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Integration of ice-core, marine and terrestrial records for the Australian Last Glacial Maximum and Termination: a contribution from the OZ INTIMATE group

C. S. M. TURNEY,[1]* S. HABERLE,[2] D. FINK,[3] A. P. KERSHAW,[4] M. BARBETTI,[5] T. T. BARROWS,[6] M. BLACK,[7] T. J. COHEN,[1] T. CORRÈGE,[8] P. P. HESSE,[9] Q. HUA,[3] R. JOHNSTON,[4] V. MORGAN,[10] P. MOSS,[11] G. NANSON,[1] T. VAN OMMEN,[10] S. RULE,[4] N. J. WILLIAMS,[12] J.-X. ZHAO,[5] D. D'COSTA,[13] Y.-X. FENG,[5] M. GAGAN,[14] S. MOONEY[7] and Q. XIA[5]

[1] GeoQuEST Research Centre, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, New South Wales, Australia
[2] Research School of Pacific & Asian Studies, Australian National University, Canberra, ACT, Australia
[3] Australian Nuclear Science and Technology Organisation, Menai, New South Wales, Australia
[4] Centre for Palynology and Palaeoecology, School of Geography and Environmental Science, Monash University, Victoria, Australia
[5] Advanced Centre for Queensland University Isotope Research Excellence (ACQUIRE), The University of Queensland, Brisbane Queensland, Australia
[6] Department of Nuclear Physics, Research School of Physical Sciences and Engineering, The Australian National University, Canberra, ACT, Australia
[7] School of Biological, Earth and Environmental Sciences, University of New South Wales, Australia
[8] Departement de Geologie et Oceanographie, UMR CNRS 5805 EPOC, Universite de Bordeaux I, Talence, France
[9] Department of Physical Geography, Macquarie University, New South Wales, Australia
[10] Antarctic Climate and Ecosystems CRC & Australian Antarctic Division, Hobart, Australia
[11] School of Geography, Planning and Architecture, University of Queensland, Brisbane, Queensland, Australia
[12] School of Geosciences, The University of Sydney, Sydney, New South Wales, Australia
[13] School of Geography and Environmental Science, Auckland University, Auckland, New Zealand
[14] Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia

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ABSTRACT: The degree to which Southern Hemisphere climatic changes during the end of the last glacial period and early Holocene (30-8 ka) were influenced or initiated by events occurring in the high latitudes of the Northern Hemisphere is a complex issue. There is conflicting evidence for the degree of hemispheric 'teleconnection' and an unresolved debate as to the principle forcing mechanism(s). The available hypotheses are difficult to test robustly, however, because the few detailed palaeoclimatic records in the Southern Hemisphere are widely dispersed and lack duplication. Here we present climatic and environmental reconstructions from across Australia, a key region of the Southern Hemisphere because of the range of environments it covers and the potentially important role regional atmospheric and oceanic controls play in global climate change. We identify a general scheme of events for the end of the last glacial period and early Holocene but a detailed reconstruction proved problematic. Significant progress in climate quantification and geochronological control is now urgently required to robustly investigate change through this period. Copyright © 2006 John Wiley & Sons, Ltd.

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* Correspondence to: C. S. M. Turney, GeoQuEST Research Centre, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW 2522, Australia. E-mail: turney@uow.edu.au

Introduction

INTIMATE (INTegration of Ice, MArine and TErrestrial records; a core programme of the INQUA Palaeoclimate Commission) was launched at the XIVth INQUA Congress held in Berlin in 1995. Its primary objective was the synthesis of records of the Last Termination from the North Atlantic region. The project was established to encourage collaboration between members of the ice-core, marine and terrestrial 'communities' in order to synthesise the large number of high-resolution stratigraphical records of the Last Termination available from the North Atlantic. Since this time, the programme has expanded to other regions of the world, with the initiation of an Australasian INTIMATE group at the XVIth INQUA Congress in Reno in 2003, where the period of interest was expanded to 30–8 ka.[†]

This period was characterised by a sequence of abrupt and extreme climate changes that included maximum glacier advance during the last glacial period (the Last Glacial Maximum or LGM), the Termination and early Holocene. Within the North Atlantic region, an event stratigraphy has been developed using the GRIP ice-core record which provides the basis for testing synchroneity between local and Greenland climatic events (Björck *et al.*, 1998; Walker *et al.*, 1999; Lowe *et al.*, 2001). Here, the LGM is dated to 21.2 ka (GS-2c in the Greenland ice-core isotope stratigraphy), rapid warming at 14.7 ka (the start of the 'Bølling' Interstadial, or GI-1) and the well-known period of severe cooling referred to as the Younger Dryas Stadial (GS-1) dated to between 12.8 and 11.5 ka.

It has been proposed that this North Atlantic 'template' of climate change would provide a useful model for interpreting the palaeoclimatic history of other parts of the world, and that the vigour of the thermohaline circulation (THC) in the North Atlantic provided the underlying mechanism driving globally synchronous, abrupt climatic change (Broecker, 2003). Direct comparisons of Antarctic and Greenland ice-core records, however, were equivocal in supporting (or refuting) the above hypothesis. While some workers concluded that millennial-scale climate changes during this period were indeed globally synchronous (Steig *et al.*, 1998), others provided a contrasting view that warming episodes in the north coincided with cooling periods in the south (Blunier *et al.*, 1998). This has led to the idea of a 'bipolar seesaw' of opposing climate tendencies between the two hemispheres after the LGM (Broecker, 1998) potentially initiated by Antarctic melting (Weaver *et al.*, 2003). More recent work (Morgan *et al.*, 2002) has challenged both scenarios, suggesting that climatic changes in the south led those in the Northern Hemisphere. The extent to which this pattern is reflected in mid–latitude palaeoclimatic records from the Southern Hemisphere is also far from clear, with evidence that climate events were synchronous (Denton and Hendy, 1994; Moreno *et al.*, 2001), asynchronous (Turney *et al.*, 2003), or gradual (Bennett *et al.*, 2000) compared to those in the Northern Hemisphere.

The only way to rigorously test the hypothesis of synchroneity (or otherwise), is to generate detailed palaeoclimatic records from different parts of the world that are independently and securely dated, and which provide an adequate temporal and spatial resolution of the key events in question to recognise regional climatic events (Lynch-Stieglitz, 2004). There is a relative dearth of sites from Australia, despite the key role climatic controls in this region have on the world. By reconstructing highly precise and accurate histories of climatic changes in the Australian region and testing the degree to which changes were synchronous (or not) with the North Atlantic region, the mechanisms by which climate signals are propagated globally can be identified. These results are critical for improving our ability to predict future climate change in the Australian region.

