communications earth & environment

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https://doi.org/10.1038/s43247-023-01124-6 OPEN

Summer insolation controlled movements of Intertropical Convergence Zone during last glacial cycle in northern South America

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A paradigm in paleoclimatology holds that shifts in the mean position of the Intertropical Convergence Zone were the dominant climatic mechanism controlling rainfall in the tropics during the last glacial period. We present a new paleo-rainfall reconstruction based on speleothem stable oxygen isotopes record from Colombia, which spans most of the last glacial cycle. The strength and positioning of the Intertropical Convergence Zone over northern South America were more strongly affected by summer insolation at high northern latitudes than by local insolation during the last glacial cycle, resulting in an antiphased relationship with climate in the Cariaco Basin. Our data also provide new insight into how orbital forcing amplified/dampened Intertropical Convergence Zone precipitation during millennial-scale events. During Greenland Stadial events, the Intertropical Convergence Zone was positioned close to the latitude of El Peñon, as expressed by more negative $\delta^{18}O$ values. Greenland Interstadial events are marked by relatively high stable oxygen isotope values and reduced rainfall in the El Peñon record, suggesting a northward withdrawal of the Intertropical Convergence Zone. During some Heinrich Stadial events, and especially Heinrich Stadial 1, the Intertropical Convergence Zone must have been displaced away from its modern location near El Peñon, as conditions were very dry at both El Peñon and Cariaco.

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Meridional movements of the Intertropical Convergence Zone (ITCZ) have produced abrupt changes in South American climate on millennial timescales, driven by changes in cross-equatorial Atlantic Sea Surface Temperature (SST) gradients[1,2]. These meridional displacements are more pronounced during abrupt transitions between extreme cold (Greenland Stadials, GS) and temperate (Greenland Interstadials, GI) climate states, which led to rapid coupled reorganizations between ocean and atmosphere[1,3–7]. A northern ITCZ position has been linked with periods of increased NH temperature during GI, resulting in increased precipitation in the Cariaco basin and dry conditions in regions of Peru and the Brazilian Amazon[8–12]. During cold GS, a displacement of the ITCZ towards the south has been inferred from proxy data, mainly during the strongest phases of Heinrich Stadials (HS)[11,12]. However, the paleoclimate records typically used for this interpretation are not directly affected by the ITCZ, as they are located far to the south, a region that is mainly influenced by the South American Monsoon System (SAMS)[11,12].

Since records located in the SAMS domain only provide indirect evidence of past ITCZ movements, precisely dated records that cover the last glacial period from regions directly affected by the ITCZ are required to resolve the large uncertainties regarding past precipitation changes in the tropical Atlantic - South America sector of the ITCZ[8–11,13,14]. For example, reconstructions of past tropical SST gradients in the Atlantic Ocean[2,4,15] and climate model simulations[1,16–18] disagree on the extent of the southward displacement of the ITCZ following the maximum ice-sheet extent in the Northern Hemisphere. Similarly, ITCZ shifts in the tropical Atlantic – South America sector, while discussed in various contexts[9–12], have not been quantified at orbital and millennial timescales. Here, we present a new paleoclimate record based on $\delta^{18}O$ values in speleothems from Colombia, located under the direct influence of the ITCZ, which documents the amplitude of the meridional displacement of the ITCZ during Greenland Stadials, Interstadials, and Heinrich events. Furthermore, we document how Northern Hemisphere summer insolation contributes to amplifying and dampening these millennial-scale events.

Our new composite speleothem $\delta^{18}O$ record comes from Caracos Cave (6°20' N, 73°45' W, Fig. 1), recording precipitation associated with the ITCZ positioning during the last 103 kyr (Fig. 1, Figs. S1–S3, and Table S1). The cave is in the El Peñon (EP) municipality, in the eastern Colombian Cordillera, at about ~2500 meters above sea level. The latitude of the study site coincides with the annual mean modern position of the ITCZ in northern South America[19,20] (Fig. 1), located to the south of the seminal paleoclimate record from the Cariaco Basin in Venezuela (~10°N) that is commonly referred to when discussing past ITCZ meridional shifts in the Atlantic-South America sector[21] (Fig. 2). The source region for the terrigenous sediments deposited in the Cariaco Basin is located between 8°53'N and 10°00'N and associated with relatively small drainage areas[21]. There is no significant contribution from the Orinoco River, the largest catchment area in the region that drains areas further inland and unlike El Peñon only has one wet season[21]. Thus, El Peñon cave is located farther south than the Cariaco Basin, which makes it a suitable site to track meridional ITCZ changes over northern South America. Precipitation in this central area of Colombia, where the EP record is located, is high during the passage of the ITCZ that occurs twice per year in response to seasonal SST changes in the tropical North and South Atlantic[19,20]. In contrast, the Cariaco basin experiences only one rainy period during boreal summer when the ITCZ reaches its northernmost position[21].

