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A Last Glacial Maximum through middle Holocene stalagmite record of coastal Western Australia climate

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A B S T R A C T

Stable isotope profiles of ^{230}Th-dated stalagmites from cave C126, Cape Range Peninsula, Western Australia, provide the first high-resolution, continental paleoclimate record spanning the Last Glacial Maximum, deglaciation, and early to middle Holocene from the Indian Ocean sector of Australia. Today, rainfall at Cape Range is sparse, highly variable, and is divided more or less equally between winter and summer rains, with winter precipitation linked to northwest cloud bands and cold fronts derived from the southern mid- to high-latitudes, and summer precipitation due primarily to tropical cyclone activity. Influences of the Indo-Australian summer monsoon at Cape Range are minimal as this region lies south of the modern monsoon margin. The interaction of these atmospheric systems helps shape the environment at Cape Range, and thus C126 stalagmite-based paleoclimatic reconstructions should reflect variability in moisture source driven by changing ocean and atmospheric conditions.

The C126 record reveals slow stalagmite growth and isotopically heavy oxygen isotope values during the Last Glacial Maximum, followed by increased growth rates and decreased oxygen isotopic ratios at 19 ka, reaching a δ^{18}O minimum from 17.5 to 16.0 ka, coincident with Heinrich Stadial 1. The origin of this oxygen isotopic shift may reflect enhanced moisture and lower oxygen isotopic ratios due to amount effect-driven changes in rainfall δ^{18}O values from an increase in rainfall derived from tropical cyclones or changes in northwest cloud band activity, although the controls on both systems are poorly constrained for this time period. Alternatively, lower C126 stalagmite δ^{18}O values may have been driven by more frequent or more intense frontal systems associated with southerly-derived moisture sources, possibly in relation to meridional shifts in positioning of the southern westerlies which have been linked to southern Australia megalake highstands at this time. Finally, we also consider the possibility of contributions of tropical moisture derived from the Indo-Australian summer monsoon. The Intertropical Convergence Zone and associated monsoon trough shifted southward during Heinrich events and other periods of high northern latitude cooling, and although clearly weakened during glacial periods, rainfall with low δ^{18}O values associated with the monsoon today suggests that even small contributions from this moisture source could have accounted for some of the observed oxygen isotopic decrease. Despite a pronounced isotopic excursion coincident with Heinrich Stadial 1, no identifiable anomaly is associated with Heinrich Stadial 2.

The Holocene is also characterized by overall low δ^{18}O values and rapid growth rates, with decreasing oxygen isotopic values during the earliest Holocene and at ~6.5 ka, roughly coincident with southern Australia megalake highstands. The origins of these stalagmite oxygen isotopic shifts do not appear to reflect increases in mean annual temperature but are tied here largely to changes in the δ^{18}O values of precipitation and may reflect a more southerly influence of the Indo-Australian summer monsoon at this time.

C126 stalagmite carbon isotopic ratios offer an important complement to the oxygen isotopic time series. Stalagmite δ^{13}C values averaged −5‰ during the Last Glacial Maximum and early deglaciation,

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and reached a plateau during the oxygen isotopic minimum at 17.5 ka. However, $\delta^{13}C$ values decreased sharply to −12‰ between 11 and 8 ka, a shift interpreted to reflect increases in plant density in response to the onset of interglacial conditions. Stalagmite $\delta^{13}C$ values at 6 ka are lower than expected for the modern C_4-dominated vegetation and thin soils of Cape Range, suggesting that a more C_3-rich environment was present during elevated rainfall conditions of the early and middle Holocene. The Cape Range stalagmite time series thus reveals for the first time the millennial-scale sensitivity of the moisture source variations in northwestern Australia, a result that has implications for precipitation dynamics across much of the continent.

1. Introduction

Identifying the timing and nature of regional responses to climatic change is necessary for developing a holistic view of the global climate system. This is particularly true for the Last Glacial Maximum (LGM) through the Holocene, an interval of profound environmental change, but attempts to construct an integrated picture of this period are hampered in some regions by a scarcity of the requisite high-resolution paleoenvironmental records. Western Australia is one such area that lacks high-resolution, Late Quaternary paleoclimate time series, particularly north of 30°S latitude. To date, the most continuous paleoclimate reconstructions from this region are based on terrestrial pollen and spores obtained from marine cores located off the Cape Range Peninsula (Fig. 1), but interpreting these data is complicated by limited temporal resolution, the potential for bioturbation and unconformities, and the likelihood that the pollen was sourced from a wide latitudinal transect (van der Kaars and De Deckker, 2002, 2003; van der Kaars et al., 2006). Cape Range is an area of particular interest because part of it and the adjacent Ningaloo Reef are UNESCO world heritage sites, and Cape Range and the surrounding region have a rich archeological record.

