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Millennial-scale variability in south-east Australian hydroclimate between 30,000 and 10,000 years ago

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ABSTRACT

Global climate variability during the late Quaternary is commonly investigated within the framework of the 'bipolar seesaw' pattern of asynchronous temperature variations in the northern and southern polar latitudes. The terrestrial hydrological response to this pattern in south-eastern Australia is not fully understood, as continuous, high-resolution, well-dated proxy records for the hydrological cycle in the region are sparse. Here we present a well-dated, highly resolved record of moisture balance spanning 30000–10000 calendar years before present (30–10 ka BP), based on x-ray fluorescence and organic carbon isotope ($\delta^{13}C_{OM}$) measurements of a sedimentary sequence from Lake Surprise in south-eastern Australia. The data provide a locally coherent record of the hydrological cycle. Elevated Si (reflecting windblown quartz and clays), and relatively high $\delta^{13}C_{OM,}$ indicate an extended period of relative aridity between 28 and 18.5 ka BP, interrupted by millennial-scale episodes of decreased Si and $\delta^{13}C_{OM}$, suggesting increased moisture balance. This was followed by a rapid deglacial shift to low Si and $\delta^{13}C_{OM}$ at 18.5 ka BP, indicative of wetter conditions. We find that these changes are coeval with other records from south-eastern Australia and New Zealand, and use a Monte Carlo Empirical Orthogonal Function approach to extract a common trend from three high-resolution records. Our analyses suggest that drivers of the regional hydrological cycle have varied on multi-millennial time scales, in response to major shifts in global atmosphere-ocean dynamics during the last glacial-interglacial transition. Southern Ocean processes were the dominant control on hydroclimate during glacial times, via a strong influence of cold sea surface temperatures on moisture uptake and delivery onshore. Following the last deglaciation (around 18 ka BP), the southward migration of cold Southern Ocean fronts likely resulted in the establishment of conditions more like those of the present day. Millennial-scale variability in records from the region is dominated by a persistent ca. 2300-year periodicity, consistent with other records across the Southern Hemisphere mid-latitudes; however, this pervasive periodicity is not obviously linked to the 'bipolar seesaw' and the mechanism remains equivocal.

1. Introduction

The late Quaternary (defined here as 30000–10000 calendar years before present; 30–10 ka BP) is the most recent period in the geological record that is characterised by abrupt shifts in global atmosphere and ocean circulation (Thomas, 2016). Unravelling

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patterns of climate variability during this period is key to understanding long-term atmosphere-ocean dynamics, and their environmental impact on centennial to millennial time scales. High-resolution methane-synchronised ice core records from the northern and southern polar regions are characterised by marked, asynchronous climate changes during the late Quaternary (c.f. the 'bipolar seesaw'), and much research has been devoted to understanding the mechanisms driving these high-latitude climate phase relationships (Blunier et al., 1998; Broecker, 1998; Blunier and Brook, 2001; EPICA Community Members, 2006). However, the manifestation of these events in the terrestrial hydrological cycle beyond the high latitudes is less well constrained. This is particularly the case in the Southern Hemisphere (SH) mid-latitudes (defined here as spanning 25–45°S) where a relative dearth of continuous, high-resolution records has limited our ability to investigate the timing and drivers of change (Vandergoes et al., 2005; Bayon et al., 2017).

Within the ocean-dominated SH mid-latitudes, coastal sites in southern Australia and New Zealand (NZ) are highly sensitive to atmosphere-ocean interactions (Gentilli, 1971; Barrows et al., 2007; Gouramanis et al., 2013), and hence are ideally located to investigate long-term drivers of terrestrial hydroclimate. Large-scale climate systems that directly influence modern southern Australian and NZ climates include the mid-latitude Southern Westerly Winds (SWW) (Hall and Visbeck, 2002; Cai et al., 2005; Meneghini et al., 2007; Pepler et al., 2016), Southern Ocean and Antarctic ice sheet dynamics (Pezza et al., 2008; Williams and Stone, 2009), and zonal sea surface temperature (SST) gradients including the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Ashok et al., 2007; Risbey et al., 2009; Pepler et al., 2014; Forootan et al., 2016). However, the extent to which these systems influence southern Australian and NZ hydroclimate on multi-millennial time scales is not clear, especially considering the confounding effect of the sea level changes associated with glacial cycles (Clark and Mix, 2002).

A range of sedimentological, palaeoecological and geochemical tracers respond strongly to changes in the terrestrial hydrological cycle, and accordingly, there are over 60 hydroclimate-related proxy records from southern Australia and New Zealand, that span the late Quaternary (Table 1, Fig. 1). Early work, relying largely on fragmentary aeolian deposits, suggested that the last glacial period was cold, windy, and mostly dry relative to deglacial and interglacial periods (Bowler, 1976). This hypothesis has been generally supported by subsequent hydroclimate records (e.g. Gingele et al., 2001; Petherick et al., 2009; Barrell et al., 2013; Petherick et al., 2013), though some exceptions have been reported (Shulmeister et al., 2016; Treble et al., 2016; Barr et al., 2017).

