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Late Glacial to early Holocene hydroclimate and environmental changes in northern Central America coupled to upstream regional monsoon convection

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ABSTRACT

Tropical oxygen isotope (δ^{18}O) records from terrestrial archives such as speleothems have been commonly interpreted as proxies for regional-scale rainfall because δ^{18}O of precipitation is inversely related to the amount of upstream rainout. However, speleothem δ^{18}O values can be decoupled from local rainfall amount at the study site, highlighting the need for local rainfall-sensitive proxies. Here we combine previously published oxygen records with carbon and uranium isotope data from four replicated, precisely dated stalagmites from Guatemala to show that local rainfall at our study site has been tightly coupled with regional upstream Caribbean atmospheric dynamics over the last deglaciation and the Holocene (18,000–4000 yr B.P.). Reduced local rainfall and diminished soil and vegetation activity coincide with widespread weakening of upstream regional convection during Heinrich Stadial 1 and the Younger Dryas. In contrast, strong regional convection aligns with enhanced local wetness during the Bølling-Allerød warm period and the early Holocene. Our multiproxy record, supported by isotope-enabled model simulations, demonstrates a strong sensitivity of local hydroclimate to changes in upstream regional monsoonal convection across Central America and the Caribbean. Furthermore, persistently low δ^{13}C values during the cold and dry HS1 and YD intervals suggest that C$_3$ vegetation likely remained dominant in the Guatemala highlands throughout the deglacial period. Our analysis shows that changes in regional atmospheric circulation strongly influence local hydrology and environmental processes in northern Central America and provides new climatic context for assessing past (and potentially future) ecosystem and biodiversity responses to rapid climate changes.

INTRODUCTION

Low-latitude speleothem δ^{18}O reflects the δ^{18}O composition of effective infiltrating rainfall (δ^{18}O$_p$), which is influenced by source-to-cave atmospheric processes and precipitation amount at and upwind of the cave site (Cheng et al., 2012; Lachniet, 2009; Wong and Breecker, 2015). However, the amount effect—the empirical negative correlation between δ^{18}O$_p$ and precipitation amount at a site—exhibits large spatial heterogeneity, driven by interacting factors including moisture history, seasonality, precipitation type, convective intensity, and local climate (Konecky et al., 2019; Sánchez-Murillo et al., 2016; Sun et al., 2022). Hence, tropical δ^{18}O$_p$ may not always reflect changes in local rainfall, necessitating the use of additional moisture-sensitive proxies (Cheng et al., 2016; Wolf et al., 2023).

Local versus regional controls on speleothem δ^{18}O and other geochemical proxies (e.g., U, Mg, Sr) remain a subject of ongoing research (Patterson et al., 2024; Sinha et al., 2015). For example, speleothem records and climate models from the Asian and South American monsoons demonstrate a strong regional control on speleothem δ^{18}O linked to upstream convection and continental rainout (Cheng et al., 2012; He et al., 2021). In contrast, complementary records of local processes derived from speleothem carbon isotopes (δ^{13}C) and other geochemical proxies commonly show a decoupling between local climate and regional atmospheric dynamics (Cheng et al., 2016; Novello et al., 2019; Wolf et al., 2023), demonstrating that processes beyond regional monsoon strength contribute to local hydroclimate changes at some tropical sites.

While the forcings on monsoon strength have been broadly recognized in Central American and Caribbean paleoclimate records (Hodell et al., 2008; Lucia et al., 2024; Warken et al., 2019), the link between regional atmospheric processes and local climate remains less understood. Previous work based on Guatemalan stalagmite δ^{18}O records demonstrated that abrupt shifts in regional monsoon convection were primarily driven by changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC) and tropical North Atlantic–Caribbean sea surface temperature (SST) during the last glacial cycle (Lucia et al., 2024) but did not explore the local hydroclimate response, leaving open questions on how regional hydroclimate changes affected local water balance and ecosystems.

