Research Article

A continental perspective on the timing of environmental change during the last glacial stage in Australia

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Abstract

The timing and duration of the coldest period in the last glacial stage, often referred to as the last glacial maximum (LGM), has been observed to vary spatially and temporally. In Australia, this period is characterised by colder, and in some places more arid, climates than today. We applied Monte-Carlo change point analysis to all available continuous proxy records covering this period, primarily pollen records, from across Australia ($n = 37$) to assess this change. We find a significant change point occurred (within uncertainty) at 28.6 ± 2.8 ka in 25 records. We interpret this change as a shift to cooler climates, associated with a widespread decline in biological productivity. An additional change point occurred at 17.7 ± 2.2 ka in 24 records. We interpret this change as a shift towards warmer climates, associated with increased biological productivity. We broadly characterise the period between $28.6 (\pm 2.8) - 17.7 (\pm 2.2)$ ka as an extended period of maximum cooling, with low productivity vegetation that may have occurred as a combined response to reduced temperatures, lower moisture availability and atmospheric CO_2 . These results have implications for how the spatial and temporal coherence of climate change, in this case during the LGM, can be best interrogated and interpreted.

Keywords: Last glacial maximum, MIS 2, MIS 3, Pollen, Palaeoclimate, Monte-Carlo change point, Age uncertainty

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INTRODUCTION

Determining the nature and timing of climatic and environmental changes across the Australian continent during the late last glacial stage (herein defined as 35,000–15,000 calendar years BP; 35–15 ka) has remained elusive. The timing of the coldest period during the last glacial stage, when global sea-level minimum and marine oxygen isotope maximum occurred (Hughes et al., 2013), is known as the last glacial maximum (LGM) (Clark et al., 2009), within Marine Isotope Stage 2 (MIS 2) (29,000–14,000 years ago) (Lisiecki and Raymo, 2005). Early definitions of the LGM suggested the global ice maximum and sea-level minimum occurred between 23–19 ka, during MIS 2 (Yokoyama et al., 2000; Mix, Bard and Schneider, 2001; Clark and Mix, 2002). Increasingly, global evidence indicates that sea levels declined during late MIS 3 and global ice volume, including

many mountain glaciers and continental ice sheets, reached their maximum extent prior to this period (Peltier and Fairbanks, 2006; Clark et al., 2009; Hughes et al., 2013; Lambeck et al., 2014; Yokoyama et al., 2018). This growing consensus has contributed to a widely accepted revision on the ice volume definition of the LGM as having occurred earlier, between 26.5–19 ka (Clark et al., 2009; Hughes et al., 2013; Lambeck et al., 2014). Whilst the timing of the occurrence of maximum global ice volume and minimum sea level has been refined, spatial variations in the occurrence of the coldest temperatures or maximum local glacial growth have been observed, particularly in the Southern Hemisphere. For Australia, the period of maximum environmental change has not been objectively defined.

Environmental changes during the LGM are characterised differently in Australia, where glacier development was a relatively minor component of the landscape, compared to the Northern Hemisphere. During the latter part of the last glacial stage and global sea-level minimum, various records from Australia document a period of low temperature, combined in many regions with more arid and highly variable climates (Miller et al., 1997; Builth et al., 2008; Petherick et al., 2008; Fletcher and Thomas, 2010; Fitzsimmons et al., 2015; Williams et al., 2015; Miller

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Figure 1. Map of Australia with sites indicated. Symbols show proxy type and colours indicate site locations. Colours change along a latitudinal gradient. Solid black line indicates the current extent of the Australian land mass and light grey line indicates the -130 m contour and the likely extent of exposed continental shelf during the global last glacial maximum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2016; Falster *et al.*, 2018). Temperatures in Australia during the last glacial stage are suggested to have been 4–8°C cooler than today (Miller *et al.*, 1997; Colhoun *et al.*, 1999; Colhoun, 2000; Fletcher and Thomas, 2010; Woltering *et al.*, 2014; Chang *et al.*, 2015). Temperature decreases of this magnitude are consistent with large changes to vegetation composition across the continent. Quantitative estimates of precipitation changes during the last glacial stage in Australia are limited; however, increased dust transport, sparse vegetation cover and the presence of sedimentary hiatuses in a range of lacustrine and palustrine sequences during this period (Supplementarily Figure 1; McKenzie, 2002; Donders *et al.*, 2006; Williams *et al.*, 2006) may indicate a decrease in precipitation and thus an increase in aridity in some regions.

The spatial extent of such climate changes has remained a matter of debate, in part due to the geographic scale and range of climate regions across the Australian continent. The limited glacial activity and inferred increase in aridity during this period limits the number of high-resolution palaeoenvironmental archives across Australia, resulting in uncertainty in the interpretation and timing of climatic changes during the traditional LGM period. Whilst having experienced limited glacial activity, the Australian landmass and ensuing climates are strongly affected by variations in global temperature, sea level, $p\text{CO}_2$ and Southern Ocean sea-ice extent. Therefore, major continental

climate changes in Australia were likely to have been linked to changes in global ice volume through various teleconnections and feedbacks. In addition, the Australian land surface plays a poorly defined role in the global climate system, primarily via the production and export of dust and its role as a global sink/source of carbon, via soils and the terrestrial biosphere (De Deckker *et al.*, 2010; Haverd *et al.*, 2013a; Haverd *et al.*, 2013b; Poulter *et al.*, 2014). The extent to which the Australian land surface exerted feedbacks on climate variability during the LGM remains a point of significant uncertainty.

Evidence for glacial and periglacial activity in Australia is restricted to high elevation sites in the Snowy Mountains of mainland southeastern Australia and in Tasmania (Barrows *et al.*, 2001, 2002; Mackintosh *et al.*, 2006; Kiernan *et al.*, 2017). In the Snowy Mountains, the oldest moraines are most likely MIS 3 or MIS 4 in age, with later glacial advances occurring between 23 and 20 ka (recalculated from Barrows *et al.*, 2001, 2002). Glaciation was more extensive in Tasmania, with evidence of numerous cirque, valley, and small ice sheet glaciations preserved at high elevation sites along the West Coast Range and the Central Plateau (Barrows *et al.*, 2002; Mackintosh *et al.*, 2006). Exposure dating of moraines indicates that ice masses formed gradually from ca. 30 ka, with their maximum extent peaking at ca. 23–0 ka (Fink *et al.*, 2000; Barrows *et al.*, 2002; Kiernan *et al.*, 2004;

Mackintosh et al., 2006; Kiernan et al., 2017). However, in several localities such as lower altitude sites in the West Coast Ranges, Mt. Field, and the Central Plateau, more extensive ice advances occurred during MIS 3 and MIS 4 (Fink et al., 2000; Barrows et al., 2002; Mackintosh et al., 2006). Deglaciation occurred rapidly after the global LGM, with the majority of ice cover disappearing between ca. 19–17 ka (Barrows et al., 2002).