The $\delta^{18}O$ values in precipitation over the eastern Andes of Colombia are mainly controlled by the local rainfall amount associated with the ITCZ activity. Low values of $\delta^{18}O$ are associated with high local precipitation at the EP cave site and the nearby Bogotá IAEA-GNIP station in all seasons (Figs. S4–S6), with more negative values observed during boreal spring and fall at the peak of deep convection, as the ITCZ passes over the study region. Back-trajectory analyses indicate that the tropical North Atlantic is the main source of moisture in the study area in all seasons, with secondary contributions from the Amazon region and the Pacific in summer and fall, respectively (Fig. S6).

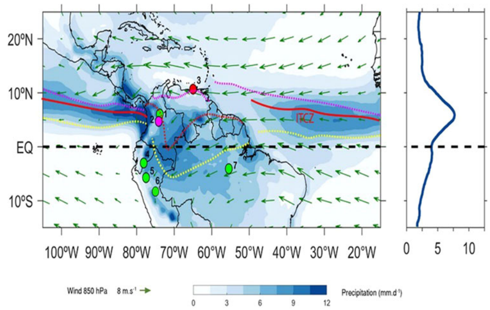

Fig. 1 Conceptual model of ITCZ shifts relative to the present-day mean position. The left panel shows a conceptual model of ITCZ shifts relative to the present-day mean position (red line); magenta dotted line indicates northern position of the ITCZ during the Glacial Interstadial (GI) events, while yellow dotted line indicates the southern position of the ITCZ during Heinrich Stadial (HS) events. Blue shading represents the present-day mean annual precipitation in mm d^{-1} from 1998 to 2017 (TRMM 3b43)[41] and the green vectors represent the present-day mean annual low-level wind field in m s^{-1} at 850 hPa from 1979 to 2018 (ERA-Interim)[42]. Pink, green, and red circles indicate lake, cave, and marine sediment locations of the records presented in the text: 1) El Peñon; 2) Fuquene[43]; 3) Cariaco[9]; 4) Santiago[11]; 5) El Diamante and Condor[28]; 6) Pacupahuain[12]; 7) Paraiso[10]. In the panel on the right, the blue line shows the zonally averaged (110 − 10°W) precipitation (mm day^{-1}) as a function of latitude from 25°N to 15°S. In both panels, the dashed black line represents the Equator.

Results

The $\delta^{18}O$ record from the EP speleothem documents substantial long-term precipitation changes in the Colombian Andes, characterized by high-amplitude swings from −2 to −10‰ (Fig. 2, Figs. S2 and S3). Throughout the Marine Isotope Stage (MIS) 5, $\delta^{18}O$ values progressively decrease until they reach a minimum during the early-mid MIS4. The middle of MIS4 to MIS3 is characterized by an abrupt change in $\delta^{18}O$ values, reaching −4‰ in the early MIS4, after which values drop to −6.4‰ at the middle of MIS3. The Last Glacial Maximum (LGM) is characterized by low $\delta^{18}O$ values in the EP record (−9.5‰), similar to the values recorded between MIS4-3 and the late Holocene (Fig. 2c). We rule out that temperature changes dominate the $\delta^{18}O$ values of rainwater, because correcting the $\delta^{18}O$ values of calcite for increased ice-volume and colder temperature during the LGM would produce an even larger reduction in the isotopic composition of precipitation by ~3‰ (see supplementary information). Hence, the highly negative $\delta^{18}O$ values in our speleothem record indicate a substantial increase in convective activity associated with the ITCZ passage over the Colombian Andes during the LGM period.

The MIS3 period is also characterized by relatively small positive and negative excursions in the isotopic values simultaneously with GI, GS, and HS events. During the Heinrich Stadial 1 (HS1) period, the El Peñon speleothems recorded an extreme dry event (the least negative $\delta^{18}O$ values of the last 100 kyr), after which values drop to eventually reach the more negative present-

