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Holocene palaeoclimate and sea level fluctuation recorded from the coastal Barker Swamp, Rottnest Island, south-western Western Australia

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ABSTRACT

The Holocene palaeoclimatic history of south-western Western Australia (SWWA) has received little attention compared to south-eastern Australia, and this has resulted in conflicting views over the impact of climate variability in the region. We present here a well-dated, high-resolution record from two overlapping sediment cores obtained from the centre of Barker Swamp, Rottnest Island, offshore Perth. The records span the last 8.7 ka, with the main lacustrine phase occurring after 7.4 ka. This site preserves both pollen and several ostracod taxa. The pollen record suggests a long-term shift from the early-mid Holocene to the late Holocene to drier conditions with less shrubland and more low-ground cover and less fire activity. A salinity transfer function was developed from ostracod faunal assemblage data and trace metal ratios (Mg/Ca, Sr/Ca and Na/Ca) and stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) analysed on selected ostracod valves. These provide a detailed history of evaporation/precipitation (E/P) differences that clearly shows that the SWWA region was subjected to significant climatic shifts over the last 7.4 ka, with a broad shift towards increased aridity after 5 ka. The swamp ranged from fresh to saline as recorded in the ostracod valve chemistry and the independently-derived salinity transfer function. The ostracod record also indicates that a sea-level highstand occurred between ca. 4.5 and 4.3 ka, with probable step-wise increases at 6.75, 6.2, and 5.6 ka, with the last vestiges of salt water intrusion at ca. 1 ka. After about 2.3 ka, the fresh, groundwater lens that underlies the western portion of the island intersected the swamp depression, influencing the hydrology of the swamp. The broad climatic changes recorded in Barker Swamp are also compared with data from southern South Africa, and it is suggested that the Southern Annular Mode appears to have been the dominant driver in the climate of these regions and that the Indian Ocean Dipole is of little importance in the southern regions of the south-western Cape of Africa and south-western Western Australia.

1. Introduction

1.1. Overview and importance

In recent reviews of global Holocene palaeoclimate change, little (e.g. Mann, 2007; Mann et al., 2008; Neukom and Gergis, 2011) or no (e.g. Mayewski et al., 2004) emphasis has been placed on the records from the coastal or continental regions of the southern Indian Ocean. This is particularly true for the south-eastern portion of the Indian Ocean in the vicinity of south-western Western Australia (SWWA), where the westerly flow of the Southern Ocean and the associated westerly wind flow first impact the Australian region. Gaining an understanding of the palaeoclimate of this region will greatly enhance model predictions of future climate change in the region (e.g. Barron et al., 2012; Silberstein et al., in press).

Unlike south-eastern Australia (SEA), which has recorded significant Holocene climatic variation, there have been relatively few palaeoclimate reconstructions undertaken in SWWA. The few palaeoenvironmental studies include a range of records including fossil pollen sequences (Churchill, 1959, 1960, 1968; Martin, 1973;

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Backhouse, 1993; Newsome and Pickett, 1993; Pickett and Newsome, 1997; Dodson and Lu, 2000; Itzstein-Davey, 2004), sedimentological studies (Semeniuk, 1986), lacustrine and dune building phases in the arid zone (Zheng et al., 2002), tree ring records (Cullen and Grierson, 2009; Sgherza et al., 2010) and sea level fluctuations (Teichert, 1950; Playford et al., 1976; Searle and Semeniuk, 1985; Searle and Woods, 1986; Semeniuk and Searle, 1986; Yassini and Kendrick, 1988; Coshell and Rosen, 1994; Semeniuk, 1996; Playford, 1997; Baker et al., 2001, 2005; Hearty, 2003; Collins et al., 2006).

There is little convergence in the Holocene climatic histories derived from the studies mentioned above. Even considering individual proxies, the results have been the source of some debate, with, for example, early palynological work (Churchill, 1968) claiming significant climatic shifts, while a re-examination of two of these sites (Newsome and Pickett, 1993; Pickett and Newsome, 1997) refuted these earlier claims by questioning the species level of identification in Churchill's (1968) work and suggesting no significant vegetation change. Other palynological studies (Dodson and Lu, 2000; Itzstein-Davey, 2004) have similarly shown little in the way of vegetation change during the Holocene. Semeniuk (1986)'s examination of calcrete formation from the coastal plain area of the Perth Basin, suggested a period of relative aridity prior to 2.5 ± 0.5 ka, with conditions then becoming more humid until today. This finding, however, conflict with those of Zheng et al. (2002), who suggest that the early to mid-Holocene was wetter than the late Holocene at Lakes Cowan and Lefroy located in the arid zone, supporting Churchill's (1968)'s earlier hypothesis.

