemblages for making the reconstructions. In addition to comparing the reconstructed climate values obtained by averaging versus pooling, we also compared these results to the reconstructions based on individual samples from each core.
7. Does the resolution of the gridded modern climate data affect the climate reconstructions? The original 0.05° gridded climate data was averaged to produce a climate data set at 0.5° resolution, which was then used to make reconstructions. We compared the results obtained using the two climatologies.

The performance of each reconstruction was measured by the RMSEP. The r^2 is used as a measure of the goodness-of-fit of the reconstructed and observed values. The best-fit regression line is not necessarily the same as the 1:1 regression line indicative of perfect prediction. We tested the distribution of the reconstructions for each variable separately using a Kolmogorov–Smirnov test, using the 95% confidence interval to determine significance. The selection of subsamples of the data (e.g. core tops versus surface samples) and averaging or pooling of samples (e.g. within time windows) means that the mean and range of observed climate used for evaluation can differ. Variations in the size of the populations were taken into account when determining the statistical significance of the tests. Different populations could sample different areas of climate space and this affects the mean and range of the target climates. Reconstructions are compared with the appropriate climate for each population, rather than attempting to sample a common area of climate space. As a final assessment, we compare the site-based reconstructions, where each site may be represented by multiple samples (in which case the median discrepancy is used), with the observed climate by overlaying the samples on our 0.5° gridded data set, using fixed intervals of each variable, based on their respective RMSEP, to indicate degree of discrepancy. No attempt has been made to standardise the discrepancies relative to the observations; thus, this comparison is particularly stringent for regions of high observed values of a given climate variable.

3. Results

3.1. Individual tests

3.1.1. Analogue selection approach

The climate reconstructions obtained using the jackknife leave-one-out and bootstrap approaches are statistically indistinguishable (Table 1). The RMSEP values are marginally better for the leave-one-out approach and the r^2 values are marginally better for the bootstrapping

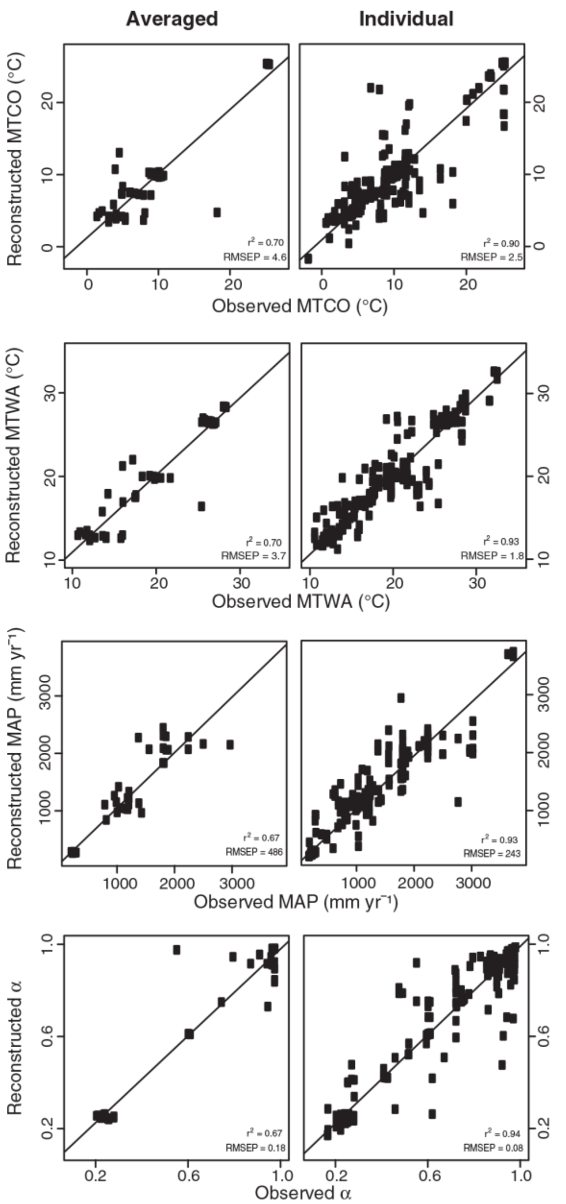

Fig. 4. Reconstructed versus observed values for mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α) for averaged and individual surface samples at a site. The line represents the r^2 value shown. The associated RMSEP values are also shown.

approach. Bootstrapping provides a more robust estimation of the variance of the distribution than the jackknife leave-one-out approach (Shao and Tu, 1995, pp. 86–90) and could also be used to estimate e.g. median values, and so it is used for all subsequent analyses.

3.1.2. Using varying numbers of analogues

The difference between reconstructions made using 5 or 10 analogues is not statistically significant, although the RMSEP values are slightly lower and the r^2 values slightly higher when only 5 analogues are used (Table 2). The reconstructions obtained using 5 analogues do not differ significantly from the automatically selected number of analogues (1 or 2) that gives the lowest RMSEP (Table 1), although the reconstructions of MTCO, MAT, α and GDD5 based on 10 analogues are significantly different from those obtained by automatic selection. Furthermore, the reconstructions based on 10 analogues are significantly different from the observed values whereas those based on 5 analogues (and the automatic selection) are not significantly different from observed. Increasing the number of analogues does not improve the reconstructions and we therefore use 5 analogues for all further analyses.

3.1.3. Choice of climate variables

The results of the first two tests suggest that all six of the climate variables can be reconstructed equally well: the bootstrap r^2 values are similar and the RMSEP values are of a similar magnitude. Nevertheless, some of these variables are highly correlated in the modern climate of Australia (Table 3). There is a particularly high degree of correlation amongst the temperature variables, for example, both MTCO and MTWA are strongly correlated with MAT ($r^2 \approx 0.90$) although less strongly correlated to one another ($r^2 = 0.69$). GDD5 is also strongly correlated with MAT ($r^2 = 1.00$). The degree of correlation is such as to rule out being able to distinguish the independent effects of these temperature variables on vegetation distribution. The performance statistics for MTWA are generally better than for the other temperature variables (Tables 1 and 2). Given that the correlation between MTCO and MTWA is the least strong, and that it is highly desirable to be able to reconstruct changes in temperature seasonality because this is a major feature of both Holocene and glacial climates (Izumi et al., 2013; Izumi et al., 2014), we have preserved these two variables but make no further attempt to reconstruct MAT or GDD5. The moisture variables are not well correlated with temperature: the correlation between MAP and MTWA is -0.3, and between MAP and MTCO is 0.3. There is also a negative correlation between α and seasonal temperature, which is moderately strong for MTWA (-0.6) but weak for MTCO (-0.1). Thus, there is probably sufficient independent information to be able to reconstruct moisture as well as seasonal temperature variables. MAP and α reflect different aspects of the moisture balance, i.e. input versus plant–water availability. The amount of plant–available water (α) is influenced by factors affecting evapotranspiration, including temperature and wind speed. MAP and α are quite highly correlated (0.84), but it should still be possible to reconstruct them independently. As a further test, we carried out a redundancy analysis (RDA; see Juggins and Birks, 2012) using all six variables to determine whether they have independent power to explain the variation in the pollen assemblages. MAP, α, MTWA and MTCO are all significant (99% level), confirming that there is sufficient information in the assemblages to reconstruct them independently, whereas MAT and GDD5 are not significant and therefore lack explanatory power.

3.1.4. Impact of European settlement

The reconstructions using pre-1850 CE and post-1850 CE samples are statistically different from one another (Table 4) for all variables except MAP. However, neither are significantly different from the appropriate observed climate, and the pre-1850 CE and post-1850 samples have comparable RMSEP and r^2 values (Fig. 2). Only 22% of the sites have pre-1850 CE samples compared to the 95% of the sites that have post-1850 CE samples. This suggests that reliable reconstructions can be obtained by using only the recent samples for analogues. In subsequent tests we only use the post-1850 CE samples.

3.1.5. Use of core tops or surface samples

The reconstructions of all the climate variables made using only core samples and only surface samples are significantly different from one another. This reflects the fact that the core tops sample a more limited amount of climate space (Fig. 3). In fact, about half of the bioclimatic space is only covered by surface samples (42–65%, depending on variable), with 0–6% being unique to core top samples. The core top reconstructions have lower RMSEP values and higher r^2 values (Table 5), reflecting the fact that several of the surface samples have very large errors and overall the reconstruction based on surface samples alone is much noisier. However, only MTCO and MAP from the surface sample reconstructions differ significantly from the observed climate (Table 5). Despite this, and given that the surface samples extend the range of sampled climate, it appears that combining surface sample and core top samples is appropriate in order to provide robust reconstructions.

3.1.6. Spatial averaging and pooling of surface samples

Surface samples are usually chosen to sample the variety of different vegetation types within a catchment. Combining multiple surface samples could potentially provide a more complete sampling of the vegetation and thus provide a better approximation of the regional pollen rain, and hence a better match to the regional climate signal.

Reconstructions made after amalgamating the surface samples from a site, whether by averaging the individual samples or by pooling them, are only significantly different from those based on the individual surface samples for MTCO (Table 6). However, the averaged and pooled samples have much higher RMSEP values and much lower r^2 values. The greater variance in the averaged or pooled samples (Fig. 4) probably reflects the reduction in the number of potential analogues. Thus, this test shows that it is better to use the individual surface samples as analogues and this is the procedure used in the final tests.

Table 7

Performance statistics for reconstructions performed using all core and surface samples from a site (individual) and after averaging or pooling all samples (average and pooled) dated to post-1850 CE. The mean climate of the two data sets is slightly different because of differences in the size of the populations and so the observed mean values for each period are given for comparison. The climate variables are mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant–available moisture index (α). Results where the reconstructions made with the averaged samples differ from the individual samples, or where the pooled samples differ from the individual samples are shown in italics; results where the reconstructions are significantly different (95% confidence limit) from the appropriate observations in bold.

Variable	Mean						RMSEP			r^2		
	Individual		Averaged		Pooled		Individual	Averaged	Pooled	Individual	Averaged	Pooled
	Observed	Reconstructed	Observed	Reconstructed	Observed	Reconstructed						
MTCO	10.7	*10.7*	10.3	***9.5***	10.3	**9.2**	2.2	5.0	5.0	0.93	0.57	0.58
MTWA	21.7	21.7	21.3	21.7	21.3	21.5	1.7	3.8	3.8	0.94	0.65	0.66
MAP	1112	1125	1149	1001	1149	1003	209	463	464	0.94	0.69	0.69
α	0.69	0.69	0.71	0.65	0.71	0.65	0.08	0.19	0.18	0.95	0.65	0.66

3.1.7. Temporal averaging and pooling of core samples

There are multiple samples within the post-1850 time window from some of the cores in the data set. This raises the issue of whether all of these samples should be treated as potential modern analogues, or whether it is better to average or pool the samples to derive a single analogue assemblage. Although the mean values of the reconstructions are not statistically different (apart from MTCO again; Table 7), the RMSEP values are very much higher and the r^2 values lower for the reconstructions based on averaged samples (Fig. 5). The same is true for the pooled samples (Table 7). As in the case of spatial averaging, this most likely reflects the reduction in the number of potential analogues. This test shows that it is better to use the individual core samples as analogues and this is the procedure used in the final tests.

3.1.8. Impact of the resolution of the climate data set

There is a significant difference between the reconstructions of all climatic variables based on analogue climates drawn from a 0.05° or a 0.5° grid (Table 8, Fig. 6). The MTCO reconstructions are significantly different from observed climate values at both resolutions, while α is also significantly different from observed for reconstructions using the 0.5° resolution grid. However, the RMSEP values for all climate variables are lower for the coarser grid. This presumably reflects the fact that the 0.5° resolution grid is closer to the size of the pollen source area (see e.g. Prentice, 1985) for most sites in the data set and suggests that it is better to use the coarser grid to derive analogues for the reconstructions. To test this, separate reconstructions were made for sites with small (<10 km^2), medium (10.1–500 km^2) and large (>500 km^2) catchments. There is a significant difference between these reconstructions for all climate variables, but none of them are significantly different from the appropriate observations (Table 9). The reconstructions based on medium-sized catchments have the lowest RMSEP values (and highest r^2) for all variables except α. Most of the medium-sized catchments occur at the saturated end of the α range and this probably contributes to the poorer performance for this variable. Reconstructions based on sites with large catchments are significantly worse than the other two sets of reconstructions, possibly because only 2% of the sampled sites are in this size range and the range of climate sampled is limited. Many of the larger basins occur in the central part of the continent, where there would otherwise be very limited sampling. Excluding reconstructions from such sites because of the large associated uncertainties would lead to a loss of information for a critical region.

3.2. Reliability of the reconstructions

There are 11 sites in our data set for which there are no analogues (i.e. no samples with an SCD value <0.9) elsewhere in the data set. For the remaining sites, there is moderately good agreement between the reconstructed and observed MTCO for individual samples from different sites (Fig. 7a). Most of the sites (61%) show agreement within 1 °C of the observed MTCO, with 78% agreeing within 2 °C. Discrepancies >2 °C occur in Queensland, and there is a single site in the far north (Groote Eylandt, 2 samples) and one in the northwest of the country (Dragon Tree Soak, 5 samples) that also show discrepancies >2 °C. There are also several sites in coastal situations in Western Australia, South Australia and the southeastern part of the country with samples that show large discrepancies. These coastal sites, and about half of the northern sites, also show large discrepancies (i.e. >2 °C) in MTWA (Fig. 7b). There are extremely steep temperature gradients inland from the coast around much of southern Australia (Sturman and Tapper, 2005, pp. 541; Jones et al., 2009), and the temperature discrepancies at coastal sites probably reflect the fact that the gridded climate data set does not capture such gradients. The discrepancies in northern Australia are more likely to reflect the comparative lack of surface samples from the tropical regions in our data set.

The worst agreement between the reconstructed and observed figures is for MAP (Fig. 7c). Only just over half of the sites (52%) show agreement to within 100 mm of the observed MAP, with 24% of sites showing disagreement >250 mm, though most of these are in areas of fairly high rainfall, such as Queensland or the southeast. Thus, these discrepancies are small compared to the actual amount of rainfall received at these sites. The reconstructions of α are moderately good, with most samples (81%) showing agreement of <0.1 (Fig. 7d). Very few sites (3%) show discrepancies of >0.3, and these are mostly sites in southwestern Australia where the temperature variables also show moderately large discrepancies. The only exceptions to this pattern are two sites in inland

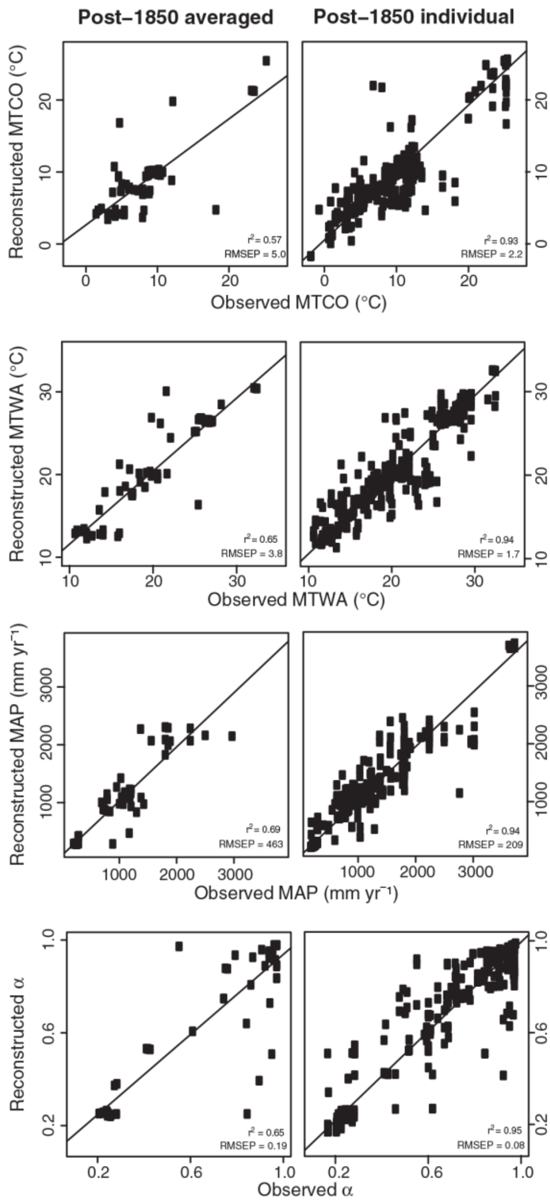

Fig. 5. Reconstructed versus observed values for mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α) performed using all samples dated to post-1850 CE from a single core and after averaging these samples. The line represents the r^2 value shown. The associated r^2 values are also shown.

Table 8
Performance statistics for reconstructions performed using modern climate values obtained from gridded climatologies of different resolution. The original climatology was on a grid of 0.05° resolution (0.05°) and second climatology was aggregated to 0.5° resolution (0.5°). The climate variables are mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α). Results where the reconstructions made using the two different data sets are significantly different from one another (95% confidence limit) are shown in italics; results which are significantly different (95% confidence limit) from the appropriate observed values are shown in bold.

Variable	Mean				RMSEP		r^2	
	0.05°		0.5°		0.05°	0.5°	0.05°	0.5°
	Observed	Reconstructed	Observed	Reconstructed				
MTCO	10.6	***10.4***	10.9	***10.7***	2.6	2.3	0.88	0.89
MTWA	21.4	*21.4*	21.9	*21.9*	2.1	1.8	0.89	0.90
MAP	1130	*1118*	1043	*1032*	280	233	0.89	0.90
α	0.70	*0.70*	0.69	***0.68***	0.10	0.09	0.91	0.91

NSW which show discrepancies of >0.2 in an area where the observed α is already low (<0.4) and also along the arid coastal area of southern Australia area where α is <0.3 (Fig. 7d). The discrepancies in these two regions are not driven by discrepancies in temperature, but likely reflect the fact that there are very few available analogues for such dry sites.

It is possible that part of the reason for poor performance reflects issues of the taxonomic resolution of some samples, particularly those from arid regions. Indeed, the use of samples dominated (>75%) by a single taxon has a significant and negative impact on the quality of the reconstructions, displaying some of the worst test statistics from any of our tests (Supplementary Table 1). However, the reconstructions still do not diverge significantly from the observed values, which highlights how robust our overall reconstructions are.

Much of Australia is characterised by large interannual variability in climate, chiefly associated with the El Niño-Southern Oscillation (ENSO) (Diaz and Markgraf, 1992). Rainfall variability leads to changes in the relative abundance of annual species between years. Given that most of the pollen samples used in this analysis integrate the pollen rain over years-to-decades, it is possible that the pollen assemblages reflect climate extremes rather than the long-term mean climate and that this might contribute to the rather large reconstruction biases particularly in MAP. However, there does not appear to be any geographic patterning in the reconstruction biases (Fig. 7) that could be linked to differences in climate variability. In general, the largest biases are for sites in regions with relatively few modern analogues. Thus, it seems likely that the uneven distribution of modern analogues is the primary explanation for the occurrence of larger reconstruction uncertainties.

4. Discussion and conclusions

Our analyses provide a methodology for the application of MAT to make palaeoclimate reconstructions for Australia. We have shown that the method of analogue selection does not significantly affect the reconstructions but the number of selected analogues does. Previous studies (e.g. Birks et al., 1990; Telford et al., 2004) have also suggested that such methodological decisions could be important.

We examined the same set of variables used in the global benchmark data set by Bartlein et al. (2011). All six of these variables (MAT, MTCO, MTWA, GDD5, MAP and α) could be reconstructed using our data set, with reasonable reliability. However, the four temperature variables (MAT, MTCO, MTWA and GDD5) are very highly correlated in the modern climate, and thus unlikely to provide independent palaeoclimate reconstructions. MTWA and MTCO were the least well correlated and produced reconstructions with good performance statistics, and thus we suggest it should be possible to provide a measure of seasonal temperature change. This is highly desirable given that changes in seasonality are a major signal in both interglacial and glacial climates (Izumi et al., 2013; Izumi et al., 2014). The moisture variables, MAP and α, show only moderate correlation with MTWA and MTCO, and thus it should also be possible to make palaeoclimate reconstructions of these aspects of the moisture balance. Again, this is highly desirable in the context of Australia because many of the largest changes in past climate have been attributed to changes in the hydrological cycle (Harrison, 1993; Harrison and Dodson, 1993, pp. 265–293; Shulmeister and Lees, 1995; Wyrwoll and Miller, 2001; Kershaw et al., 2003; Hesse et al., 2004; Pickett et al., 2004; Martin, 2006; Nanson et al., 2008; Kershaw and van der Kaars, 2012). RDA confirms that MAT and GDD5 have little explanatory power, whereas there is sufficient information in the pollen assemblages to make independent reconstructions of MAP, α, MTWA and MTCO. However, our choice of variables differs somewhat from that identified as optimal by Bartlein et al. (2011): they recommended the use of GDD5 and MTCO (rather than MTWA and MTCO) for temperature and suggested that MAP was likely to provide more robust reconstructions than α. This may reflect the preponderance of northern hemisphere extratropical sites in the data they analysed, where length of the growing season (as measured by GDD5) is likely to be more important as a control on vegetation distribution than heat stress (as measured by MTWA). In tropical and subtropical climates, heat stress may be more important (see e.g. Harrison et al., 2010). The robustness and coherency of the α reconstructions for Australia suggests that this is as valuable as MAP as a measure of the hydrological regime, and again the fact that Bartlein et al. (2011) found it to be less reliable may reflect the preponderance of samples from humid climates in their data set.

There has been considerable concern about the impact of European colonisation on Australian vegetation and whether it is possible to use modern pollen samples as analogues for palaeo-reconstructions (see e.g. D'Costa and Kershaw, 1997). While European settlement considerably altered Australian vegetation patterns (Carnahan, 1997), and indeed the presence of exotic pollen is widely used in Australia as a temporal marker in pollen diagrams (e.g. Williams et al., 2006; Black, 2006), we have shown that post-European pollen samples provide good reconstructions of the modern climate. As is true in other regions, the presence of some exotic pollen has little effect on the ability to reconstruct regional climate—in part because exotic species are also limited by climate factors and in part because they comprise a relatively small component of the regional pollen rain. Our results suggest that, other than in exceptional circumstances, human impact on the landscape of Australia has not substantially altered the regional vegetation patterns. Indeed, this is consistent with the results of Pickett et al. (2004) who were able to reconstruct local vegetation from pollen at >60% of the sites from mainland Australia. The ability to use modern (i.e. post-1850 CE) samples as palaeoclimate analogues is important because it increases the number of potential analogues in our data set by about 50%.

The interpretation of palynological data is often limited by taxonomic resolution. Although this problem is not unique to Australia, the Australian flora is characterised by a large number of genera of high diversity and broad climatic ranges. The classic case is *Eucalyptus*, with more than 700 species occupying almost all extant climatic niches across the continent. Although attempts have been made to distinguish broad ecological groups of *Eucalyptus* from their pollen morphology

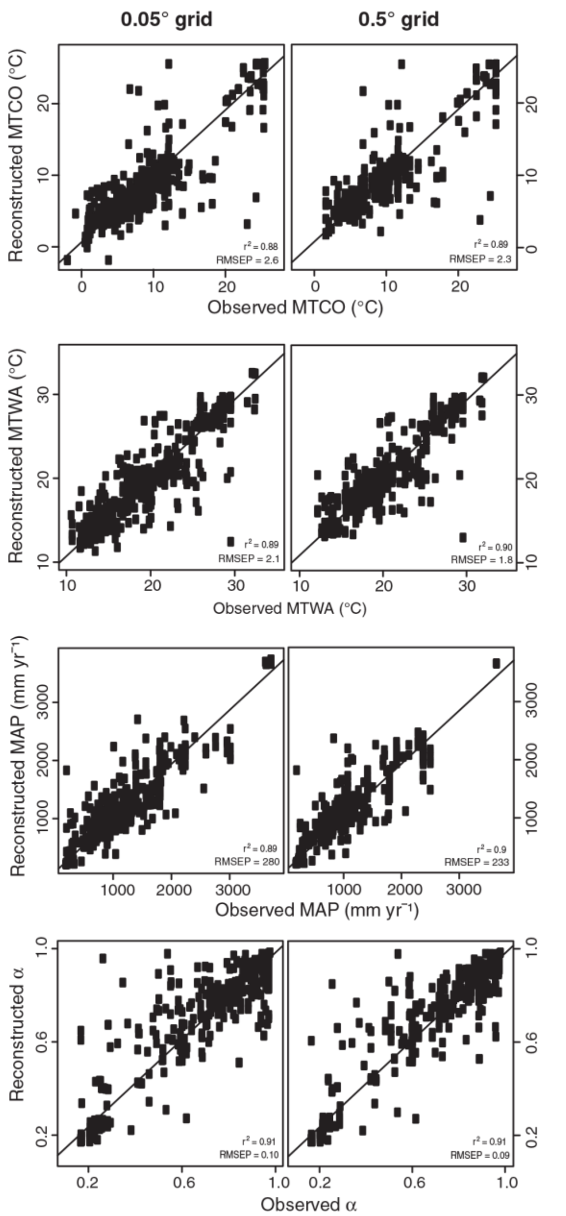

Fig. 6. Reconstructed versus observed values for mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α) based on climate data derived from a 0.05° gridded climatology and a 0.5° gridded climatology. The line represents the r^2 value shown. The associated r^2 values are also shown.