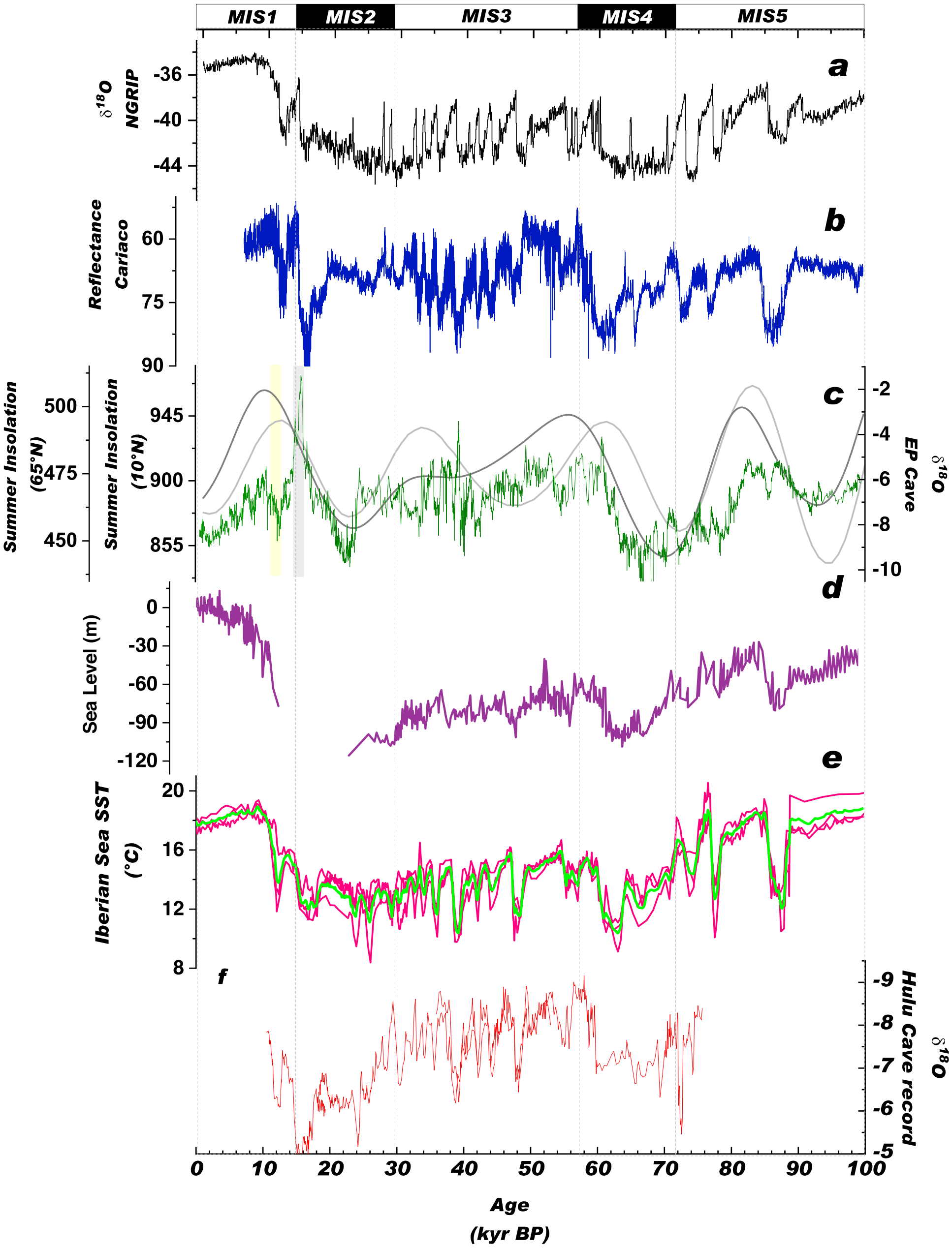

Fig. 2 Intertropical Convergence Zone in Colombia and high northern latitude teleconnections during the last ~100,000 years. a $\delta^{18}O$ from NGRIP[5]. **b** Reflectance in marine sediments from the Cariaco Basin (Venezuela)[9]. **c** $\delta^{18}O$ in speleothems of El Peñon (Colombia, this study), with summer insolation (July) for 10°N (light gray) and 65°N (dark gray)[44]; light gray bar shows HS1 event in the EP record and yellow bar shows YD. **d** Global sea level change for the last 100 kyr (purple)[23] **e** SST (°C) from ODP161-977A and MDO01-2444 cores near Iberian Peninsula (pink curve), mean SST (green line)[22]. **f** Speleothem $\delta^{18}O$ from Hulu cave (China)[33]. Thin vertical black lines delineate Marine Isotope Stages.

day values, indicating a predominant ITCZ positioning over the region (Fig. 2).

The El Peñon (EP) record at orbital timescales. The low-frequency changes seen in the EP $\delta^{18}O$ record track summer insolation at 65°N and resemble global ice volume changes, represented in the global sea level curve (Fig. 2), suggesting a close link between ITCZ rainfall in northwestern South America and climatic conditions in the extratropical Northern Hemisphere (NH). The relationship with summer insolation at 65° N is dominant throughout the last 103 kyr, with little seasonal variability in the orbital forcing (Fig. S7). There is a long-term trend towards lower $\delta^{18}O$ values from 85 to 65 kyr BP during MIS5 and into early-MIS4. During this later period, low $\delta^{18}O$ values, indicative of enhanced ITCZ precipitation, coincide with cooling in Greenland (Fig. 2)[5], culminating in ice-sheet expansion and a consequent drop in mean sea level during MIS4 (Fig. 2e). At the end of MIS4, around 65 kyr BP, both the increasing $\delta^{18}O$ values in the EP speleothem record and the decreasing reflectance values from the Cariaco Basin[9] (Fig. 2b) point to a northward shift of the ITCZ, relative to its present-day position. From 62 kyr BP to ~23 kyr BP, the EP $\delta^{18}O$ record is again characterized by a slightly decreasing trend, which suggests a gradual southward shift of the ITCZ toward Colombia, consistent with the long-term cooling of sea surface temperature (SST) in the mid-latitude North Atlantic[22] and the drop in sea level[23] during MIS3 (Fig. 2d). The early MIS2 is characterized by a decrease in $\delta^{18}O$ values, consistent with low summer insolation at 65°N, while polar ice sheets reached their maximum extent and see level was at a minimum[23] during the LGM (Fig. 2). Thus, our results suggest that the extent of the NH ice sheets exerts a significant control on the ITCZ positioning over Colombia during the last glacial period. These cold periods during MIS4 and MIS2 are characterized by low sea level and cooler SSTs in the North Atlantic (Fig. 2). Teleconnections from high northern latitudes to the tropics were likely modulated via coupled ocean-atmosphere feedbacks in the mid-latitudes that ultimately led to ITCZ displacements to the south of the EP site[17,24], indicating that high northern latitude summer insolation was a more effective forcing of ITCZ location than local insolation over South America (Fig. 2).