Recently, several very high-resolution studies have examined the historical and recent pre-instrumental record of climate variation in SWWA. Treble et al. (2003) calibrated a modern speleothem from Moondyne Cave, Leeuwin–Naturaliste Ridge, SWWA (34°16′S, 115°05′E), with historical precipitation events but could not extend their record into pre-instrumentation periods. van Ommen and Morgan (2010) calibrated a 750 year old ice core record from Law Dome, Antarctica (66°46′11″S, 112°48′25″E), with the historical SWWA precipitation and suggested that the opposing relationship between SWWA precipitation and Antarctic sea ice accumulation was directly related to variations in the Southern Annular Mode (SAM) and, consequently, precipitation-bearing frontal systems to SWWA. Cullen and Grierson (2009) examined a series of tree ring records from Lake Tay (33°1′57″S, 120°45′9″E) in central southern Western Australia, but their high-resolution record only encompasses the last 350 years and showed no relationship with the SAM, but a positive relationship with the El Niño-Southern Oscillation (ENSO). These very high-resolution records have each shown that the SWWA climate varied significantly on decadal and sub-decadal timescales in the most recent phases of the Holocene.

In this study, we aim to define the environmental history of south-western Western Australia through the analysis of a sediment record from Barker Swamp on Rottnest Island, near Perth. First studied by Backhouse (1993), and providing the only continuous record of Holocene record from the region, we revisited the site, making use of the rare opportunity the sequence represents to obtain a multi-proxy record of climatic variability at centennial to millennial scales to resolve the discordance evident in the regional literature, and better characterise the variability evident across the region.

1.2. Site description

Rottnest Island (Fig. 1) is situated 18 km west of Perth in a tectonically quiescent portion of the Perth Basin (Semeniuk and Searle, 1986), and forms the largest island off the south-western coast of Western Australia (Glenister et al., 1959). The island contains several permanent hypersaline lakes (Fig. 1) formed when sea levels lowered after the mid-Holocene sea level highstand (Hodgkin, 1959; Playford and Leech, 1977), and numerous lower salinity, ephemeral and permanent inter-dunal swamps (Edward and Watson, 1959; Edward, 1983).

Barker Swamp (32°0′4.45″S, 115°30′18.25″E; 0.15 ± 0.15 m above the Australian Height Datum (mAHD) – D. Robertson, pers. comm.), is the only unmodified swamp on the island and the ideal location for palaeoenvironmental analysis. At the time of coring, Barker Swamp had a <10 cm deep pool on its south-eastern margin.

The geology of Rottnest Island is composed of predominantly late Pleistocene carbonate aeolianite (Tamala Limestone) with minor outcrops of coral-reef limestone (Rottnest Limestone) and fossiliferous lime sands and marls around the edges of the saline lakes (Herschell Limestone) (Teichert, 1950; Glenister et al., 1959; Playford and Leech, 1977; Playford, 1997).

Currently, Barker Swamp is primarily recharged by precipitation and is hydrochemically identical to the precipitation-fed fresh groundwater lens centred to the west of Barker Swamp (see Supplementary Information). The Mg/Ca_{water} (2.27) of the swamp is currently less than half the accepted value of $Mg/Ca_{sea\ water}$ (5 ± 0.8) and the Sr/Ca_{water} (0.025) is three times that of accepted $Sr/Ca_{sea\ water}$ (0.0086 ± 0.0004). Thus, the dominant driver of modern hydrological change in Barker Swamp is the variation in precipitation causing an expansion and contraction of the freshwater lens and precipitation and evaporation from the swamp basin.

This freshwater lens overlies a saline aquifer that is in contact with, and is compositionally identical to local marine waters (Edward and Watson, 1959; Playford and Leech, 1977). The boundary of the freshwater lens and saline aquifer occur between 30 and 35 cm above mean sea level. The spatial extent of this freshwater lens has contracted significantly due to a decline in precipitation since the mid-1960s (Playford, 1997).

1.3. Modern climate and atmospheric circulation

The mid-latitude locale of Rottnest Island results in a Mediterranean-type climate with summer (winter) mean temperatures ranging from 26.5 °C to 18.7 °C (17.7 °C–12.2 °C) and a mean maximum precipitation of 6.8 mm (156 mm) (BoM, 2011). The winter climate is dominated by precipitation-bearing frontal systems, which are deflected south in summer as the zone of high pressure shifts to the south and south-west of SWWA.

The SAM (mean sea level pressure (MSLP) differential between 60°S and 45°S) is the primary driver of the intensity and number of frontal systems affecting SWWA on multi-decadal timescales (Ansell et al., 2000; Smith et al., 2000; van Ommen and Morgan, 2010). Positive phases of SAM result in stronger zonal westerly winds between 15 to 30°S and 45 to 60°S, causing a mean southerly generation and propagation of the precipitation-bearing frontal systems resulting in less precipitation in SWWA. Negative SAM phases result in the opposite conditions resulting in more precipitation in SWWA (Meneghini et al., 2007; van Ommen and Morgan, 2010; Cai et al., 2011b). The Indian Ocean Dipole (IOD), a sea-surface temperature differential between the equatorial western and eastern Indian Ocean (Saji et al., 1999), has been linked with variations in southern Australia precipitation through the formation of continent-spanning, north-west cloudbands (Murphy and Timbal, 2008; Evans et al., 2009), although these have negligible effect on the climate of SWWA. Cai et al. (2011c; 2011d) have also suggested that the IOD influences the position and intensity of the zone of high pressure in summer. ENSO has minimal impact on the climate