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North Atlantic forcing of millennial-scale Indo-Australian monsoon dynamics during the Last Glacial period

Rhawn F. Denniston [a,*], Karl-Heinz Wyrwoll [b], Yemane Asmerom [c], Victor J. Polyak [c], William F. Humphreys [d,e], John Cugley [f], David Woods [g], Zachary LaPointe [c], Julian Peota [a], Elizabeth Greaves [a]

[a] Department of Geology, Cornell College, Mount Vernon, Iowa, USA
[b] School of Earth and Environment, University of Western Australia, Perth, Western Australia, Australia
[c] Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico, USA
[d] School of Animal Biology, University of Western Australia, Perth, Western Australia, Australia
[e] Western Australia Museum, Perth, Western Australia, Australia
[f] Illawarra Speleological Society, Perth, Western Australia, Australia
[g] Department of Environment and Conservation, Broome, Western Australia, Australia

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A B S T R A C T

Recent studies of the Last Glacial period Indo-Australian summer monsoon (IASM) have revealed links to both northern and southern hemisphere high latitude climate as well as to regional ocean conditions. Particular interest has been paid to the monsoon response to Heinrich events, with variability explained by meridional shifts in positioning of the intertropical convergence zone (ITCZ), but this model has not been adequately tested. In addition, the shorter-lived Dansgaard/Oeschger (D/O) events have not been detected (beyond D/O-1, the Bølling/Allerød) in land-based records from the Indo-Pacific, despite their prominent expression in stalagmites from southern Asia, raising questions about the sensitivity of the IASM to these events. Here we present a Southern Hemisphere stalagmite oxygen isotopic time series from Ball Gown Cave (BGC), tropical northern Australia, located on the margins of the modern austral summer ITCZ, that spans 40–31 and 27–8 ka. Elevated IASM rainfall coincides with Heinrich stadials and the Younger Dryas, while decreased rainfall characterizes D/O interstadials, a response that is anti-phased with sites spanning the Indo-Pacific Warm Pool and with Chinese records of the East Asian summer monsoon. The BGC time series thus reveals a precipitation dipole consistent with a southward (northward) migration of the ITCZ during periods of high northern latitude cooling (warming) as the primary driver of millennial-scale IASM variability during the Last Glacial period. Our record indicates a strengthening of the IASM after the Younger Dryas period, likely as a result of rising sea level and sea surface temperatures, breaking the link with the high latitudes.

1. Introduction

Over the Last Glacial cycle, monsoons across Africa (Schefuß et al., 2011; Stager et al., 2011), Asia (Wang et al., 2001; Fleitmann et al., 2003), North America (Asmerom et al., 2010) and South America (Cruz et al., 2005; Wang et al., 2007; Kanner et al., 2012) varied with insolation over orbital time scales, but also exhibited millennial-scale oscillations tied to high latitude climate. Most notably, the Younger Dryas (YD) and Heinrich stadials, periods of high northern latitude cooling recorded in Greenland ice (NGRIP members, 2004) and marine sediments (Bond et al., 1997), were marked by substantial rainfall anomalies in the Northern (Wang et al., 2001) and Southern (Schefuß et al., 2011) Hemispheres. The impact of these events on rainfall in the (sub)tropics is increasingly well resolved, and is explained, in part, by meridional displacement of the ITCZ due to an expansion of ice cover or decrease in temperature at high northern latitudes, or a reduction in Atlantic Meridional Overturning Circulation, all of which occurred during the YD and Heinrich stadials (Chiang and Bitz, 2005; Lewis et al., 2010).

The ITCZ and the planetary monsoon are closely coupled, particularly in the western Pacific and across the maritime continent, areas that lack prominent topographic features such as the Tibetan Plateau that drive intense atmospheric convection

* Corresponding author.
E-mail address: RDenniston@CornellCollege.edu (R.F. Denniston).

