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Varied Response of Western Pacific Hydrology to Climate Forcings over the Last Glacial Period

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Atmospheric deep convection in the west Pacific plays a key role in the global heat and moisture budgets, yet its response to orbital and abrupt climate change events is poorly resolved. Here we present four absolutely-dated, overlapping stalagmite oxygen isotopic records from northern Borneo that span most of the last glacial cycle. The records suggest that northern Borneo hydroclimate shifted in phase with precessional forcing, but was only weakly affected by glacial-interglacial changes in global climate boundary conditions. Regional convection likely decreased during Heinrich events, but other northern hemisphere abrupt climate change events are notably absent. The new records suggest that the deep tropical Pacific hydroclimate variability may have played an important role in shaping the global response to the largest abrupt climate change events.

The response of the tropical Pacific to changes in the earth's climate system remains highly uncertain. The most recent glacial-interglacial cycle encompasses several precessional cycles, changes in ice volume, sea level, global temperature, and atmospheric pCO_2, and millennial-scale climate events, and thus provides insights into the tropical Pacific response to a variety of climate forcings. Chinese stalagmites show that East Asian monsoon strength closely tracks precessional insolation forcing over several glacial-interglacial cycles, and exhibits prominent millennial-scale variability (*1*, *2*). The timing and structure of these abrupt climate changes are nearly identical to millennial-scale events recorded in the Greenland ice cores [so-called Dansgaard-Oeschger (D/O) events] (*3*), and in sediment records that document ice-rafted debris across the North Atlantic (so-called Heinrich events) (*4*, *5*). A Borneo stalagmite record spanning the last 27,000 years provides a markedly different view of hydrology in the western tropical Pacific, with the Heinrich 1 excursion and spring/fall precessional insolation forcing explaining much of the variability (*6*). At its most basic, this finding illustrates the complexity of regional responses to various climate forcings, especially at sites located far from the North Atlantic, and demands a more exhaustive tropical Pacific hydrologic record encompassing a full glacial-interglacial cycle.

Here we present four overlapping stalagmite oxygen isotopic ($\delta^{18}O$) records from Gunung Buda and Gunung Mulu national parks, located in northern Borneo (4°N, 115°E) (fig. S1), that together span most of the last glacial cycle. The research site is located near the center of the West Pacific Warm Pool (WPWP), where changes in sea surface temperatures and sea level pressure have significant impacts on large-scale atmospheric circulation and global hydrology (*7*). Using multiple stalagmites from different caves, we distinguish shared climate-related features from cave-specific signals in the overlapping $\delta^{18}O$ records.

The four stalagmite records span portions of the last glacial cycle with many intervals of overlap, based on U-series dates (Fig. 1). Stalagmites were recovered from Secret Cave at Gunung Mulu [SC02, 37-94 kybp (thousands of years before present) and SC03, 32-100 kybp], and from Bukit Assam (BA02, 15-46 kybp) and Snail Shell Cave (SCH02, 31-73 kybp) at Gunung Buda, 25 km distance from Gunung Mulu (fig. S2). The deglacial and Holocene $\delta^{18}O$ records from stalagmite SCH02 were presented in Partin *et al.*, 2007. Eighty-six new U/Th dates measured across the 4 stalagmites fall in stratigraphic order within 2σ errors (*8*). Large uncertainties in the $^{230}Th/^{232}Th$ ratio of the contaminant phases translate into large uncertainties associated with the correction for detrital thorium contamination. Fourteen isochrons measured across stalagmites from three separate caves give initial $^{230}Th/^{232}Th$ atomic ratios of 56 ± 11 (2σ) for Bukit Assam Cave, 59 ± 13 (2σ) for Snail Shell Cave, and 111 ± 41 (2σ) × 10^{-6} for Secret Cave (*8*), which fall within the range of previously published values from our site (*6*). Absolute age errors for each U/Th date were calculated with a Monte Carlo approach that combined multiple sources of error. The resulting dating errors average ±200, ±250, ±400, and ±500 yrs (2σ) for BA02, SCH02, SC02, and SC03, respectively. Age models were initially constructed by linearly interpolating between each date, and were refined by aligning five major millennial-scale $\delta^{18}O$ excursions visible across all four records within age error (*8*). The fact that both chronologies fall nearly completely within the StalAge (*9*) algorithm's 95% confidence interval (figs. S3 to S6) adds confidence to our assigned chronologies and associated error estimates. With our 1mm sampling interval, the temporal resolution of the associated $\delta^{18}O$ records average 60 yrs/sample for faster-growing stalagmites BA02 and SCH02 and 200 yrs/sample for slower-growing stalagmites SC02 and SC03. During the 50kybp to 38kybp interval, SC02 and SC03 were sampled at 0.5mm-resolution to achieve ~100 yrs/sample resolution. Ultra-slow growth intervals (<10 μm/yr for the faster-growing stalagmites and <3 μm/yr for the slower growing stalagmites) may represent unresolved hiatuses and as such were excluded from the resulting paleoclimate reconstructions, following Partin *et al.*, 2007 (*8*).