Several earlier attempts have been made to integrate records from across Australia for key time-slices, including the period of interest here (Chappell and Grindrod, 1983; Harrison and Dodson, 1993; Kershaw, 1998; Hunt and Barrows, 1999). Since this time, however, significant developments have been made in the number and dating of potential sites. The aim of this paper is to summarise some of the principal conclusions of the Australian community that have emerged during discussions within the OZ INTIMATE group. This paper focuses on climatic and environmental events identified within ice, marine and terrestrial sources to produce a synthesis of change across the Australian region during the end of the last glacial period into the early Holocene.

Contemporary climatic controls

Several major oceanographic and atmospheric controls affect the climate of the southwest Pacific (Fig. 1). The northern part is influenced by variations in the position of the Inter-Tropical Convergence Zone (ITCZ), which migrates southwards into the extreme northern part of Australia during the austral summer and is a major control on moisture supply as far south as 30° S. The northern part of Australia also lies within the direct influence of Indo-Pacific Warm Pool (IPWP; the region where mean temperatures are above 28°C), which is a major source of global latent heat release. The size of the IPWP is sensitive to changes in the El Niño–Southern Oscillation (ENSO), and hence the strength of atmospheric circulation across the Pacific. During 'warm' ENSO (El Niño) events, the IPWP contracts towards the equator, the South Pacific Convergence Zone (SPCZ) migrates into the ITCZ and, in the mid-latitudes, a high-pressure anomaly develops over southern Australia (Hooker and Fitzharris, 1999). The degree to which the teleconnection is strengthened across the region appears to be modulated by the Interdecadal Pacific Oscillation (Salinger *et al.*, 2001).

Australia's climate is dominated by the dry, sinking air of the subtropical high-pressure belt that migrates across the continent through the year. In the mid-latitudes, westerly airflow centred over 40° S roughly tracks the flow of subantarctic waters. When the high-pressure systems moves north during the austral winter, however, southern Australia comes under the influence of the westerly winds and rain-bearing cold fronts (Sturman and Tapper, 1996).

Ocean circulation also plays a potentially important role in the transmission of ENSO signals to high southern latitudes via the Antarctic Circumpolar Wave (ACW) (White and Peterson, 1996) through the transmission of sea-surface temperature (SST) anomalies. The SST anomalies are transmitted via Rossby Waves, where they are subsequently propagated eastwards into the South Atlantic and Indian Oceans. At present, however, the long-term stability of the ACW and IPO are unknown. Independently of ENSO-generated anomalies, the oceans transport heat southward via the East Australian Current (EAC) which has a significant influence on coastal regions of eastern Australia, with approximately half of the EAC moving eastward at the Tasman Front (around 34° S) while the remainder continues south (Roughan and Middleton, 2004). The warm, low-salinity tropical Leeuwin Current (LC) flows polewards and then eastwards along the coasts of western and southern Australia (Okada and Wells, 1997).

[†]All ages reported are in thousands of calendar years before present: calibrated radiocarbon ages are given as cal. ka BP, other dating methods equivalent to calendar years are shown as ka.

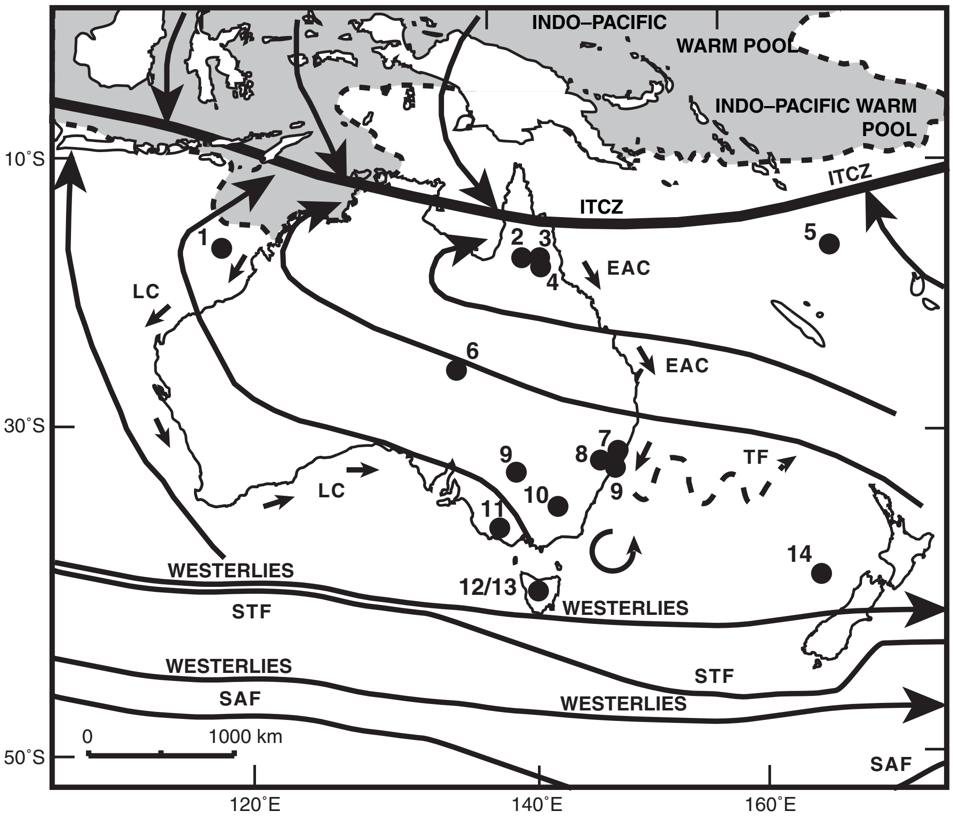

Figure 1 Location of sites and principal atmospheric circulation during the austral summer and annual mean location of ocean masses. 'ITCZ', Inter-Tropical Convergence Zone; 'EAC', East Australian Current; 'LC', Leeuwin Current; 'TF', Tasman Front; 'STF', Sub-Tropical Front; 'SAF', Sub-Antarctic Front (modified from Sturman and Tapper (1996) and Barrows *et al.* (2000). Site numbers denote the following: (1) SO14-08-05, Indian Ocean (16° 21′ S, 118° 23′ E); (2) Chillagoe, Queensland (17° 10′ S, 144° 30′ E); (3) Lake Euramoo, Queensland (17° 10′ S, 146° 38′ E); (4) Lynch's Crater, Queensland (17° 37′ S, 145° 70′ E); (5) Espiritu Santo Island, Vanuatu (15° 38′ S, 166° 53′ E); (6) Simpson Desert central Australia; (7) Redhead Lagoon, New South Wales (32° 59′ S, 151° 43′ E); (8) Gooches Swamp, New South Wales (33° 27′ S, 150° 16′ E); (9) New South Wales Murrumbidgee Riverine Plain and coastal catchments; (10) Kosciuszko, Snowy Mountains; (11) Tower Hill, Victoria (38° 19′ S, 142° 22′ E); (12) Tasmanian Highlands (Central and West Coast Ranges); (13) Huon pine, Tasmania (42° S, 145° E); (14) E26.1, Tasman Sea (40° 17′ S, 168° 20′ E). The location of Law Dome, Antarctica (66° 46′ S, 112° 48′ E), is not shown