Our speleothem record also highlights that the forcings affecting long-term changes in ITCZ rainfall are distinct from those operating over the subtropical regions of the SASM domain, although a more southerly position of the ITCZ is conducive for the strengthening of the SAMS[25]. One of the most striking differences between SASM and ITCZ forcings is that the ITCZ location and intensity appear to follow high-latitude NH climate, rather than low-latitude insolation during the glacial period. Local summer insolation is positively correlated with EP $\delta^{18}O$ values, which is physically implausible as increased summer insolation should enhance convective activity and lead to lower $\delta^{18}O$ values. Yet at the EP site, we observe the exact opposite, indicating that local insolation cannot serve as controlling mechanism for precipitation changes at orbital timescales. Speleothem records located in southern Brazil1[26–28], on the other hand, indicate a clear pacing by southern hemisphere insolation for all precessional cycles, as differential heating of the continental land mass increases the near-surface moist static energy that drives convection.

High-latitude NH summer insolation influences extratropical climate by changing the heat content and sea ice extent of the North Atlantic, which controls the SST gradient between the tropical and extratropical Atlantic[16,17,22]. The relationship between our speleothem isotope record and local insolation is weak, which implies a dominant control via extratropical climate, not only over the EP site, but also in other areas directly impacted by the ITCZ over northern South America[9–11].

The influence of glacial boundary conditions on tropical convective rainfall is a result of NH ice sheet volume, its influence on sea level, and effects on trade winds, meridional SST gradients, and ITCZ displacements[1,9,16,17,22]. Glacial conditions at high northern latitudes are transmitted to the tropics through strengthened north-easterly trades over the North Atlantic, which increase the oceanic latent heat flux that in turn leads to a progressive cooling of SSTs over the subtropical and tropical North Atlantic (Fig. 2)[29]. The dynamic mechanism linking this cooling with latitudinal ITCZ displacements involves coupled feedbacks between wind, evaporation, and SST (known as WES feedback) in the region dominated by north-easterly trades[24,29]. It is consistent with the progression of cold SST anomalies to the tropics during MIS2, resulting in a southward displacement and intensification of ITCZ-related rainfall at El Peñon (Fig. 2). Therefore, stronger northeasterlies enhance moisture transport from the Caribbean and tropical Atlantic and the precipitation in central Colombia, as reflected by the very negative $\delta^{18}O$ values in the EP speleothem record during colder periods in the NH (Fig. 2).

Insolation at high latitudes is a critical control knob for ITCZ location and precipitation amount in the Atlantic - South America sector throughout the last glacial period and can explain the negative $\delta^{18}O$ values at EP during MIS4 and the LGM. Both periods feature southward displacements of the ITCZ toward EP, as suggested by the antiphased relationship with Cariaco (Fig. 2). However, additional work is required to constrain to what extent the rainfall distribution was also affected by a meridional contraction and expansion of the convective belt[30]. In addition, the regional response of the zonal Walker circulation to high-latitude NH forcing also requires further analysis as it can also significantly modulates ITCZ rainfall over the equatorial western Atlantic Ocean as observed over eastern equatorial South America[18,30].

ITCZ shifts on millennial timescales. The EP record is punctuated by a sequence of millennial-scale events, recording abrupt isotopic excursions of about 2‰ (Figs. 3 and 4). The EP record shows a striking relationship with the GI, GS and HS events[5] (Figs. 3 and 4). The GS events are marked by more negative $\delta^{18}O$ values in the EP speleothems, consistent with the temperature decrease observed in the Greenland ice core record (NGRIP INTIMATE stratigraphy)[5]. This implies that the ITCZ positioning was closer to El Peñon during GS events. In comparison, the GI events are marked by relatively high $\delta^{18}O$ values in the EP record, again consistent with high $\delta^{18}O$ values in Greenland, and interpreted as reflecting a northward shift of the ITCZ relative to the EP cave site. The GI events are thus associated with drier and wetter conditions in central Colombia and the Cariaco Basin, respectively (Fig. 3 and 4). This shift in the center of tropical convection occurs at the approximate time of the peak increase in temperature during the onset of Greenland Interstadials, as indicated by Rasmussen et al.[5]. We have identified most of GI events in the EP speleothem record in comparison with NGRIP ice core, although a time offset of some centuries is observed (Fig. S8 and Table S1). On the other hand, these differences in the time of GIs are in general within age uncertainties of the NGRIP record.