Here, we combine new rainfall-sensitive proxy records with previously published δ^{18}O

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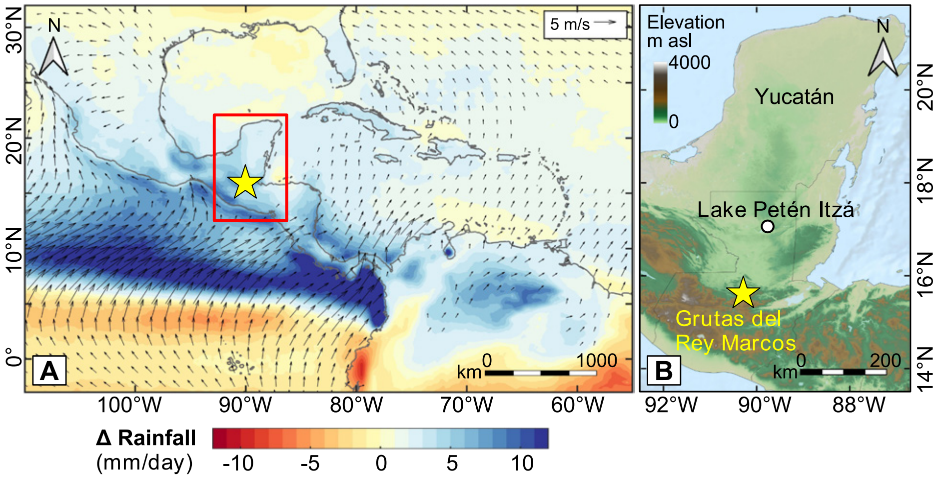

Figure 1. Modern climate and map of study area. (A) Precipitation (color scale) and surface winds (arrows) shown as difference between wet (May–November) and dry (December–April) season for 1998–2024. Source: NASA Integrated Multi-satellite Retrievals for Global Precipitation Measurement (IMERG GPM), Version 7. (B) Location of Grutas del Rey Marcos (yellow star) and Lake Petén Itzá (white circle), Guatemala, discussed in text. Solid lines in B are country boundaries; m asl—meters above sea level.

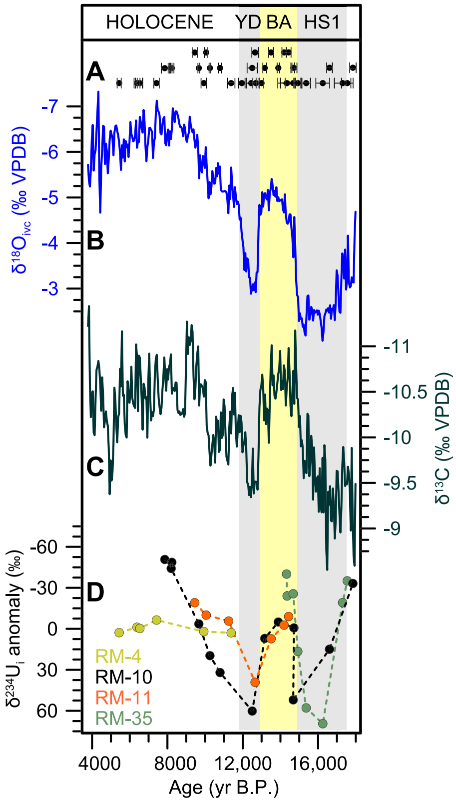

Figure 2. Last deglaciation multiproxy record from four Grutas del Rey Marcos stalagmites. (A) U-Th ages (±2σ error bars). (B) Composite ice-volume corrected $\delta^{18}O$ ($\delta^{18}O_{ivc}$). (C) $\delta^{13}C$. (D) Mean-centered initial $\delta^{234}U$ ($\delta^{234}U_i$) anomaly data from each stalagmite (color coded). *Y*-axis in B, C, and D are reversed. Vertical shading defines Younger Dryas (YD), Bølling-Allerød warm period (BA), and Heinrich Stadial 1 (HS1). VPDB—Vienna Peedee belemnite.

data (Lucia et al., 2024) from four replicated stalagmites from Grutas del Rey Marcos (Figs. S1–S4 in the Supplemental Material[1]) in the Guatemalan highlands (Fig. 1) to demonstrate a strong coupling between local hydroclimate and environmental conditions in northern Central America and upstream changes in regional monsoon convection between 18,000 and 4000 yr B.P.