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(Suppiah, 1992). As a result, the IASM, which dominates the climate across northern Australia and the Indo-Pacific, is closely linked with sea surface conditions of the Indo-Pacific Warm Pool (IPWP) and has had a somewhat complex evolution through the Last Glacial period. Paleomonsoon reconstructions along a latitudinal transect from eastern Asia through the IPWP reveal significant regional variations. In the Northern Hemisphere, stalagmites from Hulu Cave, China (32°N) (Wang et al., 2001), preserve a Last Glacial record of East Asian summer monsoon (EASM) rainfall that is nearly identical in timing and structure to temperature variations reconstructed from Greenland ice but with clearly defined Heinrich stadials preserved as periods of a weakened EASM, while D/O interstadials were characterized by sharp increases in the EASM (Fig. 1). Stalagmites from Borneo (4°N) (Partin et al., 2007) also suggest a weakened IASM during Heinrich stadial 1 (HS1) (17–15 ka) but they do not record D/O events and instead exhibit a connection to IPWP sea surface temperature (SST) as well as to southern high latitude climate, with decreased IASM rainfall coincident with the Antarctic Cold Reversal (14.5–12.5 ka) (Blunier and Brook, 2001). In the Southern Hemisphere, a stalagmite time series from Flores (8°S) is closely tied to IPWP conditions and also indicates a strengthened IASM during the YD (Griffiths et al., 2009), but the IASM response to Heinrich events at this site is less well constrained (Lewis et al., 2010, 2011). A high-resolution marine core from the south Java margin (Mohtadi et al., 2011) located at a similar latitude to Flores reveals pronounced millennial-scale changes in terrigenous sedimentation and foraminiferal isotopic chemistry interpreted as a *weakened* IASM during the YD and HS1 (and a strengthened IASM during D/O event 1) while Muller et al. (2012) document *increases* in continental weathering during HS1 from the Flores Sea. Neither the Flores nor the Java record preserves evidence of forcing in response to Antarctic climate, and no continental records from the IPWP record D/O events (other than D/O-1, the Bølling/Allerød). Fully understanding the nature of the IASM response to extra-tropical forcing requires the development of continuous, high-resolution records from the southernmost margin of the IASM. To do so, six cylindrical, calcite stalagmites (BGC5, 6, 10, 11, 14, and 16) (Fig. 2) were collected from BGC (17°2′S, 125°0′E, ~100 m elevation), located in the western Kimberley of tropical Western Australia (Fig. 1). Oxygen isotopic ratios of these samples track monsoon variability, allowing a unique examination of IASM dynamics during the Last Glacial period.

