# Persistent link between Caribbean precipitation and Atlantic Ocean circulation during the Last Glacial revealed by a speleothem record from Puerto Rico

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**Key Points:**

- Puerto Rican speleothem record documents multi-decadal to millennial-scale precipitation variability between 46.2 and 15.4 ka BP
- Climate proxies show a distinct rainfall response to abrupt North Atlantic climate change including Heinrich and Dansgaard/Oeschger events
- Compilation of regional precipitation records allows to reconstruct past changes in ITCZ patterns in the western tropical Atlantic

**Abstract**

The high sensitivity of tropical hydro-climate to the mean position of the intertropical convergence zone (ITCZ) at different time scales is well known. However, recent research suggests a more complex behaviour of the northern hemispheric tropical rain belts in the western tropical Atlantic. Here we present a precisely dated speleothem multi-proxy record from a well-monitored cave from Puerto Rico, covering the period between 46.2 and 15.4 ka BP in unprecedented resolution. This allows the investigation of multi-decadal to millennial-scale climate variability. The proxy records document a pronounced response of regional rainfall to abrupt centennial to millennial-scale climatic excursions in the North Atlantic across the Last Glacial (i.e., Heinrich Stadials and Dansgaard/Oeschger events). In particular, we observe a strong agreement between the speleothem proxy data and the strength of the Atlantic meridional overturning circulation, supporting a persistent link of regional precipitation to oceanic forcing. Spectral analysis suggests that multi-decadal to centennial variability persisted in the regional hydro-climate not only during stadial and interstadial conditions, but also during the Last Glacial Maximum, supporting the hypothesis that the Atlantic low-latitude regions respond to internal modes of climate variability on these time scales regardless of the global climate state. The compilation with other paleo-precipitation records enables the reconstruction of past changes in position, strength and extent of the ITCZ in the western tropical Atlantic in response to millennial and orbital global climate change.

**Plain Language Summary**

It is important to understand how rainfall in the western tropical Atlantic might change under a changing climate to ensure the water supply for millions of people. However, it is not well understood, how past rainfall varied in the past thousands of years, especially during the last glacial period, a time of strong climate variability and abrupt climate changes. Here, we use a stalagmite from Puerto Rico to create a new record of past changes in rainfall in this region. For this purpose, we analysed proxy data which reveal a series of wet and dry periods during the Last Glacial corresponding to rapid global climate shifts. Our rainfall-sensitive stalagmite record is able to detect changes in the tropical rainbelt on various timescales, and shows that this variability in rainfall is closely connected to changes in the strength of the ocean circulation. This suggests that the link between the ocean and the atmosphere is more stable than previously assumed. Lastly, comparison of our record with other rainfall-sensitive records from Central America and the northern Caribbean allows a more detailed reconstruction of the spatial and temporal changes of the western tropical Atlantic rainbelt.

## 1 Introduction

The evolution of precipitation patterns during glacial periods in the tropical Atlantic is a result of competing internal vs. external forcing mechanisms (Lachniet et al., 2009; Schmidt et al., 2004). Our increased understanding of the underlying controls of past precipitation changes provides valuable insight into the climate dynamics involved and more precise boundary conditions for climate models. Last Glacial precipitation reconstructions from the tropical Atlantic have documented pronounced rainfall variability on millennial to centennial timescales including periods of abrupt climate change (Deplazes et al., 2013; Hodell et al., 2008; Peterson et al., 2000). Many of these observations were thought to reflect variable positions of the Intertropical Convergence Zone (ITCZ) in response to changes in cross-equatorial temperature gradients (e.g., Broccoli et al. (2006); Schmidt and Spero (2011); Stríkis et al. (2015)). In particular, prominent millennial-scale alternations, such as Dansgaard/Oeschger (D/O) oscillations and Heinrich events were associated with a pronounced climate response of warm (interstadial) and cold (stadial) periods in the Northern Hemisphere. The generalized assumption is that latitudinal displacements of the ITCZ result from varying strengths of the Atlantic Meridional Overturning Circulation (AMOC) (Henry et al., 2016; Lynch-Stieglitz et al., 2014; McManus et al., 2004). A weaker AMOC coincides with a reduced northward heat transport, a higher cross-equatorial sea-surface temperature (SST) gradient and, consequently, drier conditions in the tropical Northern Hemisphere (Broccoli et al., 2006; Clark et al., 2001; Waelbroeck et al., 2018).

However, the details of the spatio-temporal structure and evolution of the Atlantic ITCZ are still not well understood. For instance, the magnitude and extent of its latitudinal movements, and the role of external forcing, such as insolation, in modulating this variability especially during pronounced and/or abrupt climate change events during glacial periods, such as Heinrich and D/O events, remain unclear. Especially the influence of ocean circulation on changes in Last Glacial tropical rainfall has been subject of recent debates (Burckel et al., 2015; Henry et al., 2016; Roberts & Hopcroft, 2020; Them Il et al., 2015; Waelbroeck et al., 2018). In addition, there is now increasing evidence from both modelling studies as well as proxy records that the simple explanation of a north-south-shifting ITCZ is not adequate to explain the observed rainfall patterns, especially because the most northern shifts of the Atlantic ITCZ are linked to a complex set of forcings and feedbacks on different timescales (Asmerom et al., 2020; Lachniet et al., 2009; Oster et al., 2019; Roberts & Hopcroft, 2020; Singarayer et al., 2017). For instance, a model study by Singarayer et al. (2017) demonstrated that, while asymmetric extratropical forcing (ice sheets, freshwater hosing) generally gives rise to meridional shifts in the zonal mean tropical rain belt, orbital variations produce an expansion/contraction of the global zonal mean.

Speleothem stable isotope records revealed a pronounced multi-decadal to millennial precipitation dynamic in the western tropical Atlantic (Asmerom et al., 2020; Fensterer et al., 2012; Fensterer et al., 2013; Medina-Elizalde et al., 2010). In a recent study of a 12 ka-long Guatemalan speleothem $\delta^{18}O$ record, Winter et al. (2020) suggested that the evolution of Central American rainfall in the early Holocene was closely related to Caribbean SSTs manifested as a basin-scale response to a more vigorous AMOC. Medina-Elizalde et al. (2017) presented a 3.3 ka-long, sub-decadally resolved speleothem $\delta^{18}O$ record with pronounced multi-decadal variability between 26 and 24 ka BP similar to today, suggesting that the Atlantic low-latitude regions respond to internal modes of climate variability on multi-decadal to centennial scales regardless of the global climate state.