Continuous palaeoclimate records from lowland continental Australia during the last glacial stage are predominately based on qualitative proxy records, in particular pollen archived in lacustrine and palustrine sediments. Climate reconstructions from pollen records are rarely rigorously quantitative due to the low taxonomic resolution and large climatic envelopes of many Australian taxa. However, under present day CO₂ and temperature conditions, vegetation in Australia is largely sensitive to water availability (Seddon et al., 2016). Biome distributions are strongly constrained by the timing and amount of annual/seasonal precipitation, and temperature (González-Orozco et al., 2014). The most significant environmental variable in northern Australia is precipitation, while solar radiation and temperature are most significant in southern Australia (González-Orozco et al., 2014). Although strongly influenced by climatic conditions, vegetation records may also be influenced by additional drivers, including fire and human impact. Disentangling the relative roles of rainfall, water balance, temperature, CO₂, disturbance, and potential human modification on vegetation is inherently difficult, and can result in varying interpretations of the primary drivers at individual sites. An increasing number of quantitative approaches to reconstruct temperature and hydrological conditions have been applied to lacustrine and marine records across Australia, however few terrestrial records extend through the last glacial stage (Woltering et al., 2014; Chang et al., 2015; Treble et al., 2017). Discontinuous records are also provided by periglacial, glacial, fluvial and dune deposits that reflect climatic processes and conditions at their time of formation (Barrows et al., 2002; Nanson et al., 2008; Mueller et al., 2018).

Palaeoclimate interpretations based on palynological records typically suggest a decrease in precipitation and temperature during the last glacial stage, with regional climates largely considered to have been cooler and drier relative to the Holocene (Colhoun et al., 1999; Moss and Kershaw, 2000; Kershaw et al., 2007b; Kershaw et al., 2007a; Builth et al., 2008). Vegetation records from temperate southeastern Australia indicate largely treeless landscapes dominated by Asteraceae and Poaceae, with isolated pockets of mesic communities, particularly along the east coast (Dodson and Wright, 1989; Kershaw et al., 1991; McKenzie, 1997; Builth et al., 2008; Williams et al., 2009; Ellerton et al., 2017; Hope, 2017; Mackenzie and Moss, 2017). Palynological records from tropical and subtropical Australia suggest arboreal and woody vegetation persisted through the last glacial stage, with vegetation changes marked by a decrease in rainforest elements and an increase in sclerophyllous and shrub taxa (Kershaw, 1975; Kershaw et al., 2007a; Moss et al., 2013, 2017). The mobilisation and growth of dune fields beyond the presently-defined arid region, and increased dust deposition in the Tasman Sea, have also been linked to more widespread sparse vegetative cover and increased wind strength (Hesse, 1994, 2016; Petherick et al., 2009; Fitzsimmons et al., 2013; Falster et al., 2018). These changes in vegetation composition, increased dust transport and retraction of mesic communities towards the coast may be driven by a reduction in temperature, available moisture and/or by low atmospheric CO₂ reducing biological productivity and influencing

competitive outcomes between different plant types (e.g., trees vs. grasses). Determining the magnitude and relative role of lower CO₂ on vegetation growth during the last glacial stage is confounded by the complex feedbacks between vegetation, climate, and atmospheric CO₂. Therefore, the changes in vegetation composition and cover observed during the last glacial stage may be the result of a wide range of climatic, edaphic and ecological drivers, and their feedbacks.

Fluvial and lake level records indicate intervals of high and often variable river discharge and lake levels, respectively, indicating increased available moisture, at least episodically, during the last glacial stage (Page et al., 2009; Kemp and Rhodes, 2010; Bowler et al., 2012; Fitzsimmons et al., 2015; Mueller et al., 2018; Barrows et al., 2020). Increased fluvial activity has alternatively been suggested to represent increased run-off in response to reduced catchment vegetation cover and increased headwater snowmelt (Kemp and Rhodes, 2010; Reinfelds et al., 2014; Hesse et al., 2018; Mueller et al., 2018). Geomorphic change in lowland reaches is also amplified by reduced vegetation cover.

Several authors (Colhoun et al., 1999; Barrows et al., 2001; Forbes et al., 2007; Kershaw et al., 2007b; Builth et al., 2008; Petherick et al., 2008) have argued that the establishment of the most extreme conditions commonly associated with the LGM in Australia began between 32–26 ka, earlier than the traditionally defined global LGM (23–19 ka; Yokoyama et al., 2000; Mix et al., 2001). This early onset appears to be consistent with records from other Southern Hemisphere landmasses, of decreased temperature and increased growth of montane glaciers at this time (Finch and Hill, 2008; Hughes et al., 2013; Vandergoes et al., 2013; Stewart and Mitchell, 2018). In New Zealand, a variety of records suggest a reduction in the tree line, cooler conditions, and increased mountain glacier growth from ca. 30 ka (Hellstrom et al., 1998; Suggate and Almond, 2005; Alloway et al., 2007; Newnham et al., 2007; Barrows et al., 2013; Vandergoes et al., 2013; Rother et al., 2014; Hellstrom et al., 2020). In South America, many mountain glaciers reached their maximum extent during late MIS 3 (ca. 34–29 ka) and persisted, in many cases, through to the late glacial (ca. 14 ka) (Hughes et al., 2013). In the Maloti-Drakensberg region of southern Africa, multiple proxy records suggest the period 30–28 ka was dominated by cold, periglacial conditions (Stewart and Mitchell, 2018) and the formation of niche glaciers (Mills et al., 2012). Precipitation records are regionally more variable, both in Australia and across the Southern Hemisphere more generally, perhaps reflecting the influence of regional topography and aspect on effective precipitation, or the proxies used to infer these patterns.