Climate quantification

In the Australasian region, palaeoclimatic change has generally been based on proxy data (in particular pollen) described on a qualitative basis. More recently, quantitative approaches have started to be developed. Promising results have been generated for Coleoptera (Porch and Elias, 2000), Chironomidae (Dimitriadis and Cranston, 2001), pollen (Kershaw, 1998) and plant δ^{13}C (Turney *et al.*, 1999) but these have yet to be systematically applied to the period of interest here. The greatest success in developing quantified climate changes has been in the marine realm where changes in planktonic foraminifera assemblages have generated robust temperature reconstructions for key periods (Barrows and Juggins, 2005).

In geomorphological contexts, periglacial, glacial and dune deposits can provide quantified measures of climate at the time of their formation (Galloway, 1965; Nanson *et al.*, 1995; Barrows *et al.*, 2001, 2004), though inherently they are single estimates representing a broad period of time. In addition, such deposits often have a preservation bias. A review of Late Pleistocene desert climates in Australia (Hesse *et al.*, 2004) showed that there is an exponential rise in the number of dated samples for dune material deposited between 100 ka to the present, partly due to the progressive reworking or 'younging' of older dunes. An added complication is that chronologies of glacial moraines record episodes of maximum advance or rapid collapse, while dunes are biased to episodes of waning activity and dune stabilisation. Both reflect landscape modifications that often result from combinations of climatic variables, and rarely relate to a single temperature or precipitation change.

Geochronology

Determining the timing of events from the end of the last glacial period to the early Holocene within terrestrial and marine records has principally been undertaken through radiocarbon dating. The robustness of these chronologies, however, in terms of precision and accuracy, depends upon a number of considerations including the number of radiocarbon ages available for each sequence and the nature of the samples dated (bulk sediment, selected fossils or chemical fractions) (Turney *et al.*, 2000; Lowe *et al.*, 2001). In many instances within the Australian region, only a small number of radiocarbon ages have been obtained for LGM and Termination sequences (largely from bulk sediment samples) and the standard errors on the ages are typically large (>100 yr at 1σ). As a result, it is often difficult to assess the accuracy of the ages, isolate aberrant results (resulting for example from *in situ* taphonomic or biogeochemical processes, field and/or laboratory contamination) and obtain realistic calibrated age estimates. Ideally, terrestrial plant macrofossils should be utilised as these directly reflect the atmospheric ^{14}C content; but this is rarely (if ever)

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possible within marine contexts. For the sites discussed in this study, the radiocarbon ages have been reported previously by the original workers. Here, the radiocarbon ages <20 ka ^{14}C BP have been calibrated against INTCAL04 (Reimer *et al.*, 2004), while those >20 ka ^{14}C BP have been converted using either the datasets obtained from the Cariaco Basin (Hughen *et al.*, 2004) or tropical corals (Fairbanks *et al.*, 2005).

Although single age estimates falling within plateaus may calibrate to span several centuries, a method that offers considerable promise is the use of 'wiggle-matching' of radiocarbon datasets to the global radiocarbon calibration curve. The methodology is based on the principle that inflections and wiggles in the calibration curve (such as plateaus and steep transitions) must be reflected in time–depth fluctuations in radiocarbon ages obtained from stratified sequences, and that the latter can be matched to the former to derive calendar ages for the radiocarbon-dated horizons. No lacustrine or ocean sequences have been dated to sufficient resolution to undertake such an exercise, in contrast to studies in the Northern Hemisphere (e.g. Gulliksen *et al.*, 1998). The greatest potential for such an approach has been demonstrated for the Huon pine from Tasmania (Barbetti *et al.*, 2004; Fig. 2). Here, the combined tree-ring sequence extends over 680 yr and records that the inter-hemispheric offset in radiocarbon years was small between 10.3 and 10.1 cal. ka BP (a period of rising atmospheric ^{14}C), but increased to 50 yr or more between 10.1 and 10 cal. ka BP (a period of falling atmospheric ^{14}C), differences comparable to changes over the past millennium (Hogg *et al.*, 2002). Excitingly, future work will allow the precise comparison of climate proxies derived from the Huon pine with other datasets from the Northern Hemisphere on the same absolute timescale.

Dating of events has also been achieved using thermoluminescence (TL) (Nanson *et al.*, 1992a, 1995, 2003) and *in situ* exposure dating (^{10}Be, ^{26}Al, ^{36}Cl) (Barrows *et al.*, 2001, 2002, 2004; Fink *et al.*, 2000, and unpublished data; Kiernan *et al.*, 2004), while a precise age-depth profile of ice-core ages for the Law Dome (Antarctica) has been achieved by synchronisation to the GRIP ice core through changes in gas (methane) content (Morgan *et al.*, 2002; van Ommen *et al.*, 2004). All of these methods are independent of fluctuations in atmospheric ^{14}C content.

Climatic and environmental changes from the last glacial period to the early Holocene (30–8 cal. ka BP)

Figures 3–5 present a selection of key records of climatic and environmental changes in the Australian region from the last glacial period to the early Holocene. Unlike the North Atlantic region, most of this period is not conveniently subdivided into a succession of accepted chronostratigraphic units that can form a useful basis for discussion (Mangerud *et al.*, 1974; Lowe *et al.*, 2001). For the purposes of comparing different datasets in this paper we will utilise general descriptions for major periods of change. With the problems associated with precise and accurate dating of these events and the inherent danger that some may record time-transgressive change, we do not imply that the definitions and timing of these periods are fixed. Indeed, in some cases, the events in individual sites straddle the boundaries of periods described below. We fully anticipate that more events will be identified and the age of their boundaries precisely defined with future research.