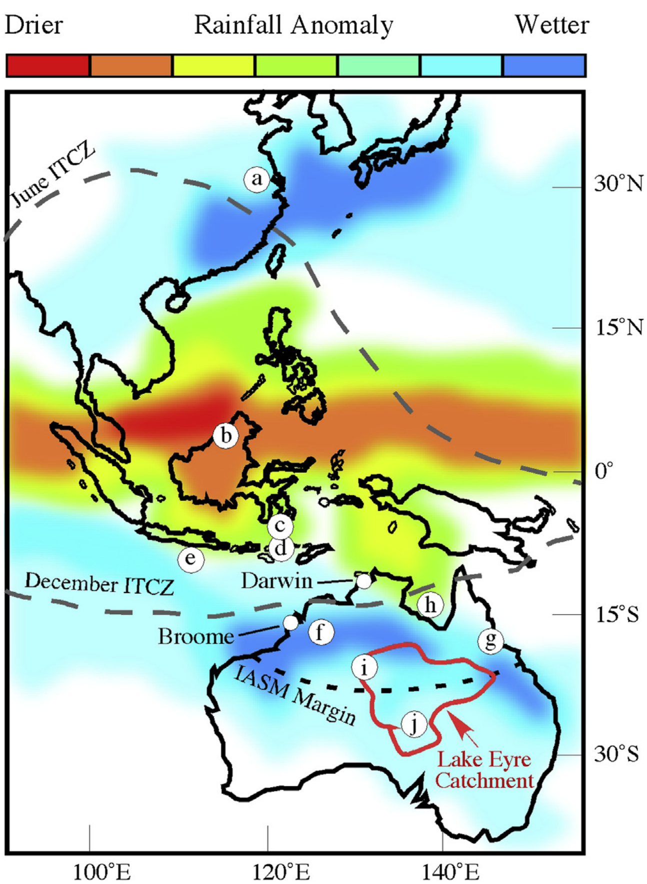

Fig. 1. Map of the western Pacific showing sites discussed in text with DJF rainfall anomalies associated with North Atlantic hosing simulations of Heinrich events (after Lewis et al., 2010): (a) Hulu Cave, China (Wang et al., 2001); (b) Gunung Buda Cave, Borneo (Partin et al., 2007); (c) Flores Sea core VM33-80 (Muller et al., 2012); (d) Liang Luar Cave, Flores (Griffiths et al., 2009); (e) south Java core GeoB 10053-7 (Mohtadi et al., 2011); (f) Ball Gown Cave (this study) and approximate location of Lake Gregory (Wyrwoll and Miller, 2001); (g) Lynch's Crater (Muller et al., 2008); (h) Gulf of Carpentaria (De Deckker, 2001; Reeves et al., 2008); (i) Lake Lewis basin (English et al., 2001); (j) Lake Eyre (Magee et al., 2004).

2. Materials and methods

2.1. ^{230}Th dating

Stalagmites were sectioned using a water-cooled saw along the vertical growth axis and inspected for signs of recrystallization. Stalagmite chronologies were constructed using 36 ^{230}Th dates obtained with a Thermo Neptune multi-collector ICP-MS at the University of New Mexico Radiogenic Isotope Laboratory using methods described by Asmerom et al. (2006) (Table 1). For dating, 50–150 mg of calcite was milled at each interval of interest using a computer-guided drill from each interval of interest and then dissolved and spiked with a mixed ^{229}Th–^{233}U–^{236}U tracer. The sample and spike were homogenized by drying the solution on a hot plate and then redissolving in 7 N HNO_3. Any organics included within the calcite were destroyed by heating in 14 N HNO_3 and perchloric acid,

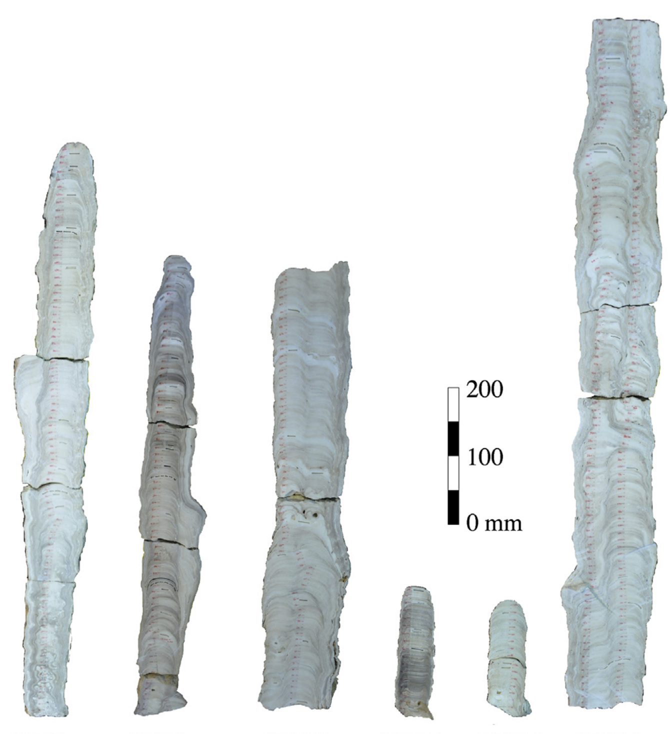

Fig. 2. Cross-section of BGC stalagmites analyzed in this study.