ARTICLE IN PRESS

Quaternary International xxx (2017) 1–13

Contents lists available at ScienceDirect

Quaternary International

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

A 25,000-year record of environmental change from Welsby Lagoon, North Stradbroke Island, in the Australian subtropics

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ARTICLE INFO

Article history:
Received 29 August 2016
Received in revised form
6 March 2017
Accepted 7 April 2017
Available online xxx

Keywords:
Palaeoclimates
Glacial maximum
Deglaciation
Subtropics
Australia

ABSTRACT

There are few continuous Australian palaeoclimate records that extend beyond the Last Glacial Maximum (LGM), meaning that knowledge of regional climates before, during and after this period is limited. Understanding late-Pleistocene climates of the subtropics is important because of the fundamental role the region plays in the large-scale, global transfer of energy from low latitudes. Palaeoclimate studies of subtropical regions can help define the extent of warming/cooling during the large global climatic events which characterise the late-Pleistocene. Here we report the results from a multi-proxy analysis of a sediment record from Welsby Lagoon on North Stradbroke Island, in the eastern Australian subtropics, spanning the past *ca.* 25,000 years. Stable C and N isotope analysis and high resolution contiguous records of macrocharcoal deposition and sediment organic content are interpreted in conjunction with a previously published pollen record. Sediment organic content displayed a very strong correlation with total organic carbon (TOC) content as determined through elemental analysis and, given the peaty nature of the sediment, is interpreted as indicative of moisture balance. The proxies reflect wet subtropical climates in the lead up to the LGM which led to an expansion of the wetland. This was followed by a cool, dry and windy LGM (*ca.* 22.3–19.7'000 years before present; kyr BP), which was punctuated by a brief wet phase *ca.* 21.7–20.4 kyr BP. A salient feature of the deglacial period is a rapid increase in TOC around 15 kyr BP, coincident with the Antarctic Cold Reversal and Bølling-Allerød warm phase. Increased fire frequency is evident in the Holocene, which is characterised by otherwise stable climate and vegetation. This study supports the notion of variable climates during the LGM and finds an onset of deglacial warming in the Australian subtropics that predates the Holocene.

1. Introduction

The south-western Pacific region is important for understanding global climate because of the presence of systems that exert substantial influence over climates of this region and beyond. These include the West Pacific Warm Pool (WPWP); a major source of global atmospheric water vapour (Pierrehumbert, 2000), the El Niño-Southern Oscillation (ENSO); which strongly influences global climates (Trenberth and Caron, 2000; Tsonis et al., 2003) and the east Australian current (EAC); which conveys large fluxes of heat and moisture from lower to higher latitudes in the Southern Hemisphere (Ridgway and Godfrey, 1994). Widely distributed and highly-resolved palaeoenvironmental studies spanning key climatic periods, such as the LGM and the last glacial–interglacial transition, are required in order to understand the behaviour and sensitivity of these systems (Turney et al., 2006a). Australia is

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http://dx.doi.org/10.1016/j.quaint.2017.04.011
1040-6182/

ideally located to contribute to understanding south-west Pacific climates; however high-resolution and continuous palaeoenvironmental records that extend beyond the LGM are uncommon in Australia (Williams et al., 2009). Moreover, the continuous sites that do exist are primarily concentrated in the northern tropics and the temperate south-east (Reeves et al., 2013a), providing little knowledge of late-Pleistocene subtropical climate history.

As a critical zone of energy and matter transport between the tropical and temperate regions (*sensu* Chiang, 2009), the subtropics are pivotal to providing a complete understanding of the complex interactions between climate systems. For instance, a rapid increase in western Pacific sea-surface temperatures around 15,000 cal yr BP (Stott et al., 2002; Visser et al., 2003), which aligns with the North Atlantic Bølling-Allerød warm stage (Pedro et al., 2016), resulted in increased moisture in the Australasian tropics (Williams et al., 2009; Reeves et al., 2013a). However, Antarctic cooling at this time (Blunier and Brook, 2001; Morgan et al., 2002; Pedro et al., 2016) is linked to increased aridity in south-eastern Australian sites (Kershaw et al., 2004, 2007). Subtropical records may provide insight into the spatial boundaries of this moisture differential and, in conjunction with pollen studies, may also inform our understanding of glacial plant refugia and patterns of post-glacial recolonisation.

An emerging suite of studies from subtropical Australia, primarily from Fraser and North Stradbroke Islands, the world's two largest sand islands, is shedding light on palaeoclimate in this region. Records of late-Pleistocene and Holocene environmental and climatic change on Fraser Island have been developed from the Lake Coomboo depression (~600 kyr BP: Longmore, 1997; Longmore and Heijnis, 1999), Lake Allom (~55 kyr BP: Donders et al., 2006) and, more recently, from Lake McKenzie (~45 kyr BP: Atahan et al., 2014; Woltering et al., 2014). These records suffer from low sedimentation rates (~1000 yr/cm in Lakes Coomboo and McKenzie), large dating uncertainties (Longmore and Heijnis, 1999) and sedimentary discontinuities. Nevertheless, systematic studies of closely spaced sites have permitted the development of a cohesive local climate history. For example, as each site has a sedimentary hiatus (of varying duration) in the 28–10 kyr BP period, it can be inferred that effective precipitation on Fraser Island was relatively low at this time (Woltering et al., 2014).