The stalagmite $\delta^{18}O$ records provide reconstructions of rainfall $\delta^{18}O$ variability at the research site, which in turn tracks the strength of regional convective activity (*10*). Consistent with the tropical amount effect (*11*, *12*), rainfall $\delta^{18}O$ variations measured at the site from 2006-2011 are significantly anti-correlated with regional precipitation amount, and closely track the El Niño Southern Oscillation on monthly timescales (*10*). A weak semi-annual seasonal cycle in rainfall $\delta^{18}O$ is characterized by relative minima in June-July and November-January, and relative maxima in February-April and August-October. Such a pattern suggests that the twice-yearly passage of the Intertropical Convergence Zone (ITCZ) over the site is associated with shifts in the moisture sources and/or trajectories that drive the observed seasonal fractionations (*10*). Dripwater $\delta^{18}O$ values match rainfall $\delta^{18}O$ values averaged over the preceding 2-6 months (*13*), suggesting a short residence time of dripwater $\delta^{18}O$ relative to our centennial-scale sampling of stalagmite $\delta^{18}O$. Timeseries of Buda and Mulu stalagmite $\delta^{18}O$ are highly reproducible

(6, 14), strongly supporting their interpretation as rainfall $\delta^{18}O$ reconstructions and, by extension, as records of past regional convective activity.

The overlapping Borneo stalagmite $\delta^{18}O$ records show orbital-scale variability related to precessional insolation forcing and glacial-interglacial (G-I) changes (Fig. 2). The similarity of our stalagmite $\delta^{18}O$ timeseries to indices of G-I variability greatly diminishes after removing the mean $\delta^{18}O$ of seawater due to changes in ice volume (8, 15) from the Borneo $\delta^{18}O$ records (Fig. 2 and fig. S7). After this correction, Last Glacial Maximum (LGM) $\delta^{18}O$ values are nearly identical to $\delta^{18}O$ values at ~85kybp, despite the presence of significantly larger ice sheets, cooler regional temperatures (16, 17), and a completely exposed Sunda Shelf during the LGM. In particular, Sunda Shelf emergence has been implicated in shaping glacial western tropical Pacific hydroclimate in previous studies (6, 18, 19). However, we find little correspondence between Borneo stalagmite $\delta^{18}O$ and an index of Sunda Shelf areal extent over the entire glacial cycle (fig. S7). For example, significant Borneo stalagmite $\delta^{18}O$ variations in the 90-70kybp interval bear little resemblance to reconstructed sea level changes, especially from ~76-71kybp (20), when a large drop in sea level almost doubled the size of the exposed shelf (fig. S7). As such, the new Borneo $\delta^{18}O$ records suggest that the cumulative influence of G-I boundary conditions, including changes in global temperature and CO_2, did not drive significant changes in rainfall $\delta^{18}O$ at our site. That said, the complexity of influences on rainfall $\delta^{18}O$ (10) means that LGM climate may have been characterized by two or more competing influences on regional rainfall $\delta^{18}O$. For example, regional drying during the LGM inferred from WPWP sediment cores (21) and modeling studies (19) may have increased rainfall $\delta^{18}O$, while longer moisture trajectories associated with the emergence of the Sunda Shelf may have decreased rainfall $\delta^{18}O$.

The Borneo stalagmite $\delta^{18}O$ records vary in phase with insolation at the equator during boreal fall in Stage 5 and the Holocene, when precessional forcing is relatively strong (Fig. 2C). The impact of precessional forcing on Borneo stalagmite $\delta^{18}O$ is weak during Stage 3, in part owing to reduced precessional amplitude during this time. Precessional forcing is also apparent in older glacial-interglacial stalagmite $\delta^{18}O$ reconstructions from Borneo (14). Taken together, the Borneo records suggest that precession may be the dominant source of orbital-scale hydroclimate variability in the WPWP. The implied sensitivity of northern Borneo hydrology to boreal fall insolation is consistent with results from a previous modeling study (22). Moreover, results from a long-term rainfall $\delta^{18}O$ monitoring program at Mulu demonstrate that mean annual rainfall $\delta^{18}O$ values depend, in part, on the magnitude of rainfall $\delta^{18}O$ enrichments during the boreal spring/fall seasons (10). In this sense, the observed sensitivity to boreal fall insolation may represent a direct response of mean annual rainfall $\delta^{18}O$ to local changes in seasonal moisture sources and trajectories. However, ENSO and the Madden-Julian Oscillations (23) have large impacts on modern Mulu rainfall $\delta^{18}O$ variability (10), such that Borneo stalagmite $\delta^{18}O$ signals may represent a combination of one or more climatic influences.