MATERIALS AND METHODS

Stable isotopes ($\delta^{18}O$ and $\delta^{13}C$ in per mil on the Vienna Peedee belemnite [VPDB] scale) were measured in each stalagmite at 0.5–1 mm resolution and anchored by 35 ^{230}Th ages (Table S1 in the Supplemental Material). Individual isotope time series replicate during coeval growth intervals (Figs. S5–S6), so we produced $\delta^{18}O$ and $\delta^{13}C$ composite records by average binning all four stalagmite isotope records at a 50-yr resolution. The $\delta^{18}O$ data were previously presented in Lucia et al. (2024) and reported as ice-volume corrected (herein $\delta^{18}O_{ivc}$; Supplemental Material). Here, we use $\delta^{13}C$ and initial uranium isotopes ($\delta^{234}U_i$) as proxies for local hydrologic and environmental processes to evaluate the local climate components of $\delta^{18}O_{ivc}$ and evaluate regional-local climate coupling. $\delta^{234}U_i$ was calculated from the U-series ages. We further conduct a proxy data-model analysis with the iTRACE simulation ensemble (He et al., 2021) to evaluate the dynamical links between regional upstream atmospheric processes and local hydroclimate in northern Central America and to test iTRACE consistency in reproducing Grutas del Rey Marcos $\delta^{18}O$ variability (Supplemental Material).

RESULTS AND DISCUSSION

Deglacial to Holocene Multiproxy Record from Guatemala

The Grutas del Rey Marcos $\delta^{18}O_{ivc}$ ranges between −7‰ and −2‰, while $\delta^{13}C$ varies between −11‰ and −8.5‰ (Figs. 2A and 2B). The most positive $\delta^{18}O_{ivc}$ and $\delta^{13}C$ values occurred during Heinrich Stadial 1 (HS1) (17,800–14,500 yr B.P.), after which both proxies show decreasing values at ca. 14,500 yr B.P., coinciding with the onset of the Bølling-Allerød warm period (BA) (14,500–12,900 yr B.P.). A sharp increase of ~2‰ in $\delta^{18}O_{ivc}$ and ~1‰ in $\delta^{13}C$ is observed at the Younger Dryas (YD) (12,900–11,700 yr B.P.). Between 12,500 and 9000 yr B.P., $\delta^{18}O$ shows a gradual decrease from −3‰ to −6.5‰, whereas $\delta^{13}C$ indicates a two-phase shift to −11‰, with a short period of positive change of ~0.8‰ between 11,700 and 10,500 yr B.P. (early Holocene [EH]). From 9000 to 4000 yr B.P., the Grutas del Rey Marcos $\delta^{13}C$ record features a pronounced variability within a range of ±2‰, while $\delta^{18}O$ exhibits ±1‰ variations superimposed on a slight negative trend.

Today, amount-weighted rainwater $\delta^{18}O$ near our cave site shows a significant negative correlation with local monthly rainfall ($r = -0.75$, $p = 0.005$; Fig. S8 and Supplemental Material), suggesting that a strong effect on $\delta^{18}O_p$ should also be encoded in speleothems. Paired stalagmite-water $\delta^{18}O$ measurements in modern Grutas del Rey Marcos samples indicate calcite precipitation in near isotopic equilibrium (Fig. S10), supporting the preservation of climate signals from rainwater to speleothem $\delta^{18}O$. Additionally, iTRACE simulated $\delta^{18}O_p$ and precipitation indicate a strong regional and local amount effect on $\delta^{18}O_p$ during the last deglaciation (Fig. S9), particularly during the May–November (MJJASON) season when regional monsoon convection is stronger. We thus propose that both rainfall amount at the cave and upstream convective rainout (Lucia et al., 2024) need to be considered when interpreting Grutas del Rey Marcos $\delta^{18}O_{ivc}$.