Today, Cape Range lies at the northern margin of the zone of winter precipitation associated with the southern hemisphere westerlies, and the southern margin of the interval of Western Australia experiencing the highest historical tropical cyclone activity (bom.gov.au). Cape Range also receives a considerable percentage of its winter moisture totals from northwest cloud bands, broad atmospheric systems stretching northwest–southeast and that can span much of the Australian continent (Telcik, 2003; Indian Ocean Climate Initiative, 2012). Cape Range also lies south of the margin of the Indo-Australian summer monsoon (IASM), but given the dynamic nature of the IASM during the last deglaciation (Muller et al., 2012; Denniston et al., 2013), it is conceivable that this system, too, may have once contributed significant quantities of rainfall to Cape Range (Fig. 1). Variations in the IASM, the southern hemisphere westerlies, and tropical cyclones have each been linked to extra-regional forcing, and thus globally expressed climate changes may be reflected in the interactions of these and related systems.

Despite this region's paucity of traditional paleoclimate archives, Cape Range Peninsula contains numerous caves and thus holds the potential for speleothem-based paleoenvironmental reconstruction. Here we present an absolute-dated stalagmite isotopic time series from cave C126 in Cape Range that marks the first high-resolution continental paleoclimate record from this region of Western Australia spanning the LGM, deglaciation, and early/middle Holocene. Dating by ^{230}Th methods reveals stalagmite growth from 26 to 15 and 11 to 6 ka, and stalagmite carbon and oxygen isotopic ratios track paleoenvironmental changes, thereby allowing a rare and detailed examination of these mechanisms by which climate variability was expressed in Western Australia during this time.

2. Geologic and environmental settings

2.1. Cape Range and Cave C126 geology

Cape Range, Western Australia lies within the Exmouth subbasin of the Carnarvon geological province, and is composed of anticlinal, middle Cenozoic marine carbonate sequences (Russell, 2004). The range itself reaches 330 m in elevation and is dissected by gorges that cut karstic limestone bedrock stretching to a coastal plain that ends in a series of raised, wave-cut terraces. Cape Range marks the closest point in Australia to the continental slope and thus remained proximal to the ocean throughout the LGM. Approximately 800 caves are identified in this area, and two stalagmites were collected in August of 1991 AD from cave C126 (22.1°S, 113.9°E), a solution pipe with lateral development at depth (approx. 54 m below the land surface; cave floor elevation approx. 50 m), that represents a typical cave morphology for this region (Hamilton-Smith et al., 1998) (Fig. 2). When visited, the cave was 21 °C with 96% relative humidity (D. Brooks, Pers. Comm.).

2.2. Regional climate

At Cape Range, regional climate is characterized by a mean annual temperature of 25 °C and summer temperatures as high as 47 °C (Fig. 3). Mean annual rainfall, which is episodic and often torrential, is only 280 mm, and potential evaporation rates are high (pan evaporation ≤ 3200 mm/year). Groundwater recharge into the unconfined aquifer system at Cape Range accounts for only 10% of average annual rainfall (Forth, 1973). Rainfall is primarily derived in roughly equal proportion from winter and summer, with the former associated with northwest cloud bands (NWCB) and fronts that are sourced at the southern mid- to high-latitudes (WAPC, 1996; Frederiksen et al., 2011). The NWCB season is from April to October, and these events represent a significant source of moisture to Western Australia, providing up to 80% of annual rainfall for northwestern Australia, particularly for (near)coastal sites (Wright, 1997; Telcik, 2003). NWCB can reach thousands of km in length, stretching from the Intertropical Convergence Zone (ITCZ) on the northwest to a cold front at their southeastern end. The development of NWCB is influenced by regional ocean and atmosphere variations including strong winds and high sea surface temperatures (SST) (Meehl, 1993), and particularly SST anomalies in the eastern Indian Ocean (Telcik, 2003). These ocean temperatures are, in turn, influenced by a number of factors including the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Telcik, 2003). NWCB are also strongly correlated with the latitude of the subtropical ridge along eastern Australia, and in wet years, are associated with an equatorward shift of the subtropical ridge and associated frontal systems tied to the mid-latitude westerlies (Pittock, 1975). Pronounced variability in NWCB has been documented over the last fifty years, with NWCB modes having increased by approximately 25% or more for each of the 1975–1994 AD and 1997–2006 AD periods, compared with the 1949–1968 AD