Last glacial period (ca. 30–20 cal. ka BP)

Three pollen records provide continuous and well-dated reconstructions through at least part of this period. A new extended pollen and charcoal record has been developed from Lake Euramoo, in the Wet Tropics World Heritage rainforest of northeast Queensland, Australia (Haberle, 2005). The 8.4-m sediment core taken from the centre of Lake Euramoo

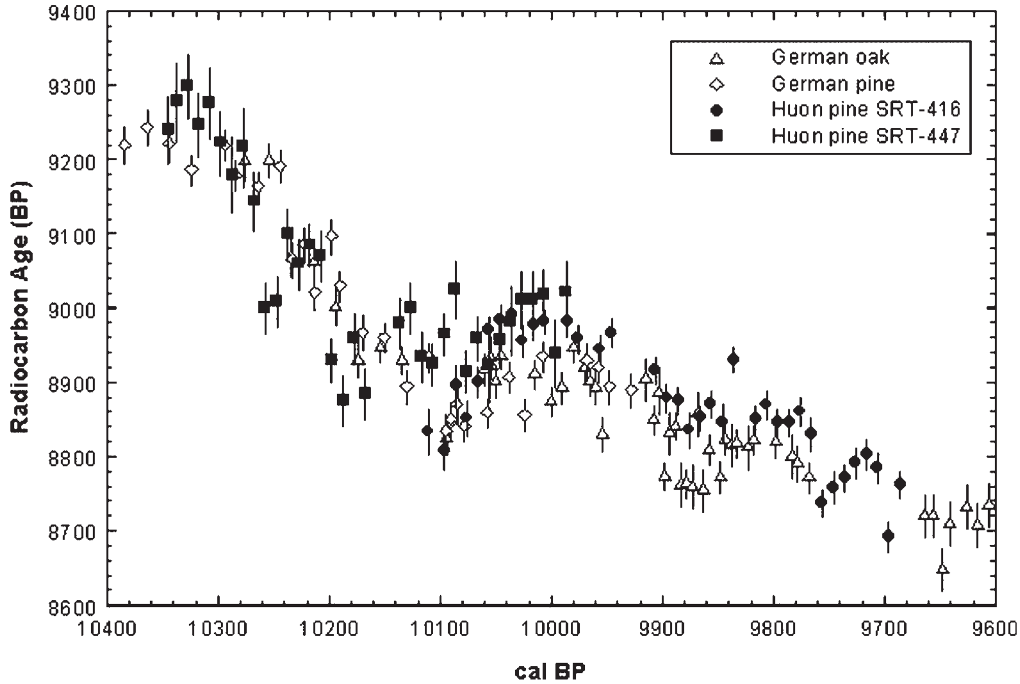

Figure 2 ^{14}C variations in Tasmanian Huon pine for the period 10.4–9.6 cal. ka BP (Barbetti *et al.* 2004). The high-precision radiometric ^{14}C data for SRT-416 are positioned by matching to the absolute German oak and pine records, with ring 1 of SRT-416 placed at 10 120 cal. BP. AMS ages from SRT-447 are placed according to the secure tree-ring match with SRT-416. All uncertainties are given at 1σ

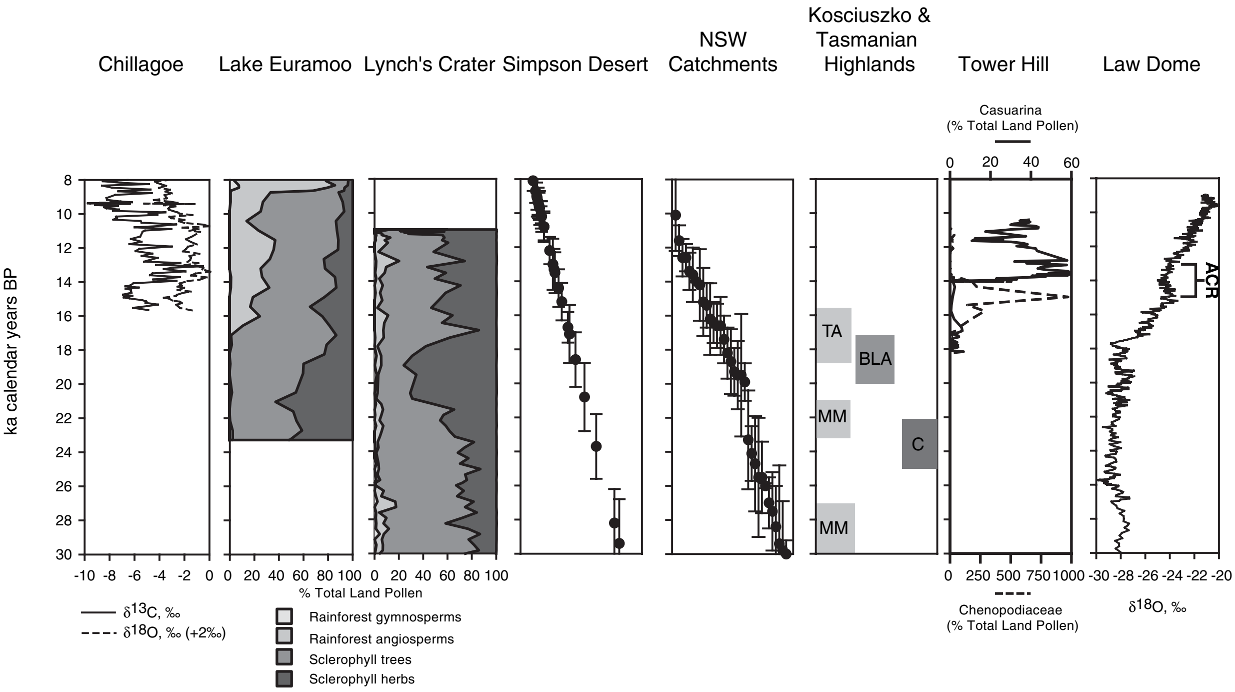

Figure 3 Selection of Australian terrestrial and Law Dome records for the period 30–8 cal. ka BP. TL ages for the Simpson Desert dunes and New South Wales (NSW) catchment (Murrumbidgee Riverine Plain and coastal) fluvial deposits are shown in chronological order. Under Kosciuszko and Tasmanian Highlands: 'TA' denotes Twynam Advance; 'BLA', Blue Lake Advance; 'MM', Mt Murchison; 'C', Cradle Mountain. Previous studies demonstrate the records from Lynch's Crater (Kershaw, 1986) and Tower Hill (D'Costa *et al.*, 1989) extend beyond that shown here but have limited chronological control and are not presented. 'ACR' denotes Antarctic Cold Reversal in Law Dome

incorporates a complete record of vegetation change and fire history spanning the period from 23 cal. ka BP (the time of crater formation) to present (Fig. 3). During the last glacial, the vegetation was dominated by sclerophyll with a peak in herbs. A virtually identical oscillation with increased representation of herbs is recognised to the immediate south in Lynch's Crater (Kershaw, 1986; Turney *et al.*, 2006), representing a contraction of rainforest taxa, and inferred to be a correlative of the cold and dry glacial conditions of the LGM. A previously published reconstruction from Tower Hill (Victoria) indicated a steppe-grassland taxa dominated the record from at least 22 cal. ka BP (D'Costa *et al.*, 1989). Taken together, the LGM as recorded by vegetation changes at these three sites appears to have spanned the period 23 and 18 cal. ka BP.