As proxies for local processes, $\delta^{13}C$ and $\delta^{234}U_i$ allow us to test for regional and local climate coupling (Fig. 2). Speleothem $\delta^{13}C$ reflects the relative contribution to cave waters of dissolved carbon sources in the atmosphere, soil, and carbonate bedrock (Wong and Breecker, 2015). In tropical humid regions like Central America, CO_2 from plant respiration and decomposition is the major source of dissolved carbon in soil and epikarst waters (McDermott, 2004). Thus, the resulting $\delta^{13}C$ of speleothems is largely

[1]Supplemental Material. Study area climatology, analytical methods and age modeling, modern water-calcite equilibrium fractionation, soil-speleothem carbon isotope equilibrium estimates, initial $\delta^{234}U$ as proxy of effective groundwater infiltration, isotope-enabled transient climate simulation (iTRACE), statistical analysis and data treatment, Figures S1–S15, and Tables S1–S3. Please visit https://doi.org/10.1130/GEOL.S.31795750 to access the supplemental material; contact editing@geosociety.org with any questions.

dominated by the isotope signatures of the vegetation type above the cave (Fairchild and Baker, 2012). However, soil moisture has been shown to also control $\delta^{13}C$ values in tropical soils, with changes of up to 2‰–3‰ due to rainfall variations, and influence the magnitude of biologic activity and plant respiration and, hence, the rate of soil CO_2 production (Cruz et al., 2006; Kohn, 2010; Wong and Breecker, 2015).

The $\delta^{13}C$ values in the Grutas del Rey Marcos stalagmites are consistent with a predominantly C_3 vegetation source feeding carbon to cave drip sites ($\delta^{13}C < -8$‰) throughout the entire study period (Kohn, 2010; McDermott, 2004), as expected for the tropical rainforest (Köppen classification Af) ecosystem at the site (Peel et al., 2007). As such, we favor an interpretation that $\delta^{13}C$ in our record primarily reflects changes in soil productivity and plant respiration responding to local wetness at the cave site, rather than acts as a proxy for C_3-C_4 vegetation change.

Beyond vegetation and soil activity, processes within the epikarst and cave such as prior calcite precipitation (PCP) can further influence speleothem $\delta^{13}C$ composition. For example, it has been suggested that PCP is the primary factor controlling speleothem $\delta^{13}C$ in some tropical sites, with higher values reflecting drier conditions, prolonged epikarst water residence times, and higher PCP (Patterson et al., 2023; Wright et al., 2023).

To test for PCP controls on $\delta^{13}C$ and further support the regional-local climate coupling, we use $\delta^{234}U_i$ as a proxy for local epikarst water residence time (Supplemental Material). Cave water and speleothem $\delta^{234}U_i$ are commonly inversely related to water flux and infiltration rates through the epikarst (Polyak et al., 2012; Zhou et al., 2005). ^{234}U is produced by ^{238}U alpha decay and accumulates in damaged crystal sites in the bedrock, which promotes preferential loss into solution. The equilibrium between production and removal of ^{234}U reflects changes of water flux though the epikarst and, hence, variations in infiltration (Lachniet et al., 2023; Pérez-Mejías et al., 2024). Although Grutas del Rey Marcos speleothems show relative intersample $\delta^{234}U_i$ offsets (~50‰–150‰) that likely reflect different flow paths of epikarst waters feeding each drip site, we find strong correlation between $\delta^{18}O_{ivc}$ and $\delta^{234}U_i$ ($r = 0.76$, $p < 0.0001$; Fig. S12A), supporting a regional hydrologic control on local water balance. We find a weaker correlation between $\delta^{13}C$ and $\delta^{234}U_i$ ($r = 0.31$, $p < 0.0001$; Fig. S12B), indicating a weaker, secondary effect of water residence time, and hence possible PCP, on Grutas del Rey Marcos $\delta^{13}C$. Thus, we interpret the 2‰–3‰ changes in our Grutas del Rey Marcos $\delta^{13}C$ record as a primary response of plant productivity and soil moisture to wetness conditions at the cave linked to regional and local atmospheric processes, as also supported by the positive correlation between Grutas del Rey Marcos $\delta^{18}O_{ivc}$ and $\delta^{13}C$ ($r = 0.68$, $p < 0.0001$; Fig. S13). Overall, the coherence between Grutas del Rey Marcos $\delta^{18}O_{ivc}$, $\delta^{13}C$, and $\delta^{234}U_i$ values substantiates our conclusion of a direct coupling between regional climate variability, local hydrology, and soil and vegetation productivity in the Central American highlands during the last deglaciation.