(see e.g. Pickett and Newsome, 1997), the lack of morphological variation generally precludes distinguishing individual species from one another. Other widespread genera which are generally not distinguished to species level in Australian pollen records include e.g. *Acacia* and *Casuarina* (Pickett et al., 2004). Our data set is not adequate to explicitly test the impact of taxonomic resolution on the climate reconstructions, but the quality of climate reconstructions is substantially downgraded in samples dominated (>75%) by a single taxon or characterised by only a very limited number of taxa. This suggests that, as Pickett et al. (2004) found in making vegetation reconstructions, the impact of poor taxonomic resolution may be overcome when the pollen assemblage includes a reasonably large number of individual taxa.

Averaging, both geographically and in time, does not significantly change the mean value of the reconstructions, but it does affect the variance. This suggests that it is better to make reconstructions using individual samples and then to average the results in order to obtain representative values for either specific time windows or regions. This is the approach generally used in providing regional reconstructions for model evaluation, which are usually averaged to the same spatial resolution as climate models (ca $2 \times 2°$ latitude, longitude) and across time windows of ca 1000 years (see e.g. Bartlein et al., 2011). This approach has a second advantage of providing an additional measure of reconstruction uncertainty in terms of temporal or within-grid cell variability.

Although there has been discussion in the literature of the impact the choice of climate data set used to obtain analogues has on reconstructions (e.g. Schäfer-Neth and Paul, 2003, pp. 531–548; Bartlein et al., 2011), there has been little consideration of the impact the resolution of these data sets has on the final reconstructions. However, it is frequently noted that modern reconstructions using gridded climate data sets in areas of high topographic diversity often show large errors (Viau et al., 2006; Thompson et al., 2008; Bartlein et al., 2011), presumably because the gridded averages of climate variables are not representative of the climate at individual pollen sites. Our analyses show that the reconstructed ranges of the climate variables are often more limited than the observed ranges, with most noticeable underestimates for the cold end of the temperature range. This is consistent with the idea that it is difficult to obtain estimates of extreme climate values using analogues selected from gridded data sets, although relatively few sites in the Australian data set occur in complex topography or are particularly high-elevation sites. Nevertheless, we have shown that better reconstructions are obtained using climate variables from a 0.5° resolution grid than from a finer resolution grid. One explanation for this could be related to the pollen-source area sampled by analogue sites. Some of our sampling sites are large and many of the sites occur in relatively open vegetation. Both characteristics mean that the pollen-source area is relatively large (Prentice, 1985; Sugita, 1994; Bunting et al., 2004; Sugita, 2007a, 2007b) and this would be consistent with our finding that the coarser resolution grid produces better reconstructions. This conclusion is also supported by the finding that sites from medium-sized catchments generally provide better reconstructions than sites from large- or small-sized catchments. Some recent studies have attempted to take account of pollen-source area in reconstructing palaeoclimate (e.g. Wang et al., 2014), and our study suggests that this issue needs to be explored further in the context of determining the appropriate resolution of the climate data used as a basis for reconstruction.

The study by Cook and van der Kaars (2006) provides the only other attempt to reconstruct modern Australian climates quantitatively from pollen data and uses transfer functions developed for three regions (northern Australia, Tasmania and mainland Southeast Australia) separately to reconstruct a suite of 11 seasonal and annual measures of moisture and temperature. Cook and van der Kaars (2006) show that it is neither possible to reconstruct all of these measures in each region nor to derive a unique set of variables that apply to all three regions. Our analyses show that this is not surprising given the high degree of correlation between different temperature variables, and the fact that the relationship between MAP and α is not completely independent implies that similarly high degrees of correlation will be found between seasonal moisture variables. Indeed, Cook and van der Kaars (2006) obtain very low significance values for the seasonal moisture reconstructions. Despite the fact that different plant species will show differential sensitivity to specific aspects of climate (Jackson and Williams, 2004; Harrison et al., 2010; Bartlein et al., 2011), there is a limit to the amount of real climate information that can be derived

Table 9
Performance statistics for reconstructions performed using samples from sites with different catchment sizes. The different sizes are small (<10 km^2), medium (10.1–500 km^2) and large (>500 km^2). The climate variables are mean temperature of the coldest month (MTCO, °C), mean temperature of the warmest month (MTWA, °C), mean annual precipitation (MAP, mm yr.$^{-1}$) and the Cramer–Prentice plant-available moisture index (α). Results where the reconstructions made using the two different data sets are significantly different from both of the others (95% confidence limit) are shown in italics; results which are significantly different (95% confidence limit) from the appropriate observed values are shown in bold.

Variable	Mean						RMSEP			r^2		
	Large catchment		Medium catchment		Small catchment		Large	Medium	Small	Large	Medium	Small
	Observed	Reconstructed	Observed	Reconstructed	Observed	Reconstructed						
MTCO	21.1	*21.8*	10.4	*10.2*	9.4	*9.2*	2.6	2.3	2.3	0.63	0.93	0.90
MTWA	29.5	*29.6*	20.6	*20.5*	20.1	*20.0*	1.5	1.5	1.7	0.78	0.93	0.91
MAP	1678	*1809*	1207	*1198*	1204	*1206*	474	154	227	0.89	0.95	0.93
α	0.63	*0.66*	0.82	*0.82*	0.76	*0.76*	0.13	0.07	0.07	0.78	0.85	0.94

from pollen assemblages, and thus it is important to test explicitly whether the reconstructed variables are reasonably independent and to select variables that are most likely to influence plant physiology, growth and distributions.

A strict comparison of our results with those obtained by Cook and van der Kaars (2006) is not possible because the climate variables selected in each study are different. Nevertheless, examination of comparable variables suggests that a better fit is obtained using regional specific calibrations than the continental calibration used in our study. For example, we obtained an RMSEP of 0.09 for α, which can be compared with values of 0.05 and 0.09 in the Cook and van der Kaars (2006) study. Similarly, we obtained an RMSEP of 1.8 for MTWA,

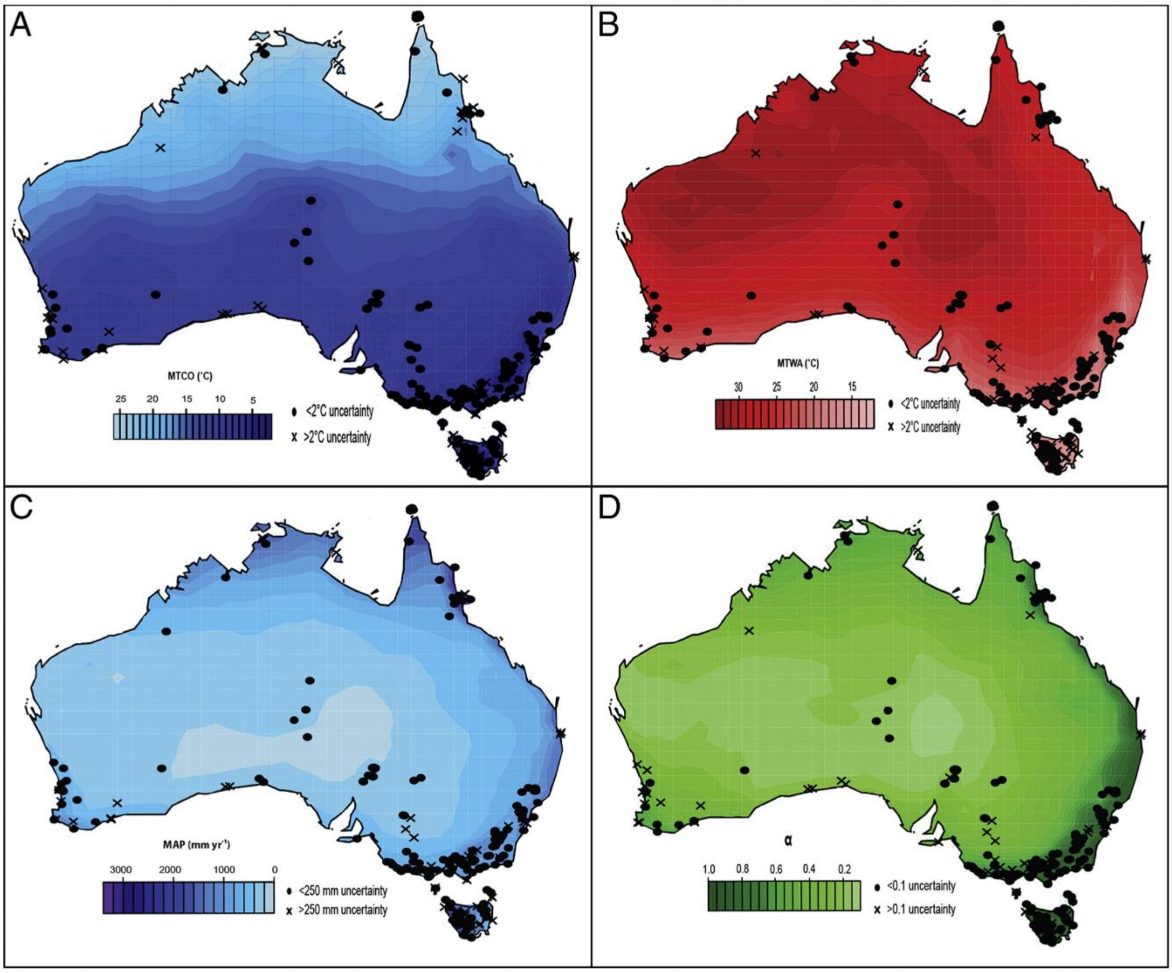

Fig. 7. Comparison of reconstructed and observed (a) mean temperature of the coldest month (MTCO, °C), (b) mean temperature of the warmest month (MTWA, °C), (c) mean annual precipitation (MAP, mm yr.$^{-1}$) and (d) the Cramer–Prentice plant-available moisture index (α). The underlying map shows the observed patterns based on the 0.5° gridded climatology. The symbols show how closely the reconstructed values capture the observed values, where the different symbols show if the discrepancies are greater or smaller than the associated RMSEP. No attempt has been made to standardise the discrepancies relative to the observations, thus this comparison is particularly stringent for regions of high observed values of a given climate variable.

which can be compared to values of 0.8 to 1.8 for mean summer temperature; an RMSEP of 2.3 for MTCO, which can be compared to values of 1.6 to 1.9 for mean winter temperature; and an RMSEP of 233 for MAP, compared to values of 159 to 474 for annual precipitation. However, as these comparisons show, even the improvement obtained by using a regionally specific calibration only pertains in some regions. Furthermore, limiting the area from which analogues can be selected will tightly constrain the palaeo-reconstructions and thus will make it more difficult to reconstruct climate radically different from present.

The ability to reconstruct modern climate from modern pollen samples does not guarantee that this approach will provide good reconstructions of palaeoclimates. Past climate changes may have led to situations that are not represented in the modern climate space (the non-analogue problem: Overpeck et al., 1985; Whitmore et al., 2005). Furthermore, under-sampling of the modern climate can lead to poor palaeo-reconstructions even though these past climates are represented in modern climate space. Despite the size of our data set, for example, cold temperatures are under-sampled, which could be problematic for reconstructions of glacial climates. Similarly, the fact that there are larger uncertainties associated with reconstructions of tropical climates suggests that we are also under-sampling this region of climate space. Nevertheless, our explorations suggest that it is worthwhile to apply the modern analogue reconstruction technique to the palaeorecord of Australia and have provided a methodology for doing so. Australia is a major gap in global target data sets (e.g. Bartlein et al., 2011). Our data compilation makes it possible to fill this gap, and our analyses provide a methodology for how to perform these reconstructions. This is important because Australia is a maritime continent, strongly influenced by the El Niño Southern Oscillation (McBride and Nicholls, 1983; Diaz and Markgraf, 1992; Fierro and Leslie, 2014). The ability to reconstruct large-scale patterns of climate change in the northern hemisphere (see e.g. Harrison et al., 2013; Izumi et al., 2013; Li et al., 2013) is no guarantee that state-of-the-art models can reliably reconstruct similar patterns in the southern hemisphere.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.revpalbo.2015.12.006.

Acknowledgements

The authors would like to acknowledge the data contributions from a large number of collaborators, particularly John Dodson, Lesley Head, Simon Haberle, Geoff Hope, Janelle Stevenson, Mathieu Prebble, Ulrike Proske, Peter Kershaw, Scott Mooney, Jamie Shulmeister, Patrick Moss, Jon Luly and Lydia Mackenzie. The relevant publications are listed as supplementary data. Initial work by Pickett et al. (2004) and the QUAVIDA working group facilitated this study. We thank Dr. Ines Hessler for assistance with the data compilation. AVH is supported by an International Postgraduate Research Scholarship at Macquarie University. The work was supported by the Australian Research Council, grant number DP1201100343 (SPH). We would like to thank three anonymous reviewers for their comments and suggestions.

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Supplementary information

Table S1, Modern sites with coordinates and relevant publications.

Site number	Site	Lat	Long	Data source
1	Above Lake Johnston	-41.9	145.55	Fletcher, M.-S., 2009. The Late Quaternary Palaeoecology of Western Tasmania. Ph.D Thesis, University of Melbourne, Australia.
2	Adamson's Peak	-43.35	146.8167	Macphail, M.K., 1979. Vegetation and Climates in Southern Tasmania since the Last Glaciation. Quaternary Res. 11, 306-341. Macphail, M.K., 1986 'Over the top': pollen based reconstructions of past alpine floras and vegetation in Tasmania. In: Barlow, B.A. (ed.) Flora and fauna of alpine Australasia: ages and origins. CSIRO/Australian Systematic Botany Society, Melbourne, Australia, pp. 173-204.
3	Aire Crossing	-38.73	143.45	D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Aust. J. Bot. 45, 583–605. McKenzie, unpublished data.
4	Airstrip	-31.75	128.083	Martin, H.A., 1973. Palynology and Historical Ecology of some cave excavations in the Australian Nullarbor. Aust. J. Bot. 21, 283-316.
5	Alexander Morrison NP	-30.067	115.567	Pickett, E.J., 1997. The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia. Ph.D. Thesis, Department of Geography, The University of Western Australia, Crawley, Australia.
6	Argan	-10.083	142.1	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and Environmental Science, Monash University, Melbourne, Australia.
7	Arkaroola, Devils Arch, ARK1	-30.3167	139.3523	McCarthy, L., 1999. A Holocene vegetation history of the Flinders Ranges South Australia: evidence from Leporillus spp. (Sticknest Rat) middens. Unpublished PhD thesis, School of GeoSciences, University of Wollongong, Australia.
8	Arkaroola, Waterfall, WF1	-30.267	139.284	McCarthy, L., 1999. A Holocene vegetation history of the Flinders Ranges South Australia: evidence from Leporillus spp. (Sticknest Rat) middens. Unpublished PhD thesis, School of

				GeoSciences, University of Wollongong, Australia.
9	Arkaroola-Mount Painter Sanctuary	-30.2783	139.2369	McCarthy, L., 1999. A Holocene vegetation history of the Flinders Ranges South Australia: evidence from Leporillus spp. (Sticknest Rat) middens. Unpublished PhD thesis, School of GeoSciences, University of Wollongong, Australia.
10	Badgingarra NP	-30.483	115.433	Pickett, E.J., 1997. The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia. Ph.D. Thesis, Department of Geography, The University of Western Australia, Crawley, Australia.
11	Bar20	-10.1333	142.2333	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and Environmental Science, Monash University, Melbourne, Australia. Rowe, C., 2007. A palynological investigation of Holocene vegetation change in Torres Strait, seasonal tropics of northern Australia. Palaeogeogr. Palaeoclim. 25 (1), 83-103.
12	Barker Swamp	-32.002	115.503	Backhouse, J., 1993. Holocene vegetation and climate record from Barker Swamp, Rottnest Island, Western Australia. J. Roy. Soc. West. Aust. 76, 53-61.
13	Barrington Tops	-31.98	151.91	Dodson, J.R., Myers, C.A., 1986. Vegetation and modern pollen rain from the Barrington Tops and Upper Hunter River regions of New South Wales. Aust. J. Bot. 34, 293-304.
14	Barron River	-16.86	145.75	Moss, P.T., Kershaw, A.P., Grindrod, J., 2005. Pollen transport and deposition in riverine and marine environments within the humid tropics of northeastern Australia. Rev. Palaeobot. Palynol. 134, 55-69.
15	Baw Baw	-37.833	146.283	D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Aust. J. Bot. 45, 583–605. Strickland, unpublished data.
16	Beattie's Tarn	-42.6667	146.6333	Macphail, M.K., 1979. Vegetation and Climates in Southern Tasmania since the Last Glaciation. Quaternary Res. 11, 306-341. Macphail, M.K., 1986. 'Over the top': pollen based reconstructions of past alpine floras and vegetation in Tasmania. In: Barlow, B.A. (ed.) Flora and fauna of alpine Australasia: ages and

				origins. CSIRO/Australian Systematic Botany Society, Melbourne, Australia, pp. 173-204.
17	Bega Swamp	-36.5167	149.5	Polach, H., Singh, G., 1980. Contemporary 14C levels and their significance to sedimentary history of Bega Swamp, New South Wales. Radiocarbon 22, 398-409. Green, D., Singh, G., Polach, H., Moss, D., Banks, J., Geissler, E.A., 1988. A fine-resolution paleoecology and paleoclimatology from south-eastern Australia. J. Ecol. 76, 790–806. Hope, G., Singh, G., Geissler, E., Glover, L., O'Dea, D., 2000. A detailed pleistocene-Holocene vegetation record from Bega Swamp, southern New South Wales. In: Magee, J., Craven, C. (eds.) Quaternary Studies Meeting. Regional analysis of Australian Quaternary studies: strengths, gaps and future directions, pp. 2000.
18	Bellenden Ker	-17.25	145.917	Kershaw, A.P., 1973a. Late Quaternary vegetation of the Atherton Tableland, north-east Queensland, Australia. PhD Thesis, Australian National University, Canberra, Australia.
19	Bibra Lake	-32.1	115.833	Pickett, E.J., 1997. The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia. PhD Thesis, Department of Geography, The University of Western Australia, Crawley, Australia.
20	Big Dam Marsh	-41.6833	147.6833	Becker unpublished data
21	Big Heathy Swamp	-41.3833	145.6333	D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Aust. J. Bot. 45, 583–605. Thomas, unpublished data.
22	Big Willum	-12.66	141.99	Stevenson, J., 2013. Unpublished data.
23	Black Swamp	-32.05	151.4667	Dodson, J.R., Greenwood, P.W., Jones, R.L., 1986. Holocene forest and wetland vegetation dynamics at Barrington Tops, New South Wales. J. Biogeogr. 13, 561-585. Dodson, J.R., 1987. Mire development and environmental change, Barrington Tops, New South Wales, Australia. Quaternary Res. 27, 73–81.

24	Blue Lake (Snowy Mts)	-36.4167	148.3167	Raine, J.I., 1974. Pollen Sedimentation in Relation to Quaternary Vegetation History of the Snowy Mountains of New South Wales. Unpublished PhD thesis Australian National Univesity, Canberra, Australia. Raine, J.I., 1982. Dimictic thermal regime and morphology of Blue Lake in the Snowy Mountains of New South Wales. Aust. J. Mar. Fresh. Res. 33, 1119–1122.
25	Blue Tea Tree	-37.62	140.52	Dodson, J.R., Wilson, I.B., 1975. Past and present vegetation of Marshes Swamp in South-eastern South Australia. Aust. J. Bot. 23, 123-150.
26	Blundell's Flat	-35.19	148.49	Hope, G., Stevenson, J. and Haberle, S., 2006. Mountain Occupation Project: Palaeoecology of Blundells Flat. Division of Archaeology and Natural History. Research School of Pacific and Asian Studies, Australian National University, Canberra, Australia.
27	Boar Pocket Rd	-17.167	145.6	Kershaw, A.P., 1973b. The numerical analysis of modern pollen spectra from northeast Queensland rain-forests. Geol. Soc. Aust. Spec. Pub. 4, 191–199.
28	Bobundara Swamp	-36.5833	150.1	Coddington, J., 1983. Landscape evolution and its effect on aboriginal occupation at Tilba, South Coast, New South Wales. BA Honours Thesis, Australian National University, Canberra, Australia. Hope, G.S., Coddington, J., O'Dea, D., 2006. Estuarine development and human occupation at Bobundara Swamp, Tilba Tilba, New South Wales, Australia. In: Lillie, M., Routledge, L. (eds.) Wetlands Archaeology and Environments: Regional Issues, Global Perspective, pp. 258-274. Oxbow Books, Oxford, United Kingdom.
29	Boco Valley	-41.65	145.6	Fletcher, M.-S., 2009. The Late Quaternary Palaeoecology of Western Tasmania. University of Melbourne PhD thesis.
30	Boggy Lake	-35.017	116.633	Churchill, D. M., 1968. The distribution and prehistory of Eucalyptus diversicolor F.Muell., E. marginata Donn ex Sm., and E. calophylla R.Br. in relation to rainfall. Aust. J. Bot. 16, 125-51. Pickett, E.J., 1990. A palynological investigation of Holocene environments for southwestern Australia. BA Honours Thesis, Department of Geography, The University of Western Australia, Crawley, Australia. Newsome, J.C., Pickett, E.J., 1993. Palynology and palaeoclimatic implications of two Holocene

				sequences from southwestern Australia. Palaeogeogr. Palaeoeclim. 101, 245-261.
31	Boggy Swamp	-31.868	151.517	Dodson, J.R., Greenwood, P.W., Jones, R.L., 1986. Holocene forest and wetland vegetation dynamics at Barrington Tops, New South Wales. J. Biogeogr. 13, 561-585. Dodson, J.R., 1987. Mire development and environmental change, Barrington Tops, New South Wales, Australia. Quaternary Res. 27, 73–81.
32	Boigu Gawat	-10.0167	142.2333	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and Environmental Science, Monash University, Melbourne, Australia.
33	Bolobek Peatland	-37.433	144.6	D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Aust. J. Bot. 45, 583–605.
34	Boomer Swamp	-38.206	141.3	Head, L.M., 1984. Environment as artefact: A palaeoecological contribution to the Prehistory of Southwestern Victoria. PhD Thesis, Monash University, Melbourne, Australia.
35	Boomer Swamp	-37.2167	141.3	Head, L., 1983. Environment as artefact: a geographic perspective on the Holocene occupation of Southwestern Victoria. Archaeol. Ocean. 18, 73-80. Head, L., 1988. Holocene Vegetation, fire and environmental history of the Discovery Bay region, southwestern Victoria. Aust. J. Ecol. 13, 21-49.
36	Boulder Flat	-37.4667	148.9667	Kenyon, C.E., 1989. A late Pleistocene and Holocene palaeoecological record from Boulder Flat, East Gippsland. BSc Honours Thesis, Monash University, Melbourne, Australia. Kershaw, A.P., 1998. Estimates of regional climatic variation within southeastern mainland Australia since the last glacial maximum from pollen data. Palaeoclim: Data Model. 3, 107–134.
37	Brachina Gorge	-31.3416	138.53	McCarthy, L., 1999. A Holocene vegetation history of the Flinders Ranges South Australia: evidence from Leporillus spp. (Sticknest Rat) middens. Unpublished PhD thesis, School of GeoSciences, University of Wollongong, Australia.
38	Brachina Gorge 1	-31.355	138.5492	McCarthy, L., 1999. A Holocene vegetation history of the Flinders Ranges South Australia:

				evidence from Leporillus spp. (Sticknest Rat) middens. Unpublished PhD thesis, School of GeoSciences, University of Wollongong, Australia.
39	Brachina Gorge 2	-31.3405	138.5443	McCarthy, L., 1999. A Holocene vegetation history of the Flinders Ranges South Australia: evidence from Leporillus spp. (Sticknest Rat) middens. Unpublished PhD thesis, School of GeoSciences, University of Wollongong, Australia.
40	Brachina Gorge 4	-31.3403	138.538	McCarthy, L., 1999. A Holocene vegetation history of the Flinders Ranges South Australia: evidence from Leporillus spp. (Sticknest Rat) middens. Unpublished PhD thesis, School of GeoSciences, University of Wollongong, Australia.
41	Breadalbane	-34.8	149.5	Dodson, J.R., 1983. Modern pollen rain in southeastern New South Wales, Australia. Rev. Palaeobot. Palyno. 38, 249–268. Dodson, J.R., 1986. Holocene vegetation and environments near Goulburn, New South Wales. Aust. J. Bot. 34, 231–249.
42	Bridgewater Caves South	-38.32	141.41	Head, L.M., 1984. Environment as artefact: A palaeoecological contribution to the Prehistory of Southwestern Victoria. PhD Thesis, Monash University, Melbourne, Australia. Head, L.M., 1985. Pollen analysis of sediments from the Bridgewater Caves archaeological site, Southwestern Victoria. Aust. Archaeol. 20, 1-15.
43	Bridgewater Lake	-38.32	141.393	Head, L.M., 1984. Environment as artefact: A palaeoecological contribution to the Prehistory of Southwestern Victoria. PhD Thesis, Monash University, Melbourne, Australia. Head, L., 1988. Holocene Vegetation, fire and environmental history of the Discovery Bay region, southwestern Victoria. Aust. J. Ecol. 13, 21-49.
44	Broadmeadows Swamp	-40.8333	145.1333	van der Geer, G., Colhoun, E.A. and Mook, W.G., 1986. Stratigraphy, pollen analysis and paleoclimatic interpretation of Mowbray and Broadmeadows swamps, northwestern Tasmania. Aust. Geogr. 17, 121-132.
45	Brooks Ridge	-36.16	148.59	Mooney, S.D., Watson, J.R., Dodson, J.R., 1997. Late Holocene environmental change in an upper Montane area of the Snowy Mountains, New South Wales. Aust. Geogr. 28 (2), 185-200.
46	Brown Marsh	-42.2167	146.5667	Macphail, M.K., 1979. Vegetation and Climates in Southern Tasmania since the Last Glaciation. Quaternary Res. 11, 306-341.