TL dating of aeolian activity near Birdsville in Queensland, and in the Finke River valley, near Finke in Northern Territory (on the eastern and western edges of the Simpson Desert respectively; Fig. 1) (Nanson *et al.*, 1995), reveals aspects of the Late Pleistocene history of the great anticlockwise whorl of dunes that cover much of central Australia. At Birdsville, the northwesterly oriented linear dunes have well defined palaeosols and are almost certainly older than the ca. 80 ka basal ages obtained so far, but they have been greatly reworked since the LGM, particularly during the Holocene (Nanson *et al.*, 1992a, 1992b). At Finke, the regional dunefield consists of dark red linear dunes aligned essentially due north before and during the LGM and Termination (30–12 ka). At Camel Flat basin in the northwest Simpson Desert, Hollands *et al.* (2006) described dunes of dark red fine sand older than 70 ka and, as at Finke, oriented almost due north.

Coupled to this anticyclonic airflow in the continental interior, Miller *et al.* (1997) reported the temperature-dependent component of the amino acid racemisation reaction in radiocarbon-dated emu eggshell fragments. Here they found that racemisation rate changes were consistent with average air temperatures being at least 9°C cooler during the last glacial period (from at least 40 ka to approximately 16 ka), possibly related to a reduction in the atmospheric moisture content at the time.

In contrast to contemporary Australia's largely arid interior, the alluvial record shows episodes when large powerful rivers drained the continent and filled Lake Eyre (Nanson *et al.*, 1992a). The lake level record from Lake Eyre shows higher, probably oscillating levels, around 40 to 30 ka but a dry playa during the LGM (Magee *et al.*, 2004). Fluvial deposits on the Murrumbidgee Riverine Plain of southeastern Australia are the most thoroughly dated in Australia and show several periods of greatly enhanced palaeochannel activity. The Gum Creek phase spanned from 35 to 25 ka. In contrast, the latter part of the last glacial (25 to 20 ka) appeared to be one of reduced fluvial activity, consistent with more arid conditions at this time (Nanson *et al.*, 2003).

Exposure dating of moraine sequences at Mt Kosciusko in the Snowy Mountains of the Australian mainland (Barrows *et al.*, 2001) and in alpine valleys of Tasmania (Fink *et al.*, 2000; Barrows *et al.*, 2002; Kiernan *et al.*, 2004, and unpublished data) are now providing new chronologies of glacial advance and retreat through this period (Fig. 3). Maximum glacial advance at Mt Kosciuszko was centred on 19.1±1.6 (Blue Lake Advance) while apparently synchronous periglacial activity was dated to 21.9 ± 0.5 cal. ka, reflecting cooling of between 9 and 11°C (Galloway, 1965; Barrows *et al.*, 2004). The glacial record emerging from Lake Rolleston, Cradle Mountain and Mt Murchison in Tasmania suggest maximum glacial advances associated with the last glacial period at 23 ± 2 and 29 ± 2 ka, though it appears that the strength of LGM advances are limited compared to Northern Hemisphere records (Fink *et al.*, unpublished data). The climatic drivers of these events are presently uncertain but there were clearly significant and sustained changes in temperature and/or precipitation (in the

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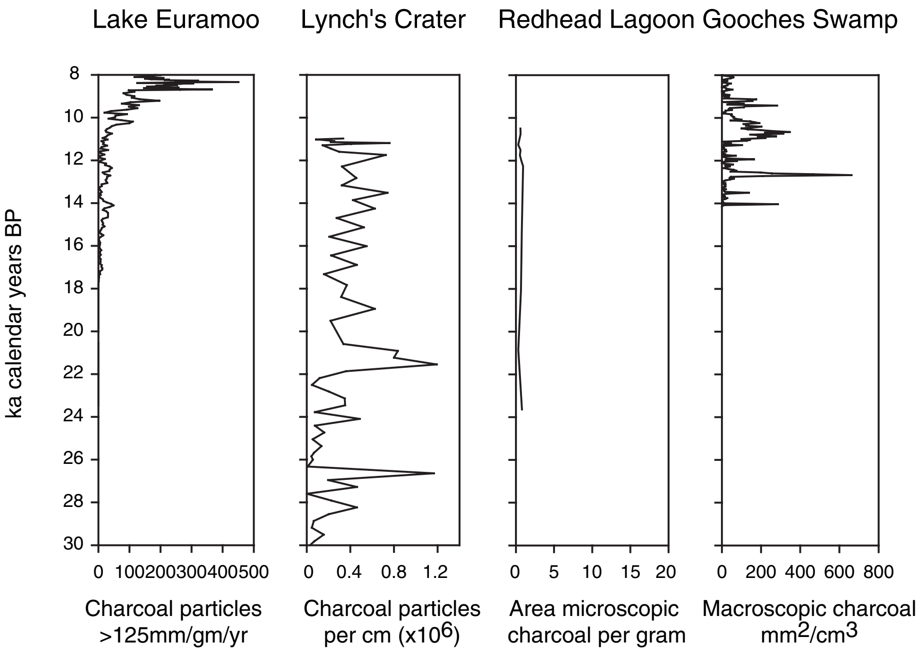

Figure 4 Selection of Australian terrestrial charcoal records for the period 30–8 cal. ka BP

form of winter snowfall) to drive major changes in the net balance of glaciers through this time.