Here we present a stable oxygen isotope record obtained from a speleothem from Larga Cave, Puerto Rico, spanning the time interval from 46.2 to 15.4 ka. Our interpretation of the speleothem oxygen isotopes is supported by trace element (Mg/Ca, Sr/Ca, Ba/Ca) data and $\delta^{13}C$ values, which have been shown to constitute a valuable tool to identify potential hydrological processes or even reconstructing past precipitation patterns (Arienzo et al., 2017; Cruz et al., 2007; Warken et al., 2018). Consequently, our multi-proxy data enables the investigation of changes in the hydrological regime in the western tropical Atlantic during major climate shifts up to sub-decadal resolution.

# 2 Materials and Methods

## 2.1 Site description

Larga Cave is located in the north-central karst region of Puerto Rico (18°19’N 66°48’W, Figure 1) at an elevation of about 350 m a.s.l. Since the region of the Greater Antilles is dominated by sea surface, ocean-atmosphere coupling is of great importance for the climate in the Caribbean which nowadays leads to comparatively small temperature variations and can therefore be classified as predominantly maritime (Granger, 1985; Schellekens et al., 2004). In the catchment of the cave, the mean annual air temperature today is 22.5°C, and annual rainfall amount is high with a mean of 2,200mm (Vieten et al., 2018a). According to the observational record from 1980 to 2020 of the closest meteorological station Arecibo observatory (18°21’N 66°45’W, 323m a.s.l, data from http://xmacis.rcc-acis.org/), mean annual air temperature ranges from ca. 20 to 24°C and rainfall amount varies between 600 and 2,700mm. The area above the cave is covered by dense tropical forest with a thin soil cover that is nearly absent on the higher elevated and exposed locations.

Inside Larga Cave, cave air parameters and various drip sites have been monitored since 2012, showing a constant temperature and relative humidity (rH) regime in the main passage with 22.5 ± 0.2°C and close to 100%, respectively. The cave air $pCO_2$ variability is dictated by the seasonal cave ventilation with a well-ventilated winter mode (low $pCO_2$ values) and a near-stagnant summer mode (high $pCO_2$ values) due to seasonal temperature differences in- and outside the cave (Vieten et al., 2016). The rainfall $\delta^{18}O$ values at the site show a seasonal pattern with more negative (-3 to -5‰ (VSMOW)) values occurring during the wet summer season and higher values (-1 to -2‰ (VSMOW)) in the dry winter season.

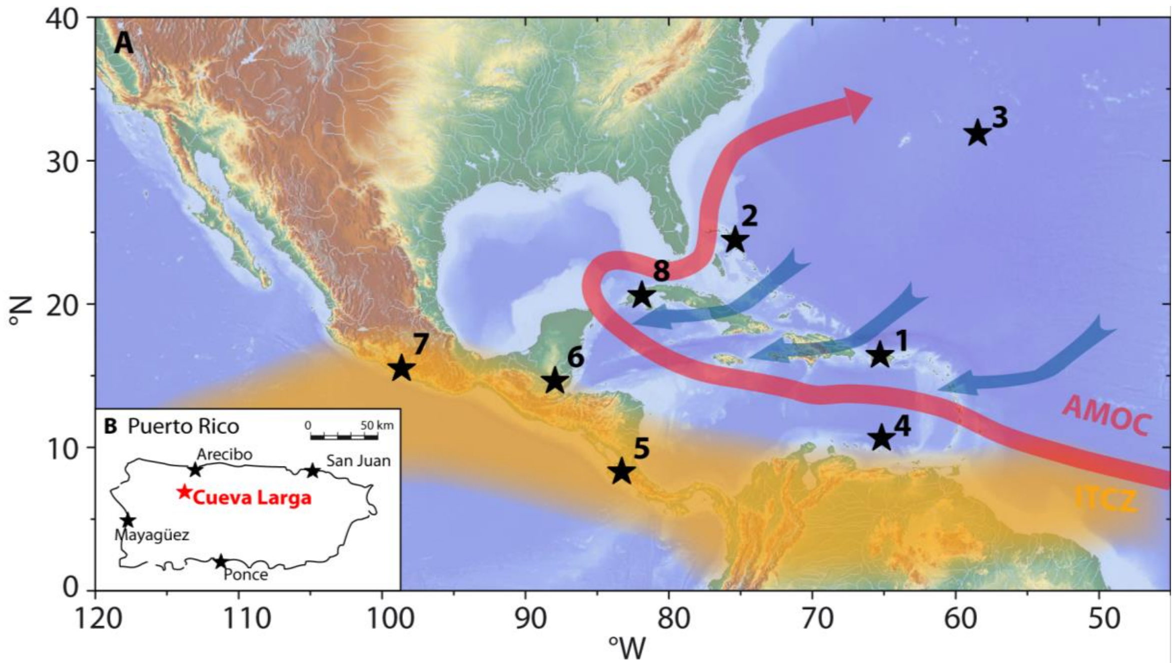


**Figure 1 (A) Relevant climatology and sites: (1) Larga Cave (Puerto Rico, this study); (2) Abaco Island (2017; Arienzo et al., 2015); (3) Bermuda Rise (Böhm et al., 2015; Henry et al., 2016; Lippold et al., 2009; McManus et al., 2004); (4) Cariaco Basin (Deplazes et al., 2013; Peterson et al., 2000); (5) Terciopelo Cave (Lachniet et al., 2009); (6) Lake Petén Itzá (Correa-Metrio et al., 2012; Escobar et al., 2012; Hodell et al., 2008); (7) Juxtlahuaca Cave (Lachniet et al., 2013); (8) Santo Tomas Cave (Warken et al., 2019). The yellow shaded area indicates the spatial range of the seasonal migration of the mean position of the ITCZ. The red arrow shows the warm surface current through the Caribbean basin as a part of the AMOC. The blue arrows indicate the mean trajectories of the easterly trade winds and convective systems transporting moisture into the western tropical Atlantic. (B) Location of Larga Cave in north-central Puerto Rico.**