Unfortunately, most records shown in Table 1 are fragmentary, or at too coarse a resolution to reliably identify millennial-scale variability. This is primarily because the largely arid to semi-arid climates of south-eastern Australia in particular are generally not conducive to continuous accumulation of sediments. The region therefore suffers from a limited network of high-resolution, temporally well-constrained, late Quaternary hydroclimate proxy records, limiting precise inter-site comparison of climatic events on both regional and global scales. This is problematic, as single-site reconstructions may be confounded by local or proxy-specific effects, rather than providing a robust representation of regional palaeoclimate that may be directly compared with high-resolution and precisely dated palaeoclimate records from more distal locations (Turney et al., 2006; Moss et al., 2013; Petherick et al., 2013; Harrison et al., 2016; Prentice et al., 2017).

This uncertainty has resulted in ambiguity in the expression of the Last Glacial Maximum (LGM) in southern Australia and NZ. The global LGM is generally considered to have occurred between 23 and 19 ka BP, when sea level was at a minimum and the global climate was relatively stable (Mix et al., 2001; Clark et al., 2009). However, the LGM has no formal stratigraphic definition *per se* (Hughes and Gibbard, 2014), and numerous Southern Hemisphere (including Australian and NZ) palaeoclimate records preserve evidence for an 'extended LGM' that manifests as a period of extreme aridity, and most likely commenced between 32 and 28 ka BP (e.g. Heusser et al., 1999; Williams et al., 2006; Kershaw et al., 2007; Newnham et al., 2007; Fogwill et al., 2015; Petherick et al., 2017), but possibly as early as ~38 ka BP (e.g. Barrows et al., 2001; Petherick et al., 2008). Furthermore, some high-resolution records from southern Australia and NZ preserve evidence for (a) two relatively arid phases centred around ~31 and 22 ka BP, separated by an interval of increased moisture balance around ~24 ka BP (Alloway et al., 2007; Petherick et al., 2008; 2017; Augustinus et al., 2011), or (b) variable hydroclimate superimposed on generally dry conditions (Moss et al., 2013). The timing, nature, and spatial distribution of LGM conditions in southern Australia and NZ is therefore equivocal, highlighting the need for more highly resolved palaeoclimate records.

Here we present a new high-resolution, multi-proxy hydroclimate record spanning 30–10 ka BP from Lake Surprise, a small, steep-walled crater lake located in south-eastern Australia (38°03′42″S, 141°55′22″E; Fig. 1). Lake Surprise is a sensitive archive of climate variability, lying at the modern northern margin of influence of the SWW (Hendon et al., 2007; Barr et al., 2014), with climate variability also modulated by the IOD and ENSO (Ashok et al., 2007; Risbey et al., 2009; Ummenhofer et al., 2009). Using comprehensive radiocarbon (^{14}C) dating in combination with high-resolution quantitative elemental composition data, and the carbon isotope composition of bulk organic matter, we infer past changes in aeolian input and variation in plant water stress within a robust geochronological framework. We subsequently apply a Monte Carlo Empirical Orthogonal Function (MCEOF) approach to key published records to objectively define a regionally coherent record of hydroclimate change. These records are all from south-eastern Australia and NZ, so we then use our findings to explore the timing and potential drivers of change in this region.

2. Methods

2.1. Study site and core acquisition

Lake Surprise occupies the crater complex of Mt Eccles, a dormant scoria cone volcano composed of nepheline hawaiite, located in the Newer Volcanics Province of south-eastern Australia (Fig. 1; Timms, 1975; Irving and Green, 1976; Boyce, 2013). Cosmogenic exposure dating of the surrounding Tyrendarra lava flow, which originated in Mt Eccles, indicates that the eruption of the volcano probably occurred 36 ± 3 ka BP (Gillen et al., 2010). Radiocarbon dates from lakes and swamps that formed following drainage diversion due to the extrusion of the Tyrendarra basalt provide minimum eruption ages of between 32 and 29 ka BP (Head et al., 1991; Builth et al., 2008); this chronological discrepancy is most likely due to the time taken for the porous basalt substrate to mature sufficiently to allow the accumulation of water and sediment. Following the eruption of Mt Eccles - and several other volcanos that erupted around the same time - there appears to have been no further volcanic activity in the Newer Volcanics Province until approximately the mid-Holocene (Sherwood et al., 2004). Based on analysis of archaeological evidence of human patterns of occupation of Australia, it is likely that Indigenous people lived in the general area from before the eruption of Mt Eccles (O'Connor and Allen, 2015), however there is no strong evidence for their exploitation of the landscape prior to the mid-Holocene (Builth