Local Hydroclimate and Environmental Sensitivity to Regional Monsoon Changes

Paleorainfall records from Mesoamerica and the Caribbean document Late Glacial and deglacial variability linked to North Atlantic ocean-atmosphere dynamics (Lachniet et al., 2013; Li et al., 2025; Lucia et al., 2024; Warken et al., 2019; Wright et al., 2023). Coherent changes in terrestrial paleoclimate were also recorded at Lake Petén Itzá in the Guatemalan lowlands (Figs. 3D–3G). Temperatures 2–5 °C cooler than today, along with marked reductions in riverine inputs and lake levels, occurred during HS1 and the YD (Correa-Metrio et al., 2012; Hodell et al., 2008), coeval with drier climate in the Maya highlands (Fig. 3).

Pollen evidence from the Lake Petén Itzá sediment record indicates abrupt vegetation turnover from the cold and arid HS1 and YD to the warm and wet BA and EH (Correa-Metrio et al., 2012; Mays et al., 2017). At Grutas del Rey Marcos, the rapid shifts in $\delta^{13}C$ show that soil and vegetation activity promptly responded to the hydroclimatic transitions between cold and dry (HS1 and YD) and warm and wet (BA and EH) intervals. Although the lack of pollen-based records prevents us from quantitatively assessing ecological changes, the persistently low $\delta^{13}C$ values (< -8‰) during HS1 and the YD suggests that vegetation at Grutas del Rey Marcos remained predominantly C_3, given that more positive stalagmite $\delta^{13}C$ values (> -8‰) would be observed following major expansion of C_4 plants (Della Libera et al., 2026; McDermott, 2004; Novello et al., 2021). This interpretation is further supported by calcite $\delta^{13}C$ values estimated at equilibrium with various carbon sources (Supplemental Material).

Our $\delta^{13}C$ data suggest that at the YD-EH transition, soil and vegetation shifted to a wet productivity mode at ca. 10,200 yr B.P., coinciding with the establishment of strong convective hydroclimate in Mesoamerica and the Caribbean, as documented in various regional speleothem records (Fig. S14). Between 10,200 and 4000 yr B.P., $\delta^{13}C$ shows higher variability relative to $\delta^{18}O_{ivc}$, potentially reflecting a weaker regional-local coupling ($\delta^{18}O_{ivc}$–$\delta^{13}C$, $r = 0.14$, $p = 0.285$) and/or enhanced $\delta^{13}C$ sensitivity to soil and karst processes during this interval.

In Lucia et al. (2024), we showed from iTRACE model outputs that AMOC slowdown and Atlantic-Caribbean SST cooling during HS1