The seasonal variations in the $\delta^{18}O$ values of rainwater are smoothed by the soil and karst system acting as a low-pass filter, resulting in a well-mixed seepage water reservoir and a transmission time of atmospheric signals of at least several months to a few years (Vieten et al., 2018a; Vieten et al., 2018b). Therefore, the isotopic composition of drip waters in Larga Cave is relatively constant over the year in most drip sites with a mean of -2.6 ± 0.2‰ (VSMOW) during the monitoring period (2012 – 2019). This value corresponds to the weighted annual mean of the $\delta^{18}O$ valus of -2.5 ± 0.1‰ (VSMOW) (Vieten et al., 2018b). The mean $\delta^{18}O$ value of recently precipitated calcite at different drip sites is -3.1 ± 0.1‰ (VPDB), which indicates that recent calcite precipitation in the cave is near isotopic equilibrium (Hansen et al., 2019; Tremaine et al., 2011). The elemental composition of the drip waters also lacks a clear seasonal cycle with rather stable values for the molar Sr/Ca (0.8 – 1.0 (x $10^{-3}$)) and Mg/Ca ratios (20 – 30 (x $10^{-3}$)).

## 2.2 Stalagmite PR-LA-1

Speleothem PR-LA-1 was collected lying on the cave floor in the main passage (Figure S 1), where the rock overburden is approximately 40 – 80 m. The specimen has a total length of 1.85 m and was removed in five pieces (L1A to L1E, from top to bottom) with individual lengths between 0.25 and 0.55 m (Figure 2). Stalagmite PR-LA-1 consists of whitish and translucent calcite, which in most parts exhibits typical convex-shaped lamination. In the bottom part of subsample L1C, between 110 and 118 cm distance from top (dft), the lamination appears more irregular with a concave “dip” in the middle of the stalagmite (Figure 2). In segment L1E, the part closest to the basis of the stalagmite, several brownish layers indicate detrital inclusions. Slabs were prepared along the growth axis of each segment, which were subsequently used for $^{230}Th/U$-dating and stable isotope and trace element analyses.

## 2.3 Analytical procedures

Samples for $^{230}Th/U$-dating were cut along the growth axis using a band saw. Analyses of U and Th isotopes was conducted using a Nu Plasma MC-ICP-MS at the Max Planck Institute for Chemistry (MPIC), Mainz. Chemical preparation of the samples and analytical methods at the MPIC followed Yang et al. (2015) and Obert et al. (2016). All ages and activity ratios were calculated using the half-lives reported by Cheng et al. (2000) in order to preserve comparability with previous publications. Age uncertainties are quoted at the 2σ-level and do not include half-life uncertainties.

Stable isotope samples were drilled with a spatial resolution of 1 mm and analysed at the University of Innsbruck using a ThermoFisher Delta V isotope ratio mass spectrometer equipped with a Gasbench II (Spötl, 2011). Raw data were calibrated against NBS19, and δ-values are reported relative to Vienna Pee Dee Belemnite (VPDB) standard. Long-term precision of the $\delta^{13}C$ and $\delta^{18}O$ values, estimated as the 1σ-standard deviation of replicate analyses, is 0.06 and 0.08‰, respectively (Spötl, 2011; Spötl & Vennemann, 2003). Element/Calcium ratios of the speleothem were measured by laser ablation ICPMS at the MPIC following the procedure of Jochum et al. (2012) and Yang et al. (2015), using the high-resolution sector-field ICPMS Thermo Element2, combined with the New Wave UP-213 Nd:YAG laser ablation system. The analysed elements were measured at low mass resolution ($m/\Delta m \sim 300$) and are reported to be interference-free (Jochum et al., 2012). Trace element line scans were performed along the growth axis of PR-LA-1 using a spot size of 110 µm and a scan speed of 10 µm/s, resulting in a spatial resolution of 7 µm per data point (scan time 0.7 s). To avoid potential surface contamination, the scan path was pre-ablated with a scan speed of 80 µm/s. In order to account for matrix effects, data reduction was carried out by calculating the blank corrected count rates of the analysed isotopes relative to the simultaneously measured internal standard $^{43}Ca$. The reference glass NIST SRM 612 was used for external calibration of the trace element analyses (Jochum et al., 2012; Jochum et al., 2011). Element/Calcium ratios are given in molar units.

### 2.4 Numerical methods

Correlation analysis was performed with a test statistic based on Pearson's product moment correlation coefficient r (x,y) following a t-distribution with length(x)-2 degrees of freedom. Reported correlation coefficients are all significant at the 0.05 level. Element/Ca ratios were interpolated to the resolution of the stable isotope records for the calculation of the correlation coefficients. The interpretation of the proxy signals is supported by using I-STAL, a model for interpreting Mg/Ca, Sr/Ca and Ba/Ca ratios in speleothems (Stoll et al., 2012), and ISOLUTION 1.0, an isotope evolution model describing the stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope values of speleothems (Deininger & Scholz, 2019). Spectral analysis was performed using REDFIT (Schulz & Mudelsee, 2002).

# 3 Results

## 3.1 Chronology of PR-LA-1

In total, 74 $^{230}$Th/U-ages were determined for PR-LA-1 (Figure 2 and Table S **2**), showing that this stalagmite covers the period from 46.2 to 15.4 ka BP with a growth interruption between 41.1 and 35 ka BP. The U content of the samples is about 0.1 - 0.3 μg/g, and in most samples, ($^{230}$Th/$^{232}$Th) activity ratios are high, but detrital $^{232}$Th content is significant. A number of samples with elevated $^{232}$Th are not in stratigraphy with the 'clean' samples, and the inversions persist when using the bulk Earth detrital ($^{230}$Th/$^{232}$Th) activity ratio of 0.8 to account for initial $^{230}$Th in stalagmite PR-LA-1. Thus, we followed an approach similar to Fensterer et al. (2010) and Beck et al. (2001) to estimate a more appropriate detrital ($^{230}$Th/$^{232}$Th) ratio for this stalagmite.

