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THEMATIC SET
SHEMAX

Preface

Introduction to the SHeMax thematic set and prospects for LGM research in the Southern Hemisphere

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INTRODUCTION

The global last glacial maximum (LGM) is considered to be the period of maximum ice volume during the global last (late Pleistocene) glaciation (e.g. Clarke et al., 2009). However, the regional signatures of this event are poorly resolved and may reflect local to regional rather than global-scale controls and drivers. The Southern Hemisphere Last Glacial Maximum (SHeMax) project was an INQUA (International Quaternary Association) Palaeoclimate Commission project that ran for the inter-congress period (2016–2019) and focused on the timing and characteristics of the LGM in a Southern Hemisphere context (Petherick et al., 2016). The project was established because there are strong indications of an earlier onset of the LGM in the Southern Hemisphere (e.g. Shulmeister et al., 2019); suggestions of multiple climatic temperature minima in the LGM *sensu lato*; and a widespread concern about moisture availability as well as temperature change in the Southern Hemisphere. Further, there are robust orbital, physiographic and climatological reasons why the Southern Hemisphere may respond differently to the Northern mid-latitudes at times of global environmental change (e.g. Darvill et al., 2016). Additionally, Southern Hemisphere proxy records outside of Antarctica are generally under-represented globally, and yet are critical to examine the relative timing of different climate phases during the period of Marine Isotope Stage (MIS) 3 and 2, and thus establishing forcing-response and phasing relations, especially between terrestrial and marine records (Knight and Fitchett, 2021).

This set of papers is derived from research that emanated from the SHeMax workshops held in Auckland, New Zealand (December 2016), in Johannesburg, South Africa (April 2017), and on North Stradbroke Island, Australia (June 2018). Key results from the SHeMax project were reported at a special session at the INQUA Congress in Dublin, August 2019. The set of papers presented here represents a mixture of new data from across the regions and new syntheses of existing data. Cumulatively, these papers represent a significant advance in knowledge of the nature and properties of the LGM across the Southern Hemisphere, whilst also highlighting the challenges that remain. These include the relatively small number of palaeoclimate researchers operating over three and a half continents (given that "Zealandia" is the half-continent) and the paucity of sites and proxies available for palaeoclimate reconstruction when compared to LGM records in Europe, East Asia or North America.

The SHeMax contributions start with *A continental perspective on the timing of environmental change during the last glacial stage in Australia* by Haidee Cadd and co-authors (Cadd et al., 2021). Exploring change-point analyses of existing proxy datasets, the paper concludes that the shift to "LGM" climates in Australia occurred at ∼28.6 ka with a switch back to relatively warm and wet conditions after ∼17.7 ka. This aligns strongly with observations in New Zealand and reinforces the concept of an early onset of the glacial maximum and the extended nature of the LGM in the Southern Hemisphere.

The work of Annika Herbert and Jennifer Fitchett (Herbert and Fitchett, 2021) on *Quantifying late Quaternary Australian rainfall seasonality changes using the Poaceae:Asteraceae pollen ratio* takes a palaeoclimate method applied in southern Africa to see whether it can be applied in Australia. The method uses pollen ratios to examine the seasonality of rainfall. The technique shows promise in providing information about regional rainfall seasonality, although it is relatively unsuccessful in Tasmania and southeastern continental Australia. Critically, it suggests a double peak in the seasonality of rainfall at 32-31 ka and 22-20 ka, which coincides with some records of initial onset of cooling (see Cadd et al., 2021 this volume) and at the peak of the global LGM.

The paper from Cassie Rowe and co-authors (Rowe et al., 2021) on *Vegetation over the last glacial maximum at Girraween Lagoon, monsoonal northern Australia* is a major contribution because sites that extend through to the LGM in the terrestrial tropics of Australia are extremely rare, especially away from the climatically atypical Atherton Tablelands. The paper highlights the reduction, but not elimination, of woody vegetation at the LGM which the authors ascribe to cool-dry conditions and reduced atmospheric CO_2 concentrations. Fire plays a relatively reduced role during the LGM, which may also be CO_2 related.