The occurrence of a simple unidirectional pattern of cool and dry conditions across Australia during the last glacial stage may be unlikely, due to the continent's geographical size and latitudinal diversity of climate regimes and drivers. The complexity and variability of interpreting Australian palaeoclimates from different archives during this period is demonstrated by the occurrence of speleothem growth and floodplain deposits in the Flinders Ranges (Haberlah et al., 2010; Treble et al., 2017), speleothem growth in southwest Western Australia (Sniderman et al., 2019), persistence of arboreal vegetation on the New South Wales tablelands (Shulmeister et al., 2016; Ellerton et al., 2017), oscillating lake levels in the Murray-Darling river system (Fitzsimmons et al., 2014; Fitzsimmons et al., 2015; Barrows et al., 2020), and increases in river discharge in eastern Australia (Kemp and Rhodes, 2010; Hesse et al., 2018; Mueller et al., 2018). The

existence of several climatic phases within the last glacial stage has been demonstrated in some high-resolution proxy records from southern and eastern Australia (Petherick et al., 2008; Falster et al., 2018). The variability implied by these records has raised questions about the potential synchronicity of environmental and climatic changes during the last glacial stage across Australia (Reeves et al., 2013).

Understanding the timing and nature of climates during the last glacial stage in Australia has been hampered by the small number of terrestrial records, the coarse taxonomic resolution of fossil pollen, low temporal proxy resolution, poor chronological constraints, and the limited application of age-depth modelling. Dating density in Australian palaeoclimate reconstructions has historically been low, both spatially and within single records, although recent advances in dating methodologies and age-depth modelling are helping to improve chronological control (Bøtter-Jensen et al., 2000; Duller, 2008; Blaauw et al., 2018). The development of chronologies to determine the timing of events during the last glacial stage are principally based on radiocarbon dating. Many of the proxy records incorporated in this synthesis were developed before current radiocarbon dating methods were available and are based on sparse and imprecise radiocarbon ages. The precision and accuracy of individual chronologies can be influenced by the number of radiocarbon ages obtained and the type of material dated (i.e., bulk sediment, plant macrofossils and microfossils, or chemical fractions) (Martin et al., 2019; Thomas et al., 2019). Many factors, including poor preservation of organic materials, high costs, and access to radiocarbon laboratories are limitations for achieving dense and robustly dated records (Blaauw et al., 2018). As a consequence of sparsely dated records and dating of sub-optimal materials, it is often difficult to determine the accuracy of ages and identify anomalous ages or depositional hiatuses (Blaauw et al., 2018). Further, interpolating ages between dated layers becomes increasingly uncertain as the number of ages decreases (Blaauw et al., 2018). Inter-site comparisons have also been inhibited by the relatively recent adoption of age-depth modelling, limiting our ability to identify coherent regional and continental climate changes. A more accurate and realistic estimation of the true timing of events may be possible through the objective use of selection criteria, application of consistent and up-to-date age modelling approaches, and recognition of the associated errors and uncertainties surrounding mean age-depth chronologies (Blaauw et al., 2018; Blaauw et al. 2020; Martin et al., 2019).

Regional syntheses of proxy records are important tools to understand the nature and scope of environmental and climate change during the last glacial stage. However, in regions where proxy records are sparse or of low or variable temporal resolution, data syntheses become increasingly challenging. The focus of this paper is to integrate all available continuous terrestrial proxy records to examine the timing and synchronicity of climate and environmental changes during the last glacial stage in Australia. In order to maximise the spatial and regional coverage, we have chosen to incorporate many low-resolution records, despite their large chronological uncertainties, because our application of consistent age modelling protocols across all records means that the relatively large errors associated with these records are made explicit.

To objectively identify the timing and spatial synchronicity of climatic changes associated within the last glacial stage, an integrated approach that treats all data consistently is required. Here we focus on the period 35–15 ka, a period broader than

the globally defined LGM between 21–18 ka, and encompassing the Southern Hemisphere summer insolation minimum at 32 ka. We develop a multi-site, multi-regional comparison of all available proxy records that cover $\geq 10,000$ years within the broader period 35–15 ka from Australia (Fig. 1). In doing so, we build on previous attempts to collate and interpret the wealth of existing proxy climate data (Turney et al., 2006a; Williams et al., 2009; Petherick et al., 2013; Reeves et al., 2013a; Reeves et al., 2013b) by applying objective selection criteria and numerical analyses. Palynological records and carbon isotope data interpreted by the original authors to represent terrestrial vegetation changes and water stress account for 36 of the total 38 records examined. The remaining two records consist of an offshore *Globigerinoides ruber* oxygen isotope record interpreted by Bostock et al. (2006) to be dominated by changes in sea level, local sea-surface temperature (SST) and surface–ocean circulation patterns, and a terrestrial aquatic record of branched glycerol dialkyl glycerol tetraether (GDGT) methylation and cyclisation, interpreted by Woltering et al. (2014) as mean annual temperature. We reanalyse all records to determine the timing and potential synchronicity of the extreme conditions associated with the last glacial stage in Australia.

METHODS

This study aimed to collate and compare as many continuous terrestrial palaeoenvironmental proxy records as possible that cover much, or all, of the period 35–15 ka from Australia (Fig. 1). Published records were identified through references of previous review papers, data repositories (e.g., PANGAEA: <https://www.pangaea.de/>), and previous data compilations. Additional records, including unpublished data, were identified through personal communications with authors.

Records were screened against the broad criteria of (1) having at least two radiometric age constraints throughout the entire record (most commonly radiocarbon dating), and (2) having an individual record that covered a continuous period of at least 10,000 years through the period 35–15 ka, inclusively. The choice to not use more restrictive criteria for inclusion of records is in part due to the relative lack of Australian palaeoclimate records covering this period, and the predominance of low-resolution proxy records.

Revised age-depth models were created for all records using Bayesian methods based on age determinations reported in original or updated publications. Recalibrated age-depth models were developed for each record using the Bacon (Blaauw and Christen, 2011) software in R version 4.0.2 (R Core Team, 2017). All published radiocarbon dates were checked for accuracy in the original publications, and/or against radiocarbon laboratory records. Terrestrial radiocarbon dates were calibrated using the Southern Hemisphere calibration curve, SHCal20 (Hogg et al., 2020). Radiocarbon dates from marine records were calibrated using SHCal20 for terrestrial macrofossil samples (Hogg et al., 2020) and the Marine20 calibration curve (Heaton et al., 2020) for dates obtained from marine organisms. An ensemble of 2000 age-depth model iterations, which fall within the margin of uncertainty, was extracted from the Bayesian age-depth model for each site, following the approach of Tibby et al. (2018).