We used linear two-endmember mixing regressions, so called Osmond type I isochrons (Ludwig & Titterington, 1994) for distinct sections with significant $^{232}$Th content (Table S **2** and Figure S 2). For each isochron, only subsamples located potentially within a few hundred years (i.e., within a distance of 1-5cm, depending on the growth rate) were selected to meet the assumption of nearly coeval deposition.

The slope of each linear correction model (Figure S 2) yielded an estimate for a more appropriate detrital ($^{230}$Th/$^{232}$Th) ratio (Wenz et al., 2016). With this approach, we derived isochron slopes between 7.04 and 22.22 for seven sections (Table S **1**), with an overall mean of 16.46 ± 10.58. Three isochrons show a correlation coefficient of $r < 0.9$, which could be related to the relatively low variability in ($^{232}$Th/$^{238}$U), but it may also indicate that the assumption of coeval deposition was not applicable. Taking into account only the correction models with $r > 0.9$, yields a mean correction factor of 19.79 ± 4.93, which was subsequently used to correct the measured U and Th activity ratios and to calculate the ages. The obtained correction factor suggests a very high $^{230}$Th contribution from cave seepage water or non-carbonate contamination compared to the commonly used bulk Earth ratio of 0.8 (Wedepohl, 1995). The composition of the initial or detrital phase can be very different from this value, e.g., due to partial leaching effects, Th adsorption, alpha recoil or non-silicate origin of the detrital phase prior to deposition (Hellstrom, 2006). Consequently, ($^{230}$Th/$^{232}$Th) activity ratios of up to 18.7 for tropical limestones have been reported by a number of studies from the Bahamas, Cuba and Puerto Rico, supporting our result (Arienzo et al., 2015; Beck et al., 2001; Fensterer et al., 2010; Rivera-Collazo et al., 2015). However, in contrast to other studies, which assumed uncertainties of the correction as high as 100%, our isochron approach yields a relatively low error for the

Th activity ratio of about ±25 %. Hence, even though the correction itself is relatively large, the propagated uncertainty due to the correction is small for nearly all corrected ages. Even for samples with the lowest ($^{230}Th/^{232}Th$) activity ratio age uncertainties remain below 5%.

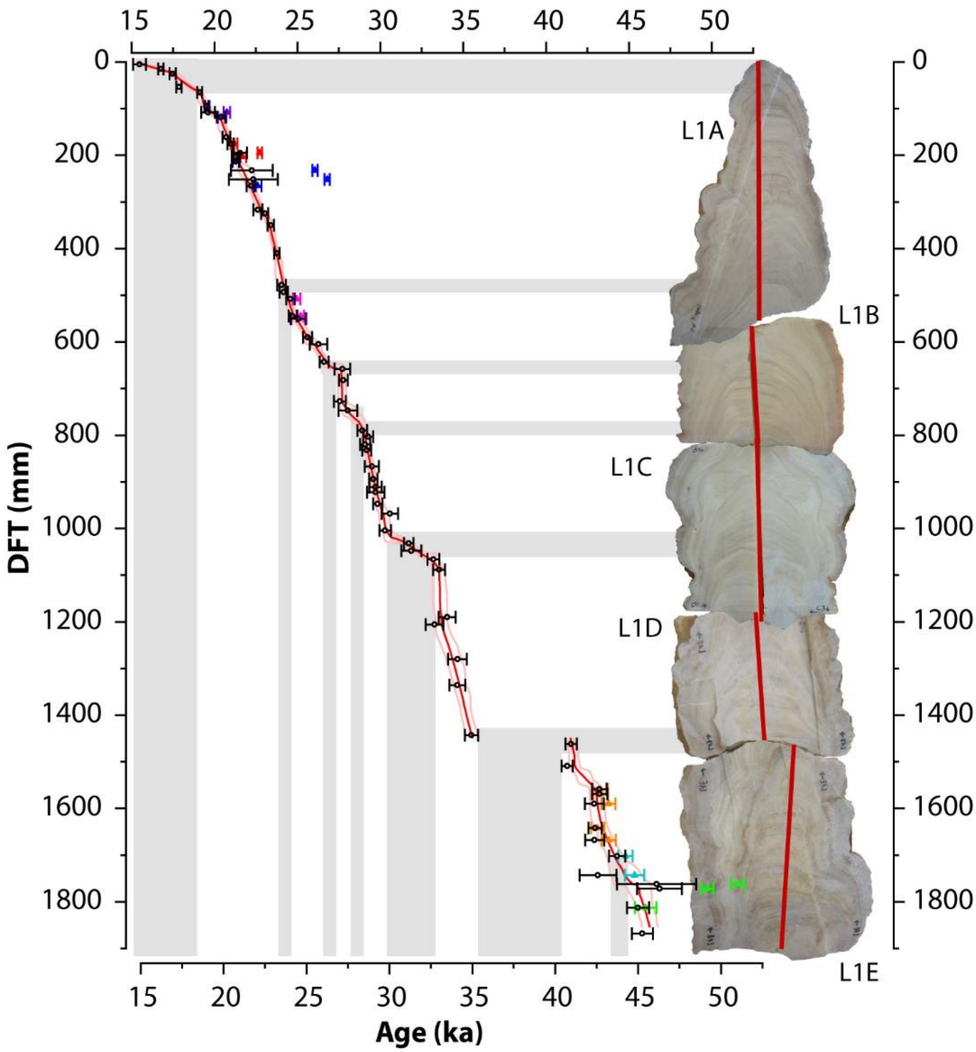


**Figure 2: Corrected $^{230}Th/U$ data (black) and age model (red) calculated using StalAge (Scholz & Hoffmann, 2011). The uncorrected ages used for the isochrons in Figure S 2 are shown in corresponding colors. Grey bars indicate periods of reduced or absent speleothem deposition. Right side: scan of the individual segments (L1A to L1E) of speleothem PR-LA-1, with approximate position of the growth axis shown by the red straight lines.**

After this correction, 9 of 74 samples of PR-LA-1 are still not in chronological order (Figure 2). These reversals might be due to diagenetic alteration, indicated by partly lower U concentrations, or changes in the initial $^{230}Th$ contribution from the detritus or seepage water. For these reasons, and considering the good agreement of the surrounding ages within the tight chronology, we did not include these ages in the final age model. The applied methods allow to construct an overall precise chronology with average uncertainties of 0.5 to 1.5 % of the corrected ages using the algorithm StalAge (Scholz & Hoffmann, 2011). This corresponds to errors in the chronology in the order of 200 to 400 years before 30 ka BP and 90 to 200 years afterwards. In sections with lower sampling density and/or significant detrital Th, the uncertainty increases up to 500 – 1000 years, which applies mostly to the bottommost sections, such as in segments L1E (45.5 and 44 ka BP) and L1C (35.5 to 33.5 ka BP).