Approximately 200 km south, on North Stradbroke Island (NSI), two sites (Native Companion Lagoon and Tortoise Lagoon) provide continuous and relatively high-resolution records over the last ~40,000 years and have been the focus of several studies. From Native Companion Lagoon, McGowan et al. (2008) reconstructed local and far-travelled aeolian sedimentation over the last 25,000 years, while Petherick et al. (2008) extended the scope of this study by including pollen analysis and geochemical ‘fingerprinting’ of mainland dust sources to determine dust pathways, with a focus on the 33–18 kyr BP period. The authors proposed the presence of two stadials, at 30.8 kyr BP and 21.7 kyr BP, during an “LGM” that lasted 10,000 years. Petherick et al. (2009) extended the record of dust source and deposition from 25 kyr BP to the present and the entire 40,000 year record is summarised in Petherick et al. (2011). Recently, a 35,000 year record of clastic sediment flux has been developed from Tortoise Lagoon (Petherick et al., 2017), the results of which largely mirror those from Native Companion Lagoon.

The continental dust records from Native Companion Lagoon and Tortoise Lagoon suggest regional climates leading into the LGM (that is, before ca. 22 kyr BP; Turney et al., 2006b; Petherick et al., 2013) were more variable than previously thought (Petherick et al., 2011) and support the notion that the Southern Hemisphere experienced an earlier onset of glacial conditions than the Northern Hemisphere (Vandergoes et al., 2005, 2013; Fogwill et al., 2015). However, these results conflict with the pollen records from Native Companion Lagoon, Tortoise Lagoon and Welsby Lagoon (Moss et al., 2013), which provide no clear evidence of a distinct cold or arid phase during this time. This discrepancy may be reconciled if climate on NSI remained relatively stable over this interval, whereas interior Australia – the source of the dust – experienced significant climatic change. This hypothesis, in conjunction with high levels of phylogenetic endemism and diversity in the subtropics (Kooyman et al., 2013), suggests the region may have hosted floral refugia during harsh climates. While some support for this hypothesis is evident in the NSI pollen records, in which the dominance of arboreal pollen suggests higher effective moisture (Moss et al., 2013) despite regional temperatures inferred to be ~4 °C cooler (Woltering et al., 2014; Chang et al., 2015), further studies are required to test this.

Here, we report a high-resolution multi-proxy record from Welsby Lagoon, North Stradbroke Island. We combined new contiguous sediment composition and macrocharcoal data, lower resolution stable carbon and nitrogen isotope data, and previously published pollen records to provide new insights into subtropical climates during key periods of major global climate change.

2. Regional setting

North Stradbroke Island (NSI; 27°27′ S:153°28′ E) is a large sand island of approximately 285 km^2 located in Moreton Bay, south-eastern Queensland (Fig. 1). The island is part of a massive volume of linked Quaternary sand deposits in southeast Queensland that include Moreton and Fraser Islands and the Cooloola sandmass. The surface geology of NSI consists primarily southeast- to northwest-oriented high parabolic dunes (Ward, 2006). The dunes reach a maximum elevation of 239 m and were sequentially deposited during glacial sea-level lowstands (Ward, 2006; Brooke et al., 2015). The ages of the NSI dunes, estimated from the degree of leaching, are purported to range from the Awinya (486–430 kyr BP) and Yankee-Jack (368 kyr BP) formations, to ‘modern’ foredunes deposited during the early-Holocene (Ward, 2006). However, contradictory thermoluminescence ages of ~120 kyr BP for Yankee-Jack dunes in the region of Welsby Lagoon (Tejan-Kella et al., 1990) suggest that the chronology of dune development is not yet well understood. Humans occupied the current island more than 20,000 years ago (Neal and Stock, 1986), well before it was isolated from the mainland during the mid-Holocene marine transgression, which flooded Moreton Bay approximately 6 kyr BP (Neal and Stock, 1986; Beaton, 1995).

North Stradbroke Island has a subtropical climate (Colls and Whitaker, 1990) with warm summers (~29 °C) and mild winters (~16 °C). Precipitation occurs predominantly in the summer, with average annual rainfall ranging from ~1670 mm at Point Lookout on the northeastern point of the island, to ~1570 mm at Dunwich on the west coast. Annual rainfall at Point Lookout is strongly correlated with rainfall in the east coast subtropical regions (Fig. 2), and can therefore be considered representative of this region. At interannual timescales, the climate of the region is strongly influenced by the ENSO (Murphy and Ribbe, 2004). Periods of extended El Niño activity are associated with a relative cooling of sea-surface temperatures in the western Pacific and a decrease in annual rainfall. Opposite conditions exist during extended La Niña states. Over longer time periods, there is strong evidence for marked ENSO variability throughout the Holocene (Moy et al., 2002; McGregor and Gagan, 2004), the impacts of which have been identified in studies of sedimentary archives from North Stradbroke Island (McGowan et al., 2008), Fraser Island (Donders et al., 2006) and through much of eastern Australia (Donders et al., 2007).

There are more than 50 groundwater dependent lakes and swamps on North Stradbroke Island (Laycock, 1975, 1978; Leach,