Romina Sanci and co-authors (Sanci et al., 2021) describe the *Late Pleistocene glaciolacustrine MIS 3 record at Fagnano Lake, Central Tierra del Fuego, southern Argentina*. Like the glacial records from New Zealand this site indicates a relatively early onset of full glacial conditions (cf. "global"), with near LGM extents achieved well before the actual onset of the global LGM. The timings of glacial advances are related to local conditions

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on Tierra del Fuego (rather than the main Patagonian Ice Sheet), and is thus related to the regional dynamics of sub-Antarctic air masses.

Richard Lewis and co-authors (Lewis et al., 2021) examines the *Patterns of aeolian deposition in subtropical Australia through the last glacial and deglacial periods*. Their key findings on the LGM from North Stradbroke Island are that dust contributions were enhanced leading into the LGM. Based on regional comparisons they also proposed that there was enhanced water stress during the entire last glacial period including the LGM.

The paper by Peter McIntosh and co-authors (McIntosh et al., 2021) on *Late Pleistocene and Early Holocene aeolian deposits of Tasmania and their climatic implication*s examines a very wide range of aeolian deposits in Tasmania. A "double peak" in the LGM climate is observed based on sedimentological data from a key site, with a strong suggestion that wind speeds were also higher at the LGM in this southern, westerly-affected area of Australia.

Aeolian records are also the focus of the paper by Peter Almond and co-authors (Almond et al., 2021) but in this case the focus is on a significant loess outcrop in eastern South Island, New Zealand: *A palaeoenvironmental record of the Southern Hemisphere last glacial maximum from the Mount Cass loess section, North Canterbury, Aotearoa/New Zealand.* This outcrop has a plethora of environmental proxies and numerous calcareous targets for radiocarbon dating, resolving the 25-21 ka period in detail. The paper demonstrates an interstadial climate prior to 24 ka with a stadial between ∼24 and ∼22.6 ka. The authors suggest a southward movement of the Sub-Tropical Front at about 26 ka to trigger the interstadial, which is roughly coincident with regional glacier retreat.

Moros et al. (2021) examine changes in *Hydrographic shifts south of Australia over the last deglaciation and possible interhemispheric linkages*. This paper focuses on determining the role of the Southern Hemisphere Westerly winds and associated Southern Ocean ventilation by examining changes in foraminifera and alkenone records from two marine cores 600 km apart. A strong although weakening linkage between water masses south of Australia and Northern Hemisphere ice sheets is proposed for the period from 23 ka to the mid-Holocene.

There is considerable community enthusiasm for progressing this research and we look forward to continuing the ideas developed in the SHeMax project, and to continuing developing research capacity and interdisciplinary research across Southern Hemisphere nations and institutions.

WHERE TO FROM HERE?

The *meaning* and *significance* of the global LGM as expressed in Southern Hemisphere records are based on different baselines and portfolios of evidence found in different southern sectors (Australia, New Zealand, South America, southern Africa) (e.g. Heine 2000; Hodgson et al., 2014; McIntosh et al., 2021). Therefore, the varied regional LGMs used for inter-regional correlation may not always be comparable. Many of the records presented here and elsewhere now suggest that MIS 3 was more important in terms of environmental change in the Southern Hemisphere, with increased cooling and glacier growth from ∼35 ka onwards. Glaciers were of greater extent during MIS 3 (e.g. Sanci et al., 2021; Shulmeister et al., 2019) when compared to the traditionally defined "global" LGM, which had a more subdued signature in many Southern Hemisphere records, perhaps due to to relatively increased aridity in the Southern Hemisphere at the global LGM (Berman et al., 2016). Further, the evidence across the Southern Hemisphere for multiple glacial advances spanning the broad period 32–18 kyr (e.g. Darvill et al., 2016) supports multiple forcings for glacier dynamics at this time (Putnam et al., 2013; Shulmeister et al., 2018). Other records also suggest some Southern Hemisphere glaciers reached maximal positions around 65 ka, within MIS 4 (Schaefer et al., 2015; Shulmeister et al., 2019), which requires further investigation. This range of evidence therefore questions the meaning and significance of the MIS 2 "Last Glacial Maximum" (Hughes et al., 2013) as can be applied to the Southern Hemisphere.