For each pollen record, multivariate compositional pollen data were reduced to a single one-dimensional Principal Curve (PrC) to summarise the major patterns of change within the vegetation at each site. PrCs were estimated using percentage pollen data of

Figure 2. Schematic of the analytical process used in this synthesis. Step 1: Records were identified and collated (see Table 1 and Figure 1). Step 2: An updated Bayesian age model was determined for each record using Bacon (Blaauw and Christen, 2011) and the SH20 calibration curve for radiocarbon dates. 2000 age iterations were extracted from each age model. New age models were compared to original age-model, plotted as an orange line on age-model plot. Step 3: A Principal Curve was applied to compositional data (e.g., pollen spectra) to reduce the data to a single curve. Data for each record [pollen Principal Curves, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, and Branched glycerol dialkyl glycerol tetra-ethers (GDGTs)] was then plotted using the weighted mean age from the updated age model (black line). Individual proxy samples are indicated by black squares. Proxy data were plotted using the 2000 age iterations extracted in step 2 (blue shading; 95% and 68% CI). Change point analysis was conducted on each record to determine the timing of changes in the mean of proxy data. Step 4: Identified change points were extracted and each plotted as a Probability Distribution Function. The probability of change (height of peak) results from the likelihood of a change occurring at that time. The uncertainty associated with the timing of change (width of distribution) results from the spread of age iterations determined in step 2. This process was repeated for each identified site. Sites that met the broad criteria were incorporated into further analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

terrestrial vegetation types in the analogue package (Simpson, 2007) in R. A PrC is a smooth, nonlinear, one-dimensional curve fitted through the n -dimensional proxy data (Hastie and Stuetzle, 1989; Simpson, 2007). During optimisation, PrCs are initially determined using the first correspondence analysis axis. Successively, the PrC is fitted towards the data by projected n smooth splines to individual pollen taxa. The maximum number of iterations was set to 10. If the PrC did not converge sufficiently close to the previous iteration after 10 iterations, the 10th iteration was used. A generalised cross-validation was used to determine the smoothing of splines to each taxon within the PrC. A penalty of 1.4 was applied on the degrees of freedom to avoid overfitting.

Proxy records (pollen PrCs, $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and mean annual air temperature (MAAT) inferred from branched GDGTs) were plotted vs. age using the weighted mean of the 2000 extracted age-depth model iterations. Temporal uncertainty was incorporated by plotting proxy records against all 2000 age-depth model iterations creating an uncertainty window of all potential age-depth and proxy relationships for each record between 35–15 ka.

Change point analyses were conducted on each iteration within the ensemble of records vs. age for each site using the changepoint package (Killick, 2014) in R (e.g., Sniderman et al.,

2016; Tibby et al., 2018). Change point analysis was used to determine statistically significant changes in the mean for each record using the binary segments method with a penalty of $2 \cdot \log(n)$ (where n = the length of the original dataset). Depending on the temporal resolution of each proxy record, a minimum segment length (>3 data points) between change points was specified. A change point was identified as a significant change in mean values, and the timing of each change point was defined as the median age between the two bracketing data points. Additional change point methods were explored during analysis of datasets, including EnvCpt, with a model-selection approach (Beaulieu and Killick, 2018). However, given the low resolution and uneven nature of the datasets compiled, it was considered that a mean change point model would be a reasonable model for the time series analysed in this study. A more detailed analysis of individual time series, which is beyond the scope of this work, may reveal that other models (e.g., trend change points) are a better fit in individual cases.

For each record ensemble, the frequency distribution of change points of each ensemble member was compiled and used to calculate the probabilistic age distribution of the timing of change. A probability density function (PDF) was derived for each change

Figure 3. Examples of the different change points identified in the 38 records analysed. (1) Record exhibiting a single change point. (2) Record exhibiting two change points. (3) Record exhibiting three change points. (4) Record exhibiting four change points between 35–15 ka. Change points denoted by vertical lines (orange represents weighted mean of 2000 age-depth model iterations; red represents median of 2000 age-depth model iterations). Light blue shade represents 95% of age-depth vs. proxy relationships, darker blue shading represents 68% of age-depth vs. proxy relationships. Y axis is orientated so that up indicates an increase in biological activity, temperature, or rainfall and down represents a decrease in biological activity, temperature, or rainfall as indicated by coloured arrows. Black line and squares represent proxy data plotted on weighted mean of 2000 age-depth model iterations. See Figure 1 for locations. See Supplementary Materials for change points identified from all records. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1. Locations of continuous palaeoclimate and palaeoenvironmental records identified from across Australia covering the last glacial stage (35–15 ka) and included in this synthesis.

Site	Record Length (ka)	No. of dates	Proxy Type	Latitude	Longitude	References
Lake Carpentaria MD972128	32	9	Pollen	13°50'S	139°0'E	Chivas et al., (2001)
Lake Carpentaria MD972133	43	6	Pollen	13°50'S	139°0'E	Chivas et al., (2001)
Lake Carpentaria GC-2	36	16	Pollen	13°50'S	139°0'E	Torgersen et al., (1988)
ODP820	60	21	Pollen	16°38'S	146°18'E	Moss and Kershaw, (2000); Moss et al., (2017)
Bromfield Swamp	50	34	Pollen	17°22'18"S	145°32'37"E	Kershaw, (1975); Burrows et al., (2016)
Lynch's Crater	40	15	Pollen	17°22'S	145°42'E	Turney et al., (2006b); Kershaw et al., (2007a)
FR197-GC12	35	9	$\delta^{18}\text{O}_{\text{G. Ruber}}$	23°34'37"S	153°46'94"E	Bostock et al., (2006)
Moon Point	35	5	Pollen	25°12'41"S	153°2'32"E	Moss et al., (2016)
Lake McKenzie	50	14	GDGTs	25°26'45"S	153°03'25"E	Atahan et al., (2014); Woltering et al., (2014)
Lake Coomboo	80	5	Pollen	25°13'10"S	153°11'45"E	Longmore, (1997)
Welsby Lagoon	25	11	Pollen	27°27'00"S	153°28'00"E	Moss et al., (2013); Barr et al., (2017)
Tortoise Lagoon	25	12	Pollen	27°30'59"S	153°28'26"E	Moss et al., (2013); Petherick et al., (2017)
Native Companion Lagoon	40	18	Pollen	27°40'36"S	153°24'39"E	Petherick et al., (2008, 2009)
Cuddie Springs	37	10	Pollen	30°22'46"S	147°18'42"E	Field et al., (2002)
Ulungra Springs	35	3	Pollen	31°44'25"S	149°5'38"E	Dodson and Wright, (1989)
Penrith Lakes	38	4	Pollen	33°42'50"S	150°40'38"E	Chalson and Martin, (2008)
Mammoth Cave	32	32	Pollen	34°03'29"S	115°01'50"E	Sniderman et al., (2019)
Core 112VC046	31	5	Pollen	33°50'S	152°0'E	Ferland and Roy, (1997)
Lake Baraba	46	6	Pollen	34°13'S	150°13'E	Black et al., (2006)
Pine camp Playa	30	4	Pollen	34°45'0"S	141°7'48"E	Cupper, (2005, 2006)

(Continued)

Table 1. (Continued.)