While cold NH conditions tend to lead to a southward displacement of the ITCZ and strong convection over the EP site, the amplitude of NH cooling will ultimately determine how far to the south the ITCZ may be displaced. Very intense NH cooling can thus shift the ITCZ to an even more southern location, resulting in drier conditions at El Peñon. This was likely the case during HS events HS1, HS2, HS4, and HS6, when both El Peñon and Cariaco Basin experienced drier conditions (Figs. 2 and 3). Therefore, even though GS and HS events are both characterized by a cold NH, the hydroclimatic response at El Peñon during these two types of events is different, as reported in previous studies with speleothems from the SAMS domain in eastern Brazil[31,32].

The meridional movements of the ITCZ during millennial-scale HS, GS, and GI events[12,25,27] strongly affect the SAMS. For instance, ITCZ displacements to the south of its modern location near EP lead to a strong SAMS regime[25,27,28]. Indeed, the highest $\delta^{18}O$ values in the EP record are found during HS1 between 17 and 15 kyr BP (~2‰) and denote a large departure of about ~7‰ relative to the minimum values recorded during the LGM in the $\delta^{18}O$ EP speleothem record (Fig. 2), consistent with highest reflectance values observed in the Cariaco record[9]. This finding documents a collapse of rainfall in the northern sector of the ITCZ due to the displacement of the convective activity to the southern sector.

In addition, the EP speleothem record also documents a varying strength of its response to the HS and the Younger Dryas (YD) events, which appears to be linked to differences in the magnitude of the NH temperature change during these events, affecting the displacement of the ITCZ over northern South America to a varying degree. Because the El Peñon cave site is located at the core latitude of the modern ITCZ, it is very likely that the $\delta^{18}O$ excursions in our speleothems record changes in