				Macphail, M.K., Hope, G.S., 1985. Late Holocene mire development in montane southeastern Australia: a sensitive climatic indicator. Search 15, 344–348. Macphail, M.K., 1986. 'Over the top': pollen based reconstructions of past alpine floras and vegetation in Tasmania. In: Barlow, B.A. (ed.) Flora and fauna of alpine Australasia: ages and origins. CSIRO/Australian Systematic Botany Society, Melbourne, Australia, pp. 173-204.
47	Brownes Lake	-37.75	140.75	Dodson, J.R., 1975. The pre-Settlement vegetation of the Mt. Gambier area, South Australia. T. Roy. Soc. South Aust. 99 (2), 89-92.
48	Bunya Mountains	-26.85	151.567	Kershaw, A.P., 1976. A late Pleistocene and Holocene pollen diagram from Lynchs Crater, north-eastern Queensland, Australia. New Phytol. 77, 469–498.
49	Bunyip Bog	-36.7833	146.7667	Binder, R.M., 1978. Stratigraphy and pollen analysis of a peat deposit, Bunyip Bog, Mt Buffalo, Victoria. Monash Publications in Geography No. 19, Dept Geography Monash Univ., Melbourne, Australia, pp. 52. Binder, R., Kershaw, A.P., 1978. Late Quaternary pollen diagram from southeastern highlands of Australia. Search 9, 44–45.
50	Burns Plains	-42.1	146.21	Fletcher, M.-S., 2009. The Late Quaternary Palaeoecology of Western Tasmania. University of Melbourne PhD thesis.
51	Burraga Swamp	-32.0833	151.45	Dodson, J.R., Roberts, F.K., De Salis, T., 1994. Palaeoenvironments and human impact at Burraga Swamp in Montane Rainforest, Barrington Tops National Park, New South Wales, Australia. Aust. Geogr. 25 (2), 161-169.
52	Burralow Creek Swamp	-33.56	150.6	Chalson, J.M., 1991. The Late Quaternary vegetation and climatic history of the Blue Mountains, N.S.W. Australia. Unpublished PhD thesis, University of New South Wales, Sydney, Australia.
53	Butchers Swamp	-31.9167	151.4	Dodson, J.R., Greenwood, P.W., Jones, R.L., 1986. Holocene forest and wetland vegetation dynamics at Barrington Tops, New South Wales. J. Biogeogr. 13, 561-585. Dodson, J.R., 1987. Mire development and environmental change, Barrington Tops, New South Wales, Australia. Quaternary Research 27, 73–81.
54	Buxton	-37.4483	145.6919	McKenzie, G.M., 1989. Late Quaternary vegetation and climate in the central highlands of Victoria: with special reference to Nothofagus cunninghamii (Hook.) Oerst. rainforest. PhD

				Thesis, Monash University, Melbourne, Australia. McKenzie, G.M., Busby, J.R., 1992. A quantitative estimate of Holocene climate using a bioclimatic profile of Nothofagus cunninghamii (Hook.) Oerst. J. Biogeogr. 19, 531–540.
55	Caledonia Fen	-37.3333	146.7333	Joyce, L.J., 1979. The late quaternary history of Caledonia Fen, Snowy Plains region, central-eastern Victoria. BA Honours Thesis, Monash University, Melbourne, Australia. Kershaw, A.P., Southern, W., Williams, J.M., Joyce, L.J., 1983. The vegetation record of the southeastern highlands of mainland Australia, 18+/-2 ka. Proceedings of the first CLIMANZ Conference, held at Howman's Gap, Victoria, Australia, February 8–13, 1981: a symposium of results and discussions concerned with late quaternary climatic history of Australia, New Zealand and surrounding seas. Kershaw, A.P., 1998. Estimates of regional climatic variation within southeastern mainland Australia since the last glacial maximum from pollen data. Palaeoclim.: Data Model. 3, 107–134. Kershaw, A. P., McKenzie, G. M,. Porch, N., Roberts, R. G., Brown, J., Heijnis,H., Orr, M. L., Jacobsen G., and Newall, P. R., 2007. A high-resolution record of vegetation and climate through the last glacial cycle from Caledonia Fen, southeastern highlands of Australia. Journal of Quaternary Science 22 (5), 481-500.
56	Cameron's Lagoon	-41.9667	146.6833	Thomas, I., 1984. Liawenee Moor: the post-glacial history of a Tasmanian alpine grassland, unpublished B.Sc.Hons. Thesis, Australian National University, Canberra, Australia. Thomas, I. and Hope, G.S., 1994. An example of Holocene vegetation stability from Camerons Lagoon, a near treeline site on the Central Plateau, Tasmania. Australian Journal of Ecology 19, 150-158.
57	Carlisle Perched Lake	-37.9167	143.6667	Bottomley, C., 1994. Late Quaternary palaeoenvironments of Carlisle Perched Lake in the Otway Ranges, Victoria. Unpublished B.A. (Honours) thesis. Dept. of Geography and Environmental Science. Monash University, Melbourne, Australia.

				D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605.
58	Cascade Bog	-37.85	146.3167	Strickland, K.M., 1980. Studies on the relationship between the pollen rain and the vegetation in the vicinity of Cascade Creek on the Baw Baw Plateau, Victoria. Unpublished B.Sc. (Honours) thesis, Department of Geography, Monash University, Melbourne, Australia. D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605.
59	Casuarina campus	-12.37	130.88	Stevenson, J., Harberle, S.G., Johnston, F.H., Bowman, D.M.J.S., 2007. Seasonal distribution of pollen in the atmosphere of Darwin, tropical Australia: Preliminary results. Grana 46 (1), 34-42.
60	Cave Bay Cave	-40.5	144.8333	Hope, G.S., 1978. Late Pleistocene and Holocene vegetational history of Hunter Island, northwestern Tasmania. Australian Journal of Botany 26, 493–514.
61	Chambers Gorge	-30.9451	139.1957	McCarthy, L.P., 1993. Stick-nest rat middens: tools for palaeoecological investigations in the northern Flinders Ranges. BSc thesis, University of Wollongong, Australia. McCarthy, L., Head, L., Quade, J., 1996. Holocene palaeoecology of the northern Flinders Ranges, South Australia, based on stick-nest rat (Leporillus spp.) middens: a preliminary overview. Palaeogeogr. Palaeoclim. 123, 205-218. McCarthy, L., 1999. A Holocene vegetation history of the Flinders Ranges South Australia: evidence from Leporillus spp. (Sticknest Rat) middens. Unpublished PhD thesis, School of GeoSciences, University of Wollongong, Australia. McCarthy, L., Head, L., 2001. Holocene variability in semi-arid vegetation: new evidence from Leporillus middens from the Flinders Ranges, South Australia. Holocene 11 (6), 681-689.

62	Chambers Gorge, Medlin Site.	-30.9703	139.2793	McCarthy, L., 1999. A Holocene vegetation history of the Flinders Ranges South Australia: evidence from Leporillus spp. (Sticknest Rat) middens. Unpublished PhD thesis, School of GeoSciences, University of Wollongong, Australia.
63	Chapple Valley	-38.6833	143.5667	McKenzie, G.M., Kershaw, A.P., 1997. A vegetation history and quantitative estimate of Holocene climate in Chapple Valley, in the Otway region of Victoria, Australia. Australian Journal of Botany 45, 565-581.
64	Chewko	-17.067	145.367	Kershaw, A.P., 1976. A late Pleistocene and Holocene pollen diagram from Lynchs Crater, north-eastern Queensland, Australia. New Phytologist 77, 469–498.
65	Cobrico Swamp	-38.5	145.05	Yezdani, G.H., 1970. A study of the Quaternary vegetation history in the volcanic lakes region of Western Victoria. PhD Thesis, Monash University, Melbourne, Australia. Dodson, J.R., Frank, K., Fromme, M., Hickson, D., McRae, V., Mooney, S., Smith, J.D., 1994. Environmental systems and human impact at Cobrico Crater, south-western Victoria. Aust. Geogr. Stud. 32, 27–40.
66	Coolimba	-29.867	115.1	Pickett, E.J., 1997. The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia. PhD Thesis, Department of Geography, The University of Western Australia, Crawley, Australia.
67	Copper Hills Station	-27.8856	134.3172	Pearson, S., 1998. Sticknest rat middens as a source of palaeoenvironmental data in central Australia. Unpublished PhD thesis. School of Geography, Univesity of New South Wales, Sydney, Australia. Pearson, S., 1999. Late Holocene biological records from the middens of sticknest rates in the central Australian arid zone. Quaternary International 59, 39-46.
68	Corroboree Rock	-23.5	134.5	Pearson, S., 1998. Sticknest rat middens as a source of palaeoenvironmental data in central Australia. Unpublished PhD thesis. School of Geography, Univesity of New South Wales, Sydney, Australia. Pearson, S., 1999. Late Holocene biological records from the middens of sticknest rates in the central Australian arid zone. Quatern. Int. 59, 39-46.

69	Cotter Source Bog	-35.9667	148.8167	Hope, G., O'Dea, unpublished data.
70	Cotter's Lake	-38.56	146.16	Hope, G.S., 1974. The Vegetation History from 6,000 B.P. to Present of Wilsons Promontory, Victoria, Australia. New Phytologist 73, 1035-1053.
71	Coturaundee	-31.06	142.88	Allen, V., Head, L., Medlin, G., Witter, D., 2000. Palaeo-ecology of the Gap and Coturaundee Ranges, western New South Wales, using stick-nest rat (Leporillus spp.) (Muridae) middens. Austral Ecol. 25, 333-343.
72	Couridjah Lake	-34.23	150.54	Clark, D.J., 1997. A palaeoenvironmental study of Thirlmere Lakes: applications to contemporary vegetation management. Unpublished BSc Hons Thesis, School of Geography, University of New South Wales, Sydney, Australia.
73	Cradle Link Road	-41.54	145.89	Fletcher, M.-S., 2009. The Late Quaternary Palaeoecology of Western Tasmania. University of Melbourne PhD thesis.
74	Cranbourne Annexe	-38.117	145.267	Aitken, D.L., Kershaw, A.P., 1993. Holocene vegetation and environmental history of Cranbourne Botanic Garden, Victoria. Proc. Roy. Soc. Vic. 105 (1), 67-80.
75	Crystal Bog	-36.7333	146.7833	Williams, J.M., 1980. Crystal Bog, Mt. Buffalo: a palaeoecological study of a subalpine peat deposit. Working paper 8, Department of Geography, Monash University, Melbourne, Australia. Williams, J.M., 1982. Crystal Bog, Mount Buffalo: a palaeoecology of a subalpine peat deposit. MA Thesis, Monash University, Melbourne, Australia. Kershaw, A.P., 1998. Estimates of regional climatic variation within southeastern mainland Australia since the last glacial maximum from pollen data. Palaeoclim.: Data Model. 3, 107–134.
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83	Diprose Cave	-30.95	131.3833	Martin, H.A., 1973. Palynology and Historical Ecology of some cave excavations in the Australian Nullarbor. Australian Journal of Botany 21, 283-316.
84	Discovery Bay	-38.312	141.388	Head, L.M., 1984. Environment as artefact: A palaeoecological contribution to the Prehistory of Southwestern Victoria. PhD Thesis, Monash University, Melbourne, Australia.
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89	Eagle Tarn	-42.6833	146.5833	Macphail, M.K., 1979. Vegetation and Climates in Southern Tasmania since the Last Glaciation. Quaternary Research 11, 306-341.
90	Egg Lagoon	-39.6514	143.9972	D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605.
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92	Enoggra State Forest	-28.25	153.167	Kershaw, A.P., 1976. A late Pleistocene and Holocene pollen diagram from Lynchs Crater, north-eastern Queensland, Australia. New Phytologist 77, 469–498.
93	Fitzerald River National Park	-34.188	119.414	Hassell, unpublished data.
94	Fitzgerald Inlet	-34.292	119.458	Hassell, unpublished data.
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105	Governor Bog	-42.1833	145.65	Colhoun, E.A., van de Geer, G., Fitzsimons, S.J., 1991. Late Glacial and Holocene vegetation history at Governor Bog, King Valley, western

				Tasmania, Australia. Journal of Quaternary Science 6, 55–66.
106	Granite Downs	-26.57	133.29	Pearson, S., 1998. Sticknest rat middens as a source of palaeoenvironmental data in central Australia. Unpublished PhD thesis. School of Geography, University of New South Wales, Sydney, Australia. Pearson, S., 1999. Late Holocene biological records from the middens of sticknest rates in the central Australian arid zone. Quaternary International 59, 39-46.
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118	Ingar Swamp	-33.7699	150.4564	Chalson, J.M., 1991. The Late Quaternary vegetation and climatic history of the Blue Mountains, N.S.W. Australia. Unpublished PhD thesis, University of New South Wales, Sydney, Australia.
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128	Killiecrankie	-39.7833	147.8833	Ladd, P.G., Orchiston, D.W., Joyce, E.B., 1992. Holocene vegetation history of Flinders Island. New Phytologist 122, 757–767.
129	King River Railway Bridge	-42.15	146.65	van de Geer, G., Fitzsimons, S.J., Colhoun, E.A., 1991. Holocene Vegetation History from King River Railway Bridge, Western Tasmania. Pap. Proc. R. Soc. Tasman. 125, 73-77.
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133	Kuranda	-16.817	145.633	Kershaw, A.P., 1973. The numerical analysis of modern pollen spectra from northeast Queensland rain-forests. Geological Society of Australia Special Publications 4, 191–199.
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137	Lake Burn	-38.29	143.73	Mills, K., Gell, P., Kershaw, P., 2013. The recent Victorian drought and its impact. Without precedent? March 2013, Australian Government Rural Industries Research and Development Corporation RIRDC Publication no. 12/040.
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140	Lake Colac	-38.3	143.59	Mills, K., Gell, P., Kershaw, P., 2013. The recent Victorian drought and its impact. Without precedent? March 2013, Australian Government Rural Industries Research and Development Corporation RIRDC Publication no. 12/040.
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145	Lake Dove	-41.7	145.95	Fletcher, M.-S., 2009. The Late Quaternary Palaeoecology of Western Tasmania. University of Melbourne PhD thesis.
146	Lake Elusive	-37.75	149.45	Kenyon, unpublished data. Kershaw, A.P., 1998. Estimates of regional climatic variation within southeastern mainland Australia since the last glacial maximum from pollen data. Palaeoclim.: Data Model. 3, 107–134.
147	Lake Euramoo	-17.1667	146.633	Haberle, S., Tibby, J., Dimitriadis, S., Heijnis, H., 2006. The impact of European occupation on terrestrial and aquatic ecosystem dynamics in an Australian tropical rain forest, Journal of Ecology 94, 987-1002.
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151	Lake George	-35.0833	149.4167	Singh, G. and Geissler E.A., 1985. Late Cainozoic vegetation history of vegetation, fire, lake levels and climate, at Lake George, New South Wales, Australia, Philosophical Transactions for the Royal Society of London B 311, 379-447.

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156	Lake Keilambete	-38.2	142.8667	Dodson, J.R., 1974a. Vegetation and climatic history near Lake Keilambete, western Victoria. Australian Journal of Botany 22, 709–717.
157	Lake Lascelles	-35.717	142.367	D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. McKenzie, unpublished data.
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162	Lake Ranfurlie	-34.1833	142.1167	D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. McKenzie, unpublished data.
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166	Lake Tiberias	-42.4347	147.3694	Macphail, M.K., Jackson, W.D., 1978. The late Pleistocene and Holocene history of the Midlands of Tasmania, Australia: pollen evidence from Lake Tiberias. Philosophical Transactions of the Royal Society of Victoria 90, 287–300.
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168	Lake Tyrrell	-35.25	142.87	Luly, J., 1990. Holocene palaeoenvironments at Lake Tyrrell, Victoria. PhD Thesis, Australian National University, Canberra, Australia.
169	Lake Vera	-42.2667	145.8667	Macphail, M.K., 1979. Vegetation and Climates in Southern Tasmania since the Last Glaciation. Quaternary Research 11, 306-341.
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172	Lamington National Park	-28.2	153.167	Kershaw, A.P., 1976. A late Pleistocene and Holocene pollen diagram from Lynchs Crater, north-eastern Queensland, Australia. New Phytologist 77, 469–498.
173	Lanyon House	-35.483	149.068	Hope, G., O'Dea, unpublished data.
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183	Mathinna Plain	-41.3667	147.8167	D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. Thomas, unpublished data.
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282	Torres Strait rainforest	-10.2	142.2333	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and Environmental Science, Monash University, Melbourne, Australia.

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				Palaeogeography, Palaeoclimatology, Palaeoecology 25 (1), 83-103.
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303	West Lake Muir Swamp	-34.467	116.6	Churchill, D. M., 1968. The distribution and prehistory of Eucalyptus diversicolor F.Muell., E. marginata Donn ex Sm., and E. calophylla R.Br. in relation to rainfall. Australian Journal of Botany 16, 125-51.
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305	Wilpena Creek	-30.87	138.92	Lachlan, T.J., 1996. Holocene vegetation and environments ay Wilpena Pound, South Australia. Honours thesis, University of Wollongong, Australia.
306	Windin	-17.317	145.783	Kershaw, A.P., 1973. The numerical analysis of modern pollen spectra from northeast Queensland rain-forests. Geological Society of Australia Special Publications 4, 191–199.
307	Wolgan	-33.24	150.14	Chalson, J.M., 1991. The Late Quaternary vegetation and climatic history of the Blue Mountains, N.S.W. Australia. Unpublished PhD thesis, University of New South Wales, Sydney, Australia.

308	Wood Nymphs Dell Forest	-33.7	150.4	Chalson, J.M., 1991. The Late Quaternary vegetation and climatic history of the Blue Mountains, N.S.W. Australia. Unpublished PhD thesis, University of New South Wales, Sydney, Australia.
309	Wriggly Stick Swamp	-37.75	149.433	D'Costa, D.M., Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. Kenyon, unpublished data.
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311	Wyndham	-15.4675	128.0994	Proske, U. 2013. Unpublished data.
312	Yalgorup	-32.867	115.667	Pickett, E.J., 1997. The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia. PhD Thesis, Department of Geography, The University of Western Australia, Crawley, Australia.
313	Yanchep NP	-31.283	116.067	Pickett, E.J., 1997. The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia. PhD Thesis, Department of Geography, The University of Western Australia, Crawley, Australia.
314	Yarlington Tier	-42.535	147.3008	Harle, K.J., Kershaw, A.P., Macphail, M.K., Neyland, M.G., 1993. Palaeoecological analysis of an isolated stand of Nothofagus cunninghamii (Hook.) Oerst. in eastern Tasmania. Australian Journal of Ecology 18(2), 161-170.
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Table S2, Performance statistics for reconstructions performed using only single taxon dominated (>75%) samples and excluding single taxon dominated samples. Results where the reconstructions made using the two different datasets are significantly different from one another (95% confidence limit) are shown in italics; results where the reconstructions are significantly different (95% confidence limit) from the appropriate observations in bold.

Variable	**Mean**				**RMSEP**		**r^2**	
	Single taxon dominated samples		No single taxon dominated samples		Single	No single	Single	No single
	Observed	Reconstructed	Observed	Reconstructed				
MTCO	12.9	*13.3*	10.7	*10.5*	5.5	1.9	0.33	0.92
MTWA	25.6	*25.9*	21.6	*21.5*	3.9	1.7	0.53	0.91
MAP	687	*712*	1070	*1075*	355	215	0.72	0.91
α	0.44	*0.45*	0.70	***0.71***	0.15	0.08	0.78	0.92

Chapter 3

Quantitative reconstruction of Australian climate change since the Last Glacial Maximum using pollen

Chapter 3: Quantitative reconstruction of Australian climate change since the Last Glacial Maximum using pollen

Based on the outcomes of chapter 2, the next natural step is to use the devised methodology to perform quantitative palaeoclimate reconstructions for Australia using the same database. These reconstructions are presented in this chapter.

Contribution of co-authors: A.V.H was responsible for data analysis, figure and table generation, with guidance from S.P.H.; A.V.H. wrote the text, all other authors provided data and will be asked to contribute to the text before submission.

Quantitative reconstruction of Australian climate change since the Last Glacial Maximum using pollen.

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Abstract

Large scale quantitative palaeoclimate reconstructions are vital for our understanding of the climate system and for evaluating climate model performance. We present the first continent-scale quantitative palaeoclimate reconstruction for Australia going back continuously to the Last Glacial Maximum (LGM). Despite a possible regional bias in the temperature reconstructions brought on by a lack of training set samples from the extreme ends of the temperature range, several significant, large-scale climatic events were identified, including the cold event associated with glacial re-advance in Tasmania and the Snowy Mountains. The mid-Holocene appears to have been significantly wetter than today in the interior and the glacial period may have been terminated by a sudden increase in bio-available moisture. Whilst future studies need to improve the temperature coverage of the training set, this study proves the viability of performing large scale quantitative palaeoclimate reconstructions using pollen data from across Australia.

Keywords

Climate reconstructions, Modern Analog technique, bioclimatic variables, paleoclimate benchmarking.

1. Introduction

Quantitative reconstructions of past climates are widely used around the world to further our understanding of the forces influencing the climate system by analysing how the climate has changed over many millennia. This will inevitably help improve simulations of future climate changes, and their potential impact on human life, but reconstructions can also be used in a more direct way to evaluate the performance of climate models (Braconnot *et al.,* 2012). This is particularly valuable as the relatively short period of time covered by the observational record does not provide a large enough range of climate variability to properly assess climate model performance. Where the observational record can be used to evaluate climate model simulations of the present day and recent past, palaeoclimate reconstructions can be used to evaluate palaeoclimate simulations for key periods going back thousands of years. In order to perform these evaluations properly, large-scale quantitative palaeoclimate reconstructions are needed, but the large majority of palaeoclimate studies have focused on North America and Europe, with a serious lack of studies from the Southern Hemisphere. The only continent-wide attempt to quantitatively reconstruct palaeoclimate for Australia to date is a global study performed by PAGES 2k (2013), a study only spanning the last 1000 years. In addition, Prentice *et al.* (2017) used the same database of pollen samples used in this paper to reconstruct moisture for the LGM. There have, however, been studies performing qualitative climate reconstructions (D'Costa and Kershaw, 1997; Pickett *et al.,* 2004), or quantitative reconstructions on a sub-continental scale (Cook and van der Kaars, 2006). There are many data sources available for quantitative reconstructions in Australia, such as pollen (D'Costa and Kershaw, 1997), chironomids (Chang *et al.,* 2015), beetles (Porch and Elias, 2010), tree rings (Cook *et al.,* 2000), diatoms (Tibby and Haberle, 2007) and speleothems (Denniston *et al.,* 2013). Pollen records are the most widely used as they are the most spatially extensive and widely accessible terrestrial data source, as well as being easily dated through radiocarbon dating (Whitmore *et al.,* 2005). Thanks to this and the fact that vegetation distribution is highly controlled by climate (Harrison *et al.,* 2010), there is a long history of quantitative palaeoclimate reconstructions using pollen worldwide and large-scale reconstructions have been possible on most continents, e.g. North America (Viau *et al.,* 2006), Europe (Davis *et al.,* 2003), Eurasia (Tarasov *et al.,* 1999), Africa (Peyron *et al.,* 2000) and China (Guiot *et al.,* 2008). However, due to the arid nature of much of Australia, preservation of pollen grains is an issue, with palaeosites being confined to areas with sufficient long-term rainfall, mainly along the coast.

In addition to the preservational issues, there has been suggestion that European settlement in Australia had a large impact on the capability of modern samples to act as suitable analogues, due to a number of exotic taxa having been introduced and the large-scale land-use changes that has taken place since this settlement (Gell *et al.,* 1994; Mooney and Dodson, 2001; Dodson and Mooney, 2002). Kershaw *et al.* (1994) specifically examined the impact European settlement had on pollen assemblages and found it to have had such an impact that the subsequent South-East Australian database was created using only pre-European samples as the modern baseline and source of modern analogues (Kershaw and Bulman, 1996). However, when the ability of modern samples to reconstruct modern climate was tested against samples pre-dating European settlement, it was found not to make a significant difference when using a large dataset (Herbert and Harrison, 2016).

There are also specific issues associated with the decisions and assumptions involved in performing the reconstructions, ranging from which climatic variables to reconstruct to the number of analogues used for the reconstructions. It is not possible to reconstruct all climate variables equally well for any given set of samples (Bartlein *et al.,* 2011). The reliability of the reconstructions depends on the modern range of the variable represented in the training set. For example, a training set of pollen samples from a wet, tropical environment will not produce reliable reconstructions for a dry, desert-like environment, and vice versa. It is also important to select variables that are not highly intercorrelated, so that they can produce independent reconstructions (Telford and Birks, 2005). Finally, the selection of the number of analogues to use as a basis for the reconstructions also depends on the dataset used. The number of analogues chosen needs to minimise the risk of statistical selection errors, such as determining two samples to be analogues when they are not (type 1 error) and considering two analogous samples not to be analogues (type 2 errors; Telford and Birks, 2011). For some datasets one analogue can be used (e.g. Viau *et al.,* 2006), for others 5 or 8 may be more suitable (Nakagawa *et al.,* 2002; Frechette *et al.,* 2008)

The purpose of this study is to provide continental-scale quantitative palaeoclimate reconstructions for Australia, in order to evaluate climate models.