Within the ocean realm, the most comprehensive study to date has been for the LGM time-slice, dated using radiocarbon and oxygen isotope stratigraphy (Barrows and Juggins, 2005). Here, SST reconstructions based on planktonic foraminifera assemblages demonstrate that the coldest period was centred on 20.5 ± 1.4 cal. ka BP. Intriguingly, this pre-dates the maximum in oxygen isotope records at 18.2 ± 1.5 cal. ka BP. Cooling in the tropics was between 0 and 3°C with a maximum depression along the western Australian coast of 4°C. The temperate southwestern Pacific Ocean cooled by 3–5°C, while the largest SST anomalies occurred south of latitude 40° S, with temperatures as much as 8°C lower than present day. The IPWP was significantly smaller during the LGM, centred to the northeast of present day, while the LC and EAC were in operation but transporting cooler waters than present day. The SPCZ appears to have been absent at this time. The northward expansion of sea ice in the Southern Ocean appears to have contributed to a steeper SST gradient relative to present day.

Studies of dust in marine sediments around Australia provide evidence of climate change in the northwestern and southeastern arid zone source areas (Hesse and McTainsh, 2003). Within core E26.1 in the Tasman Sea (Fig. 5), glacial dust flux was up to seven times higher during minimum SSTs (inferred to be the LGM). Associated with this increase in dust deposition, was a northward shift of around 3°. The implied northward shift in the summer westerly circulation and greater wind erosion is in broad agreement with the increased aridity inferred from dune activity, reduced fluvial activity and the steeper SST

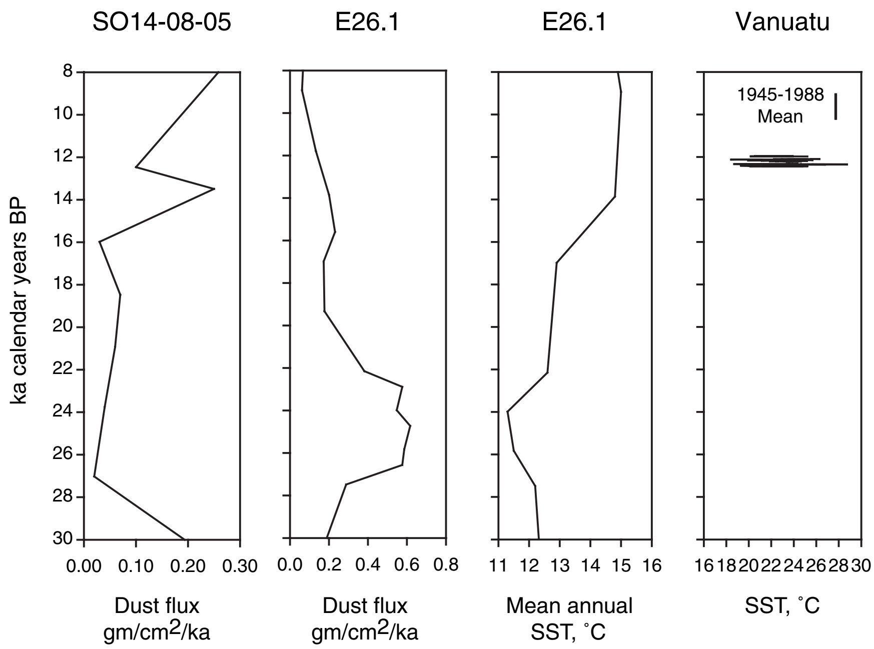

Figure 5 Selection of Australian marine records of dust flux and sea-surface temperature (SST) reconstructions for the period 30–8 cal. ka BP

gradient observed in the Southern Ocean (Fig. 5). The discrepancy between the timing of the LGM as recorded in E26.1 (centred on 25 cal. ka BP) to elsewhere is most probably due to the limited number of radiocarbon ages for the marine sequence and the uncertainty in reservoir ages through this period. Particle size studies of the Tasman dust (Hesse and McTainsh, 1999) have revealed that LGM wind speeds were comparable to present day, and that source area supply and deposition mechanisms were the dominant control on dust flux. In contrast, glacial dust flux at around 20 ka was significantly lower in the Indian Ocean core of SO14-08-05 (Fig. 5) but of coarser particle size than during the Holocene. This followed an interval of higher dust deposition around 30 ka. The cause of this significant variability is still unclear.

In the Antarctic record of Law Dome (van Ommen *et al.*, 2004), the ice accumulation rate at the LGM is estimated to have been less than ca. 10% of the modern value. Throughout this period, depleted ^{18}O values are inferred to represent sustained cooling throughout this part of the record (Fig. 3). No phase of maximum cooling comparable in timing to the LGM on the Australian mainland was identified.

Last Termination (ca. 20–11.5 cal. ka BP)

In Lake Euramoo at 16.8 cal. ka BP, a limited suite of rainforest angiosperm and gymnosperm taxa and sclerophyll taxa first appear near the site, possibly as incipient rainforest patches forming mosaics with wet sclerophyll woodland. This is almost 4000 yr earlier than similar changes noted in Lynch's Crater (Walker and Chen, 1987; Hiscock and Kershaw, 1992) and may reflect closer proximity of Lake Euramoo to glacial rainforest refugia as precipitation and temperature increased through the Termination. Increased organic accumulation and biomass burning are associated with this phase (Haberle, 2005), suggesting that a rise in woody plant biomass may have been a factor in rising charcoal particle accumulation rates in the sediments (Fig. 3).

Two periods of significant climatic change can be identified from Tower Hill (D'Costa *et al.*, 1989; Turney *et al.*, 2006) within this period. An increase in temperature is indicated by the first sustained increase in *Eucalyptus* pollen at 17 cal. ka BP, replacing the steppe grassland taxa of the LGM. Conditions appear to have been relatively dry after this time, with an increase in Chenopodiaceae suggesting salt marsh invasion of an ephemeral saline lake (Turney *et al.*, 2006). Around 14 cal. ka BP there is the beginning of a substantial rise in pollen of the tree family Casuarinaceae (Fig. 3), together with a decrease in Asteraceae (steppe), suggesting a further increase in temperature took place. Wetter conditions appear to have developed around 13.7 cal. ka BP with the replacement of Chenopodiaceae by *Botryococcus* (a fresh to brackish water alga) (Turney *et al.*, 2006).

The oxygen isotopic data from a speleothem in Chillagoe, north Queensland (Fig. 3) suggests that stalagmite growth commenced within a moderately mild period (15.4–14 ka), followed by a relatively dry reversal between 14 and 10 ka (characterised by more enriched ^{18}O values). The carbon isotopic trend appears to follow that of $\delta^{18}O$, probably owing to corresponding vegetation changes. Unfortunately, these inferred changes are not easily reconciled with the Wet Tropics pollen records. Whether this indicates decoupled environmental/climatic changes across Queensland at this time is unclear.