The average growth rate is in the order of 100 µm/a, but the age model suggests very fast rates of up to more than 1 mm/a between 43.2 – 43.0, 41.5 – 41.1, 33.7 – 33.5 and 27.8- 27.6 ka BP. Comparably low deposition rates down to 10 – 30 µm/a occurred between 43.2 – 41.3, 33.5 – 30.3, 28.9 – 27.8 and 17.5 – 15.4 ka BP, as indicated by the grey bars in **Figure** 2.

### 3.2 Speleothem climate proxy patterns

Figure 3 shows the speleothem $\delta^{18}O$ and $\delta^{13}C$ values as well as the Mg/Ca, Sr/Ca and Ba/Ca records. In the earlier part of the record, from 46.2 to about 17 ka, the three element ratios show a variability of roughly ±50% around the mean values, with a Mg/Ca baseline of 1.0 ± 0.5mmol/mol, and Sr/Ca (Ba/Ca) values of 0.06 ± 0.03 mmol/mol (0.08 ± 0.04 µmol/mol). After 17 ka, Mg/Ca, Sr/Ca and Ba/Ca values strongly increase towards their highest values of the whole record. $\delta^{18}O$ and $\delta^{13}C$ values show a similar pattern with $\delta^{18}O$ values around 0 ± 2‰, and reaching the highest values of 1 - 2‰ between 17 and 15.4 ka, whereas $\delta^{13}C$ values vary around -9 ± 3‰. On longer timescales, $\delta^{13}C$, $\delta^{18}O$, and Mg/Ca values follow the general pattern of the speleothem growth rate (Figure 3). Regarding the whole record between 15.4 and 46.2 ka, $\delta^{18}O$ and $\delta^{13}C$ values show a strong correlation ($r_{\delta13C/\delta18O}$ = 0.52) and a similar pattern with Mg/Ca values ($r_{Mg/\delta18O} = r_{Mg/\delta13C}$ = 0.40). Sr/Ca and Ba/Ca are also correlated ($r_{Sr/Ba}$ = 0.49), but show only a weak relationship with Mg/Ca ($r_{Mg/Sr}$ = 0.32).