2. Methods

We used the pollen dataset developed by Pickett *et al.* (2004), subsequently updated by the QUAVIDA working group (quest.bris.ac.uk/research/wkg-gps/QUAVIDA.html) and Herbert and Harrison (2016). A further update was completed for this paper to add samples in areas found to be lacking in the latter study. All sites containing palaeosamples are shown in Figure 1, with the southeast and Tasmania enlarged due to the large concentration of sites. This dataset uses a standardised protocol for dating records, utilising IntCal09 (Reimer *et al.,* 2009) with a Southern Hemisphere offset for all records, which means the chronologies of many of the records had to be updated and may differ from the original publications.

Climate data were obtained from the ANUCLIM software package (Xu and Hutchinson, 2011), which uses the ANUSPLIN thin-plate spline fitting package (Hutchinson, 2004) to interpolate meteorological data from the period 1970-1999 to a 0.05° grid cell resolution climatology. We averaged this dataset to produce a climate dataset at 0.5° resolution, as suggested by Herbert and Harrison (2016) to be more suitable for the training set used. These data were then used to calculate mean temperature of the coldest and warmest months (MTCO and MTWA, respectively), mean annual precipitation (MAP) and the Cramer-Prentice plant-available moisture index (α, Cramer and Prentice, 1988). α is the ratio of actual to equilibrium evapotranspiration (Cramer and Prentice, 1988) and was calculated from monthly temperature, precipitation and percentage of sunshine hours using a simple soil water-balance model (Wang *et al.,* 2013) with soil field water-holding capacity based on a single soil type for the continent. This is the set of variables used by Herbert and Harrison (2016), based on the set of variables used by Bartlein *et al.* (2011) and tested for their efficacy on the Australian data. Through this process, MAT (Mean annual Temperature) and GDD5 (Growing Degree Days above 5°C) were excluded due to high correlations to other variables. In addition, we have excluded MAP as these reconstructions had large associated errors and were deemed unreliable.

Taxa likely to represent local conditions (i.e. aquatic taxa, mangroves, parasitic plants, mosses, agricultural crops, halophytes and ferns) were removed from the pollen dataset prior to analysis. Tree ferns were retained in the dataset because their presence conveys information about plant-available moisture (α). Taxa with a pollen sum of less than 5% for all samples were also removed. The sample counts were standardised to percentages, based on the sum of all remaining taxa. Samples dominated by one taxon (>75%) or containing 5 or fewer taxa were removed. Reconstructions were performed using the Rioja package in R (Juggins, 2012), with an SCD (Squared Chord Distance; Overpeck *et al.,* 1985) cutoff of 0.9, the 2.5^{th} percentile of the distribution of SCD values for the training set, which uses all samples younger than 100 years BP. SCD is a measure of the dissimilarity between fossil and modern pollen assemblages, ranging from 0 for a perfect analogue and 2 for maximum dissimilarity. For these analyses, any paired fossil and modern samples with an SCD value greater than the chosen threshold of 0.9 were considered to be non-analogues. This threshold was chosen by using a Monte Carlo simulation to determine a threshold that is unlikely to have occurred by chance (Sawada *et al.,* 2004). The performance of each reconstruction is measured by a sample-specific RMSE, with r^2 giving a measure of goodness of fit of the training set against prediction. 10 analogues were used for the reconstructions, in contrast to the 5 used in Herbert and Harrison (2016), as using 10 reduced the average RMSE for the palaeosamples.

Climate anomalies (the difference between the target period and the present day) were calculated for each 0.5° grid cell where data was available and for the key time slices 6 ± 0.5 ka BP (mid-Holocene) and 21 ± 1 ka BP (LGM). This was done to maximise comparability with large-scale data synthesis papers such as Bartlein *et al.* (2011) and palaeoclimate modelling studies, as they also make use of anomalies, with model anomalies being calculated compared to a pre-industrial control run (Taylor *et al.,* 2009). Here, just as in Bartlein *et al.* (2011), the anomalies are calculated compared to reconstructions of modern climate using the training set. An average anomaly for each grid cell was calculated along with a pooled estimate of the associated error. In grid cells where there were too few samples to pool, the average error was used instead. The anomalies were then mapped, the colour shade reflecting the magnitude of the anomaly and the symbol size reflecting the significance of the anomaly, a large symbol signifying that the absolute value of a *t*-statistic calculated using the anomaly values and the pooled error exceeds 2.0 (i.e. that the anomaly exceeds twice the pooled error for the cell). This follows the same procedure as that of Bartlein *et al.* (2011).

Hovmöller graphs (Hovmöller, 1949) were plotted for each variable, with latitude plotted against time with the same climatic anomalies as in the aforementioned maps, except averaged in 100 year time windows as well as by grid cell, to aid interpretation. Samples from the western part of the continent and the interior have been excluded, as these areas will have been influenced by different climatic forces than their equivalent latitude bands along the east coast and their inclusion may skew the results. The range of values incorporated in the averages were plotted in separate Hovmöller graphs, as were the density and distribution of samples and grid cells containing reconstructions through time. Finally, time series were plotted of average anomalies within 100 year time windows for the whole 22,000 year time period for Australia as a whole as well as two areas with a high density of sites, namely Tasmania and the southeast, defined as -40° to -30°S to 140-155°E. The pooled associated errors have been added as error bars.

3. Results

3.1 Mid-Holocene and LGM anomaly maps

According to figure 2a, the mid-Holocene appears to not have been significantly different from today in most areas, except in South Australia around the Flinders Ranges and one grid cell in the southeast, which our reconstructions indicate being significantly wetter at this time. There are also some cells that are significantly drier, two in the southeast and one in the Gulf of Carpentaria.

Neither of the temperature reconstructions for the mid Holocene (Figure 2b, c) show a coherent picture for the southern part of the continent, with no points being significant for MTCO, and only one significantly warmer point for MTWA in the southeast, plus two significantly cooler MTWA points in the interior. Both MTCO and MTWA show significant decreases for most northern cells, except one in the Gulf of Carpentaria indicating a significantly warmer mid-Holocene. This is the same cell that shows a significant drying, indicating that the dry anomaly may be due to the warmer temperatures, not necessarily an actual decrease in precipitation.

For the LGM, figure 2d shows a quite confusing picture of reconstructed α, with very few significant changes, one of drying in the north, another of drying in the southeast, but close to a significantly wetter grid cell. The Flinders Ranges again show a significant increase in bio-available moisture compared to today.

The only significant temperature changes at the LGM (Figure 2e, f) are cold anomalies, mainly in the north, with only two points in the south being significant.

3.2 Hovmöller plots

The temperature reconstructions (Figure 3b, c) appear to suggest a geographical bias, with the most northern sites almost always showing cold anomalies and southern samples almost always showing warm anomalies, especially for MTWA (Figure 3c). This may indicate oversampling of mid-range sites, but some patterns can still be discerned. There seems to be significant warm periods for most of the latitudinal range at around 2.5 and 11 ka BP, and a significant cold period at around 17 BP. This cold period appears to coincide with a significant increase in bio-available moisture (Figure 3a), and there also appears to be a significant local increase in moisture shortly after the apparent warm period around 11 ka BP, the period itself coinciding with a dry period. Figure 3a also suggests that the period around the LGM at 21 ka BP was dry, but there appears to have been a sudden increase in bio-available moisture at mid-latitudes shortly afterwards. There appears to have been another dry period at around 4 ka BP, coinciding with a possible warm period. Finally, there is an increase in moisture at mid- to high-latitudes towards the very end of the record, though this peak may be due to the higher associated errors indicated by the contours. Higher errors may also be responsible for the dry period at around 4 ka, as this whole trough coincides with a peak in the associated errors. According to figure 4a, both these periods are also associated with peaks in the intersample range, meaning increased uncertainty regarding the mean value. Similarly, the peak in MTCO at around 3 ka BP corresponds to a peak in the associated errors and may therefore not be significant. However, this period does not correspond to a peak in the intersample range (Figure 4b). The peaks in temperature intersample range (Figure 4b, c) do not correspond with any significant periods of change in figures 3b and 3c, probably because the anomalies were of opposite signs, and so produced a large range but small mean.

3.3 Sample density and non-analogues

Unsurprisingly, figure 5 shows that the number of samples and cells containing samples decreases with time. The contours in figure 5a represent the number of samples for which no modern analogue could be found. The number of non-analogue samples also appears to decrease with time, but not showing any significant peaks in figure 5b. This increase may simply be due to the larger number of samples and cells containing samples, meaning there is a greater chance for some of the samples to be non-analogues. The error peak in figure 3b may be associated with the peak in non-analogue samples around this time across most of the latitudinal range. Most of the other non-analogue peaks are very localised, apart from one close to present day and one at around 7-8 ka BP.

3.4 Regional and national time series

According to figure 6, there have not been any significant climatic changes in Australia during the Holocene. However, the associated errors are quite large and the only significant changes are during the deglacial period. The large and sudden oscillations during this period may in part be due to the lack of samples, as seen in figure 5. The significant cold period at around 17 ka BP seen in figure 3 can also be seen here, along with another significant cold snap at around 21 ka BP. Focussing in on the southeast in figure 7, there appears to have been a significant and sudden increase in bio-available moisture at 20 ka BP, gradually decreasing from about 16 ka BP. This coincides with a significantly reduced MTWA, suggesting that summer temperature drove bio-available moisture at this time. The lack of samples in the decglacial period is especially evident in figure 8, showing Tasmanian samples. This chart appears to oscillate significantly up until 15 ka BP, but this may simply be due to local forces impacting on a handful of sites with differing temporal resolution. The difference in temporal resolution would mean that the different signals could not be averaged out in the 100 year time windows applied to the data.

4 Discussion and conclusions

This study represents the first attempt to perform continent-wide quantitative palaeoclimate reconstructions for Australia going back to the Last Glacial Maximum (LGM).

They indicate a variable climate during the mid-Holocene, with significant cooling in the north and increased bio-available moisture in the interior (figure 2a-c). This increase in bio-available moisture is consistent with a multi-proxy study from close to the Flinders Ranges showing elevated lake levels during the mid-Holocene (Gliganic *et al.,* 2014). The reason most of the cells in the north show consistently significant changes in figure 2 may be because these cells have generally low pooled errors and relatively small anomalies would be significant. However, the error contours in figure 3 suggests this might not be the case. Nor is it likely that it is due to a large range of the high concentration of samples in the south, as figure 4 indicates there are only a few limited periods that show high intersample ranges. The increase of climatic variability during the mid-Holocene, both geographically and temporally (e.g. Petherick *et al.,* 2013) may explain the lack of a distinct mid-Holocene pattern in figure 2. This spatial variability can be seen in the range of magnitude of the anomalies, especially in the southeast, and may also be the reason most of these are not significant. The size of the time window and the presence of multiple sites within the same grid cell may have led to a wide range of values within a cell, and if some of these are of opposite sign, the resultant average anomaly may be classified as not significant.

The LGM reconstructions in figure 2d-f show significant cooling in both the north and south, as is shown in multiple Australian studies (e.g. Williams *et al.,* 2009; Fletcher and Thomas, 2010, Woltering *et al.,* 2014; Chang *et al.,* 2015). The seemingly inconsistent pattern of bio-available moisture is also supported by previous studies, with lake-level studies indicating generally arid conditions, but with higher-than-present lake levels in the interior, possibly due to a change in rainfall seasonality (Harrison, 1993; Cohen *et al.,* 2012). There is also evidence for multiple flood events in the Flinders Ranges between ~24 and 18 ka BP, based on silt analysis by Haberlah *et al.* (2010). Even though previous studies have suggested that the floral assemblages present during the LGM are not present anywhere on the continent today and that consequently any study using modern pollen assemblages to reconstruct LGM climate may not be able to locate the necessary analogues (Galloway, 1965; Dodson, 1998), figure 5 suggests that our dataset does not contain any non-analogue samples from the LGM. There are, however, multiple samples that had to accept a reduced number of analogues for this period. This, plus the general lack of samples also evident in figure 5, is probably the cause of the rapid changes seen at about 22-16 ka BP in figures 6-8, with it being particularly evident in figure 8. Some of these rapid changes may also be due to the general climatic instability associated with the deglacial period (e.g. Hughen *et al.,* 1996).

Despite the apparent regional bias of the temperature reconstructions seen in figure 3, some large changes are still evident, and will most likely represent significant climatic changes for large sections of the continent. The mid-latitude increase in α shortly after 20 ka BP (Figure 3a) may be associated with a sudden end to glacial conditions in these areas, even though this pattern is not evident in the temperature reconstructions in Figure 3. There is evidence for a slight cold period at about 17 ka BP, with an increase in bio-available moisture in some places. This cold period may be linked to a short-lived glacial re-advance in the Snowy Mountains and Tasmania about this time (Petherick *et al.,* 2013), and can also be seen in figures 6-8. The increase in moisture at this time is supported by evidence that Lake Mega-Frome was full about 17.6-15.8 ka BP (Cohen *et al.,* 2012).

There is a significant, but brief, warm and wet period at about 11 ka BP, coinciding with the beginning of the Antarctic Climatic Optimum (ca 11 500-9000 yr BP, Masson *et al.,* 2000) and a sudden warming of tropical sea surface temperatures according to a modelling study (Bostock *et al.,* 2006), as well as the latest marine transgression in the Gulf of Carpentaria, ending its latest lake phase (Reeves *et al.,* 2007). There appears to have been a warm and possibly dry period at around 2.5 ka BP. This corresponds to a dry period at around 4-2.2 ka BP across southern Australia as reconstructed from ostracods by Gouramanis *et al.* (2013) and from pollen by Donders *et al.* (2007), as well as a dry period between ca 2.3 and 1.8 ka BP across the southeast, as summarised by Gouramanis *et al.* (2013). Finally, towards the end of the records presented in figure 3, there appears to be another significant cold and wet period, at least for mid- to low-latitudes. This wet period is supported by previous studies showing elevated lake levels and Megalake filling at about 1 ka BP (Cohen *et al.,* 2012; Gliganic *et al.,* 2014).

In conclusion, despite an apparent lack of modern samples at the higher and lower end of the temperature scale and the reconstructional bias this has caused, several significant climatic events are evident from the reconstructions. Most of these events are supported and explained either by other studies or the regional anomaly maps for the mid-Holocene and LGM presented here, as well as the sample density graphs and regional and national time series. This signifies an important first step towards further continent-scale quantitative palaeoclimate reconstructions for Australia, but any future studies will need to improve the temperature ranges represented by their training set, as well as increase the density of samples for the last glacial and deglacial periods.

Acknowledgements

The authors would like to thank Dr Ines Hessler for assistance with the data compilation, and all the researchers who contributed their data to the dataset used here. AVH is supported by an International Postgraduate Research Scholarship at Macquarie University. The work was supported by the Australian Research Council, grant number DP1201100343 (SPH).

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Figure captions

Figure 1, Distribution of sites with pollen samples with ages >100 yr BP, used in the analyses. Coordinates for multiple sites within the same 0.5° grid cell have been averaged to a single point to minimise overlapping points. For a full list of sites with coordinates and data sources, see supplementary table S1.

Figure 2, Reconstructed (a, d) α, (b, e) MTCO and (c, f) MTWA at (a, b, c) 6 ka BP and (d, e, f) 21 ka BP. Large symbols indicate grid points with significant anomalies (i.e. those that exceed twice the pooled error of the reconstructions) while small symbols indicate anomalies that are not significant by this measure.

Figure 3, Hovmöller plots with anomaly of palaeoclimate reconstruction to modern climate reconstructions with contours showing sample-specific RMSEP, for (a) α, bio-available moisture, (b) MTCO, Mean Temperature of the Coldest Month, and (c) MTWA, Mean Temperature of the Warmest Month.

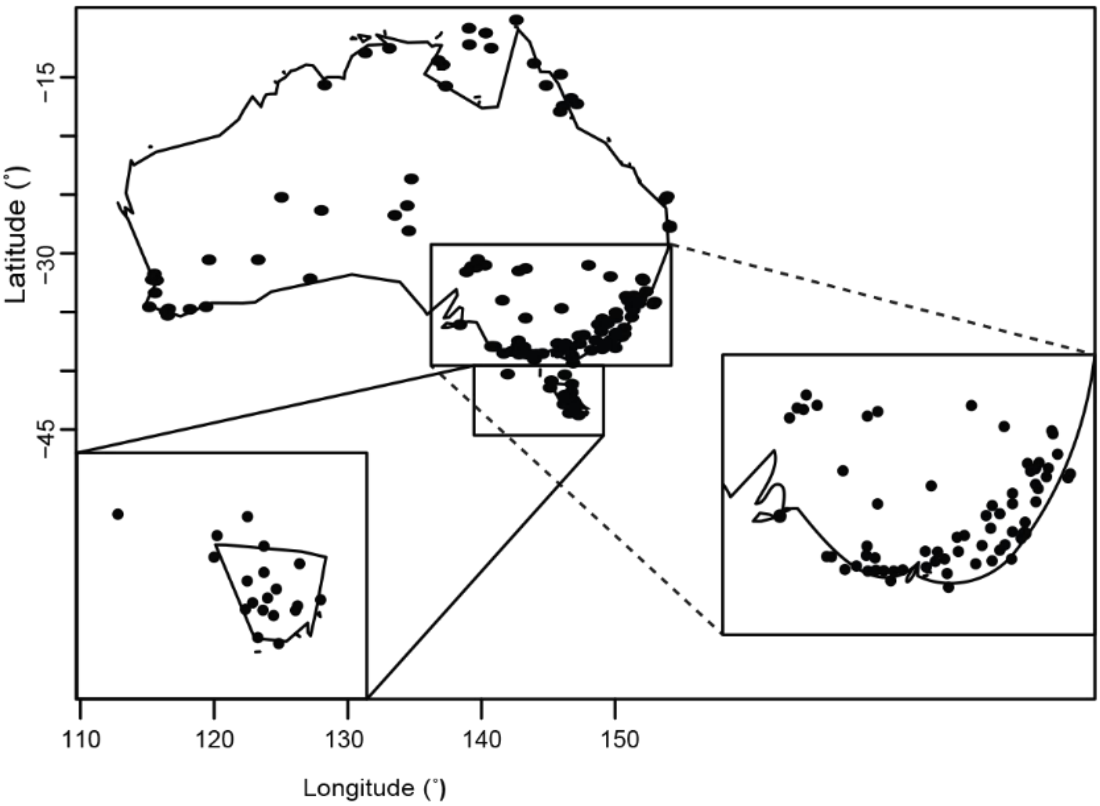
Figure 4, Hovmöller plots with the intersample range for gridcells with multiple samples within the centennial time window, for (a) α, bio-available moisture, (b) MTCO, Mean Temperature of the Coldest Month, and (c) MTWA, Mean Temperature of the Warmest Month.

Figure 5, a) Hovmöller plot of sample density, with contours signifying samples with no modern analogue. b) Line chart showing the distribution of number of grid cells, samples and non-analogue samples through time.

Figure 6, Line charts for average difference to modern values for the whole of Australia for (a) α, bio-available moisture, (b) MTCO, Mean Temperature of the Coldest Month, and (c) MTWA, Mean Temperature of the Warmest Month.

Figure 7, Line charts for average difference to modern values for southeastern Australia (-40° to -30°S by 140-155°E) for (a) α, bio-available moisture, (b) MTCO, Mean Temperature of the Coldest Month, and (c) MTWA, Mean Temperature of the Warmest Month.

Figure 8, Line charts for average difference to modern values for Tasmania for (a) α, bio-available moisture, (b) MTCO, Mean Temperature of the Coldest Month, and (c) MTWA, Mean Temperature of the Warmest Month.



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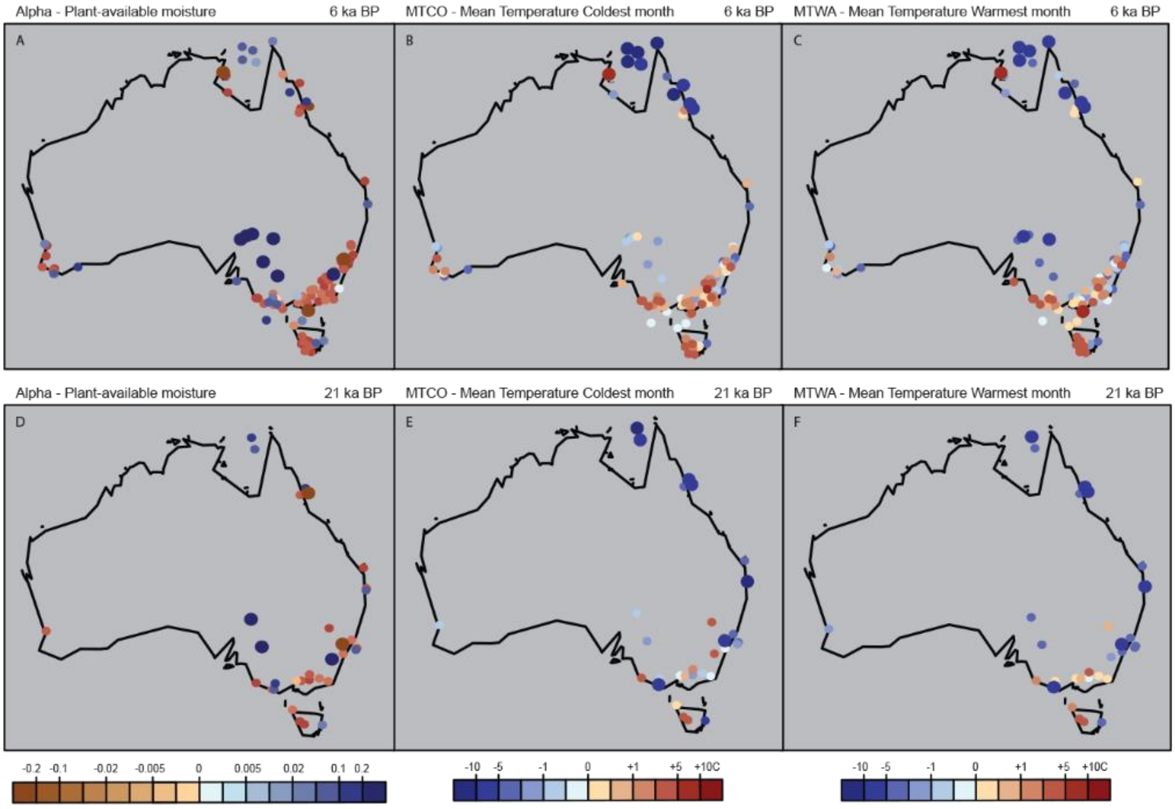

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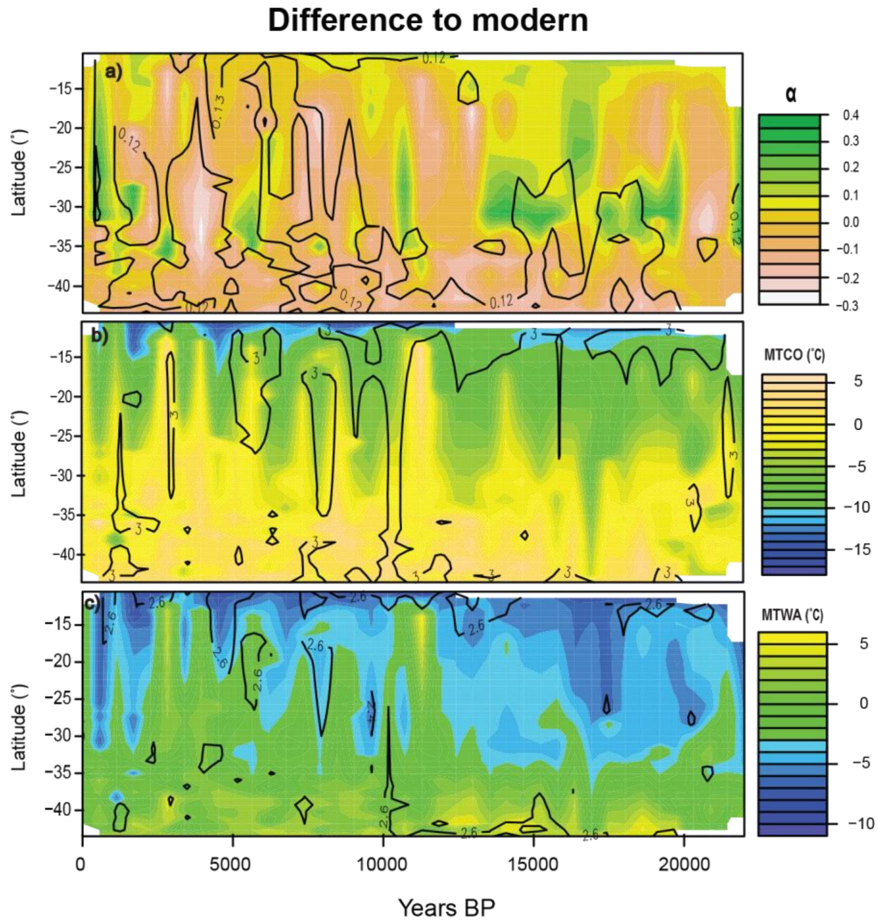