The Borneo stalagmite $\delta^{18}O$ records are dominated by six millennial-scale increases in $\delta^{18}O$ that coincide with Heinrich events, inferring a decrease in regional convection during these abrupt climate changes (Fig. 2). Indeed, a nearby Sulu Sea sediment core (Fig. 2E) also documents increased planktonic foraminiferal $\delta^{18}O$ values during Heinrich events (24), consistent with a reduction in regional convective activity. The dominant paradigm to explain millennial-scale tropical hydroclimate anomalies is that they are driven from the North Atlantic region, either from weakening of the Atlantic thermohaline circulation or from a dramatic albedo change due to sea ice cover, both of which drive a southward migration of the ITCZ that dries most of the northern tropics (25, 26). A similar chain of events is used to describe D/O abrupt climate changes that are well-documented outside of the tropical Pacific, most notably in Chinese and Peruvian stalagmite $\delta^{18}O$ records (1, 2, 27) and in a high-resolution ice core $\delta^{18}O$ record from the south Atlantic sector of Antarctica (28). However, the Borneo stalagmite $\delta^{18}O$ records lack any coherent signature of D/O events (Fig. 2 and fig. S8). The Borneo stalagmite $\delta^{18}O$ records show no consistent response to D/O events 8 and 12, the prominent D/O events that occur on the heels of Heinrich events 4 and 5 (fig. S8). Of particular note, the records show little millennial-scale variability from ~30-40kybp across D/O events 5-8 (fig. S8). The records do bear a strong resemblance to the Chinese $\delta^{18}O$ records during the 50-60kybp interval, as both records contain a significant $\delta^{18}O$ increase at ~55kybp. This shared $\delta^{18}O$ enrichment may reflect the influence of an additional Heinrich event, referred to as "Heinrich 5a" in one study (29), or may indicate a regional hydrological sensitivity to the relatively prolonged D/O events that occurred during this time interval. Contrary to inferences drawn from a deglacial Borneo stalagmite $\delta^{18}O$ record (6), there is no evidence for a southern hemisphere influence on millennial-scale variability in Borneo hydroclimate over the last glacial cycle (fig. S8).

The unambiguous signature of Heinrich events in the Borneo stalagmite $\delta^{18}O$ records stands in stark contrast to the lack of consistent D/O-related signals in the records, implying a selective response of WPWP hydrology to high-latitude abrupt climate change forcing. Specifically, the absence of any readily identifiable D/O signals in the Borneo $\delta^{18}O$ record represents a clear challenge to our understanding of abrupt climate change mechanisms. Indeed, the new Borneo records suggest that one of two possibilities must be true: (i) if D/O events reflect a similar mechanism to Heinrich events, then they must not be strong enough to significantly affect northern Borneo hydrology, or (ii) D/O events and Heinrich events are characterized by fundamentally different climate mechanisms and feedbacks.

The largest millennial-scale anomaly in the Borneo records is not a Heinrich event, but rather an abrupt increase in $\delta^{18}O$ that occurs at 73.42 ± 0.30(2σ) kybp, coincident with a similarly large and abrupt increase in Chinese stalagmite $\delta^{18}O$ (Fig. 2). Whether this event is associated with the Toba super-eruption, dated at 73.88 ± 0.64(2σ) kybp (30), and/or a prominent early abrupt climate change event visible in Greenland ice core $\delta^{18}O$ (Fig. 2A) merits investigation in additional high-resolution paleoclimate records from the Indo-Pacific.

The Borneo composite records demonstrate the sensitivity of western equatorial Pacific hydrology to both high-latitude and low-latitude forcings. However, the response of northern Borneo hydroclimate to these forcings is not uniform: glacial conditions and D/O events apparently had much smaller impacts on regional hydrology than either insolation or Heinrich-related forcing. Our results imply that once the hydrological response threshold is reached, then climate feedbacks internal to the tropics may serve to amplify and prolong a given climate change event, whether the trigger originates from internal dynamics or external radiative forcing.