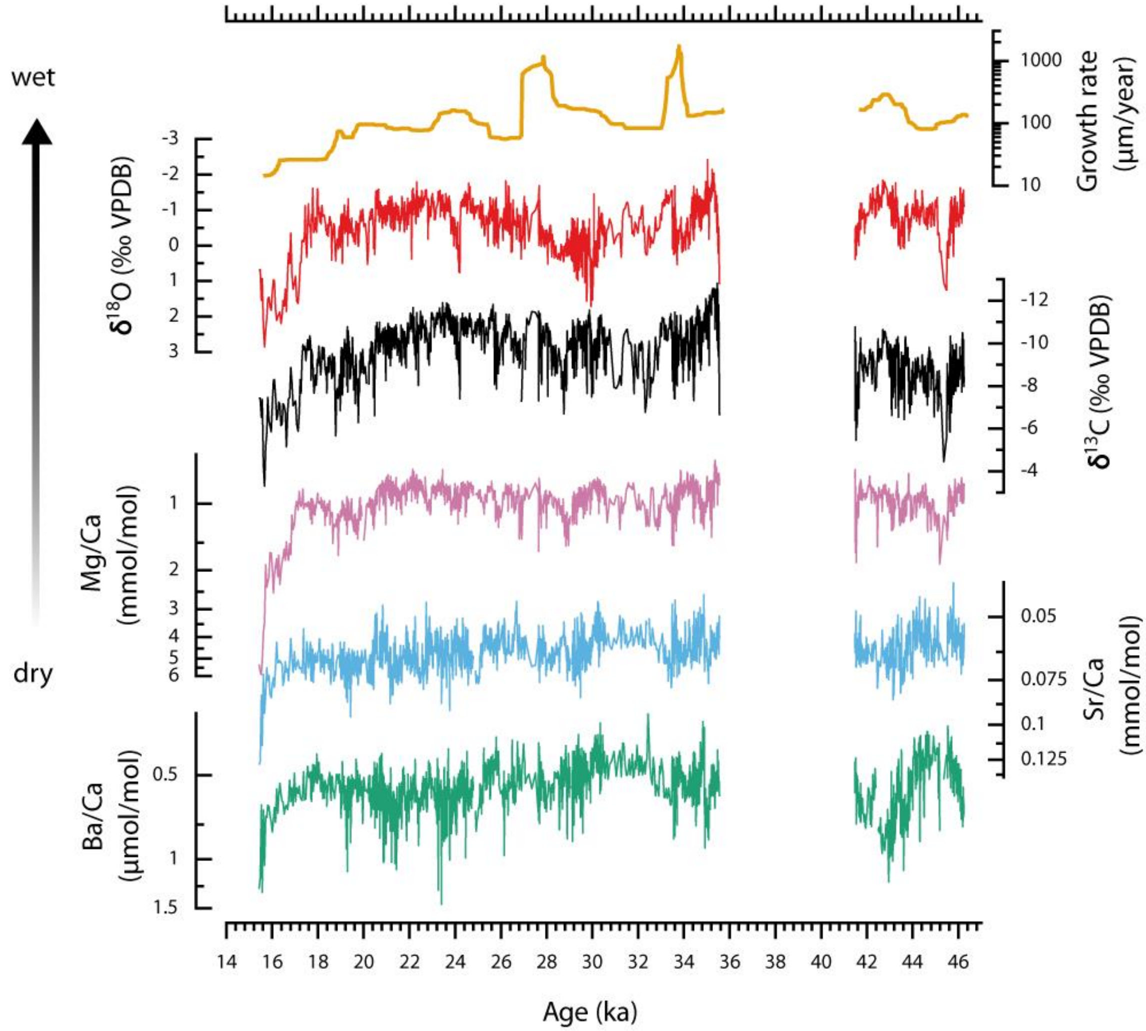


**Figure 3: Speleothem climate proxies in PR-LA-1 (from top to bottom): Growth rate (dark yellow, derived from the age model); stable isotopes of oxygen ($\delta^{18}O$ values, red), stable isotopes of carbon ($\delta^{13}C$ values, black); Mg/Ca (purple); Sr/Ca (blue); and Ba/Ca (green). Note the inverted scale of all proxies, which indicates the interpretation as proxies for wet/dry conditions (section 4). Mg/Ca, Sr/Ca and Ba/Ca are plotted on a logarithmic scale.**

### 3.3 Spectral analysis

For periods of relatively slow growth (with deposition rates in the order of 10 µm/a), the temporal resolution of the stable isotopes is on centennial timescales. For intervals with higher growth rates of up to 1 mm/a, even multi-decadal scales are resolved. To assess the power of sub-millennial variability of the proxies, spectral analysis was performed using REDFIT (Schulz & Mudelsee, 2002) for different time slices across the record. For this purpose, stadial and interstadial periods were chosen with a) relatively high growth rate to allow for multi-decadal resolution, and b) at least 500 years of continuous coverage. This includes the Last Glacial Maximum (LGM, 24 – 18 ka BP), Greenland stadials 3 (27 - 24.3 ka BP), 5.1 (30.2 - 28.7 ) and 7 ( 34.3 – 33.7 ka BP), Greenland interstadials 7 ( 35.4 – 34.3 ka BP), 11 (43.3 – 41.5 ka BP) and 12 (45.0 – 43.9 ka BP) as well as Heinrich stadials 1 (17.5 – 15.4 ka BP) and 2 (24.2 – 23.8 ka BP). The $\delta^{18}O$ spectra show enhanced power in multi-decadal to centennial periods during the LGM, Greenland stadials and interstadials (Figure 4). The spectral power variability of $\delta^{13}C$ and Mg/Ca is generally weaker, but they also show enhanced power for multi-decadal periods (**Figure S 5** and **Figure S 6**).

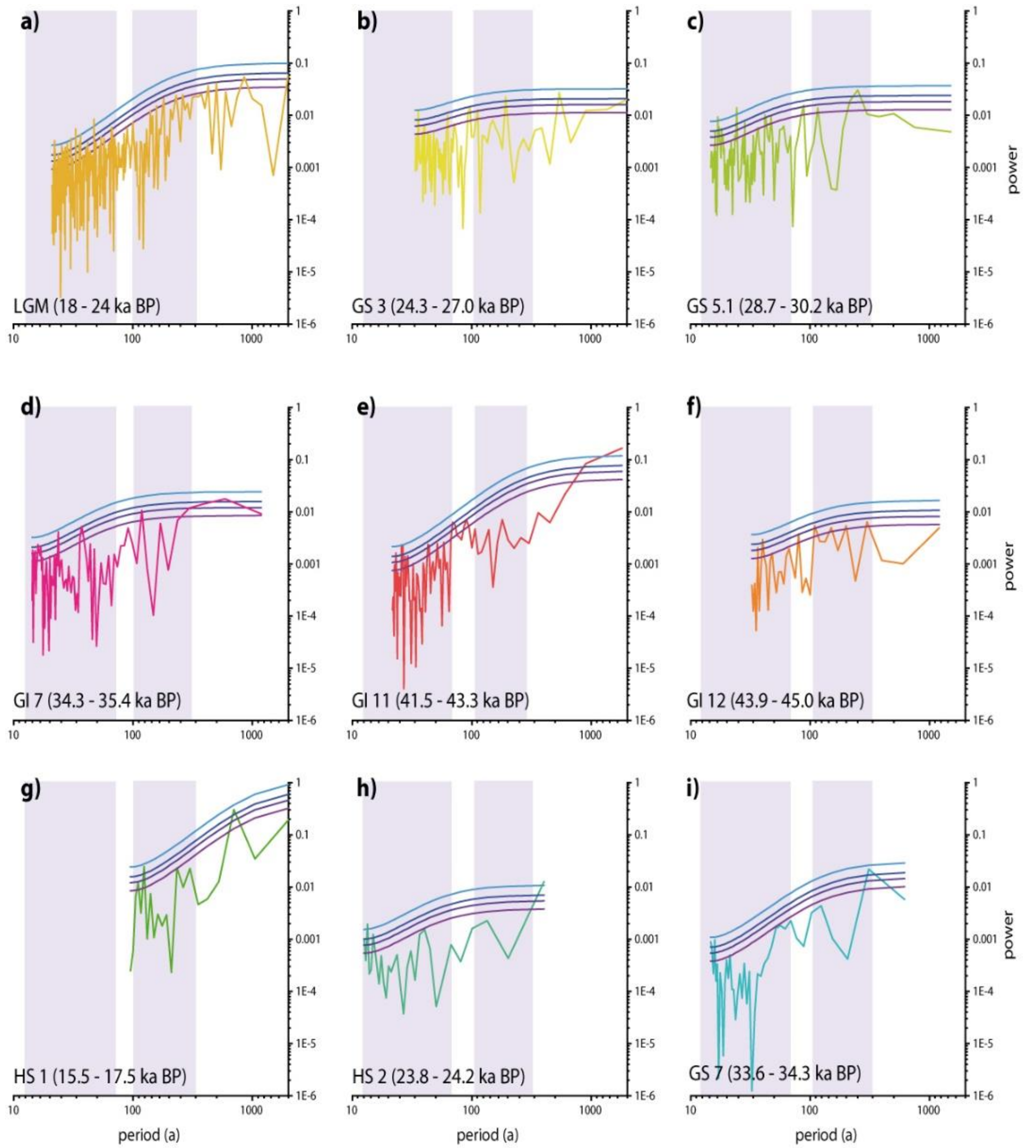


**Figure 4: Spectral power for different intervals of the PR-LA-1 $\delta^{18}O$ record calculated with REDFIT (Schulz & Mudelsee, 2002). Coloured lines indicate the calculated AR(1) false-alarm levels of 80% (purple), 90% (violet), 95% (dark blue) and 99% (light blue), respectively. Purple rectangles indicate the multi-decadal and centennial period bands. For all shown spectra, the AR(1) passed the REDFIT runs test, which checks the equality of theoretical AR(1) and data spectrum.**