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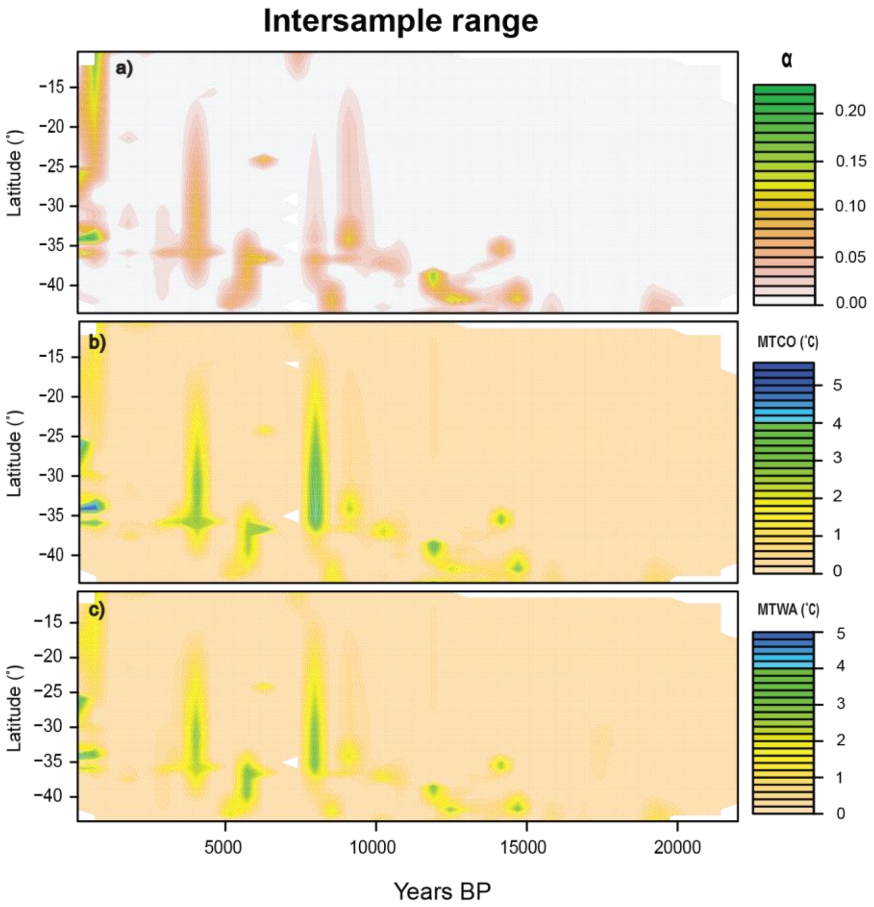

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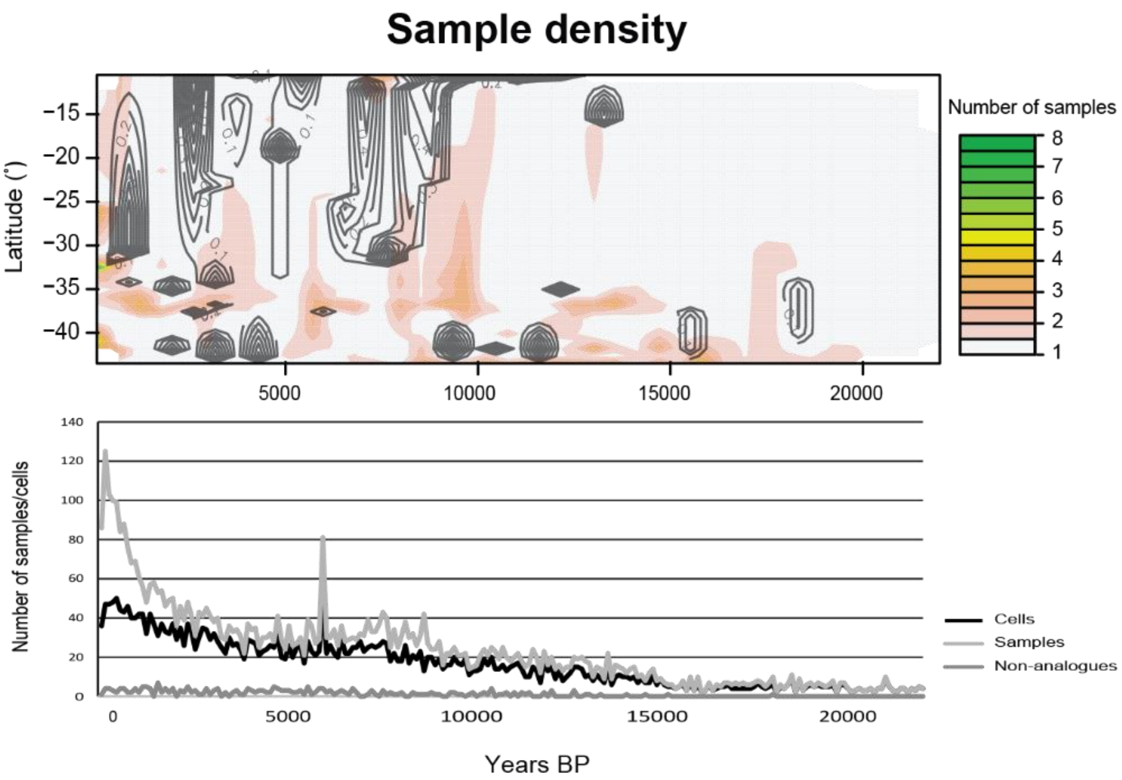

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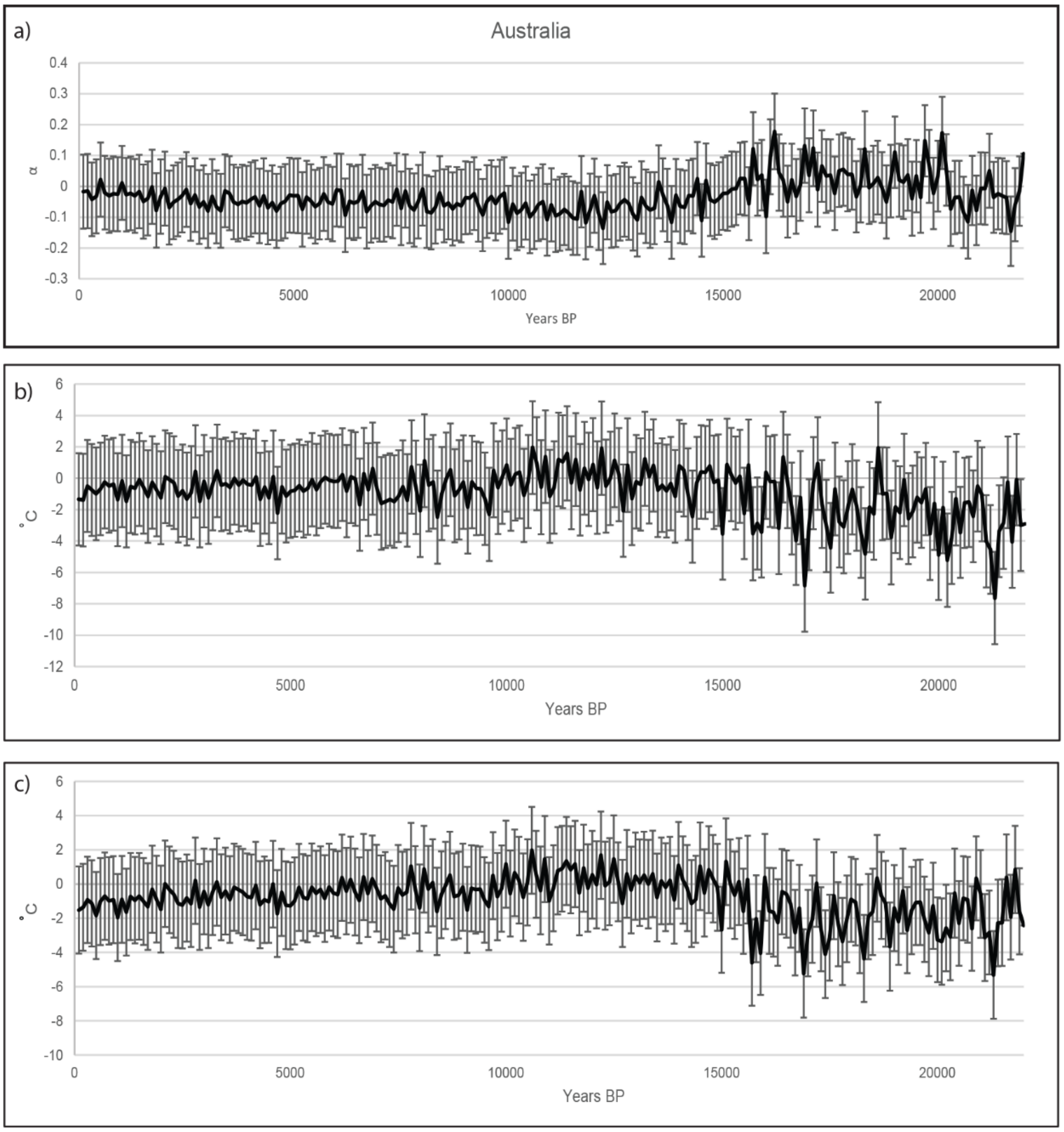

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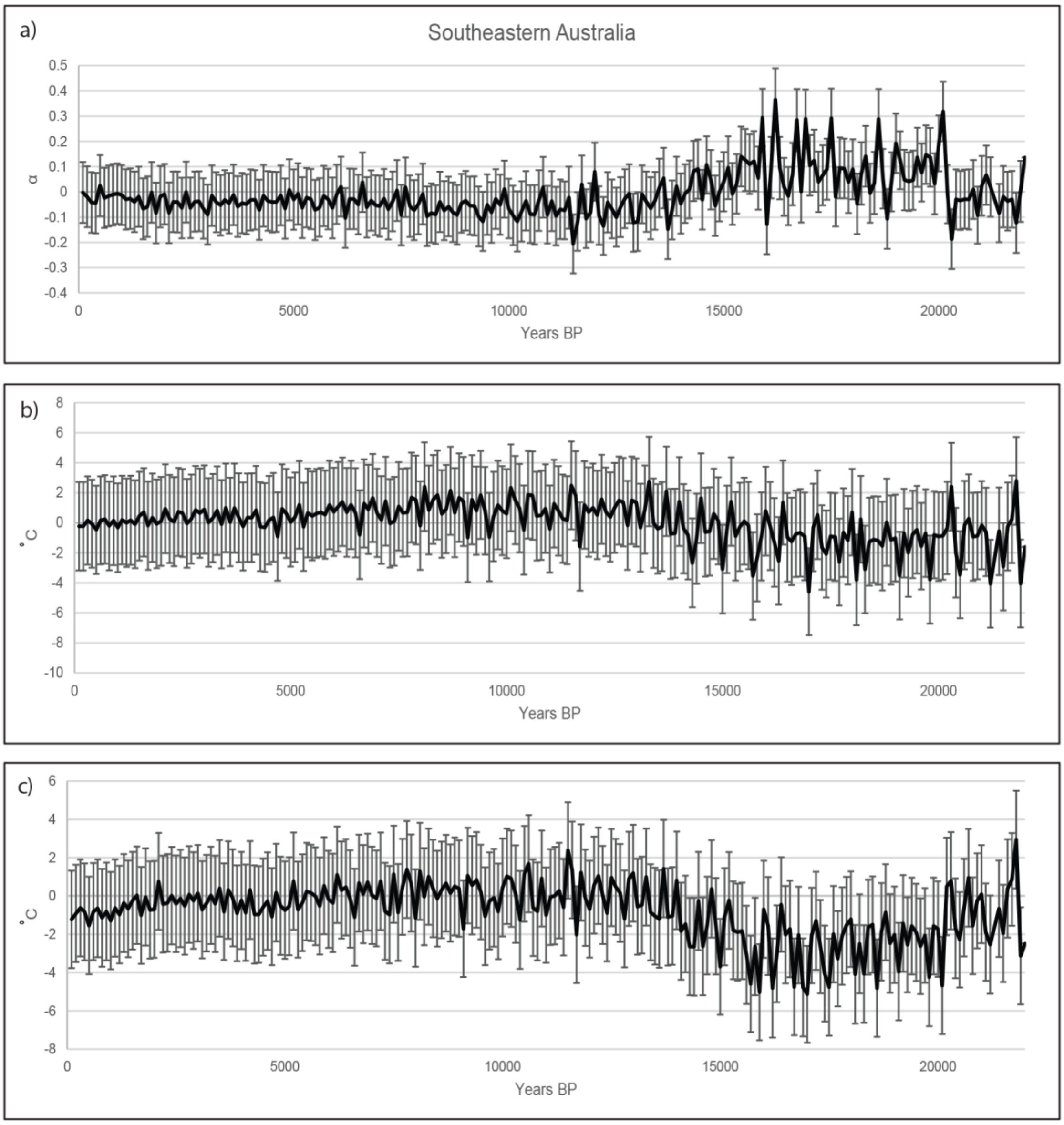

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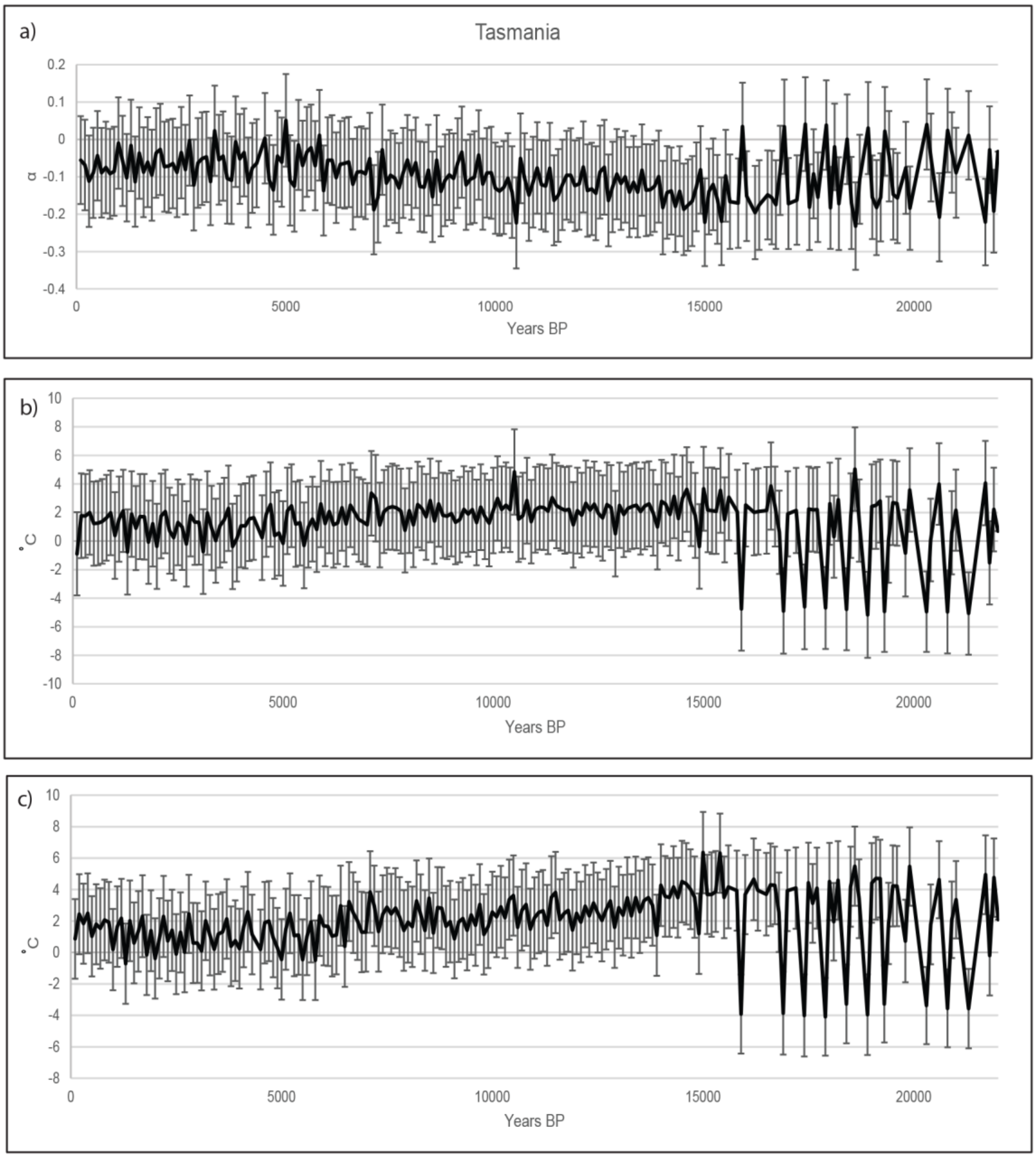

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Supplementary information

Table S1, Sites with coordinates and relevant publications.

	Site	Lat	Long	Source
1	Above Lake Johnston	-41.9	145.55	Fletcher, M.-S., 2009. The Late Quaternary Palaeoecology of Western Tasmania. University of Melbourne PhD thesis.
2	Adamson's Peak	-43.35	146.8167	Macphail, M.K., 1975. The history of the vegetation and climate in Southern Tasmania since the late Pleistocene (ca. 13.000 - 0 BP). PhD thesis, University of Tasmania. Macphail, M.K., 1979. Vegetation and Climates in Southern Tasmania since the Last Glaciation. Quaternary Research 11, 306-341. Macphail, M.K., 1986. 'Over the top': pollen based reconstructions of past alpine floras and vegetation in Tasmania. In: Barlow, B.A. (ed.) Flora and fauna of alpine Australasia: ages and origins. pp. 173–204. CSIRO/Australian Systematic Botany Society, Melbourne.
3	Aire Crossing	-38.73	143.45	D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. McKenzie unpublished data.
4	Airport Swamp	-31.54	159.08	Dodson, J.R., 1982. Modern pollen rain and recent vegetation history on Lord Howe Island: Evidence of human impact. Review of Palaeobotany and Palynology 38, 1-21.
5	Airstrip	-31.75	128.083	Martin, H.A., 1973. Palynology and Historical Ecology of some cave excavations in the Australian Nullarbor. Australian Journal of Botany 21, 283-316.
6	Alexander Morrison NP	-30.067	115.567	Pickett, E.J., 1997. The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia. PhD Thesis, Department of Geography, The University of Western Australia, Crawley, Australia.
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13	Barrington Tops	-31.98	151.91	Dodson, J.R., Myers, C.A., 1986. Vegetation and modern pollen rain from the Barrington Tops and Upper Hunter River regions of New South Wales. Australian Journal of Botany 34, 293-304.
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98	Dublin Bog	-41.717	146.233	Colhoun, E.A., van de Geer, G., Fitzsimons, S.J., 1991. Late Glacial and Holocene vegetation history at Governor Bog, King Valley, western Tasmania, Australia. Journal of Quaternary Science 6, 55–66.
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102	Enoggra State Forest	-28.25	153.167	Kershaw, A.P., 1976. A late Pleistocene and Holocene pollen diagram from Lynchs Crater, north-eastern Queensland, Australia. New Phytologist 77, 469–498.
103	Fitzerald River National Park	-34.188	119.414	Hassell unpublished data
104	Fitzgerald Inlet	-34.292	119.458	Hassell unpublished data
105	Five Mile Beach	-38.95	146.4667	Ladd, P.G., 1971. A Pollen Diagram from Five Mile Beach Swamp, Wilsons Promontory, Hons. B.Sc. Thesis, University of Melbourne, Melbourne. Ladd, P.G., 1979. A Holocene vegetation record from the eastern side of Wilson's Promontory, Victoria. New Phytologist 82, 265–276.
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112	Garden Creek Swamp	-15.66	144.3	Stephens, K., 1990. A late Quaternary vegetation history from south east Cape York derived from swamp and archaeological sediments. Honours thesis, University of Wollongong.
113	Giandarra Bog	-35.85	148.49	Thomas, A., 1991. Giandarra Bog, NSW - A Natural Record of Environmental Change., B.Sc (Honours) Thesis, ADFA.
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116	Gordon Inlet	-34.292	119.458	Hassell unpublished data
117	Governor Bog	-42.1833	145.65	Colhoun, E.A., van de Geer, G., Fitzsimons, S.J., 1991. Late Glacial and Holocene vegetation history at Governor Bog, King Valley, western Tasmania, Australia. Journal of Quaternary Science 6, 55–66.
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130	Hinchinbrook Channel	-18.3167	146.1167	Crowley, G.M., Grindrod, J., Kershaw, A.P., 1994. Modern pollen deposition in the tropical lowlands of north east Queensland, Australia. Review of Palaeobotany and Palynology 83, 299-327.
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156	Lake Burn	-38.29	143.73	Mills, K., Gell, P., Kershaw, P., 2013. The recent Victorian drought and its impact. Without precedent? March 2013, Australian Government Rural Industries Research and Development Corporation RIRDC Publication no. 12/040.
157	Lake Carpentaria	- 11.8708	139.4775	Torgersen, T., Luly, J., De Deckker, P., Jones, M.R., Searle, D.E., Chivas, A.R., Ullman, W.J., 1988. Late Quaternary environments of the Carpentaria Basin, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 67, 245-261. Chivas, A.R., Garcia, A., van der Kaars, S., Couapel, M.J.J., Holt, S., Reeves, J.M., Wheeler, D.J., Switzer, A.D., Murray-Wallace, C.V., Banerjee, D., Price, D.M., Wang, S.X., Pearson, G., Edgar, N.T., Beaufort, L., De Deckker, P., Lawson, E., Cecil, C.B., 2001. Sea-level and environmental changes since the last interglacial in the Gulf of Carpentaria, Australia: an overview. Quaternary International 83-85, 19-46.
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164	Lake Curlip	-37.833	148.5	Ladd, P.G., 1978. Vegetation history at Lake Curlip in Lowland Eastern Victoria, from 5200 B.P. to Present. Australian Journal of Botany, 26, 393-414.
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167	Lake Euramoo	-17.1667	146.633	Haberle, S., 2005. A 23,000-yr pollen record from Lake Euramoo, Wet Tropics of NE Queensland, Australia. Quaternary Research 64, 343-356. Haberle, S., Tibby, J., Dimitriadis, S., Heijnis, H., 2006. The impact of European occupation on

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288	Rotten Swamp	-35.7	148.8833	Clark, R.L., 1986. The fire history of Rotten Swamp, ACT. Unpublished report to ACT Parks and Conservation Service, CSIRO, Canberra, ACT, Australia. Dodson, J.R. and Wright, R.V.S., 1989. Humid to arid to subhumid vegetation shift on Pilliga Sandstone, Ulungra Springs, New South Wales. Quaternary Research 32, 182-192.
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291	Ryans Swamp	-35.1528	150.65	Radclyffe, E., 1993. Fire and people in Jervis Bay: toward a fire history in an occupied landscape. Unpublished BA Honours thesis, Department of Geography, Australian National University.
292	Salt Lake	-37.583	142.317	D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. McKenzie unpublished data.
293	Sandy Creek	-15.57	144.42	Stephens, K., 1990. A late Quaternary vegetation history from south east Cape York derived from swamp and archaeological sediments. Honours thesis, University of Wollongong.
294	Sapphire Swamp	-32.0667	151.5667	Dodson, J.R., Greenwood, P.W., Jones, R.L., 1986. Holocene forest and wetland vegetation dynamics at Barrington Tops, New South Wales. Journal of Biogeography 13, 561-585. Dodson, J.R., 1987. Mire development and environmental change, Barrington Tops, New South Wales, Australia. Quaternary Research 27, 73–81.