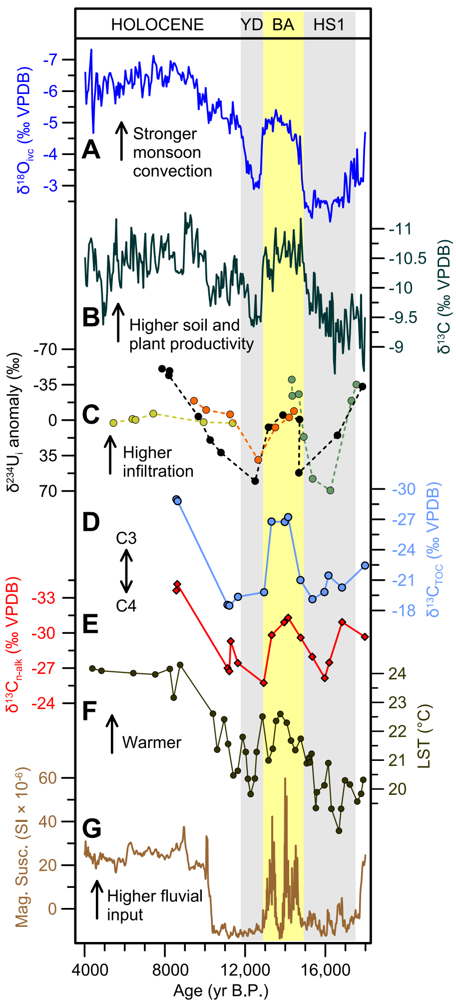

Figure 3. Coherent hydroclimate and environmental changes in northern Central America over the last deglaciation. (A) Grutas del Rey Marcos ice-volume corrected $\delta^{18}O$ ($\delta^{18}O_{ivc}$). (B) Grutas del Rey Marcos $\delta^{13}C$. (C) Grutas del Rey Marcos initial $\delta^{234}U$ anomaly ($\delta^{234}U_i$) (colored by stalagmite; see Fig. 2). (D–G) Proxy records from Lake Petén Itzá. (D, E) Total organic carbon (TOC) and alkenone (*n*-alk) $\delta^{13}C$ (Mays et al., 2017). (F) Pollen-based land surface temperature (LST) reconstruction (Correa-Metrio et al., 2012). (G) Magnetic susceptibility (Hodell et al., 2008). Vertical bars define Younger Dryas (YD), Bølling-Allerød warm period (BA), and Heinrich Stadial 1 (HS1). VPDB—Vienna Peedee belemnite.

and the YD reduced MJJASON rainfall across Central America and the Caribbean, associated with intensified sea-level pressure and zonal surface winds in the Atlantic warm pool, which in turn reduced regional atmospheric convection and moisture supply to Central America (Fig. S15). Here, correlation analysis between Grutas del Rey Marcos $\delta^{18}O_{ivc}$ and 50-yr binned iTRACE data (Table S1) and between full-resolution 1-yr iTRACE outputs with Guatemala-averaged $\delta^{18}O_p$ (Table S2) further demonstrates strong consistency of speleothem $\delta^{18}O$ with $\delta^{18}O_p$ from both the grid boxes encompassing our cave