# 4 Discussion

## 4.1 Climate proxy variability and interpretation

### 4.1.1 Inferences from modelling of cave and karst processes

Speleothem PR-LA-1 grew during the second half of the last glacial period (115 – 11.7 ka BP), when the climate in the Caribbean area was generally drier compared to the Holocene (Correa-Metrio et al., 2012; Hodell et al., 2008; Peterson et al., 2000; Schmidt & Spero, 2011), and Caribbean SST reconstructions (Hagen & Keigwin, 2002; Lea et al., 2003) report colder temperatures by 2 - 4°C. The PR-LA-1 $\delta^{18}O$ record exhibits a pattern of millennial-scale variability reminiscent of Dansgaard/Oeschger oscillations recorded in Greenland ice cores (Figure 5), which is also visible in other proxies, such as $\delta^{13}C$ and Mg/Ca (Figure 3), indicating a common driving process. In agreement with previous hydro-climate reconstructions from the tropical Atlantic realm (Arienzo et al., 2017; Lachniet et al., 2009; Winter et al., 2020), we associate lower (higher) speleothem $\delta^{18}O$ values during interstadial (stadial) phases with wetter and warmer (drier and cooler) conditions and greater (less) convective rainfall intensity.

In the main passage of Larga Cave, where PR-LA-1 was collected, Vieten et al. (2016) found a pronounced present-day seasonal cave air $pCO_2$ cycle, with a well-ventilated (i.e., low $pCO_2$) regime during the dry winter season and a near-stagnant, high $pCO_2$ mode during the wet summer. In addition, drip interval variations on intra- and inter-annual scale in response to recharge have been observed in Larga Cave at modern drip sites (Vieten et al., 2018b;Vieten et al., 2018a). In combination with the observed co-variation of speleothem stable isotope and trace element ratios (Figure 3), we suggest a strong hydrological control of these proxies influenced by cave and karst processes and the saturation state of the drip water (Cruz et al., 2007; Sinclair et al., 2012; Wassenburg et al., 2019). The degree of supersaturation is determined by cave air temperature and $pCO_2$, the initial Ca concentration and the degree of prior calcite precipitation (PCP). Longer drip intervals may further coincide with an increase in PCP and result in higher Mg/Ca, Sr/Ca and Ba/Ca ratios (Mattey et al., 2010; Stoll et al., 2012) as well as higher $\delta^{18}O$ and $\delta^{13}C$ values (Dreybrodt & Scholz, 2011; Hansen et al., 2019) of the drip water. A higher degree of PCP also decreases the saturation state of the drip water and therefore slows down stalagmite growth, reducing the partitioning of Sr and Ba, which may explain weak or even absent correlations of these elements in stalagmite PR-LA-1 (Stoll et al., 2012; Warken et al., 2018). Enhanced cave ventilation also leads to lower $pCO_2$ in the cave atmosphere and accordingly lower Ca equilibrium concentrations (Baker et al., 2014; Mattey et al., 2010). We regard these processes as very likely to act as controlling elements of drip water saturation and varying elemental and isotopic signatures in speleothems from Larga Cave. Numerical simulation of the observed elemental variability in stalagmite PR-LA-1 with I-STAL (Stoll et al. (2012), supplementary material S1) support this interpretation. For instance, the simulations indicate that the drip of PR-LA-1 indeed experienced a large drip interval variability (Figure S 3) and a variable effective cave air $pCO_2$ (i.e., the $pCO_2$ recorded by the stalagmite during the season of main calcite precipitation), which is potentially linked to seasonally variable ventilation. The influence of these processes on the $\delta^{18}O$ and $\delta^{13}C$ values of the speleothem was additionally explored using the ISOLUTION model (Deininger and Scholz (2019), supplementary material S1). This analysis reveals that the highest speleothem $\delta^{18}O$ (and $\delta^{13}C$) values can only be explained by assuming drip water values of 0 ‰ for $\delta^{18}O$ (-6‰ for $\delta^{13}C$), which is significantly higher than the modern values of -2.6 ‰ (and -13‰). This suggests that the observed magnitude of the excursions in the stable isotope record cannot be explained solely by cave-internal isotope fractionation effects during calcite precipitation, but must partially originate from the composition of the infiltrating water, which is, in turn, related to changes in the environmental conditions above the cave.

#### 4.1.2 Speleothem $\delta^{18}O$ values as a proxy for regional precipitation amount and convective intensity

In Larga Cave, drip water $\delta^{18}O$ values predominantly represent rainfall $\delta^{18}O$ values, which are linked to rainfall amount (Vieten et al., 2018a; Vieten et al., 2018b). Therefore, we consider speleothem $\delta^{18}O$ values as a proxy of past precipitation and convective activity in the western tropical Atlantic, which enables us to reconstruct changes of last Glacial precipitation patterns. Compared to modern calcite (-3.1‰), $\delta^{18}O$ values in speleothem PR-LA-1 are about 3-4‰ higher with an average level of about 0±1‰ during the LGM, which cannot solely be explained by cave and karst processes (section 4.1.1). On glacial-interglacial timescales, a number of additional effects can significantly impact the $\delta^{18}O$ values of drip water and speleothems, such as the changing $\delta^{18}O$ value of source waters due to increased continental ice volume, lower SSTs and salinity values (Baker & Fritz, 2015). For the (sub)tropical Atlantic, these account for a change in the $\delta^{18}O$ value of sea water of up to 2‰ during glacial periods (Hagen & Keigwin, 2002; Schmidt & Spero, 2011), which reduces the effective difference between modern calcite and speleothem PR-LA-1 $\delta^{18}O$ values to about 2‰. This suggests that Puerto Rico experienced a drier and predominantly non-convective regime during glacial times.