295	Scott River Swamp	-34.3	115.283	Churchill, D. M., 1968. The distribution and prehistory of Eucalyptus diversicolor F.Muell., E. marginata Donn ex Sm., and E. calophylla R.Br. in relation to rainfall. Aust. Journal of Botany 16, 125-51.
296	Shark Bay	-26.2257	114.2292	Newsome, J.C., 1999. Pollen-vegetation relationships in semi-arid southwestern Australia. Review of Palaeobotany and Palynology 106, 103-119.
297	Sheet of Water	-37.167	142.35	D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. McKenzie unpublished data.
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299	Sluice Creek	-17.517	145.567	Kershaw, A.P., 1973. The numerical analysis of modern pollen spectra from northeast Queensland rain-forests. Special Publications Series of the Geological Society of Australia 4, 191–199.
300	Smelter Creek	-42.1833	145.6333	Colhoun, E.A., van de Geer, G., Fitzsimons, S.J., 1992. Late Quaternary organic deposits at Smelter Creek and vegetation history of the Middle King Valley, western Tasmania. Journal of Biogeography 19, 217–227.
301	Snobs Creek	-37.3911	145.9281	McKenzie, G.M., 1989. Late Quaternary vegetation and climate in the central highlands of Victoria: with special reference to Nothofagus cunninghamii (Hook.) Oerst. rainforest. PhD Thesis, Monash University, Melbourne, Victoria, Australia. McKenzie, G.M. and Busby, J.R., 1992. A quantitative estimate of Holocene climate using a bioclimatic profile of Nothofagus cunninghamii (Hook.) Oerst. Journal of Biogeography 19, 531–540.
302	Snow Hill Marshes	-41.9	147.85	Becker unpublished data. D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for

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303	Snowy Flats	-35.5655	148.8642	Hope, G., Macphail, M., Keaney, B., 2006a. Report for Mountain Occupation Project: Mires of the Australian Capital Territory Region. Hope, G., Macphail, M., Keaney, B., 2006b. Mountain Occupation Project: Mires of the Australian Capital Territory region. Unpublished report. Department of Archaeology and Natural History, Australian National University, Canberra. Version 2.
304	South Salvation Creek Swamp	-33.63	151.26	Kodela, P.G. and Dodson, J.R., 1988. A late Holocene vegetation and Fire Record from Ku-ring-gai Chase national park, NSW. Proceedings of the Linnaean Society of N.S.W 110 (4), 317-326.
305	Stencils cave	-31.467	129.7	Martin, H.A., 1973. Palynology and Historical Ecology of some cave excavations in the Australian Nullarbor. Australian Journal of Botany 21, 283-316.
306	Stirling Moss	-37.1333	146.5	D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. McKenzie unpublished data.
307	Stockyard Swamp	-40.55	144.75	Hope, G.S., 1999. Vegetation and fire response to late Holocene human occuptation in island and mainland north west Tasmania. Quaternary International 59, 47-60.
308	Stonehaven Creek	-42.21	145.99	Fletcher, M.-S., 2009. The Late Quaternary Palaeoecology of Western Tasmania. University of Melbourne PhD thesis.
309	Storm Creek	-37.4442	145.8069	McKenzie, G.M. and Busby, J.R., 1992. A quantitative estimate of Holocene climate using a bioclimatic profile of Nothofagus cunninghamii (Hook.) Oerst. Journal of Biogeography 19, 531–540. McKenzie, G.M., 1997. The late Quaternary vegetation history of the south-central highlands of Victoria, Australia. I. Sites above 900 m. Australian Journal of Ecology 22, 19–36.
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315	Tamaringa Billabong	-37.15	145.4833	D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. Reid unpublished data.
316	Tarcutta Swamp	-35.6667	148.0333	Williams unpublished data.
317	Tarn Shelf	-42.6667	146.5	Macphail, M.K., 1979. Vegetation and Climates in Southern Tasmania since the Last Glaciation. Quaternary Research 11, 306-341. Macphail, M.K., 1986. 'Over the top': pollen based reconstructions of past alpine floras and vegetation in Tasmania. In: Barlow, B.A. (ed.) Flora and fauna of alpine Australasia: ages and origins. pp. 173–204. CSIRO/Australian Systematic Botany Society, Melbourne.
318	Tarraleah Bog	-42.3	146.433	Macphail, M.K., 1984. Small-scale dynamics in an Early Holocene wet sclerophyll forest in Tasmania. New Phytologist 96, 131-147.
319	Tawonga Bog	-36.6833	147.1333	Kershaw, A.P. and Green, J.E., 1983. Tawonga Bog revisited: the history of a low altitude peat deposit. The Victorian Naturalist 100, 256–259.

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321	Three Quarter Mile Lake	-13.7473	143.4874	Luly, J.G., Grindrod, J.F., Penny, D., 2006. Holocene palaeoenvironments and change at Three-Quarter Mile Lake, Silver Plains Station, Cape York Peninsula, Australia. The Holocene 16 (8), 1085-1094.
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324	Tiger Snake Swamp	-38.117	145.267	Aitken, D.L and Kershaw, A.P., 1993. Holocene vegetation and environmental history of Cranbourne Botanic Garden, Victoria. Proceedings of the Royal Society of Victoria 105(1), 67-80.
325	Tinaroo Range	-17.117	145.567	Kershaw, A.P., 1973. The numerical analysis of modern pollen spectra from northeast Queensland rain-forests. Special Publications Series of the Geological Society of Australia 4, 191–199.
326	Tinaroo Road	-17.117	145.517	Kershaw, A.P., 1973. The numerical analysis of modern pollen spectra from northeast Queensland rain-forests. Special Publications Series of the Geological Society of Australia 4, 191–199.
327	Tom Burns	-37.3856	145.8181	McKenzie, G.M. and Busby, J.R., 1992. A quantitative estimate of Holocene climate using a bioclimatic profile of Nothofagus cunninghamii (Hook.) Oerst. Journal of Biogeography 19, 531–540.

				McKenzie, G.M., 1997. The late Quaternary vegetation history of the south-central highlands of Victoria, Australia. I. Sites above 900 m. Australian Journal of Ecology 22, 19–36.
328	Tom Gregory Swamp	-35.38	148.49	Hope, G., 2005. Tom Gregory Bog: an infilled meander of the upper Cotter River, Australian Capital Territory. Unpublished Report. Department of Archaeology and Natural History, Australian National University, Canberra.
329	Tooperoopna	-34.0014	141.6369	Cupper, M.L., Drinnan, A.N., Thomas, I., 2000. Holocene palaeoenvironments of salt lakes in the Darling Anabranch region, south-western New South Wales, Australia. Journal of Biogeography 27, 1079-1094. Cupper, M., 2005. Last Glacial to Holocene evolution of semi-arid rangelands in southeastern Australia. The Holocene 15 (4), 541-553.
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331	Torres Strait coastal	-10.0667	142.15	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and Environmental Science, Monash University.
332	Torres Strait lowland	-10.2	142.3	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and Environmental Science, Monash University.
333	Torres Strait rainforest	-10.2	142.2333	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and Environmental Science, Monash University.
334	Torres Strait sclerophyll	-10.1333	142.2333	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and Environmental Science, Monash University.
335	Tortoise Lagoon	-27.52	153.47	Moss, P.T., Tibby, J., Petherick, L., McGowan, H., Barr, C., 2013. Late Quaternary vegetation history of North Stradbroke Island, Queensland,

				eastern Australia. Quaternary Science Reviews 74, 257-272.
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338	Tumoulin Swamp	-17.55	145.45	Kershaw, A.P., 1976. A late Pleistocene and Holocene pollen diagram from Lynchs Crater, north-eastern Queensland, Australia. New Phytologist 77, 469–498.
339	Two Mile Lake	-34.5	118.27	Chalson, J.M., 1991. The Late Quaternary vegetation and climatic history of the Blue Mountains, N.S.W. Australia. Unpublished PhD thesis, University of N.S.W., Sydney. Itzstein-Davey, F., 2003. Changes in the abundance and diversity of the Proteaceae over the Cainozoic in south-western Australia. University of Western Australia PhD thesis.
340	Tyndall Ranges	-41.93	145.58	Macphail, M.K., 1986. 'Over the top': pollen based reconstructions of past alpine floras and vegetation in Tasmania. In: Barlow, B.A. (ed.) Flora and fauna of alpine Australasia: ages and origins. pp. 173–204. CSIRO/Australian Systematic Botany Society, Melbourne.
341	Ulungra Springs	-31.74	149.09	Dodson, J.R., Wright, R.V.S., 1989. Humid to arid to subhumid vegetation shift on Pilliga Sandstone, Ulungra Springs, New South Wales. Quaternary Research 32, 182-192.
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344	Upper Lake Wurrawina	-42.53	146.25	Macphail, M.K. and Colhoun, E.A., 1982. Upper Lake Wurawina cirque, Denison Range, central Southern Tasmania. In: Holocene research in Australia 1978-1982, Occasional Papers no 33, pp. 106-107. Department of Geography, University of New South Wales: Duntroon. Macphail, M.K., 1986. 'Over the top': pollen based reconstructions of past alpine floras and vegetation in Tasmania. In: Barlow, B.A. (ed.) Flora and fauna of alpine Australasia: ages and origins. pp. 173–204. CSIRO/Australian Systematic Botany Society, Melbourne.
345	Upper Timk Lake, Mt Anne.	-42.9333	146.45	Harle, K.J., 1989. Palaeoenvironments of the Mount Anne region in Southwestern Tasmania. BSc Honours Thesis, Monash University, Clayton, Victoria. D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605.
346	Vale of Belvoir	-41.54	145.89	Fletcher, M.-S., 2009. The Late Quaternary Palaeoecology of Western Tasmania. University of Melbourne PhD thesis.
347	Wanteen	-31.707	128.417	Martin, H.A., 1973. Palynology and Historical Ecology of some cave excavations in the Australian Nullarbor. Australian Journal of Botany 21, 283-316.
348	Warrananga Salt Lake	-33.9672	141.5517	Cupper, M.L., Drinnan, A.N., Thomas, I., 2000. Holocene palaeoenvironments of salt lakes in the Darling Anabranch region, south-western New South Wales, Australia. Journal of Biogeography 27, 1079-1094. Cupper, M., 2005. Last Glacial to Holocene evolution of semi-arid rangelands in southeastern Australia. The Holocene 15 (4), 541-553.
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350	Warrimoo Oval Swamp	-33.72	150.61	Chalson, J.M., 1991. The Late Quaternary vegetation and climatic history of the Blue Mountains, N.S.W. Australia. Unpublished PhD thesis, University of N.S.W., Sydney.
351	Waruid	-10.0667	142.15	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and

				Environmental Science, Monash University, Melbourne. Rowe, C., 2007. A palynological investigation of Holocene vegetation change in Torres Strait, seasonal tropics of northern Australia. Palaeogeography, Palaeoclimatology and Palaeoecology 25 (1), 83-103.
352	Waterhouse Marsh	-40.8667	147.6333	D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. Thomas unpublished data.
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354	Wathumba	-24.9812	153.2572	Moss, P., Tibby, J., Shapland, F., Barr, C., Fairfax, R., 2012. A report into the fire history of the Patterned Fens of the Great Sandy Region, South East Queensland. Unpublished report to the Burnett Mary Regional Group, Bundaberg, Queensland. Moss, P., Tibby, J., Shapland, F., Fairfax, R., Stewart, P., Barr, C., Petherick, L., Allen Gontz, A., Sloss, C., (in press) Patterned fen formation and development from the Great Sandy Region, south east Queensland, Australia. Marine and Freshwater Research.
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356	Welsby Lagoon	-27.44	153.45	Colhoun, E.A., 1986. Field problems of radiocarbon dating in Tasmania. Papers and Proceedings of the Royal Society of Tasmania 120, 1-6.
357	West Basin	-38.3167	143.45	Gell, P.A., Barker, P.A., DeDeckker, P., Last, W., Jelicic, L., 1994. The Holocene history of West Basin Lake, Victoria, Australia: chemical changes based on fossil biota and sediment mineralogy. Journal of Palaeolimnology 12, 235-258.
358	West Lake, Muir Swamp	-34.467	116.6	Churchill, D. M., 1968. The distribution and prehistory of Eucalyptus diversicolor F.Muell., E. marginata Donn ex Sm., and E. calophylla

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359	Wet Lagoon	-34.7833	149.4167	Dodson, J.R., 1983. Modern pollen rain in southeastern New South Wales, Australia. Review of Palaeobotany and Palynology 38, 249–268. Dodson, J.R., 1986. Holocene vegetation and environments near Goulburn, New South Wales. Australian Journal of Botany 34, 231-249.
360	Willsmere Billabong	-37.7833	145.05	McNess, A., 1988. A fine resolution vegetation history from a Melbourne metropolitan park. BA Honours Thesis, Monash University, Melbourne, Victoria, Australia. D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605.
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362	Windin	-17.317	145.783	Kershaw, A.P., 1973. The numerical analysis of modern pollen spectra from northeast Queensland rain-forests. Special Publications Series of the Geological Society of Australia 4, 191–199.
363	Witherspoon Swamp	-17.8167	145.4	Moss, P.T., Cosgrove, R., Ferrier, Å., Haberle, S.G., 2012. Holocene environments of the sclerophyll woodlands of the Wet Tropics of northeastern Australia. Terra Australis 34, 329-341.
364	Wolgan	-33.24	150.14	Chalson, J.M., 1991. The Late Quaternary vegetation and climatic history of the Blue Mountains, N.S.W. Australia. Unpublished PhD thesis, University of N.S.W., Sydney.
365	Wood Nymphs Dell Forest	-33.7	150.4	Chalson, J.M., 1991. The Late Quaternary vegetation and climatic history of the Blue Mountains, N.S.W. Australia. Unpublished PhD thesis, University of N.S.W., Sydney.
366	Woorady	-40.4	146	Blom, W.M., 1988a. Late quaternary facies of Bass Strait, southeastern Australia: their environmental significance and response to sea-level change. PhD thesis University of Sydney. Blom, W.M., 1988b. Late Quaternary sediments and sea-levels in Bass Basin, southeastern Australia - a preliminary report. Search 19, 94-96.

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367	Wriggly Stick Swamp	-37.75	149.433	D'Costa, D.M. and Kershaw, A.P., 1997. An expanded recent pollen database from south-eastern Australia and its potential for refinement of palaeoclimatic estimates. Australian Journal of Botany 45, 583–605. Kenyon unpublished data.
368	Wrights Creek Valley	-33.3096	150.991	Jones, R.L. and Dodson, J.R., 1997. A Holocene vegetation record from Wrights Creek Valley, New South Wales. Proceedings of the Linnaean Society of New South Wales 118, 2-22.
369	Wyelangta	-38.65	143.4667	McKenzie, G. M., and Kershaw, A.P., 2000. The Last Glacial cycle from Wyelangta, the Otway region of Victoria, Australia. Palaeogeography Palaeoclimatology Palaeoecology 155 (1-2), 177-193.
370	Wyndham	-15.4675	128.0994	Proske, U. 2013. Unpublished data. Proske, U., Heslop, D., Haberle, S., 2014. A Holocene record of coastal landscape dynamics in the eastern Kimberley region, Australia. Journal of Quaternary Science 29 (2), 163-174.
371	Wyrie Swamp	-37.67	140.42	Dodson, J.R., 1977. Late Quaternary paleoecology of Wyrie Swamp, southeastern South Australia. Quaternary Research 8, 97–114.
372	Wyvuri Swamp	-17.35	146.017	Crowley, G.M., Grindrod, J., Kershaw, A.P., 1994. Modern pollen deposition in the tropical lowlands of north east Queensland, Australia. Review of Palaeobotany and Palynology 83, 299-327.
373	Yalgorup	-32.867	115.667	Pickett, E.J., 1997. The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia. PhD Thesis, Department of Geography, The University of Western Australia, Crawley, Australia.
374	Yam Camp	-15.66	144.3	Stephens, K., 1990. A late Quaternary vegetation history from south east Cape York derived from swamp and archaeological sediments. Honours thesis, University of Wollongong.
375	Yanchep NP	-31.283	116.067	Pickett, E.J., 1997. The late Pleistocene and Holocene vegetation history of three lacustrine sequences from the Swan Coastal Plain, southwestern Australia. PhD Thesis, Department of Geography, The University of Western Australia, Crawley, Australia.

376	Yarlington Tier	-42.535	147.3008	Harle, K.J., Kershaw, A.P., Macphail, M.K., Neyland, M.G., 1993. Palaeoecological analysis of an isolated stand of Nothofagus cunninghamii (Hook.) Oerst. in eastern Tasmania. Australian Journal of Ecology 18(2), 161-170.
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378	Zurath Islet	-10.2667	142.1	Rowe, C., 2006. A Holocene history of vegetation change in the western Torres Strait region, Queensland, Australia. Unpublished PhD thesis, School of Geography and Environmental Science, Monash University, Melbourne. Rowe, C., 2007. A palynological investigation of Holocene vegetation change in Torres Strait, seasonal tropics of northern Australia. Palaeogeography, Palaeoclimatology and Palaeoecology 25 (1), 83-103.

Chapter 4

Comparing model outputs with statistical temperature reconstructions derived from a comprehensive pollen database for Australia

Chapter 4: Comparing model outputs with statistical temperature reconstructions derived from a comprehensive pollen database for Australia

Based on the outcomes of chapter 3, the next natural step is to use the quantitative palaeoclimate reconstructions produced and compare them to, and use them to evaluate, output from palaeoclimate models. These comparisons are presented in this chapter.

Contribution of co-authors: A.V.H was responsible for data analysis, figure and table generation, with guidance from S.P.H.; A.V.H. wrote the text.

Comparing model outputs with statistical temperature reconstructions derived from a comprehensive pollen database for Australia.

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Abstract

Comparing model output to large-scale quantitative palaeoclimate reconstructions or syntheses is a powerful tool for model improvement as well as improving our knowledge of the Earth's climate system. This study uses the first continuous continental scale quantitative palaeoclimate reconstruction going back further than 1000 years for Australia to evaluate PMIP3 model output and identify areas for model improvement. We found that the simulated anomalies for the Last Glacial Maximum (LGM) are slightly closer to previously reconstructed temperatures for the Australian LGM than the examined reconstructions are, probably due to a lack of cold climate analogues in the training set used. The mid-Holocene simulations, on the other hand, were highly variable, both geographically and between models, especially for MTCO. This may indicate that the models have failed to properly take into account all controls on Australian winter climate during the mid-Holocene. While it is unclear what specific controls these might be, they are not geographically restricted. Further studies are needed to clarify the nature of these controls.

Keywords

Climate modelling, climate reconstructions, mid-Holocene, Last Glacial Maximum, paleoclimate benchmarking.

1. Introduction

Performing large-scale palaeoclimate simulations is a powerful tool for understanding our climate system better and for evaluating modelling procedures and specific models used for simulations of possible future climate changes. Modelling possible future climate scenarios is of vital importance to understand and mitigate the potential dangers involved in these scenarios. In order for the simulations to be as accurate as possible the model performance needs to be tested against known scenarios. However, the instrumental records only goes back at most about 300 years (Manley, 1953), a period of relatively stable climate without climate forcings near the scale we are predicted to face in the future. Therefore it is important to quantitatively reconstruct past changes in climate, especially for periods with large external forcings, such as the Last Glacial Maximum (LGM, 21 000 years before present, 21 ka BP, Braconnot *et al.,* 2012), to provide a basis for comparison.

Modelling past periods for which the changes in climate are well known through ample quantitative palaeoclimate reconstructions will also help us understand the climate system better, as hypotheses regarding the causes of climate events can be tested. Key time periods to use for these types of studies are the mid-Holocene (6 ka BP) and the LGM. The mid-Holocene is important not only due to this period being well-studied, but also because it was the subject of different climatic forcings compared to today, for example with seasonality being reduced in the Southern Hemisphere by around 5% and increased by about the same in the Northern Hemisphere (Joussaume *et al.,* 1999, Brown *et al.,* 2008). The LGM is a key time period as the radiative forcing during this time was approximately opposite to the future RCP4.5 scenario used by the Intergovernmental Panel on Climate Change (IPCC, Chavaillaz *et al.,* 2013), and it is also a well-studied period with numerous quantitative reconstructions available for comparison. Both of these time periods are part of core experiments for the Palaeoclimate Modelling Intercomparison Project (PMIP) and the Coupled Modelling Intercomparison Project (CMIP).

In order to properly evaluate climate model performance using palaeoclimate reconstructions, large-scale data syntheses are needed, either in terms of databases of climate reconstructions (i.e. Bartlein *et al.,* 2011) or databases of raw data such as pollen samples, from which climate reconstructions can be performed (i.e. Pickett *et al.,* 2004). Whilst there has been many such studies for North America (e.g. Viau *et al.,* 2006) and

Europe (e.g. Davis *et al.,* 2003), there has been a lack of them elsewhere, especially in the Southern Hemisphere. For instance, there has been only one continuous continental scale quantitative palaeoclimate reconstruction for Australia going back more than 1000 years to date (Herbert *et al.,* in prep.). The lack of suitable palaeoclimate studies in the Southern Hemisphere means that when the few records that do exist are contradictory, such as for changes in the southern westerly wind belt during the LGM (Kohfeld *et al.,* 2013), the reconstructions are not able to provide suitable restrictions for modelling studies, hence their results may also be contradictory (e.g. Rojas *et al.,* 2009).

As mentioned previously, there are two major modelling groups, CMIP and PMIP, both founded in the 1990's to facilitate cooperation between climate modellers and comparisons between models, in order to improve climate model performance. The projects run by these groups are run according to the same protocol and perform the same core experiments for comparison and evaluation purposes. Despite these precautions, individual climate models may differ significantly, so the mean of an ensemble of models is recommended for use according to the CMIP/PMIP protocol (Taylor *et al.,* 2009). To facilitate comparability between experiments, pre-industrial control runs are used as a baseline, and the difference to this control run is presented for each experiment.

Due to the lack of large-scale quantitative palaeoclimate reconstructions for Australia, very few regional palaeoclimate model-data comparison studies have been performed to date, with the recent study by Ackerley *et al.* (2016) being a noticable exception. This paper is a step towards amending this further, with the aim to compare the simulations for Australia with the reconstructions, and with the other simulations.

2. Methods

The quantitative palaeoclimate reconstructions for the mid-Holocene (6 $\pm$ 0.5 ka BP) and Last Glacial Maximum (LGM, 21 $\pm$ 1 ka BP) from Herbert *et al.* (in prep.) were compared to climate model output from an ensemble of PMIP3 models (Table 1, data downloaded from https://pcmdi.llnl.gov/projects/esgf-llnl/). α could not be calculated from these data, so only the temperature variables mean temperature of the coldest and warmest months (MTCO and MTWA, respectively) were used.

The anomalies between the target period simulations and the pre-industrial control runs were calculated for each of the models and both variables, then mapped. Since the models use different spatial resolutions (Table 1), the coarsest grid was chosen (3.7°) and all the anomalies from the other models were averaged up to match this grid size before the ensemble mean was calculated. The range of values incorporated in the ensemble were added to the ensemble plot as a contour. The difference between individual models and the ensemble mean was plotted separately. The anomalies for the reconstructions were calculated compared to the modern reconstructions using the training set, as per Bartlein *et al.* (2011) and Herbert *et al.* (in prep.). These anomalies were averaged to match the grid cell sizes of each model and the ensemble separately before being added to the appropriate plots as points, size and shape depending on how closely they match the model. Large points signify that the reconstructed anomaly is more than twice the size of the associated error, i.e. it is significant. Small points signify that the reconstructed anomaly is within the error range. Hollow points mean that the reconstructed anomaly is of the same sign as the simulated anomaly for the same grid cell, solid points indicating that they are of opposite sign.

Most statistical measures for model evaluation are either designed solely for inter-model comparisons or require a higher density of data than is available for most of Australia. Individual grid cells are difficult to use due to the large size of the grid cells involved and the need to have multiple values for each model and reconstruction in these grid cells in order for the comparisons to be statistically robust. We therefore base our comparisons on the average simulated and reconstructed anomalies for the whole continent. The comparisons were performed using a Kolmogorov-Smirnov test with a 95% confidence interval to determine significance, after testing for normality (using a Shapiro-Wilk test) and heterogeneity of variance (using a Fligner-Killeen test). These tests were run both on the values for each model and the ensemble mean compared to the reconstructions.

3. Results

3.1 Model maps

From figure 1a it is clear that the biggest difference between the models is over eastern Australia, with the averaged values not being larger than half a degree, but the range being close to 1.5 degrees. Most of the reconstructions also show very small anomalies for this time period, only a few points in the north being significant. These points agree with the ensemble mean that MTCO was lower during the mid-Holocene. The colour schemes differ slightly between the models due to the difference in range of values that they cover, but as no anomalies are greater than a degree, this does not make a great difference to the comparisons. All models capture the aforementioned reduction in temperature captured by the reconstructions, but elsewhere there are significant differences. For instance, CSIRO-Mk3-6-0 and GISS-E2-R (figure 1b and e) are almost diametrically opposed, with CSIRO simulating cooling in the northwest and warming in the southeast, while GISS simulates warming in the northwest and cooling in the southeast. According to figure 2c, the FGOALS-g2 simulation is consistently lower than the ensemble mean, whereas CSIRO (figure 2b) is only below the ensemble mean in a band across central Australia.

According to figure 3a, the model ensemble mean consistently simulates a reduction in MTWA for the mid-Holocene, the largest cooling occurring in the east. This matches the significant reconstruction anomalies from the interior and in the north. The largest difference between the models is in the northeast. All the models simulate this reduction in temperature in the east, with the CNRM-CM5 simulation (figure 3b) being the only model with a different scale, as the cooling for this model is a lot smaller than for the other models. This is can also be seen in figure 4a, which shows that the CNRM-CM5 simulation is mostly warmer than the ensemble mean, except for Tasmania.

The largest simulated reduction in MTCO for the ensemble mean during the LGM is along the coast, but this is also where the largest ranges of simulated values are located (figure 5a). Even though FGOALS-g2 (figure 5e) looks different from the other simulations, this is largely due to the difference in scales being used, the FGOALS scale skewed by positive values over the sea southeast of the continent, which can also be seen in figure 6d. The largest reductions for all simulations are along the coast, the range plotted in figure 5a due to the difference in the size of the reductions. All the significant reconstructions also show reductions in MTCO.

For the ensemble mean simulation of LGM MTWA (Figure 7a), the whole continent shows a cooling, the smallest being in the far north and over Tasmania. The largest difference between the models is in the far north and over the sea southeast of the continent. All the significant reconstructions also show a reduction in LGM MTWA. The individual simulations show quite different patterns, with most models showing local pockets of warming and significant cooling for most of the rest of the continent, except MIROC-ESM (figure 7g), which only shows a large reduction in the Gulf of Carpentaria and the sea north of Australia. According to figure 8, only CNRM-CM5 consistently simulates a higher MTWA than the ensemble mean, the other models simulating both above and below the ensemble mean, FGOALS-g2 only simulating above the ensemble mean over the sea southeast of the continent, MPI-ESM-P simulating above the ensemble mean over the sea north of the continent.

3.2 Statistical comparisons

From Table 2 it is clear that the MTCO anomalies for the mid-Holocene vary greatly between the models, some showing an increase in MTCO compared to the pre-industrial runs, some a negligible change, other still a decrease. This variation is probably the reason all the individual simulations are significantly different from the ensemble mean, and from the reconstruction anomaly. For MTWA, all anomalies are negative, but the individual simulations are still significantly different from the ensemble mean and the reconstruction mean. This might be because the significance tests that were performed tests not only the difference in averages, but also the distribution of component values (Massey, 1951). The simulated changes in seasonality are again all significantly different from the reconstructed change in seasonality, but three out of the seven individual simulations are not significantly different from the ensemble mean, namely CNRM-CM5, FGOALS-g2 and MIROC-ESM.