Site	Record Length (ka)	No. of dates	Proxy Type	Latitude	Longitude	References
Lake George	45	4	Pollen	35°06'37"S	149°26'5"E	Singh et al., (1981); Singh and Geissler, (1985)
MD03-2607	33	35	$\delta^{13}\text{C}_{\text{n-alkanes}}$	36°43'48"S	136°32'54"E	Lopes dos Santos et al., (2013); De Deckker et al., (2019)
Caledonia Fen	140	16	Pollen	37°20'0"S	146°43'60"E	Kershaw et al., (2007b)
Storm Creek	25	4	Pollen	37°26'39"S	145°48'2"E	McKenzie, (2002)
Boulder Flat	31	4	Pollen	37°27'0"S	148°54'E	Kenyon, (1989)
Tom Burns	40	5	Pollen	37°27'0"S	145°48'0"E	McKenzie, (1997)
Lake Leake	48	4	Pollen	37°37'27"S	140°36'14"E	Dodson, (1975)
Wyrie Swamp	50	6	Pollen	37°38'0"S	140°16'56"E	Dodson, (1977)
Lake Surprise	30	32	$\delta^{13}\text{C}_{\text{OM}}$	38°3'40"S	141°55'20"E	Falster et al., (2018)
Tyrendarra Swamp	32	4	Pollen	38°11'55"S	141°45'45"E	Builth et al., (2008); Builth et al., (2008)
Tower Hill	25	5	Pollen	38°19'1"S	142°21'46"E	D'Costa et al., (1989)
Lake Wangoom	80	7	Pollen	38°21'0"S	142°35'60"E	Harle et al., (2002)
Cave Bay Cave	35	9	Pollen	40°31'47"S	144°46'26"E	Hope, (1978)
Tullabardine Dam	35	6	Pollen	41°40'30"S	145°39'8"E	Colhoun and van de Geer, (1986)
Lake Selina	80	6	Pollen	41°52'43"S	145°36'32"E	Colhoun et al., (1999)
Lake St Clair	30	5	Pollen	42°4'S	146°10'E	Hopf et al., (2000)
Hazards Lagoon	25	3	Pollen	42°10'20"S	148°17'21"E	Mackenzie and Moss, (2017)

point, in all records, along with the weighted average and median values for each PDF. The height of individual peaks within the PDF indicates the probability of the statistically significant change point occurring. The width of the PDF is derived from the 2000 age ensembles and represents the associated age uncertainty for each change point. A visual demonstration of the methodological workflow undertaken in this study is presented in [Figure 2](#).

Individual change points determined from each record were examined in further detail to identify the direction of the proxy signal and potential climate drivers of each change point. Pollen records are interpreted as responding, in part, to changes in regional climate (primarily mean annual air temperature (MAAT) and change in rainfall amount and seasonality). However, atmospheric CO₂ (Prentice et al., 2017), site-specific factors, disturbance (i.e., fire), and human modification are also potential contributors to the observed changes (Bond et al., 2005; Higgins and Scheiter, 2012; Bakker et al., 2016). The primary climate driver of individual pollen records is likely to vary regionally, with the relative influence of changes in MAAT or hydrology difficult to quantify. The $\delta^{13}\text{C}$ records are also suggested to be a record of catchment vegetation, however with a strong hydrological climate component (Lopes dos Santos et al., 2012; Falster et al., 2018). The $\delta^{18}\text{O}$ record reflects variation in sea level, sea-surface temperatures and surface-ocean circulation patterns (Bostock et al., 2006), while the GDGT record is primarily interpreted as a record of mean annual temperature (Wolterring et al., 2014).

Changes in biological productivity were converted to simplified climate indices to facilitate inter-site and multi-proxy comparisons. A change point indicating a decline in biological productivity (i.e., from arboreal to grass taxa) is suggested to represent a distinct shift to cooler climates in conjunction with a decrease in available moisture and/or low atmospheric CO₂ (herein referred to as a decreasing change point). A change point indicating an increase in biological productivity (i.e., from grass to arboreal taxa) is suggested to represent a distinct shift to warmer climates in conjunction with an increase in available moisture and/or increase in CO₂ (herein referred to as an increasing change point). These simplified indices used for assigning climatic changes do not assess the magnitude of changing conditions associated with individual change points and are unlikely to always represent the full range of variability within each dataset. However, the aim of this study, to determine the timing of broad scale regional climate changes in existing palaeoenvironmental records, and the likelihood of synchronous climate changes between those records, dictates the need for a simplified approach to each individual dataset.

Using the change point information from all records, four periods of change were identified, although not all change points are identified in each individual record: (1) An initial shift to decreasing climate conditions if the records preserved evidence of warmer and/or wetter conditions after 35 ka, before a transition to decreasing climate conditions. (2) A middle change point to increasing climate conditions if a record displayed evidence of a change to increasing climate conditions preceding a decrease in climate conditions. (3) A shift to further decreasing climate conditions if a record displayed a second change point from depressed climate conditions to further decreasing climate conditions, or from increased climate conditions to decreasing climate conditions after an initial change point. If a record displayed evidence of experiencing depressed climate conditions prior to 35 ka (as in Core FR0197) or a record began after 30 ka and already

suggested depressed conditions (as in Tortoise Lagoon), a change point to further decreasing conditions was also considered a further change. (4) A transition to increasing climate conditions if a change was categorised as a final transition to increasing climate conditions without a further decrease in climate conditions prior to 15 ka ([Fig. 3](#)).