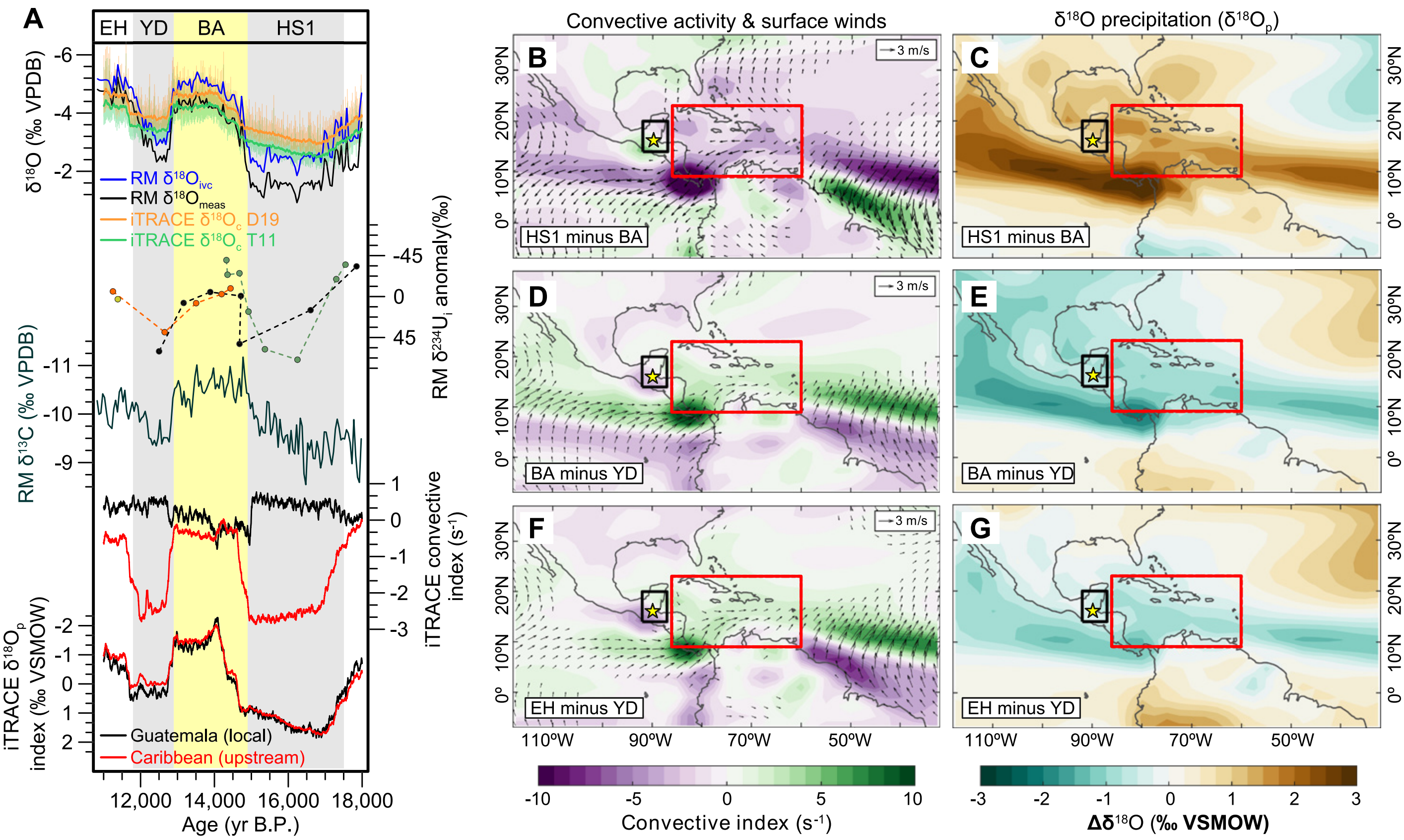

Figure 4. Proxy-model analysis of upstream-to-local hydroclimate coupling. (A) From top: Grutas del Rey Marcos ice-volume corrected δ¹⁸O ($\delta^{18}O_{ivc}$) (blue) and measured δ¹⁸O ($\delta^{18}O_{meas}$) (gray), and iTRACE δ¹⁸O of calcite ($\delta^{18}O_c$) using fractionation factors ($\alpha_{calcite\text{-}water}$) from Daëron et al. (2019) (orange) and Tremaine et al. (2011) (green); Grutas del Rey Marcos (RM) initial δ²³⁴U ($\delta^{234}U_i$) anomaly values (colored by stalagmite; see Fig. 2); Grutas del Rey Marcos δ¹³C (dark green); and iTRACE May to November (MJJASON) convective activity and δ¹⁸O of effective infiltrating precipitation ($\delta^{18}O_p$) indices over the upstream Caribbean (red) and Guatemala (black). (B–G) Maps of iTRACE MJJASON convective activity index, near-surface wind (arrows), and $\delta^{18}O_p$ anomalies for Heinrich Stadial 1 (HS1) minus Bølling-Allerød warm period (BA) (B, C), BA minus Younger Dryas (YD) (D, E), and early Holocene (EH) minus YD (F, G). Red and black boxes in B–G indicate the Caribbean and Guatemala grid boxes where iTRACE output was extracted, respectively. Yellow star marks Grutas del Rey Marcos. VPDB—Vienna Peedee belemnite: VSMOW—Vienna standard mean ocean water.

site and the upstream Caribbean (Fig. 4). Modeled δ¹⁸O of calcite ($\delta^{18}O_c$; Supplemental Material) also indicates that iTRACE robustly reproduces the temporal structure of δ¹⁸O observed in speleothems (Fig. 4A). Most importantly, our data-model analysis indicates that upstream convective changes modulate local rainfall and $\delta^{18}O_p$ more than changes in local convection, supporting the direct and coherent response of local hydroclimate to regional upstream monsoon convection changes (Figs. 4B–4G). Our results further show that speleothem δ¹⁸O from northern Central America can capture climate signals at both regional and local scales, in contrast to some tropical monsoon regions (e.g., South Asia, South America), where speleothem δ¹⁸O is largely dominated by regional monsoon signatures and decoupled from local climate dynamics.

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