Despite most of the average anomalies in table 3 showing a cooling of around 2 K at the LGM, all the simulated anomalies are significantly different from the reconstructions, and all individual simulations are significantly different from the ensemble mean, for both variables. Again, this is most probably due to differences in the distributions. For the change in seasonality, most anomalies are about 0.5 K, including the reconstruction, yet the only simulation that shows a seasonality change greater than a degree, is also the only one not significantly different from the reconstruction value.

4. Discussion and conclusions

The reduced seasonality in the Southern Hemisphere during the mid-Holocene, as suggested by other studies (e.g. Berger, 1978; Joussaume, 1999) and most of the models as well as the ensemble mean in figures 1 and 3, is quantified in table 3. The change in seasonality is negative for all simulations and the reconstructions, the anomalies for MTCO higher than those for MTWA, meaning warmer winters, cooler summers and hence reduced seasonality. The simulated anomalies for MTCO show a greater variability than for MTWA, with all models agreeing on the reduced MTWA in the east, for example. For MTCO all models do agree on the cooling in the north, and while this is a much smaller area than the area of MTWA agreement, it does mean that for both variables all the models simulate the same sign as most of the significant reconstructed anomalies present, the exceptions being a few sites in the north for both variables, but only for the individual models. The conclusion that MTCO shows greater variability than MTWA is supported by table 2, where the average MTWA anomalies are consistently negative, whereas the average MTCO anomalies may be positive (CNRM-CM5, CSIRO-Mk3-6-0), negative (FGOALS-g2, GISS-E2-R, MIROC-ESM) or negligible (MPI-ESM-P, MRI-CGCM3). The reconstruction anomaly is negative, so the three models simulating a reduction in MTCO might be more realistic. The variation may be due to the difference in resolution (Table 1), as the three models simulating the reduction also have the coarsest resolution. Finer resolution models are generally expected to provide better simulations compared to models with coarser resolution. However, models with a coarser grid are typically more complex, as they are more computer efficient (Flato *et al.,* 2013). In this case it is possible that the increased complexity of the coarser models capture something in the mid-Holocene winter climate system of Australia that the finer resolution models fail to capture.

The temperature variability during the mid-Holocene may be due to the increased influence of El Niño Southern Oscillation (ENSO) during this time period (Donders *et al.,* 2007), which is known to cause significant interannual climate variability in Australia in the present day (Dodson, 2001). As the anomalies here are averaged over a 1000-year time window (6 ± 0.5 ka BP), interannual variability cannot be detected, but ENSO will affect areas differently, and the geographical variability seen in figures 1-4 may still be due to the influence of ENSO, just as it has been suggested to affect temperature variability in other Australian palaeoclimate studies (Gouramanis *et al.,* 2013; Petherick *et al.,* 2013). This hypothesis is supported by the varying ability of CMIP5 models to simulate ENSO amplitude, despite improvements compared to earlier versions (Bellenger *et al.,* 2014; Rotstayn *et al.,* 2010).

For the LGM, all models show a similar decline in both temperature variables for Australia, (Figures 5, 7 and table 3), although for MTCO there are localised increases in the cooling along the coast (Figure 5), whereas for MTWA there is localised warming along the coast (Figure 7). The reduction in MTCO is greater than that for MTWA for all models as well as the reconstruction mean (Table 3). All this leads to the increase in seasonality quantified in table 3, for all models except COSMOS-ASO, which shows a negligible reduction in seasonality. This is also the model which has the greatest reduction in temperature overall, as well as being the model with the coarsest resolution (Table 1), so the difference may be due to the increased complexity this coarse resolution allows. In this instance the increased complexity may have led to a less realistic simulation, because an increase in seasonality at the LGM in the Southern Hemisphere is supported by previous studies (e.g. Drost *et al.,* 2007).

The reconstructions show a less pronounced decrease in temperature than most of the simulations, possibly due to the lack of cold climate analogues in the training set used, a known issue for Australian palaeoclimate studies, the floral assemblages present during the last glacial not being present anywhere on the continent today (Galloway, 1965; Dodson, 1998). Most reconstructions of Australian LGM temperatures show a decrease of between 4 and 12°C (Galloway, 1965; Miller *et al.,* 1997; Fletcher and Thomas, 2010; Woltering *et al.,* 2014; Chang *et al.,* 2015). Whilst this is quite a large range of estimates, the smallest reduction still represents a slightly greater temperature reduction than the greatest reduction of any of the simulations or reconstruction anomalies presented in table 3. This is most likely due to the variability in simulated MTWA anomalies (Figure 7), where some areas show increases, including CNRM-CM5 and MRI-CGCM3, which are the only simulations to contain a grid cell that has an anomaly of opposite sign to its associated significant reconstruction. This point is the same for both models, being in the Gulf of Carpentaria, an area of warming during the LGM according to these models. The Gulf of Carpentaria being an area of warming in these two models is also clear from figure 8, which shows that this is the area these models differ most from the ensemble mean, over 3 degrees above for both. These models are amongst those with the finest resolution, so the reason they have captured this localised warming may be due to some small-scale feedback mechanism that the coarser grid models have missed, such as tropical low cloud feedback (Kamae *et al.,*

2016) or cloud response to changing CO_2 concentrations (Taylor *et al.,* 2009). As the CO_2 concentrations at the LGM are known to have been significantly lower than today (Braconnot *et al.,* 2012), this is a likely explanation.

This paper provides a valuable comparison between palaeoclimate output and the first continuous continental scale quantitative palaeoclimate reconstruction going back further than 1000 years for Australia. We have shown that these reconstructions agree with the models when it comes to the magnitude of the reduction in temperature for both winter and summer during the Last Glacial Maximum as well as the reduction in summer temperature during the mid-Holocene. The simulated MTCO anomalies for the mid-Holocene vary greatly between the models, but the spatial variability of the simulated anomalies for this period is supported by previous studies as well as by the spatial variability of the reconstructed anomalies. However, the fact that the inter-model variability is greatest for MTCO suggests that the models may be underrepresenting the climate forcings affecting Australian mid-Holocene winter temperatures, something possibly captured by the models with coarsest resolution. The models used in this study have been found to have difficulty in accurately simulating ENSO-related patterns, and ENSO is known to affect climate variability in eastern Australia (Dodson, 2001). Further studies are needed to determine if this is indeed the cause of the high degree of inter-model variability when it comes to simulating Australian winter temperature for the mid-Holocene.

Acknowledgements

The authors would like to thank the data contributors and the PMIP3 community. AVH is supported by an International Postgraduate Research Scholarship at Macquarie University. The work was supported by the Australian Research Council, grant number DP1201100343 (SPH).

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Figure and table captions

Figure 1, Maps of MTCO anomalies between 6 ka BP and pre-industrial simulations of PMIP3 models. Statistical reconstruction plotted as points, large points signify reconstruction anomalies larger than twice the associated error. Hollow points signify that the reconstruction anomaly is of the same sign as the model anomaly for the same grid cell, solid points signify that the reconstruction anomaly is of the opposite sign. a) Ensemble mean with the difference between the models plotted as contours, b-h) individual models.

Figure 2, Maps of the difference between the ensemble mean and the individual models for MTCO at 6 ka BP.

Figure 3, Maps of MTWA anomalies between 6 ka BP and pre-industrial simulations of PMIP3 models. Statistical reconstruction plotted as points, large points signify reconstruction anomalies larger than twice the associated error. Hollow points signify that the reconstruction anomaly is of the same sign as the model anomaly for the same grid cell, solid points signify that the reconstruction anomaly is of the opposite sign. a) Ensemble mean with the difference between the models plotted as contours, b-h) individual models.

Figure 4, Maps of the difference between the ensemble mean and the individual models for MTWA at 6 ka BP.

Figure 5, Maps of MTCO anomalies between 21 ka BP and pre-industrial simulations of PMIP3 models. Statistical reconstruction plotted as points, large points signify reconstruction anomalies larger than twice the associated error. Hollow points signify that the reconstruction anomaly is of the same sign as the model anomaly for the same grid cell, solid points signify that the reconstruction anomaly is of the opposite sign. a) Ensemble mean with the difference between the models plotted as contours, b-i) individual models.

Figure 6, Maps of the difference between the ensemble mean and the individual models for MTCO at 21 ka BP.

Figure 7, Maps of MTWA anomalies between 21 ka BP and pre-industrial simulations of PMIP3 models. Statistical reconstruction plotted as points, large points signify reconstruction anomalies larger than twice the associated error. Hollow points signify that the reconstruction anomaly is of the same sign as the model anomaly for the same grid cell, solid points signify that the reconstruction anomaly is of the opposite sign. a) Ensemble mean with the difference between the models plotted as contours, b-i) individual models.

Figure 8, Maps of the difference between the ensemble mean and the individual models for MTCO at 21 ka BP.

Table 1, PMIP2 and CMIP5 models used to simulate Mid-Holocene (6 ka BP) and LGM climates (21 ka BP), from Harrison *et al.* (2014) and Schmidt *et al.* (2014).

Table 2, Model output summary, 6 ka BP-Pre-industrial. For the reconstructions, modern reconstructions were subtracted from the 6 ka BP reconstructions. Seasonality was calculated by subtracting the MTCO anomalies from the MTWA anomalies. Simulations significantly different from the reconstructions at the 95% confidence level are in italics, datasets significantly different from the ensemble mean at the 95% confidence level are marked with an asterisk.

Table 3, Model output summary, LGM-Pre-industrial. For the reconstructions, modern reconstructions were subtracted from the LGM reconstructions. Seasonality was calculated by subtracting the MTCO anomalies from the MTWA anomalies. Simulations significantly different from the reconstructions at the 95% confidence level are in italics, datasets significantly different from the ensemble mean at the 95% confidence level are marked with an asterisk.

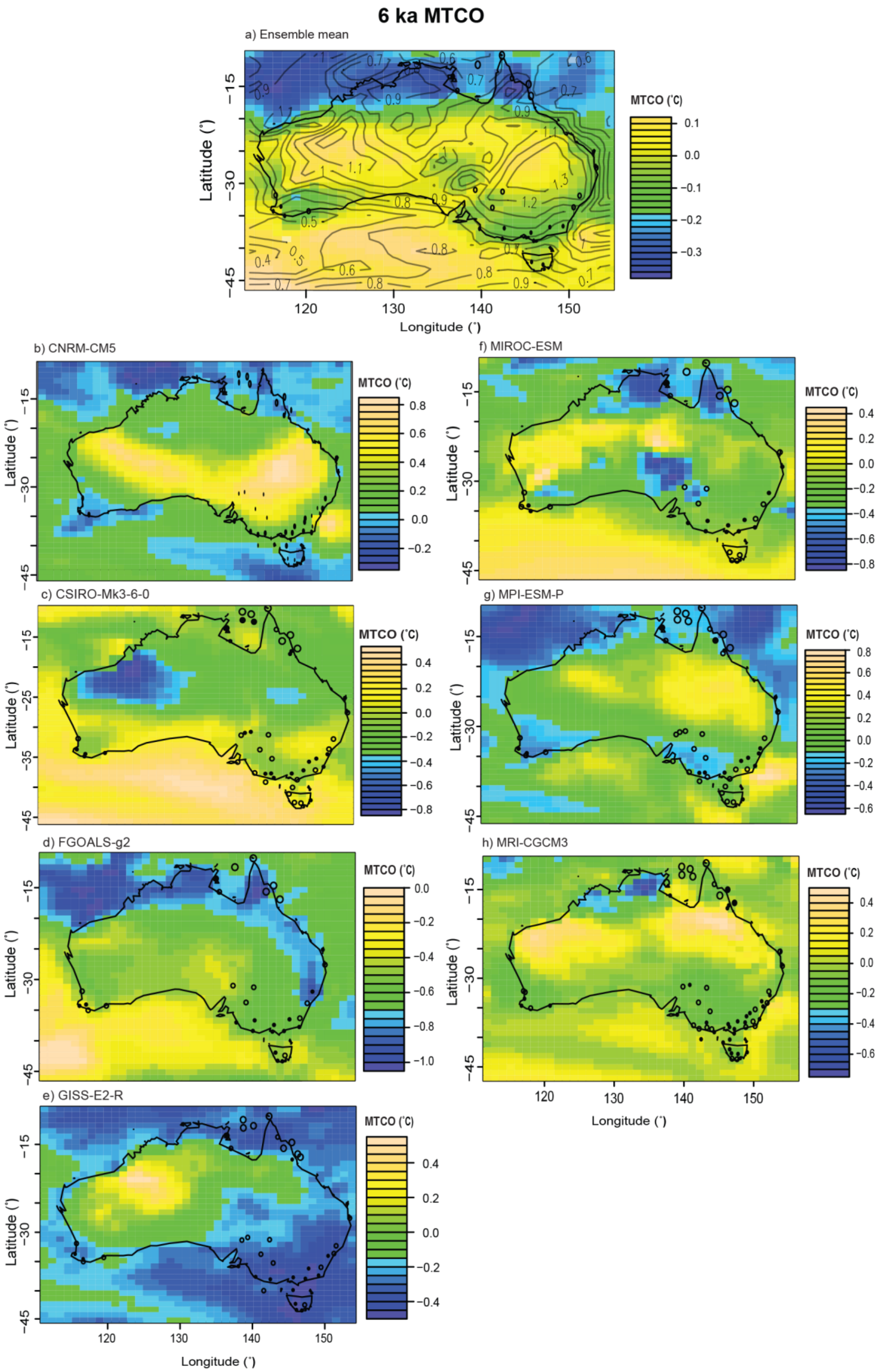

Figure 1, Maps of MTCO anomalies between 6 ka BP and pre-industrial simulations of PMIP3 models. Statistical reconstruction plotted as points, large points signify reconstruction anomalies larger than twice the associated error. Hollow points signify that the reconstruction anomaly is of the same sign as the model anomaly for the same grid cell, solid points signify that the reconstruction anomaly is of the opposite sign. a) Ensemble mean with the difference between the models plotted as contours, b-h) individual models.

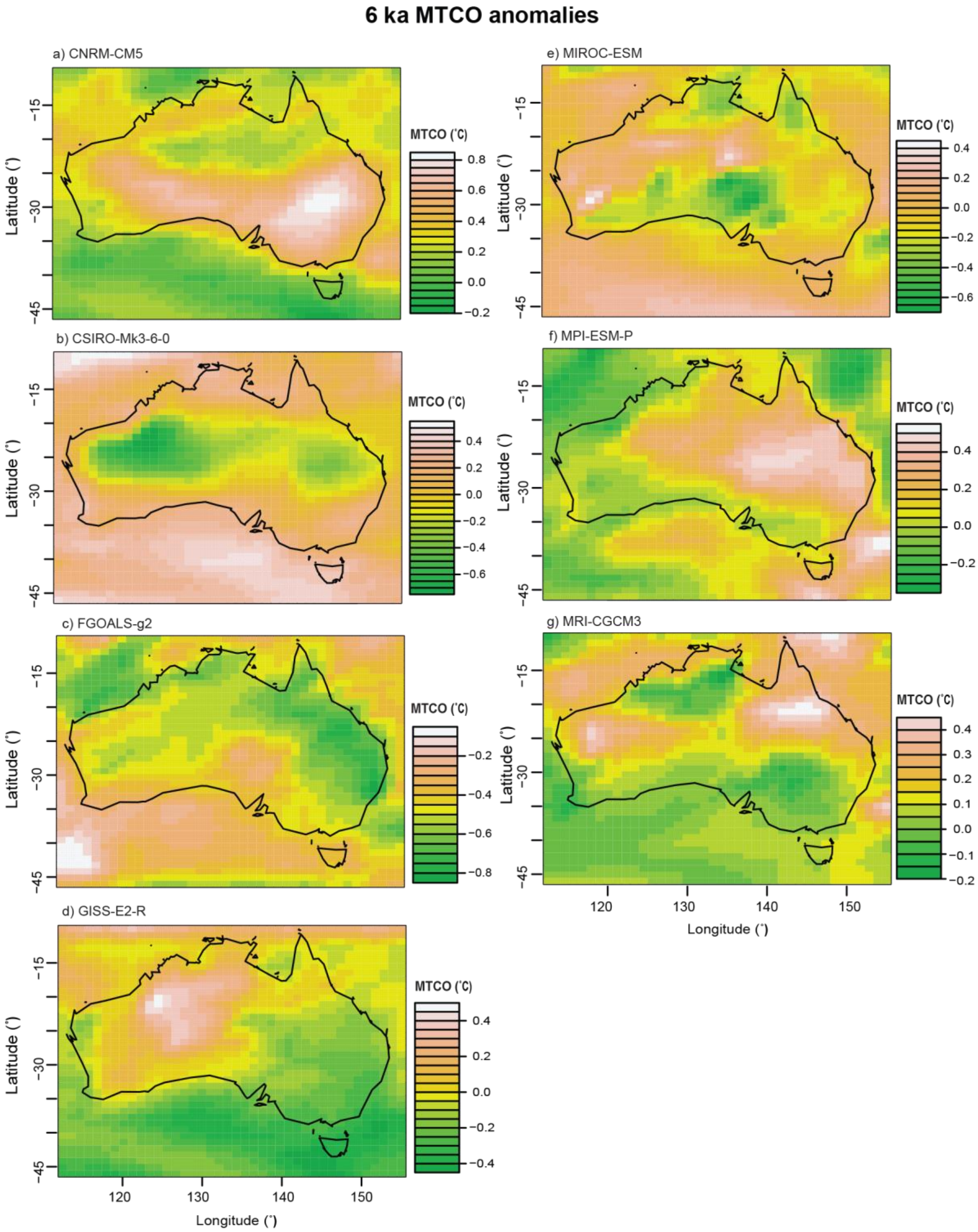

Figure 2, Maps of the difference between the ensemble mean and the individual models for MTCO at 6 ka BP.

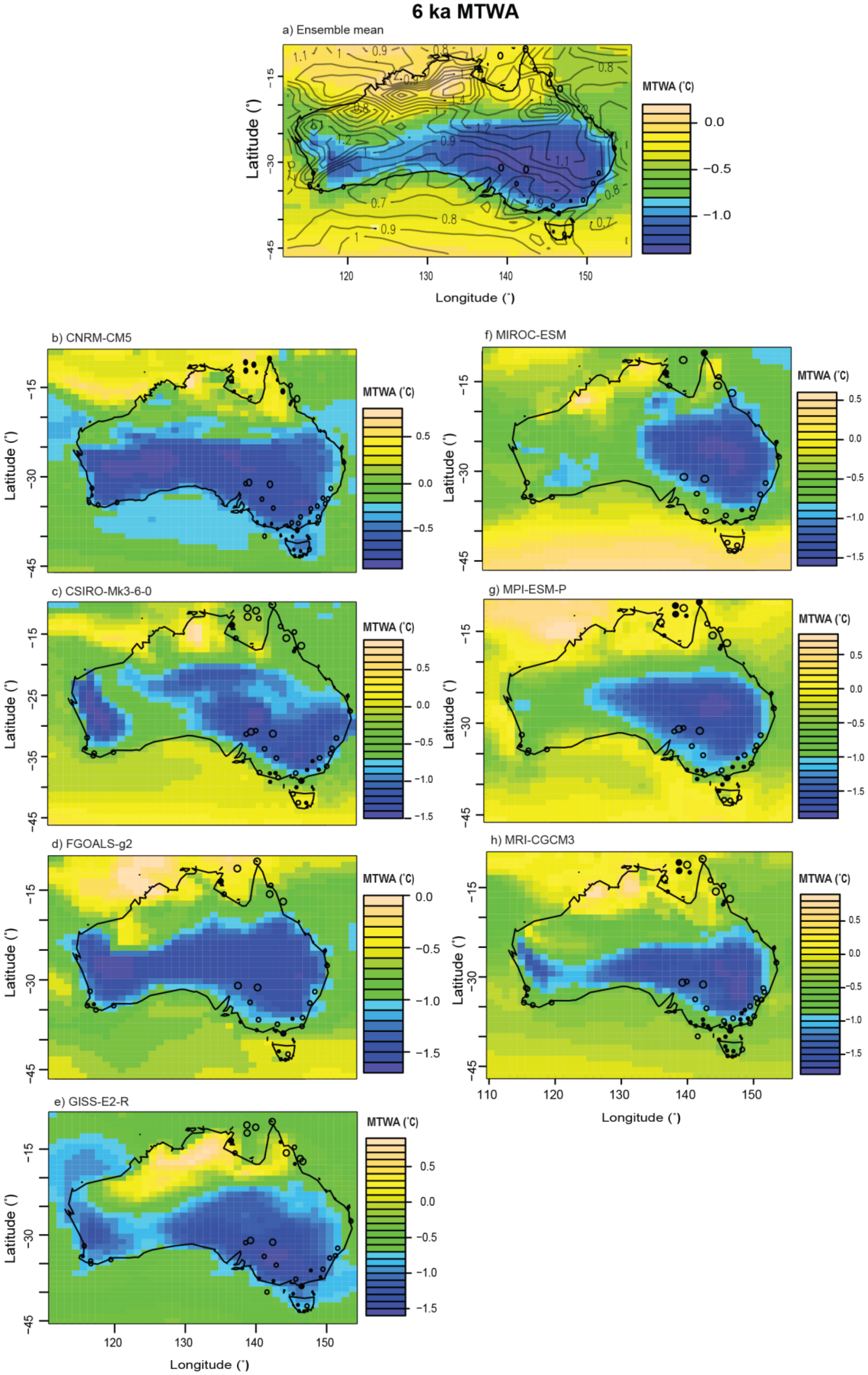
6 ka MTWA
a) Ensemble mean
b) CNRM-CM5
c) CSIRO-Mk3-6-0
d) FGOALS-g2
e) GISS-E2-R
f) MIROC-ESM
g) MPI-ESM-P
h) MRI-CGCM3
MTWA (˚C)
Latitude (˚)
Longitude (˚)

Figure 3, Maps of MTWA anomalies between 6 ka BP and pre-industrial simulations of PMIP3 models. Statistical reconstruction plotted as points, large points signify reconstruction anomalies larger than twice the associated error. Hollow points signify that the reconstruction anomaly is of the same sign as the model anomaly for the same grid cell, solid points signify that the reconstruction anomaly is of the opposite sign. a) Ensemble mean with the difference between the models plotted as contours, b-h) individual models.

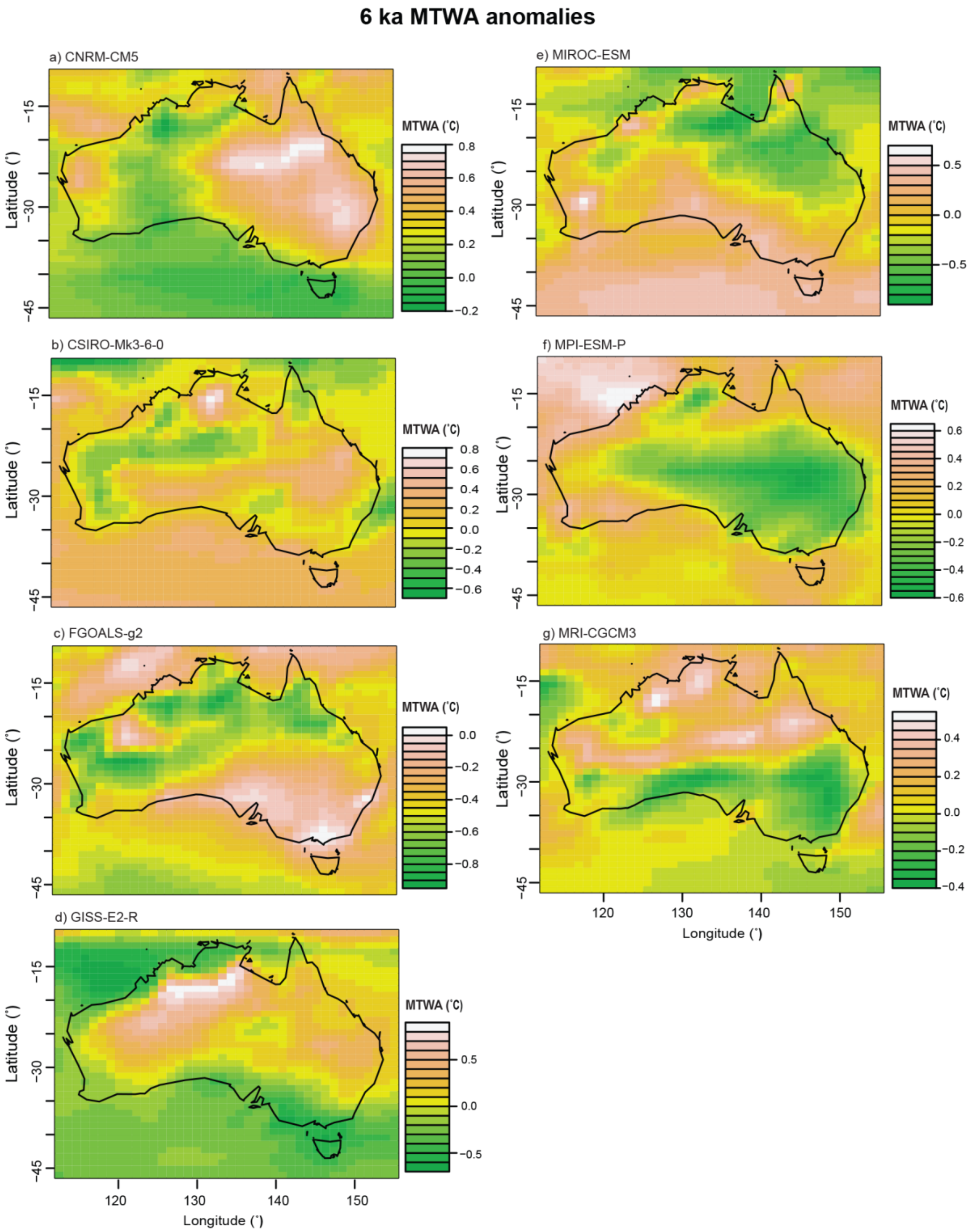

Figure 4, Maps of the difference between the ensemble mean and the individual models for MTWA at 6 ka BP.