RESULTS

Sites included in this synthesis are listed in [Table 1](#). During the age-depth modelling process, sites that did not meet the criteria of encompassing $\geq 10,000$ years between 35–15 ka, or with obvious depositional hiatuses, were excluded from further analysis (Supplementary Fig. 1). The length of individual sedimentary records and number radiocarbon dates are shown in [Table 1](#). The length of records is variable; however, 37 records cover the entire period from 25–15 ka and 36 from 29–25 ka. The number of records extending beyond 30 ka is fewer, and only 15 records that extended beyond 35 ka were identified. The location of all 37 records included in the synthesis are shown in [Figure 1](#). The total number of radiometric ages obtained from the original published records and used in this study was 413 (ranging from 0–47.6 ka). The number of individual radiometric ages from each record varied between 3 and 35 (median = 8).

The number of change points identified was variable across records. A single change point was identified in 18 records, two change points in 14 records, three change points in one record, and four change points in three records. Full details of individual records (see references listed in [Table 1](#)) and identified change points are available in the supplementary materials (Supplementary Figs. 3a–ak).

A total of 27 records display evidence for at least one change point identified as decreasing climate conditions (i.e., shift to cooler climates in association with decreased moisture and/or atmospheric CO₂), with these change points occurring from 35.6–17.4 ka ([Fig. 3](#), Supplementary Figs. 3a–ak). Frequency distribution of the timing of decreasing change points indicated that the greatest proportion of changes occurred between 26–31 ka ($n = 19$) ([Fig. 4](#)). The remaining nine records do not include a change point identified as decreasing climate conditions. These nine records display evidence of experiencing cool and/or dry conditions prior to 35 ka, or when the proxy record commenced. A total of 28 records display evidence of at least one change point identified as increasing climate conditions (i.e., shifts to warmer climates in association with increased moisture and/or CO₂), with these change points occurring between 28.1–14.6 ka ([Fig. 3](#), Supplementary Figs. 3a–ak). Frequency distribution of the timing of increasing change indicates that the greatest proportion of change points occurred between 21–15 ka ($n = 21$) ([Fig. 4](#)). The remaining twelve records do not record a change to increasing warm and/or wet conditions prior to 15 ka and display evidence for the continuation of cool and/or dry climate conditions after 15 ka (Supplementary Figs. 3a–ak).

Change points categorised as representing an initial decreasing shift in climate conditions occur at 28.6 ± 2.8 ka ($n = 25$) (median and one standard deviation of all mean change points). Change points characterised as a middle increasing climate change occur at 26.8 ± 2.1 ka ($n = 4$). Change points categorised as a further shift to decreasing climate conditions occur at 21.4 ± 1.8 ka ($n = 8$). Change points categorised as representing a final increasing shift in climate conditions occur at 17.7 ± 2.2 ka ($n = 24$) ([Figs. 4](#) and [5](#)).

Figure 4. Frequency distribution of the weighted mean of all significant change points identified in all 38 analysed records. Shading denotes the simplified climate indices assigned to each significant change point as either a decrease in biological activity, temperature, or rainfall (orange) or an increase in biological activity, temperature, or rainfall (blue). Coloured lines indicate change points identified as the initial onset of decreasing climate conditions (i.e., shift to cooler climates in association with decreased moisture and/or atmospheric CO₂) (dark orange line), further decrease in climate conditions (light orange line), a middle change to increasing climate conditions (i.e., shift to warmer climates in association with increased moisture and/or atmospheric CO₂) (light blue line) and a final increase or termination of extreme conditions (dark blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

DISCUSSION

An extended period of extreme conditions in Australia

The frequency distribution of the change point analysis conducted on all 37 analysed records indicates two main periods of change, between 30–26 ka, and 20–16 ka (Fig. 4). The compilation of change point analyses indicates consistent timing of change points early in the last glacial period at 28.6 ± 2.8 ka (Figs. 4, 5, and 6). This timing is evident across all climate regions sampled and occurs in 25 of the 27 records that cover the entire 35–15 ka period, suggesting that this change point signal is robust and widespread (Fig. 5). Similarly, a widespread consistent timing of change points occurs late in the last glacial period at 17.7 ± 2.2 ka (Figs. 4 and 5). This change point was recorded in 24 of the 37 records analysed and occurs in all climate regions sampled.

The primary focus of our research is to address the timing of change associated with the extreme conditions of the last glacial stage across Australia, and in order to do so it was necessary to reduce the datasets to simple indices—namely increasing or decreasing indicators (including temperature, rainfall, and CO₂). Whilst undoubtedly subject to uncertainty, and requiring of more detailed site-specific consideration, we believe these interpretations provide a useful first-order indicator of the nature of broad changes across the continent. On this basis, analysis of the proposed climatic signal from individual change points from each record show that 88% of change points that occur prior to 26 ka indicate a change to decreasing climate conditions (Figs. 4 and 6). Similarly, of the 28 change points recorded after 21 ka, 79% indicate a change to increasing climate conditions (Figs. 4 and 6). The widespread transition to decreasing climate conditions at $28.6 (\pm 2.8)$ ka, and then the subsequent shift towards increasing climate conditions at $17.7 (\pm 2.2)$ ka provides objective bracketing for a period of environmental change, consistent with an extended period of cooler and probably more arid climate conditions.

The consistent timing of a change point at 28.6 ± 2.8 ka (shaded orange bar, Figs. 5 and 7) is coincident with the timing of a rapid fall in global sea level (Fig. 7) (Lambeck et al., 2014). Sea levels dropped by ~40 m between ca. 31–29 ka (Lambeck et al., 2014; Yokoyama et al., 2018). The sharp drop in sea level

would have increased the area of the Australian continent, increasing continentality and changing synoptic atmospheric and ocean circulation patterns, leading to changes in regional climates. The timing of this change point corresponds to a modest decline in atmospheric CO₂ concentrations of ca. 10 ppm at 27.2 ka (Fig. 7), perhaps indicating that CO₂ concentrations were not the primary driver of the vegetation changes identified here. However, the sustained low atmospheric CO₂ concentrations during this period may have influenced competitive outcomes, particularly between woody and herbaceous plants, and this may have made vegetation communities more susceptible to small changes in climatic conditions (Cwiling and Sykes, 1999; Williams et al., 2000; Vicente-Serrano et al., 2013) (Fig. 7). A change in climate conditions and/or vegetation cover is indicated at this time from discontinuous geomorphic records, with an increase in dune field activity and dust transport evident after ca. 30 ka (Fitzsimmons et al., 2013; Hesse, 2016). The timing of these widespread environmental changes in Australia is in agreement with palaeoclimate records from New Zealand which record reductions in arboreal vegetation, lowering of the tree line, and widespread glacial conditions from 28 ka (Hellstrom et al., 1998; Suggate and Almond, 2005; Alloway et al., 2007; Newnham et al., 2007; Barrows et al., 2013; Vandergoes et al., 2013).