Climate modelling suggests MIS 3 was more environmentally unstable than MIS 2, with more clearly marked millennial-scale Dansgaard-Oeschger cycles and with stronger climate seasonality (Van Meerbeeck et al., 2009). The implications of such (Northern Hemisphere-dominated) events for the Southern Hemisphere are not understood. However, this may include the position of the Antarctic Polar Front and associated Southern Ocean circulation patterns (Drost et al., 2007; Falster et al., 2018, but see arguments by Moros et al., 2021), driving temperature, precipitation and glacier mass balance (Kaplan et al., 2008; Darvill et al., 2016). The role of atmospheric CO_2 concentration in LGM changes is also another area of future research investigation.

By contrast, non-glacial records in the Southern Hemisphere are more widespread geographically and are more diverse in their proxy type and environment of deposition (e.g. Fitzsimmons et al., 2013; Webb et al., 2014; Almond et al., 2021; Lewis et al., 2021; Webb et al., 2014; Rowe et al, 2021). As such, developing an understanding of these varied non-glacial proxies is vital, and this must be framed in a spatial, geomorphological and environmental context. However, interpretation of non-glacial proxy records is not straightforward with respect to climate forcing or different climatic parameters, and covariation between different proxies requires understanding of the feedbacks that take place within individual depositional environments. This means that comparing different records for any time period should be set in an understanding of their climatic and environmental contexts. Identifying the nature of regional LGMs, based on evidence from different types of records, therefore requires the following properties:

- That different palaeoclimatic and environmental records covering the same time period are present within a single region;
- That chronological controls on these records exist and that consistent methodologies and protocols are used for chronological comparison, modelling and calibration both within and between individual sites, commensurate with the dating methods used;
- That these records inform on specific climatic parameters (e.g. temperature, precipitation, CO_2, wind strength and direction, etc);
- That these inferred parameters provide a record of changes in climate over time, into and out of the period of interest; and
- That there is sufficient variability within the time series to identify start and end points of the regional LGM, and the peak (in timing and magnitude) of the regional LGM, as presented by different proxies.

We cannot over-emphasise the need for fundamental work to increase the quantity and quality of records across the Southern Hemisphere. Despite the dominance of oceans in the Southern Hemisphere, there is a limited number of cores available, these

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are not evenly located spatially, and many of these from IODP legs do not sufficiently resolve the late Quaternary. On land, there are many areas without palaeoclimate records of any sort, and this is a limitation not only for the spatial distribution of records, but also when interpolating values across space. Identifying and formalizing regional LGMs as has been carried out for New Zealand (Alloway et al., 2007; Barrell et al., 2013) and Australia (Reeves et al., 2013). Developing regional LGMs for other sectors (e.g. Knight and Fitchett, 2021) should be seen as a key future priority in order to better understand the meaning and significance of the LGM in the Southern Hemisphere, as well as allowing for correlation between different records, and a better calculation of temperature and precipitation during the LGM. Statistical analyses to determine the timing of regional events, such as using change point analysis (Cadd et al., 2021), is critical to advance these correlations. Quantifying the scale and type of change is also important (e.g. Falster et al., 2018; Herbert and Fitchett, 2021). Only after we address these issues can Southern Hemisphere research fully inform debates about interhemispheric climate linkages. This is important because it seems that Northern Hemisphere forcing of southern circulation systems does indeed occur (e.g. Alley et al., 2002; Moros et al., 2021) and these linkages may be very important to global climate processes such as those associated with CO_2 feedback mechanisms during deglaciation (e.g. Denton et al., 2021).

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