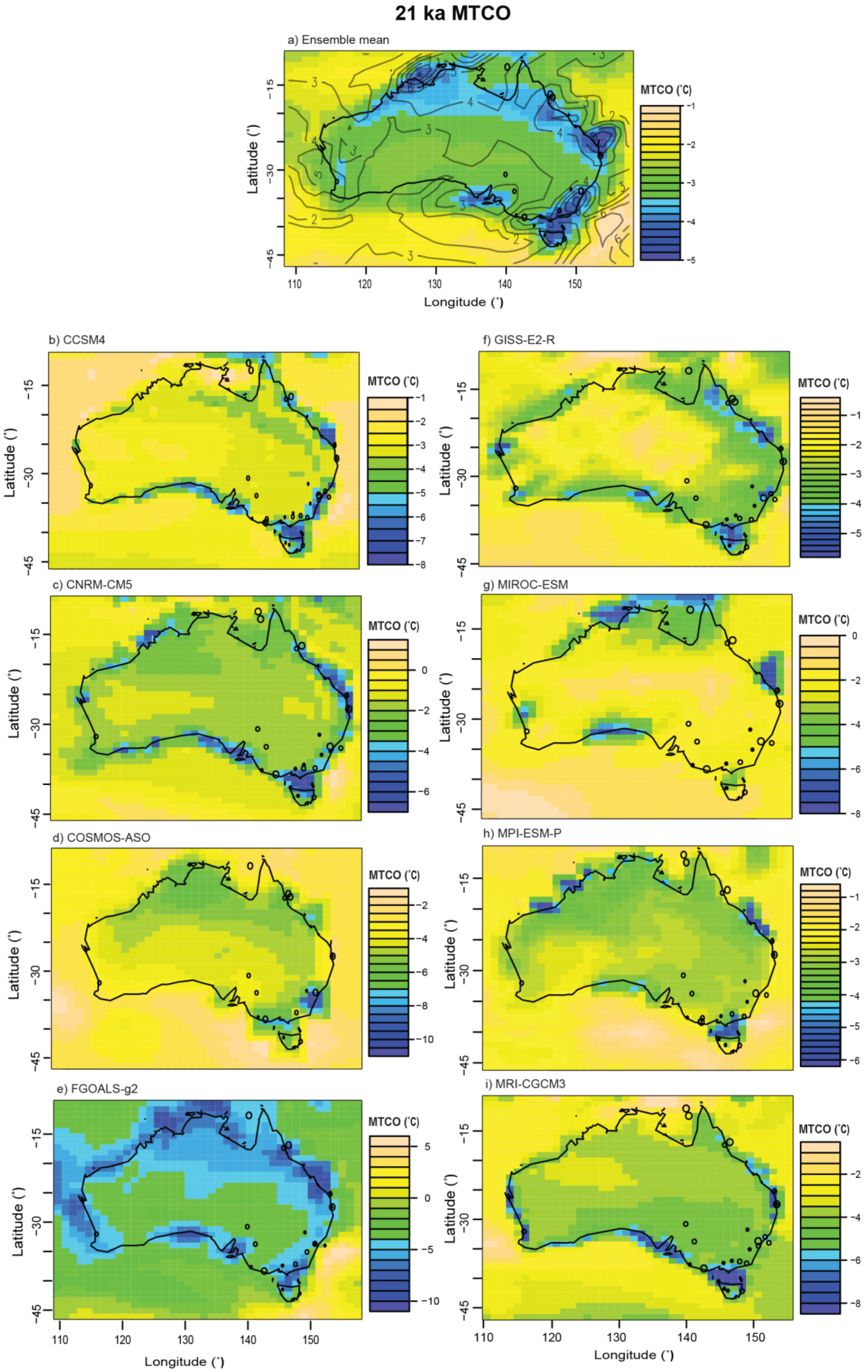
21 ka MTCO
a) Ensemble mean
b) CCSM4
c) CNRM-CM5
d) COSMOS-ASO
e) FGOALS-g2
f) GISS-E2-R
g) MIROC-ESM
h) MPI-ESM-P
i) MRI-CGCM3
MTCO (˚C)
Latitude (˚)
Longitude (˚)

Figure 5, Maps of MTCO anomalies between 21 ka BP and pre-industrial simulations of PMIP3 models. Statistical reconstruction plotted as points, large points signify reconstruction anomalies larger than twice the associated error. Hollow points signify that the reconstruction anomaly is of the same sign as the model anomaly for the same grid cell, solid points signify that the reconstruction anomaly is of the opposite sign. a) Ensemble mean with the difference between the models plotted as contours, b-i) individual models.

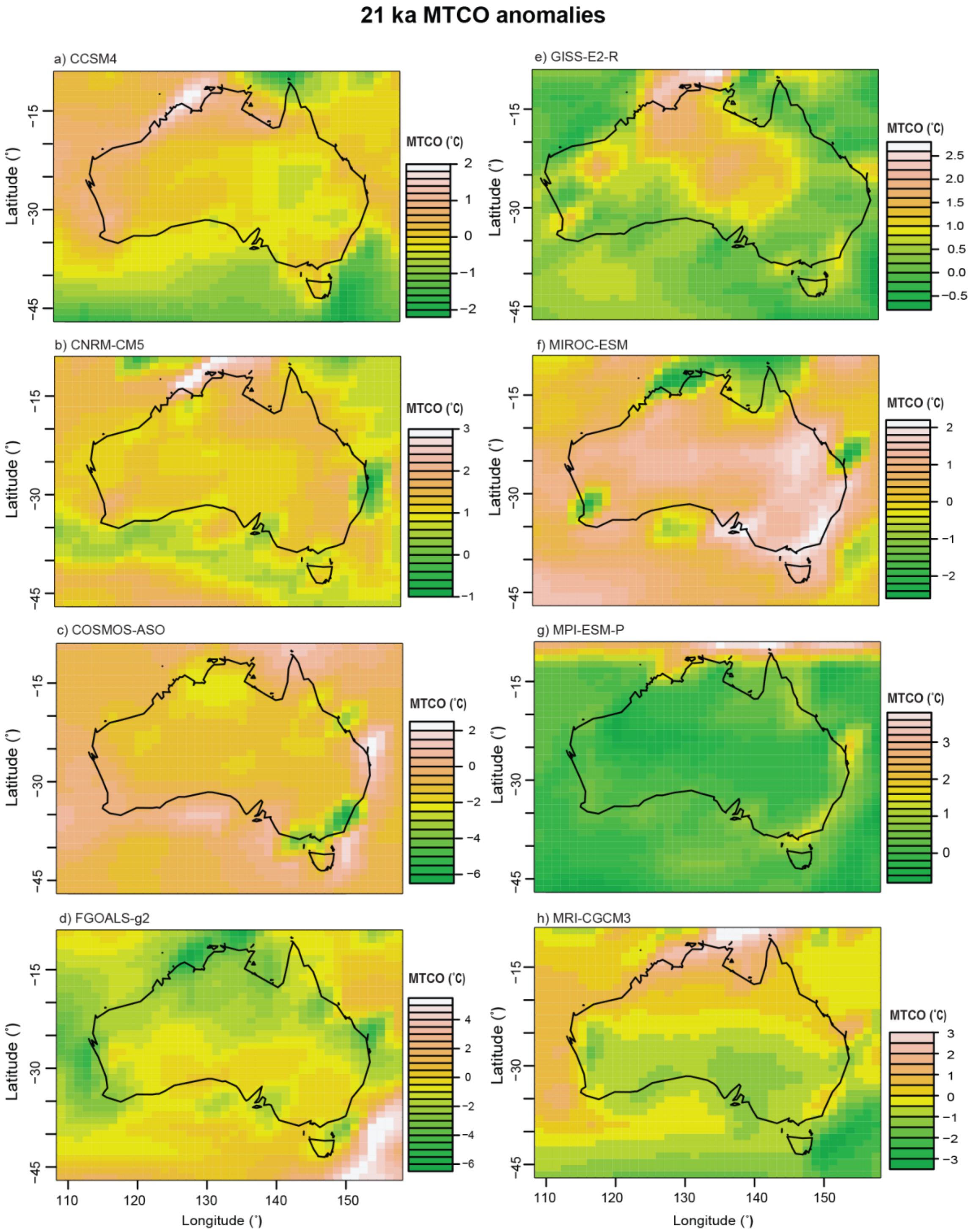

Figure 6, Maps of the difference between the ensemble mean and the individual models for MTCO at 21 ka BP.

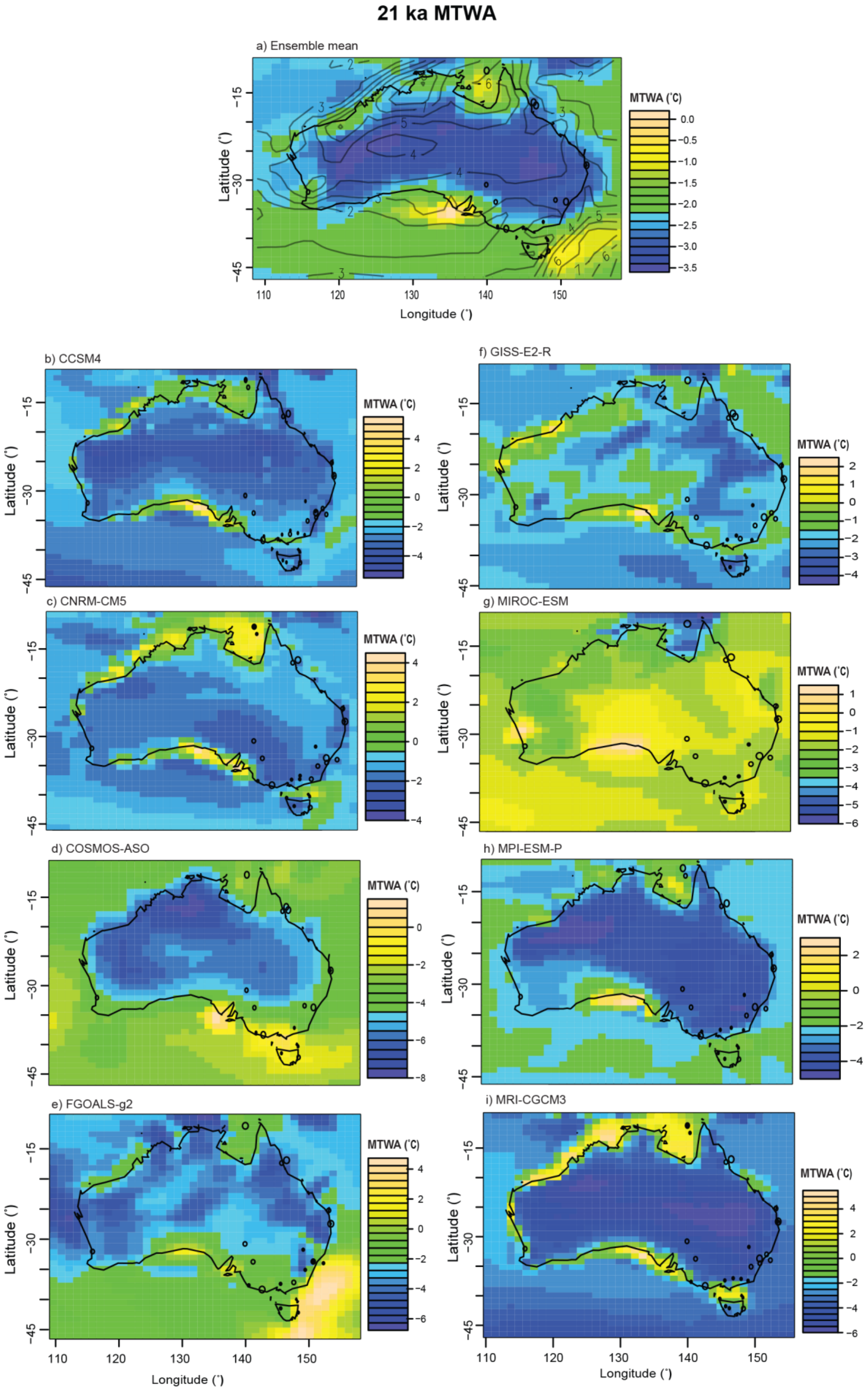
21 ka MTWA
a) Ensemble mean
b) CCSM4
c) CNRM-CM5
d) COSMOS-ASO
e) FGOALS-g2
f) GISS-E2-R
g) MIROC-ESM
h) MPI-ESM-P
i) MRI-CGCM3
MTWA (°C)
Latitude (°)
Longitude (°)

Figure 7, Maps of MTWA anomalies between 21 ka BP and pre-industrial simulations of PMIP3 models. Statistical reconstruction plotted as points, large points signify reconstruction anomalies larger than twice the associated error. Hollow points signify that the reconstruction anomaly is of the same sign as the model anomaly for the same grid cell, solid points signify that the reconstruction anomaly is of the opposite sign. a) Ensemble mean with the difference between the models plotted as contours, b-i) individual models.

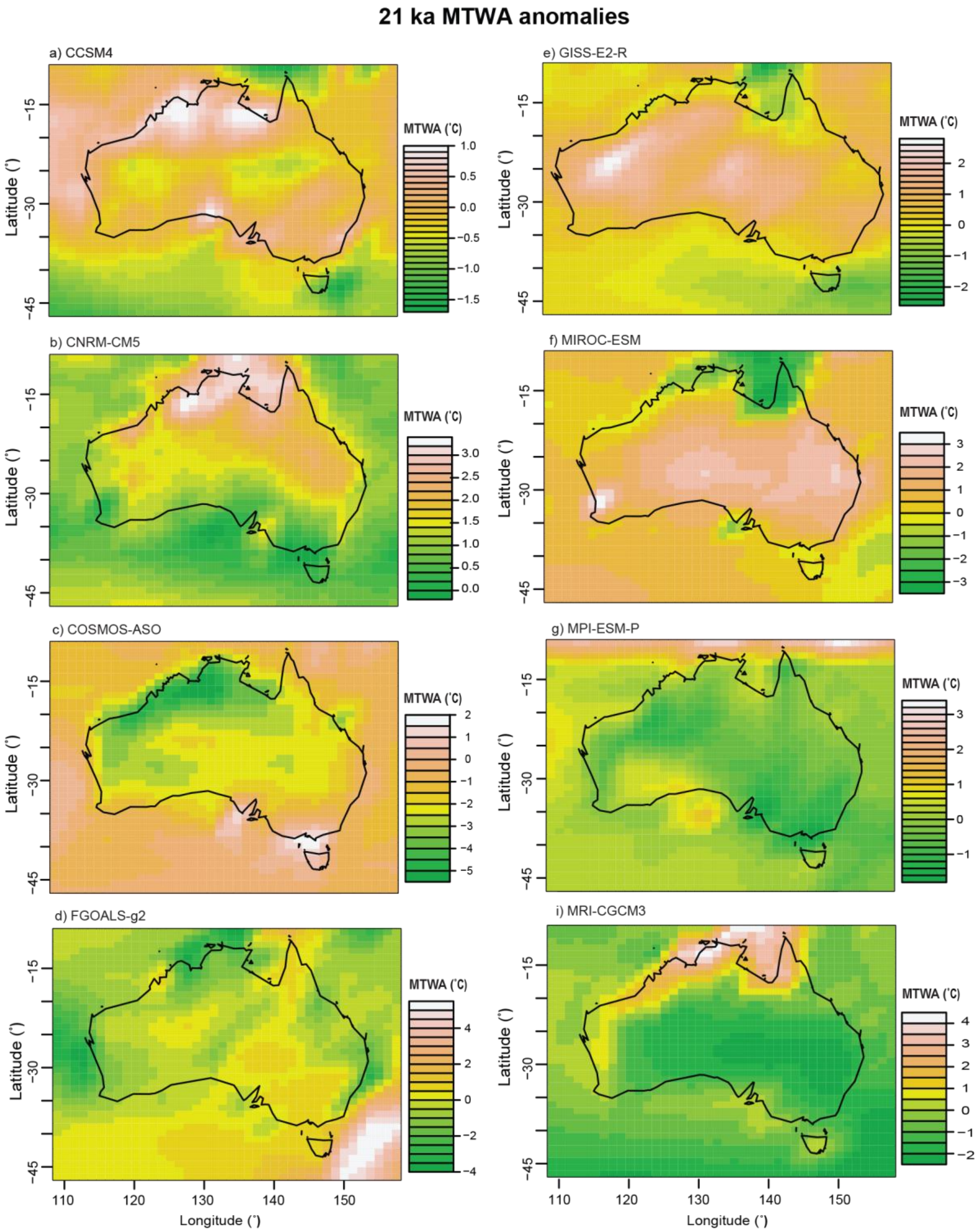

Figure 8, Maps of the difference between the ensemble mean and the individual models for MTWA at 21 ka BP.

Table 1, PMIP2 and CMIP5 models used to simulate Mid-Holocene (6 ka BP) and LGM climates (21 ka BP), from Harrison *et al.* (2014) and Schmidt *et al.* (2014).

	Model	Institution	Resolution	Experiments	Model type (coupled components)
1	MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan.	2.8° x 2.8°	Mid-Holocene, LGM	Earth System Model, Ocean Atmosphere Carbon-cycle.
2	MRI-CGCM3	Meteorological Research Institute, Tsukuba, Japan.	1.1° x 1.1°	Mid-Holocene, LGM	Coupled Global Climate Model, Ocean Atmosphere.
3	MPI-ESM-P	Max Planck Institute for Meteorology, Hamburg, Germany.	1.87° x 1.87°	Mid-Holocene, LGM	Earth System Model, Ocean Atmosphere.
4	GISS-E2-P	NASA Goddard Institute for Space Studies, USA.	2° x 2.5°	Mid-Holocene, LGM	Ocean Atmosphere
5	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence, Australia.	1.87° x 1.87°	Mid-Holocene	Ocean Atmosphere
6	CNRM5-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique, France.	1.4° x 1.4°	Mid-Holocene, LGM	Ocean Atmosphere
7	NCAR-CCSM4	National Centre for Atmospheric Research, US/Department of Energy/NSF, USA.	1.25° x 0.94°	LGM	Ocean Atmosphere
8	FGOALS1	LASG, Institute of Atmospheric Physics, Chinese Academy of Science; and CESS, Tsinghua University, China.	2.8° x 2.8°	Mid-Holocene, LGM	Ocean Atmosphere
9	COSMOS-ASO	Community combination model.	3.7° x 3.7°	LGM	Earth System Model, Atmosphere,

	Ocean, Vegetation.

Table 2, Model output summary, 6 ka BP-Pre-industrial. For the reconstructions, modern reconstructions were subtracted from the 6 ka BP reconstructions. Seasonality was calculated by subtracting the MTCO anomalies from the MTWA anomalies. Simulations significantly different from the reconstructions at the 95% confidence level are in italics, datasets significantly different from the ensemble mean at the 95% confidence level are marked with an asterisk.

Model	**MTCO**	**MTWA**	**Seasonality**
CNRM-CM5	_0.18*_	_-0.18*_	_-0.36_
CSIRO-Mk3-6-0	_0.01*_	_-0.38*_	_-0.39*_
FGOALS-g2	_-0.54*_	_-0.84*_	_-0.31_
GISS-E2-R	_-0.19*_	_-0.6*_	_-0.41*_
MIROC-ESM	_-0.13*_	_-0.45*_	_-0.32_
MPI-ESM-P	_0.006*_	_-0.42*_	_-0.42*_
MRI-CGCM3	_0.007*_	_-0.41*_	_-0.41*_
Ensemble mean	_-0.1_	_-0.45_	_-0.35_
Reconstruction	-0.37*	-0.64*	-0.27*

Table 3, Model output summary, LGM-Pre-industrial. For the reconstructions, modern reconstructions were subtracted from the LGM reconstructions. Seasonality was calculated by subtracting the MTCO anomalies from the MTWA anomalies. Simulations significantly different from the reconstructions at the 95% confidence level are in italics, datasets significantly different from the ensemble mean at the 95% confidence level are marked with an asterisk.

Model	**MTCO**	**MTWA**	**Seasonality**
CCSM4	_-2.9*_	_-2.5*_	_0.45*_
CNRM-CM5	_-1.7*_	_-1.0*_	_0.63*_
COSMOS-ASO	_-3.7*_	_-3.7*_	_-0.02*_
FGOALS-g2	_-3.3*_	_-1.9*_	1.4*
GISS-E2-R	_-2.4*_	_-1.9*_	_0.4*_
MIROC-ESM	_-2.1*_	_-1.9*_	_0.22*_
MPI-ESM-P	_-2.5*_	_-2.4*_	_0.17*_
MRI-CGCM3	_-3.4*_	_-2.8*_	_0.61*_
Ensemble mean	_-2.7_	_-2.3_	_0.47_
Reconstruction	-2.4*	-1.8*	0.57*

Chapter 5

Conclusions

Chapter 5: Conclusions

Evaluating the quality of climate models using quantitative palaeoclimate reconstructions is a major aim of the Palaeoclimate Modelling Intercomparison Project (PMIP, Braconnot *et al.,* 2012). Large-scale reconstructions or syntheses are needed to perform these evaluations, but there has been a lack of these types of studies for the Southern Hemisphere (Bartlein *et al.,* 2011). To properly perform such reconstructions, it is important to first examine the inherent decisions and assumptions involved in the chosen statistical technique, so that the most statistically robust and reliable methodology is used. In chapter 2 such a study was performed using the Modern Analogue Technique on a modern Australian pollen dataset. It concluded that it was worthwhile to apply the modern analogue reconstruction technique to the palaeorecord of Australia using the suggested methodology. This methodology included the use of the bootstrapping cross-validation approach to select 5 analogues, a 0.5° grid climatology and both individual core top samples and individual surface samples post-dating European settlement.

The next step towards evaluating palaeoclimate model output for Australia was to perform the first continuous continental scale quantitative palaeoclimate reconstruction going back more than 1000 years, the 1000 year reconstruction having been performed by PAGES 2k (2013) using tree ring data, and moisture having been reconstructed for the Last Glacial Maximum (LGM) time window by Prentice *et al.* (2017) using the same database of pollen samples used in this thesis. Our reconstruction using the aforementioned methodology from chapter 2, except with 10 analogues instead of 5 to reduce the associated error, was presented in chapter 3 and found several significant, large-scale climatic events. These events were supported and explained by previous studies. For example, we found evidence for a significant cold period at 17 ka BP, possibly related to a glacial readvance in the Snowy Mountains and Tasmania (Petherick *et al.,* 2013). We also found evidence for a warm period at about 2.5 ka BP, and a dry period at about 4 ka BP, possibly corresponding to a dry period at around 4-2.2 ka BP across southern Australia as reconstructed from ostracods by Gouramanis *et al.* (2013) and from pollen by Donders *et al.* (2007). Thanks to this supportive evidence, the reconstructions were deemed reliable enough to be used to evaluate climate model performance, an evaluation presented in chapter 4. This evaluation concluded that the palaeoclimate model simulations for the LGM produced temperature estimates slightly closer to previous studies than the reconstructions from chapter 3, probably due to a lack of cold-climate analogues in the training set. The mid-Holocene simulations, on the other hand, presented great variability, both geographically and between models, especially evident for the simulations of mean temperaure of the coldest month (MTCO). We suggest that this is most probably due to the models underrepresenting the climate forcings affecting Australian mid-Holocene winter temperatures. However, due to the lack of a geographical pattern, it is not clear what forcings this might be, just that they are not likely to be the geographically restricted southern westerly winds, and they might have been captured best by the models with the coarsest resolution, these being closer to the reconstructions. It could be related to the El Niño Southern Oscillation (ENSO), as CMIP5 models have been found to have difficulty in accurately simulating ENSO-related patterns, and ENSO is known to affect climate variability in eastern Australia (Dodson, 2001; Rotstayn *et al.,* 2010; Gouramanis *et al.,* 2013; Bellenger *et al.,* 2014).

1. **Future directions**

The quantitative palaeoclimate reconstructions presented in chapter 3 tend to overestimate Australian temperature for the LGM, with increases reconstructed for some areas, though in most cases not significantly above the associated error, something that is unsupported by previous studies. Unfortunately, no analogues for the LGM environments exist in Australia today, so any future studies may have to use semi-qualitative means of reconstructing LGM temperatures, or incorporate data sources other than pollen. As the averaged LGM temperature reconstructions presented here were in the same range as the averaged simulated LGM temperatures, it is possible the reconstructions can be improved further through statistical means, such as grouping the taxa into their Plant Functional Types before performing the reconstructions. Further studies are needed to determine the cause of the inter-model variability in the simulated mid-Holocene MTCO anomalies. Identifying the source of the variations will no doubt help to improve simulations of Australian climate in the future, especially winter temperature simulations.

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