The transition out of the extreme climate conditions associated with the last glacial stage and towards the Holocene at 17.7 ± 2.2 ka (shaded blue bar, Figs. 5 and 7), occurring during the deglacial period, correspond to rises in sea level between 20.5–16.6 ka and a substantial increase in global CO₂ concentrations beginning at 17.2 ka. The relative importance of different influences on the vegetation communities is difficult to assess across such a broad geographical range, from both monsoonal northern and temperate southern regions. Vegetation records north of 20°S predominantly retain arboreal or woody vegetation cover during the last glacial stage, while vegetation records south of 30°S largely display a shift to grass and herb dominated taxa during this period. The climate forcing required to initiate a change between tree-dominated biomes may be smaller than that required to initiate recovery and recolonization of woody vegetation. The precipitation and temperature increases required

Figure 5. Compilation of identified change points for each site. Weighted mean timing of change points is indicated by coloured symbols. Age uncertainty (95% confidence interval), determined from the ensemble of 2000 age-depth models, associated with each change point is indicated by error bars. Sites are plotted along a latitudinal gradient. **(A)** All change points identified for each site. **(B)** Only change points identified and determined as representing the onset of extreme conditions and change decreasing climate indicators (including temperature, precipitation, and CO₂) (mean = dashed orange line, SD = shaded orange bar) and the termination of extreme conditions representing increasing climate indicators (including temperature, precipitation, and CO₂) (mean = dashed blue line, SD = shaded blue bar). Density of dates curves above panels **A** and **B** are kernel density plots of **A**. Kernel density estimate of both mean and uncertainty of timing of all identified change points derived from the ensemble of 2000 age-depth models and **B** Kernel density estimate of both mean and uncertainty of timing of change points identified as the onset of extreme conditions (orange line), termination of extreme conditions (blue line) derived from the ensemble of 2000 age-depth models. Change points not assigned to either the onset or termination of extreme conditions are shown by dashed lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to transition from grass and herb vegetation to woody or arboreal vegetation are likely compounded by low atmospheric CO₂ levels, increasing the advantage of some functional plant types, while reducing the resilience of other vegetation communities. Many records display additional and, in some cases, increasingly large changes in vegetation or climate leading into and during the Holocene (e.g., records from tropical north Queensland, Bromfield Swamp, and Lynch's Crater), however this later transition is beyond the scope of this paper.

Millennial scale variability

Between the two main periods of change identified in the frequency distribution, a further 12 change points are identified (Figs. 4, 5 and 6) in nine different records. These change points indicate a variable climate between 28.6–17.7 ka at each of these sites. The climatic implications of the 12 identified change points during this time are not consistent, with eight of the change points indicating a change to decreasing climate indicators (including temperature, rainfall, and CO₂), and four indicating a change to increasing climate indicators (including temperature, rainfall and CO₂). The occurrence of multiple change points

during this period highlights the variable nature of climate and environmental conditions across Australia during the last glacial stage and underscores the challenges associated with interpretation of simplified climate indices.

Of these identified change points, three records indicate a two-step change from decreasing climate conditions to further decreased conditions (Bromfield Swamp, Ulungra Springs, and Murray Canyons). A further three records register a change point towards decreasing conditions after 25 ka (Tortoise Lagoon, Lake George, and Boulder Flat). These records do not extend beyond 30 ka and demonstrate relatively cool and/or dry conditions when each record began. The FR0197 *G. ruber* δ¹⁸O record indicates lower sea levels, potentially coupled with different surface–ocean circulation patterns and/or cool SST, throughout the period 35–25 ka, before a shift at 23 ± 3.5 ka.

The remaining two records (Native Companion Lagoon and Lake Surprise) suggest the extended period of uniform climate conditions was interrupted by a period of warmer and/or wetter conditions. Neither the timing of the onset or the termination of this period, nor the duration of this warmer and/or wetter period, is the same in these records. The limited number of records indicating the presence of a millennial scale change during an

Figure 6. Probability density functions for all sites (coloured lines) and summed probability of (a) all change points, (b) all change points identified as representing a change to decreasing climate indicators (including temperature, precipitation, and CO_2), and (c) all change points identified as representing a change to increasing climate indicators (including temperature, precipitation, and CO_2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

otherwise extended period of relative climate stability may indicate this phenomenon was not widespread. However, the limited identification of this millennial scale change may be a function of the number of sufficiently resolved records able to detect short-term fluctuations in climate during this period. Many of the proxy records analysed here have too coarse a temporal resolution to reliably identify millennial scale variability. The presence of this signal in records from the east coast (Native Companion Lagoon) and southwest Victoria (Lake Surprise) may suggest any millennial-scale cycles in this period (need they be synchronous

or separate events) may have been geographically widespread, at least on the eastern half of the continent. This period of altered climatic conditions may have been insufficient to drive substantial changes in vegetation composition in various ecological settings. In addition, the resilience of various vegetation communities under the low atmospheric CO_2 conditions during the last glacial stage may have restricted a rapid response of ecosystems to brief periods of increased temperature and/or moisture availability.

Whilst a period of increased temperature and/or moisture availability displayed in Native Companion Lagoon and Lake Surprise is

Figure 7. (A) Summed probability density function of all change points identified as representing a change to decreasing climate indicators (including temperature, precipitation, and CO₂) (orange line) and all change points identified representing a change to increasing climate indicators (including temperature, precipitation, and CO₂). (B) Compilation of ice core atmospheric CO₂ measurements (ppm) for the period 35–15 ka (Köhler et al., 2017). (C) Ice volume equivalent sea level (m) (black line) and 95% probability limiting values (grey shading) (Lambeck et al., 2014). Vertical shaded lines indicate the mean and standard deviation of change points identified as representing the onset of extreme conditions (orange) and termination of extreme conditions (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

not manifest in any other records analysed here, an additional six records have a second change point to decreasing climate conditions (including temperature, rainfall, and CO₂). These change points can be characterised either as a shift from already depressed climate conditions to further decreasing climate conditions (Ulingra Springs and MD03-2607), further reduction in sea level (FR0197), or a change to decreasing climate conditions in records

that do not extend from 35–30 ka (Tortoise Lagoon and Lake George). Combined with the two records that record a shift to decreasing climate conditions at the termination of a period of increased temperature and/or moisture availability (Native Companion Lagoon and Lake Surprise), a change to decreasing climate conditions at 21.4 ± 1.8 ka in eight records is indicated during the originally defined global LGM (Yokoyama et al., 2000). The

Figure 8. Change points identified and determined as representing an initial change to decreasing climate indicators (including temperature, precipitation, and CO₂), a further decrease in climate indicators, a middle shift to increasing climate indicators and a final increase in climate indicators (including temperature, precipitation, and CO₂). Size of circle represents the age uncertainty (95% confidence interval), determined from the ensemble of 2000 age-depth models, associated with each change point. Individual records are ordered by latitude from north (13°S) to south (42°S). Non-pollen records are indicated in red text.

occurrence of a change point toward further decreasing temperature, moisture availability, or CO₂ in this subset of records, coincident with the timing of the absolute global sea-level minimum, suggests that this period was potentially represented by a further reduction in either effective precipitation or temperature that culminated in maximum glaciation in Australia (Barrows *et al.*, 2002).