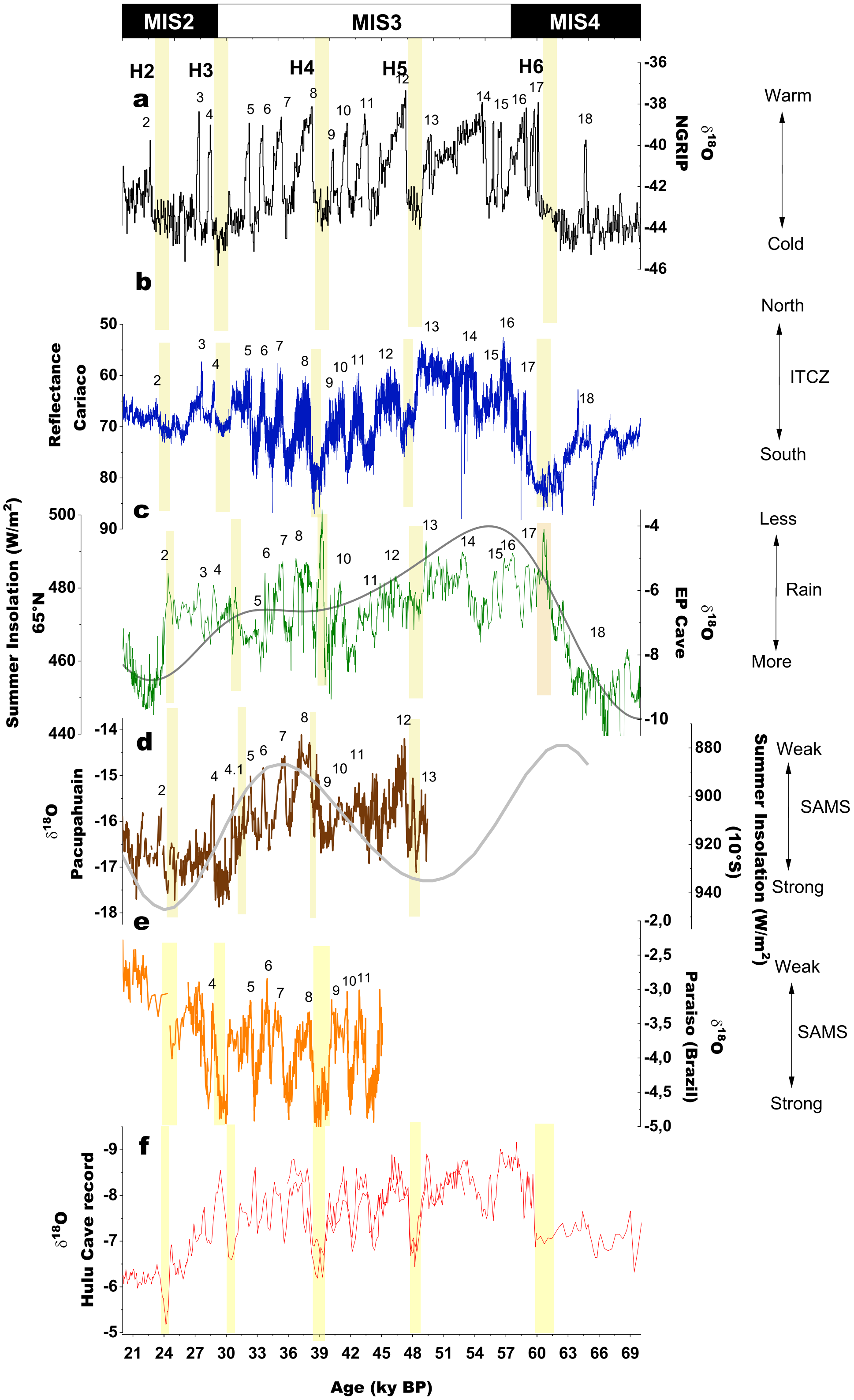

Fig. 3 Millennial-scale events during the last glacial period from 70 to 20 ky BP in the South American ITCZ and monsoon sector. Black numbers refer to GI events, yellow bars denote HS events. a NGRIP $\delta^{18}O$ record[5]. **b** Reflectance in sediment cores from the Cariaco Basin (Venezuela)[9]. **c** Speleothem $\delta^{18}O$ from El Peñon (Colombia) with insolation curve for July at 65°N[44]. **d** Speleothem $\delta^{18}O$ from Pacupahuain Cave (central Peru)[12] and summer insolation curve in November at 10°S[44]. **e** Speleothem $\delta^{18}O$ from Paraiso Cave, eastern Amazon (Brazil)[10]. **f** Speleothem $\delta^{18}O$ from Hulu cave (China)[33].

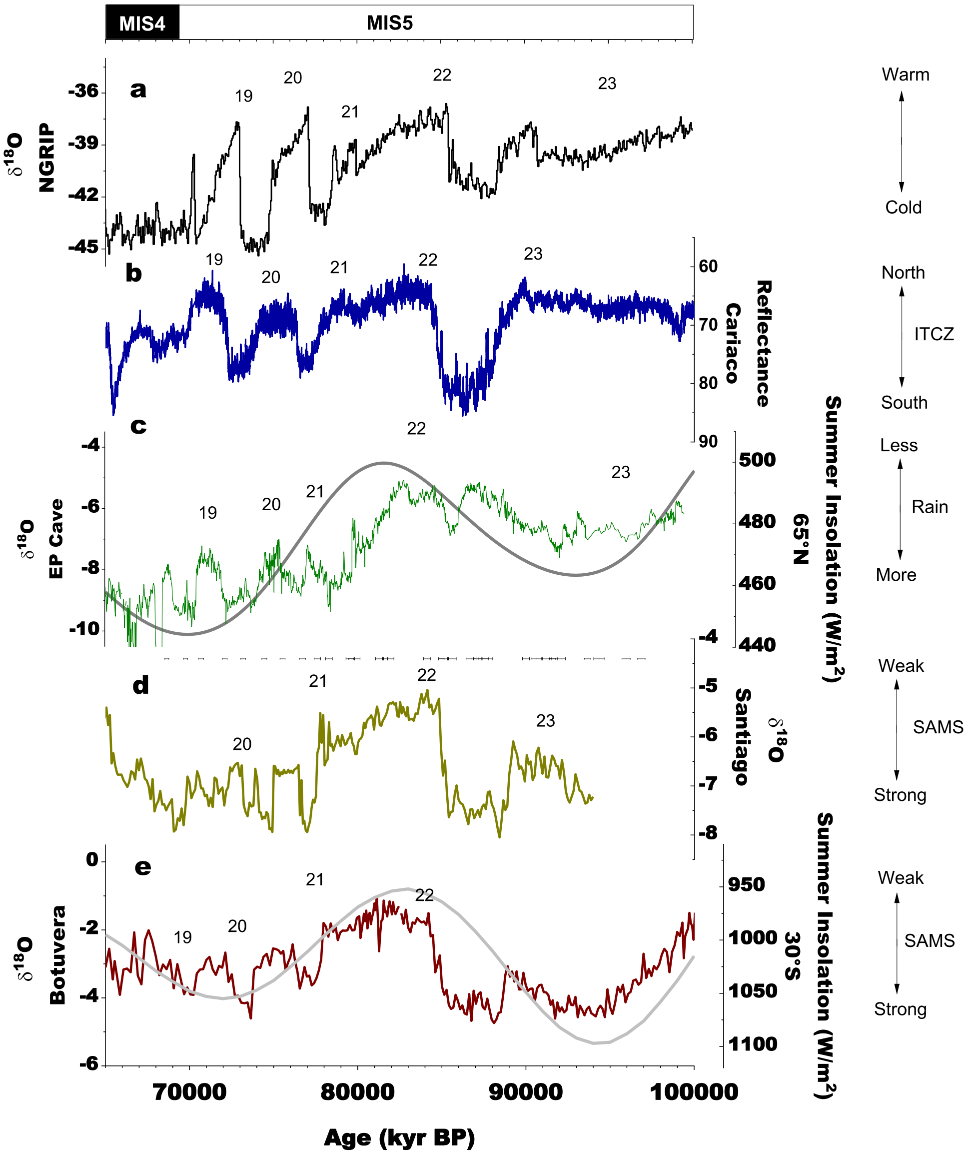

Fig. 4 Millennial-scale events during the last glacial period from 100 to 63 ky BP in the South American ITCZ and monsoon sector. Black numbers refer to GI events. a NGRIP δ18O record[5]. **b** Reflectance in sediment cores from the Cariaco Basin (Venezuela)[9]. **c** δ18O of El Peñon and summer insolation (July–August) for 65°N[44]. **d** Speleothem δ18O from Santiago Cave (Ecuador)[11]. **e** Speleothem δ18O from Botuverá Cave (Brazil)[27] and summer insolation (February) for 30°S[44].