Intriguingly, mostly younger source-bordering sand dunes (17 to 0 ka) immediately north of the Finke River indicate a very substantial wind shift by some 25°, from due south to southeasterly, over this period (Nanson *et al.*, 1995). As at Finke, Hollands *et al.* (2006) also identify a post-LGM windshift from due south to the southeast. The wind field that controls linear-dune alignments in the Australian deserts shifted southwards some 160 km, or 1.5°, after the LGM but before the Holocene dunes were aligned, most probably associated with the migration of the high-pressure system over Australia at this time.

Small New South Wales (NSW) catchments, such as those of the Nambucca and Bellinger Rivers, experienced similar precipitation and flow-regime changes to the much larger rivers in eastern NSW. Their confined nature, however, has meant that they have been flushed of most of their older Pleistocene deposits but have retained a sensitive record of the less pronounced flow regime changes (Nanson *et al.*, 2003). The Yanco phase of enhanced fluvial activity spanned between 20 and 13 ka and is widely preserved as a period of major flow and alluvial reworking. Alongside this increased moisture availability, fire frequency around this time appears to have been relatively low (Fig. 4). In the New South Wales sites of Gooches Swamp (Black and Mooney, in press) and Redhead Lagoon (Williams, 2005), charcoal concentration indicates that these areas experienced little fire throughout much of this time.

Against the backdrop of warming temperatures on the Australian mainland and offshore, exposure dating of recessional moraine sequences at a number of Tasmanian sites show that glacial retreat commenced at about 20–19 ka and continued unabated to ca. 14–15 ka (Barrows *et al.*, 2001, 2002; Fink *et al.*, 2002, and unpublished data); supporting the interpretation of a warming trend through this transitional period. Barrows *et al.* (2001, 2002), however, report an advance centred on 16.8 ± 1.4 cal. ka (Mt Twynam Advance) in both the Snowy Mountains and the Tasmanian Highlands. Coupled to this, there might have been a reactivation of periglacial activity dated to 16.6 ± 0.7 cal. ka, though whether the latter was widespread in alpine areas is unclear (Barrows *et al.*, 2004). Increasing temperatures implied by the vegetation alongside temporary glacial growth appears at first to be contradictory. One potential scenario is that this period experienced increased seasonality (Kershaw, 1995), with summer–dry, winter–wet climatic conditions, though this remains uncertain.

Associated with many of these changes, the ocean record of SO14-08-05 indicates a sustained increase in dust flux from ca. 16 cal. ka, consistent with a strengthening of the Australian monsoon at this time, though pre-dating the 14 cal. ka onset reported elsewhere (Wyrwoll and Miller, 2001). In contrast, the dust flux from E26.1 decreased significantly following the LGM, suggesting westerly airflow over southeastern Australia moved southward and became more humid after the LGM (Hesse, 1994; Hesse and McTainsh, 1999).

At Vanuatu, high-resolution analyses of skeletal Sr/Ca and $\delta^{18}O$ for a giant fossil *Diploastrea heliopora* coral indicate that sea-surface temperatures were on average 4.5 ± 1.3°C cooler than present day (Corrège *et al.*, 2004). The dating of this coral was obtained by U-series dating and indicates the record spans the period 12.4 to 11.7 ka, providing a unique high-resolution record of changing SST in the tropical Pacific. The amplified annual cycle of sea-surface temperatures, relative to today, indicates that cooling was caused by the compression of tropical waters towards the equator. A positive correlation was found in the record between the oxygen isotope ratios of sea water and SST, suggesting that the SPCZ (which brings ^{18}O-depleted precipitation to the area today), was not active from the LGM (Barrows and Juggins, 2005) to the time of the Vanuatu coral formation. Conditions at this time were comparable to contemporary El Niño events.

Similar trends suggesting persistent El Niño conditions are recorded throughout the Pacific region. In the Great Australian Bight, a marine record indicates enrichment of ^{18}O in surface waters spanning 12.3–11.1 cal. ka BP (Andres *et al.*, 2003), which appeared to coincide with circulation changes. Originally interpreted to represent cold oceanic conditions, these results are also consistent with clear skies under anticyclonic pressure systems and increased evaporation. Further afield, speleothem growth in southwestern USA indicates a sustained period of wet conditions between 12.4 and 11 cal. ka BP, consistent with El Niño disruption of the California Current (Polyak *et al.*, 2004). It is possible that long-term changes in ENSO activity may have played an important role in regional climate change during the end of the Last Termination and beginning of the Holocene, though dating and quantification needs to be significantly improved.

This period in the coastal Antarctic record of Law Dome is one of pronounced warming, commencing around 17.7 ka (Morgan *et al.*, 2002). This warming trend continued through to the Holocene, except for a brief interruption, spanning between 15 and 13 ka. Described as the Antarctic Cold Reversal (ACR), the latter event is chronologically distinct from the Younger Dryas Stadial of the Northern Hemisphere, and is identified in numerous ice cores across Antarctica (Blunier *et al.*, 1998. The precise dating possible through linking gas records between Greenland and the high-resolution Law Dome core demonstrates that the cooling at the start of the Antarctic Cold Reversal led the abrupt warming during the northern Bølling Interstadial (GI-1) around 14.7 ka (Morgan *et al.*, 2002). This implies that changes in Southern Ocean temperature are not a direct response to abrupt changes in North Atlantic thermohaline circulation (cf. Broecker, 1998). The implications of this are still to be fully realised.

Early Holocene (ca. 11.5–8 cal. ka BP)

In the Lake Euramoo sequence, between 12.6 and 9.6 cal. ka BP, a number of rainforest taxa disappear, including *Agathis* and *Podocarpus*, while a peak representation of *Casuarina* is recorded at this time (Haberle, 2005). This may represent a reversal towards drier climatic conditions. Rainforest taxa continue to make initial appearances in the record, however, suggesting that taxa disappearances may represent shifts in canopy dominance through competitive advantage rather than a reversal in climatic conditions necessarily restricting rainforest advancement into the area.

Between 9.6 and 8.7 cal. ka BP, Lake Euramoo records a maximum rate of increase in rainforest, led by taxa typical of lower montane rainforest. This most likely represents the local establishment of closed canopy rainforest under the influence of increasing precipitation at the site. $\delta^{18}O$ values from Chillagoe also suggest high precipitation between 10 and 7 ka, supporting a regional event. The rainforest establishment occurs within a 900-yr period and is comparable to the period of time recorded at other sites on the Atherton Tablelands where the transition from sclerophyll woodland to rainforest dominance has been estimated to have taken between about 400 and 1000 yr (Hiscock and Kershaw, 1992). The final phase of rainforest development involves the gradual exclusion of sclerophyll woodland prior to the peak development of lower montane rainforest at 7.3 cal. ka BP. Local dominance of rainforest was achieved despite the persistent recurrence of fires that appear to have maintained local patches of sclerophyll woodland and may have retarded the encroachment of rainforest around the site.