Climate implications

The records compiled for this multi-site comparison primarily reflect vegetation change and therefore represent environmental responses to climate change (Fig. 1, Table 1). As such, assigning definitive climate drivers to such changes is difficult. However, the consistent timing of changes within the pollen records indicates that, although vegetation changes are susceptible to multiple drivers and time-transgressive responses, there is likely an overarching first-order climatic driver operating on most records analysed here (Figs. 5, 6, and 8). The clear climatic signal evident in the large number of pollen records analysed may be indicative of the extreme and substantial climatic changes during this period, as well as the potential sensitivity of different Australian ecosystems to climate forcing. Whilst individual pollen records may not record a primary climate signal, the compilation of several records across regional spatial scales can increase the confidence in the likelihood of climate as a primary driver. The large number of pollen records that demonstrate the same signal, across a broad spatial range, enables regional interpretations of climate to be made.

Future research directions

The work presented here provides evidence for synchronous, widespread environmental change across Australia associated with both the onset and termination of extreme climate conditions during the LGM (Fig. 7). To provide more detailed information on the potential widespread nature of the changes identified here requires the development of more continuous palaeoclimate records from under-represented climate regions. The distribution of continuous terrestrial archives in Australia is largely restricted to the eastern and southern regions of the continent (Fig. 1). The potential for developing palaeoclimate records that are continuous through the last glacial period from the western, northwestern, and centre of the continent is more limited. However, recent work from some of these regions has identified continuous proxy records that extend to this time period (Field *et al.*, 2018; Rowe *et al.*, 2020). Incorporation of discontinuous geomorphic archives of palaeoclimate into future syntheses, and improved climatic interpretations of such records, would broaden the spatial coverage to regions where preservation of continuous terrestrial archives is incomplete or less dense.

The proxy resolution and age uncertainty of many records analysed in this compilation make it difficult to provide a more precise timing of climate changes associated with the last glacial stage, including the onset and termination of these changes. There are few records currently available that allow sub-millennial scale changes, precise timing of regional variations, and external climate drivers to be accurately determined. In order to more precisely identify the timing of key environmental events and their

relationships to climate change, high resolution proxy data coupled with independently and densely dated chronologies are required. The continued incorporation of high-resolution geochemical records from micro X-ray fluorescence analysis (μ XRF) core scanning could provide an important additional proxy dataset that can be compared to more traditional palynological datasets and substantially improve the resolution of records of environmental change during the last glacial stage. The methods employed here incorporate the chronological uncertainty associated with age-depth model development and interpolation between dated depths, however no assessment is made of the quality of the radiometric dates used. Identification of anomalous radiometric ages and accurate quantification of individual age determinations requires an increase in the density of dated layers (Blaauw et al., 2018) and dating of multiple sediment fractions (Martin et al., 2019; Thomas et al., 2019). The presence of sedimentary hiatuses in records used in this compilation may currently be masked by the limited number of radiometric ages analysed from some sites (Supplementary Fig. 2). Verification of ages by a form of independent age control (e.g., optically stimulated luminescence or uranium-thorium methods) would provide additional chronological certainty. Enhanced application of rigorous chronological modelling methodologies and accounting for inherent age uncertainties will further enhance the capacity for inter-site comparisons and regional syntheses (Blaauw et al., 2018; Blaauw et al., 2019; Blaauw et al. 2020).

Improvement of proxy resolution and reduction of age-uncertainty will further increase the potential for more robust statistical analysis and record comparison. Here, we used a mean change point analysis, from the *changepts* package in R, to attempt to identify the timing of the most extreme conditions during the last glacial stage from proxy records of varying temporal resolution. Implementation of a mean change point method was chosen to provide a simple and repeatable measure of timing of changes within datasets incorporated in this synthesis, which vary strongly in their temporal resolution and in the 'noisiness' of their proxy signals. However, the mean change point approach assumes that all time series can be adequately represented by a series of n segments, each with a stationary mean and randomly fluctuating noise components. In fact, time series data can be more complex, with linear trends, changes in trend and red noise all common features of palaeoclimate timeseries (Beaulieu and Killick, 2018). This work is a first step in the use of change point analysis to compare and synthesise multiple palaeoenvironmental records of varying temporal and proxy resolution. Exploration of change point methodologies with greater complexity of analysis afforded by newly developed software, such as those implemented in the *EnvCpt* change point package (Beaulieu and Killick, 2018), will continue to improve conclusions of spatial and temporal synthesis.

Palaeoclimate reconstructions derived from biological and geomorphological proxy evidence may be influenced by a variety of additional factors (e.g., atmospheric CO_2 variations and human modification) and display time-transgressive responses to climate forcing. An accurate understanding of the magnitude of past climate changes and their influence on local environmental conditions requires a network of quantitative precipitation and temperature reconstructions, based on organic and/or isotope geochemical tracers (e.g., GDGTs, alkenone palaeothermometry, oxygen and hydrogen isotopes) across a variety of climate regions. Validation of interpreted changes via independent estimates of both temperature and precipitation across both terrestrial and oceanic records would

further allow the magnitude of changes and interactions between climate variables to be disentangled. Comparison of these independent, quantitative hydrological and temperature records with records of vegetation change would reduce the ambiguity of the role of precipitation, temperature, $p\text{CO}_2$, or disturbance in driving vegetation transitions. In addition, incorporation of quantitative local climate reconstructions would provide a foundation on which to test how variations in atmospheric CO_2 influence vegetation resilience and response to climate changes.

Supplementary Material. The supplementary material for this article can be found at <https://doi.org/10.1017/qua.2021.16>

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