the latitude of its mean position through time. Indeed, the high δ18O values observed during HS6 and HS1 indicate an in-phase relationship with climate conditions in Cariaco, which suggests a shift of the ITCZ to the south of El Peñon. In comparison, the HS3, HS2, and the YD events are characterized by approximately neutral climate conditions in ITCZ latitude, relative to its modern position (Figs. 2 and 3).

The comparison of the δ18O records from EP, Hulu cave[33], and NGRIP[5] (INTIMATE chronology) documents the high temporal coherence among the three records during the GI, GS, and HS events (Figs. 2 and 3). This is especially evident during MIS3 (Fig. 3). The occurrence of GI events in the EP record is consistent (within error margins) with the dates derived from the INTIMATE chronology produced for NGRIP[5] (Fig. 2). All GI events from 23 to 2, during the MIS5, MIS4, and MIS3 periods, are recognized in our EP record, except for GI 9. The HS events are also clearly expressed in the EP δ18O record, especially HS6, HS4, HS2 and HS1, and their timing is consistent with the GS chronology suggested by Rasmussen et al. (2014)[5]. (Figs. 3 and 4).

The GI periods on the other hand are associated with higher δ18O values at EP, which suggests a more distant location of the ITCZ, northward of EP, given that southern monsoon records also indicate prevailing dry conditions over the SASM domain[10–12,27–35], while conditions were wet in the Cariaco Basin (10° N)[9]. In addition, the antiphased pattern observed between Cariaco and EP during most GI periods (Fig. 4) indicates that the joint analysis of both records allows reconstructing the positioning of the ITCZ during these millennial-scale events. These specific GI periods are characterized by an ITCZ to the north of EP, resulting in reduced rainfall in our study area and dry conditions in regions to the south of the equator, which are under the domain of the SASM. Hence, records from EP (Colombia), Santiago (Ecuador)[11], Pacupahuain (Peru)[12], and Paraiso (Brazil)[10] present in-phase relationships.

During GS periods, a similar antiphased relationship between EP and Cariaco is apparent—this time with very negative δ18O values observed in the EP speleothem record, suggesting a wetter climate in Central Colombia (Figs. 3 and 4). At the same time, drier conditions prevailed over the Cariaco Basin[9], due to a displacement of the ITCZ towards the south. This suggests that the mean ITCZ position was situated close to the cave site, as otherwise less negative isotopic values would be expected (Fig. 1b). Anomalously negative $\delta^{18}O$ values are also observed during GS periods in speleothem records located further to the south in Peru[12,28], Ecuador[11], and Brazil[27,28,31,32,34], suggesting an enhanced SASM.

Our results support the idea that strong teleconnections existed between the ITCZ in the Atlantic-South America sector and the high-latitude North Atlantic during the last glacial period. The increase in NH ice volume led to a cooling in the North Atlantic, inducing a meridional temperature and pressure gradient, which in turn resulted in stronger north-easterly trade winds in the NH subtropics, thereby enhancing latent heat release from the surface ocean and inducing further oceanic cooling. This positive wind-evaporation-sea surface temperature (WES)[24,30], feedbacks further amplified the anomalous cross-equatorial meridional SST gradient and enhanced the southward displacement of the ITCZ. Our findings reveal long periods of strong convective activity over the ITCZ region that coincides with MIS4, the LGM, and the late Holocene. Finally, the similarities and differences between equatorial and subtropical isotope records in South America suggest that a southern ITCZ can enhance the SASM when superimposed on tropical insolation forcing. This is most evident during high-amplitude precessional cycles over subtropical South America.

Methods

Cave location and samples. Speleothems CAR7, CAR12, CAR21 and CAR26 (Fig. S2a and S2b) were collected from Caracos Cave (6°20' N, 73°45' W; 2500 masl), which is in the central-eastern portion of Colombia, in the Andean region (Fig. 1). The cave has a small entrance and is overlain by the Lower Cretaceous Rosablanca Formation, which primarily consists of gray limestones, dolomites and shales with sandstones in the upper part[36,37]. The samples were collected at ~1500 m from the cave entrance, in a lower chamber, where the relative humidity is near 100%. The samples were cut longitudinally along the central growth axis and polished to clearly expose the growth laminae.