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Supplementary Materials
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Materials and Methods
Figs. S1 to S12
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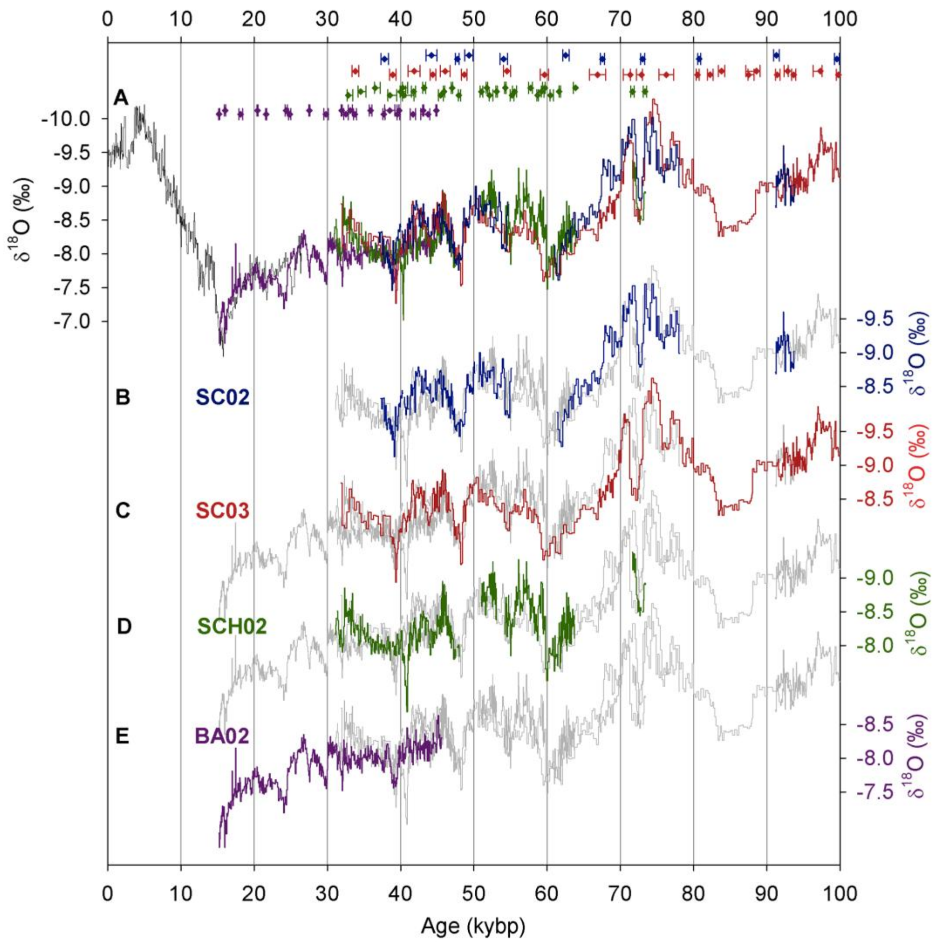

Fig. 1. Comparison of four overlapping stalagmite $\delta^{18}O$ records from northern Borneo. (**A**) $\delta^{18}O$ records from SC02 (navy), SC03 (red), SCH02 (green), and BA02 (purple) are overlain after aligning five major millennial-scale $\delta^{18}O$ excursions shared across all four stalagmites to within 2σ dating errors (*8*), plotted with previously published stalagmite $\delta^{18}O$ data from our site (black) (*6*). SC03 and SC02 mean $\delta^{18}O$ have been offset +0.2‰ and BA02 mean $\delta^{18}O$ has been offset -0.45‰ to match the absolute value of SCH02, consistent with the prior use of SCH02 as a benchmark for the deglacial/ Holocene Borneo records (*6*). (**B**) The $\delta^{18}O$ record for SC02, plotted using its raw age model (navy), plotted with the three other overlapping Borneo stalagmite $\delta^{18}O$ records using their raw age models (gray). (**C**) Same as (B), but for SC03 (red). (**D**) Same as (B), but for SCH02 (green). (**E**) Same as (B), but for BA02 (purple). U–Th-based age model used to construct the aligned composite $\delta^{18}O$ record plotted in corresponding colors at top, shown with 2σ uncertainty limits (*8*).