Reworking of part of the dunefield by palaeochannels of the Todd River created a younger surface on which Holocene dunes could form (Hollands *et al.*, 2006). Asymmetrical cross-sections with steeper eastern flanks are characteristic of most of the linear dunes of the Simpson Desert. This morphology appears to have been acquired in the Late Pleistocene since the LGM. What climatic conditions caused this eastward-leaning tendency is unclear. A likely cause would be a shift in the prevailing winds to more westerly some time after the primary north–south strike of the dunes was defined, thereby forming a steeper eastern lee-side or slip-face. This could explain those at Birdsville where the prevailing wind today tangentially intersects the dunes from the west (Nanson *et al.*, 1992a). Importantly, however, it would require some of these dunes to have migrated *into* the prevailing wind, those with an eroded Pleistocene-age core on their eastern flank. The dunes at Finke do not help resolve this issue; their steeper eastern flanks face the prevailing wind and are known to have done so for at least the past 5 ka (Nanson *et al.*, 1995). A final conundrum is that both the oldest and youngest linear dunes at Camel Flat are eastwardly asymmetrical, yet the prevailing wind direction is almost perfectly aligned with the strike of the youngest dunes and tangentially approaching the steeper eastern face of the older dunes. Interpreting the occurrence and possible chronology of wind shifts on the basis of linear-dune asymmetry remains fraught with problems.

Something approaching the present phase of fluvial activity in coastal eastern Australia commenced around 12 ka (Nambucca phase), with much lower flows than those of the late Pleistocene, but they were certainly more pronounced than those of today. The catchments were well forested, shedding largely sediment-free water, hence alluvial deposits are scarce (Cohen *et al.*, in press). In contrast to the Termination, a period of sustained fire appears to have taken place at Gooches Swamp between 11 and 10 cal. ka BP (Fig. 4).

At Tower Hill, a climatic reversal is inferred between 12.5 and 10.9 cal. ka BP, with reduced percentages for Casuarinaceae pollen, higher values of grass and a limited, but persistent, presence of Chenopodiaceae pollen (Turney *et al.*, 2006; Fig. 3). High erosion commenced after 10.9 cal. ka BP, as indicated by the onset of clastic material input from the catchment sides (Turney *et al.*, 2006). This appears to have coincided with wetter conditions, reflected by increased arboreal development, that appear to have prevailed in the early Holocene (D'Costa *et al.*, 1989).

Results from Law Dome indicate that the present high-accumulation regime (ca. $0.7\,m\,yr^{-1}$ ice-equivalent) was established some time after ca. 7 ka, following an increase of approximately 80% from early to mid-Holocene. The change between the two modes of accumulation occurred progressively through the early Holocene, possibly reflecting insolation driven changes in atmospheric moisture content and circulation. The overall effect of which appears to have been a shift to more cyclonic activity (van Ommen *et al.*, 2004), resulting in a contrasting precipitation regime to that recorded by other cores in the continental interior. Perhaps the largest difference between the Law Dome record and other Antarctic sequences, however, is in the period after 11 ka, during which prolonged warming took place before reaching an early Holocene maximum at around 9.5 ka (Morgan *et al.*, 2002).

Future challenges

Climatic changes across Australia most probably reflect latitudinal variations in the positions of the ITCZ, the westerlies and ocean masses (Kershaw, 1995; McGlone, 1995; Hesse *et al.*,

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2004; Barrows and Juggins, 2005), but few local records are available that enable the frequency, timing and latitudinal span or even direction of migration to be reconstructed with great confidence. Yet understanding the climate history of the Australian region has potentially global implications. For example, IPWP expansion and changes in sea-surface temperatures have recently been interpreted to have led Northern Hemisphere ice melting (Visser *et al.*, 2003). Also, ENSO cyclicity is now considered to have operated continuously during the last cold stage at the interannual, millennial and semi-precessional timescales (Tudhope *et al.*, 2001; Turney *et al.*, 2004), potentially exerting a global influence on climate.

Prerequisites for robust testing of hypotheses of synchronous/asynchronous inter-hemispheric climate change through this period are the development of more refined and robust geochronological datasets and the quantitative reconstruction of former climatic conditions across the region. At present, the majority of the sites are concentrated on the eastern seaboard of Australia.

With regard to dating, most terrestrial sites have inadequate chronological frameworks to robustly test hypotheses of climate change. By undertaking comprehensive radiocarbon dating of sequences <20 ka ^{14}C BP, it should be possible to replicate the ^{14}C calibration curve in individual sequences, providing a considerably higher level of chronological precision. For the period >20 ka ^{14}C BP, where no accepted international radiocarbon calibration curve exists, intensive dating would identify steep transitions and plateaus in stratigraphic sequences, allowing direct and precise correlation between sequences on a continental and global scale (Turney and Bird, 2002). These changes would provide robust relative-age frameworks, independent of the development of an accepted radiocarbon calibration curve and uncertainties in the inter-hemispheric offset. Unfortunately, the problems are magnified within the context of ocean sequences where the limited potential of tephras in the Australian region precludes the quantification of the marine reservoir age over time (cf. Sikes *et al.*, 2000; Siani *et al.*, 2001).

Significant potential exists for developing quantified climate estimates through this period. At present, many of the events recognised through the LGM and into the early Holocene have been identified through biological and geomorphological changes. As such, most are not truly climatic events but reflect environmental responses to these changes. Depending on the sensitivity of sites and the local responses to climatic events, the boundaries of these different events would be anticipated to be diachronous. Time-trangression may play a significant role in the offset between the ages of events that may have the same climatic origin. For instance, it is unclear precisely when climatic conditions associated with the onset of the Holocene became established across the region. Considerable potential exists for quantified climate estimates in lacustrine sequences using Coleoptera, Chironomidae, pollen and stable isotopes to help resolve this and other associated issues. At present, however, the most robust regional quantified climate estimates for Australia are only available from the marine realm for just a few time slices (Barrows and Juggins, 2005).

Regardless of the above, significant changes are evident in the records presented here to signify that a North Atlantic template is inappropriate to describe climatic changes in the Australian region. Future work is urgently required in climatic quantification and geochronological control to investigate just how different the two regions were.

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