Chronology. The stalagmites were dated by U-Th method at the Isotope Laboratory of the University of Minnesota (USA) and Xi'an Jiaotong University (China). A total of 97 powdered carbonate samples (~100 mg) from the stalagmites were drilled using a carbide dental drill following stratigraphic horizons (see results in the Data File S1). To separate uranium and thorium, the chemical procedure described in Cheng et al.[38,39] was applied. After the separation of uranium and thorium each sample was dried and diluted for injection into the spectrometer. The analysis was performed using a multi-collector inductively coupled plasma mass spectrometry technique in a MC-ICP-MS, Thermo-Finnigan NEPTUNE, according to the techniques described in Cheng et al.[39].

To produce a composite of the El Peñon isotope speleothem record we use the *Iscam* algorithm from[40]. The *Iscam* algorithm uses a Monte Carlo approach on absolute age determinations to find the best correlation between time series. Age uncertainties at 68%, 95%, and 99% significance levels are obtained from an evaluation of a set of 2000 first-order autoregressive processes (AR1) for each record, which have the same statistical characteristics as the individual records. This method allows significantly reducing the age uncertainty within the overlapping periods and it can be tested if the signal of interest is indeed similar in all the records. The output from *Iscam* integrating the isotope records from CAR12, 21, and 26 is presented in Fig. S1b.

In general, the chronology of the composite derived from CAR12, 21, and 26 is very similar to the chronology constructed based on linear interpolation between ages (Fig. S1b). Both age models (linear and *Iscam* algorithm) present the same timing of isotopic excursions at secular and longer timescales. In addition, speleothems from the same cave often present significant discrepancies in terms of absolute isotopic values. Such differences can be observed in $\delta^{18}O$ between CAR12 and CAR21 (Fig. S1a). The *Iscam* algorithm corrects for such offsets by adjusting the values of one record based on the difference in their means during the overlapping time interval (Fig. S1b).

Stable isotope analysis. For carbonate speleothems, the oxygen isotope ratios are expressed in δ notation, the per mil deviation from the Vienna Pee Dee Belemnite (VPDB) standard. In total 4110 samples (Supplementary Data 1), each containing ~100 µg of powder, were drilled from the speleothems and analyzed with an on-line, automated, carbonate preparation system linked to a Thermo-Finnigan Delta Plus Advantage at the Centro de Pesquisas Geocronológicas of the Geosciences Institute of the University of Sao Paulo (CPGeo-IGc-USP). The speleothem reproducibility of standard materials is 0.1‰ for $\delta^{18}O$. The mean temporal resolution of the $\delta^{18}O$ speleothem record is ~20 years.

Data availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. https://figshare.com/articles/dataset/Ramirez_et_al_xlsx/24438010.

Received: 16 September 2022; Accepted: 15 November 2023;
Published online: 21 December 2023

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Acknowledgements

We thank Alyne Barros for her support during the stable isotope data acquisition at the University of São Paulo. We are grateful to Jesús Fernández, Juan Carlos Silva, Jean-Sébastien Moquet, Leda Zogbi, and Carlos Grohmann for assistance in the field during the collection of stalagmite samples and Yolanda Luiz Rivera for collecting rainwater samples at El Peñon in Colombia. This work was supported by the São Paulo Research Foundation (FAPESP) grants 2017/50085-3 and 2022/08359-7 to FWC. We also acknowledge the grants FAPESP 2016/15807-5 to V.F.N. and the US National Science Foundation (NSF) AGS-1303828 and OISE-1743738 to M.V., DFG grants to VFN, National Natural Science Foundation of China: grants NSFC 41888101 to H.C., NSFC 42261144753 to H.Z., NSF- AGS 1602962 to C.I.W. and 1103403 to R.L.E. and H.C., as well as a Brazil CAPES PhD fellowship to V.M.R. VRM and FWC were additionally funded by the ERC project LAST JOURNEY (ERC_Adv_834514). C.M.C. acknowledges the financial support from FAPESP (grants 2018/15123-4 and 2019/24349-9), CAPES (grant 8881.712022/2022) and CNPq 312458/2020-7). ET is funded by a Marie Skłodowska-Curie Action (ITHACA-101024389). We thank Henry Hooghiemstra and Suzette Flantua for providing the pollen assemblage record from Fuquene (Colombia) and Igor Martins Venâncio for their comments and suggestions. We very much appreciate the efforts from the editor, Dr. Yama Dixit, and comments by Dr. Nick Scroxton and two anonymous referees that helped to improve the manuscript.

Author contributions

F.W.C., N.M.S., V.M.R. and J.P.B. were responsible for the field work. F.W.C. and V.M.R. conceived, designed the study and paper. V.M.R. performed the isotope analyses. A.A., M.V., N.M.S., E.T. and V.M.R. analyzed the rainfall data and isotopic data from stations in Colombia. V.M.R. and F.W.C. prepared the manuscript with direct help from M.V., N.M.S., V.N., J.P.B., C.M.C., M.D., and Y.A.B. N.M.S., W.J.D. V.N., H.W.C., H.Z., R.L.E. and assisted with the 230Th/U analyses. J.L.C. assisted with statistical analysis.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-023-01124-6.

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Peer review information *Communications Earth & Environment* thanks Nick Scroxton and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Yama Dixit and Aliénor Lavergne.