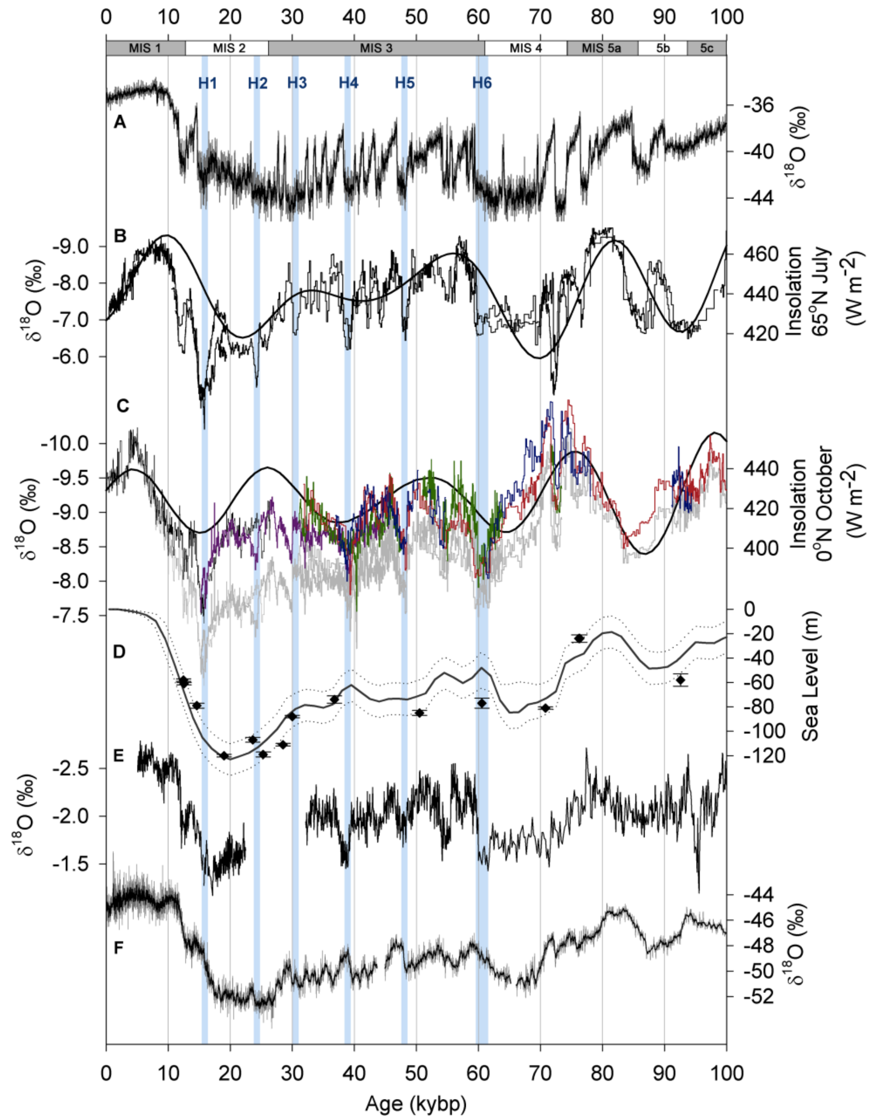

Fig. 2. Comparison of Borneo stalagmite $\delta^{18}O$ records to climate forcings and records of paleoclimate from key regions. (**A**) Greenland NGRIP ice core $\delta^{18}O$ (gray) (*31*) with 100yr averages (black), plotted using the GICC05modelext age model (*32*). (**B**) Hulu/Sanbao cave stalagmite $\delta^{18}O$ records from China (*1*, *2*); where Sanbao has been offset by +1.6‰ to match Hulu), plotted with July insolation at 65°N (*33*). (**C**) Borneo stalagmite $\delta^{18}O$ records, plotted with age models aligned and adjusted to account for changes in ice volume-related changes in global seawater $\delta^{18}O$ (*8*). Also plotted are October insolation at 0°N (black) (*33*) and non-ice-volume-corrected versions of the Borneo stalagmite $\delta^{18}O$ records (gray). (**D**) Coral-based estimates of paleo-sea level record (*20*, *34*, *35*) (black symbols) and derived global mean sea level record (*15*) (solid line: average, dotted line: minimum and maximum). (**E**) Sulu Sea planktonic foraminifera $\delta^{18}O$ (*24*), plotted with revised age model using updated IntCal09 calibration curve 41kybp-modern and aligning 60kybp $\delta^{18}O$ excursion to the Hulu/Sanbao stalagmite $\delta^{18}O$ records. (**F**) EPICA Dronning Maud Land (EDML) ice core $\delta^{18}O$ (gray) (*28*) with 7-year averages (black). Vertical blue bars indicate the timing of Heinrich events H1-H6 (*5*) as recorded by the Hulu/Sanbao stalagmite $\delta^{18}O$ records (*1*, *2*).