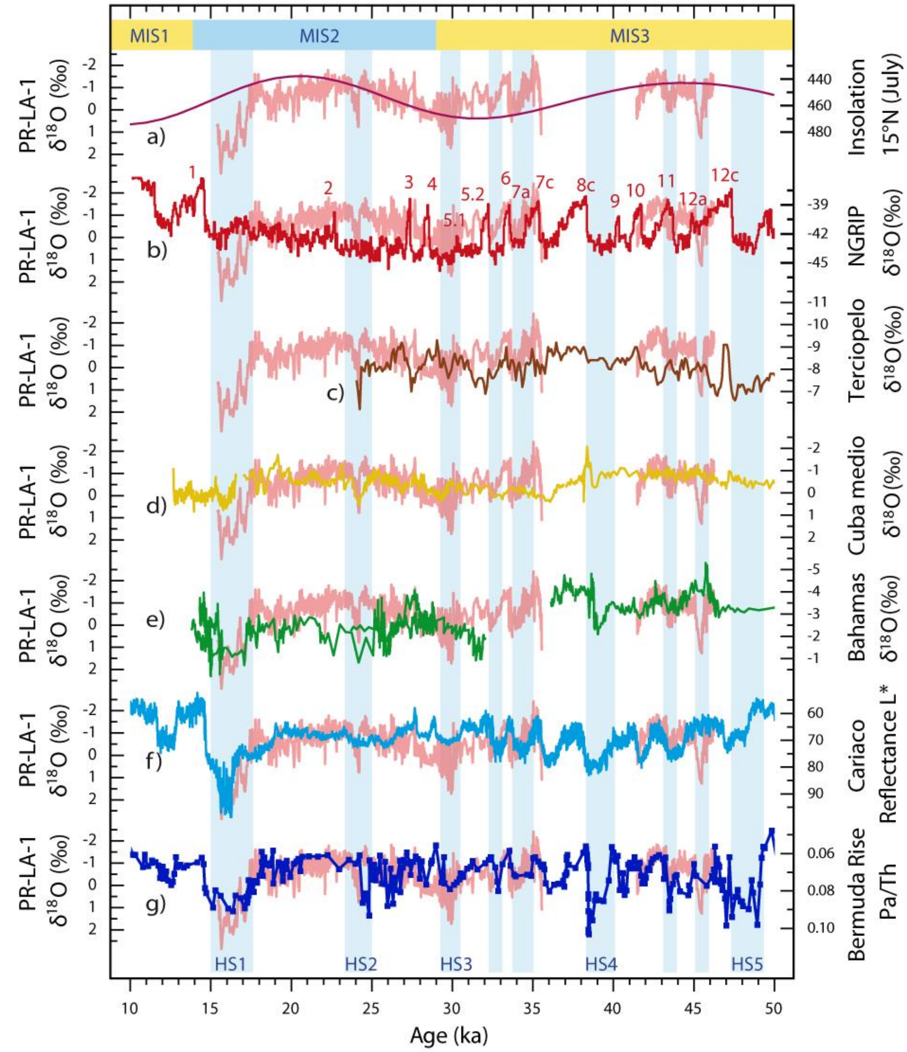


**Figure 5: PR-LA-1 $\delta^{18}$O values in comparison with (from top to bottom) (a) 15°N summer insolation (axis inverted); (b) $\delta^{18}$O values from the NGRIP ice core using the GICC05 timescale (Svensson et al., 2008). Numbers indicate the Greenland interstadials after Rasmussen et al. (2014); (c) speleothem $\delta^{18}$O values from Terciopelo Cave, Costa Rica (Lachniet et al., 2009); (d) speleothem $\delta^{18}$O values from Santo Tomas Cave, Cuba (Warken et al., 2019); (e) $\delta^{18}$O values from Abaco island, Bahamas (Arienzo et al., 2017); (f) Reflectance record from the Cariaco basin off Venezuela reflecting the mean meridional position of the ITCZ (Deplazes et al., 2013); (g) $^{231}Pa/^{230}Th$ compilation from the Bermuda Rise reflecting the strength of the AMOC (Böhm et al., 2015; Henry et al., 2016; Lippold et al., 2009; Lippold et al., 2019; McManus et al., 2004). Vertical blue bars indicate intervals of weak AMOC, such as Heinrich stadials 1-5.**

Compared to the modern average annual rainfall amount at Larga Cave, an increase of 1‰ in $\delta^{18}O$ values roughly corresponds to a rainfall decrease of about 50% (Vieten et al., 2018a). However, we regard this value as an upper limit. Enhanced moisture recycling has been observed at the location of Larga Cave during the dry season and is especially visible in the d-excess of rainwater (Vieten et al., 2018b). This mechanism may shift the weighted annual mean of the $\delta^{18}O$ values of the drip water towards higher values. Thus, the relative change of precipitation amount could be overestimated. The difficulty of quantifying this effect for the last glacial period prohibits a robust calibration of glacial speleothem $\delta^{18}O$ values with rainfall. Enhanced moisture recycling may be of particular importance for the driest intervals of our record, of which Heinrich Stadial 1 (17 to 15.4 ka BP) stands out, where speleothem $\delta^{18}O$ values (and all other proxies) show a strong increase of up to 6‰ compared to modern calcite. A decreased temperature of about 4°C during the coldest intervals of the Last Glacial compared to recent times (Arienzo et al., 2015) would only explain about 1‰ change in cave temperature-related isotope fractionation during carbonate precipitation. As discussed in section 4.1.1 and the supporting information S1, disequilibrium isotope fractionation effects during very cold and dry intervals would lead to a maximum change of +1-2‰, thus still leaving a residual shift in speleothem $\delta^{18}O$ values of about 1-2‰, which cannot be explained by glacial boundary conditions (Arienzo et al., 2017; Escobar et al., 2012). We note that a calibration study from the north-eastern Yucatán peninsula (Medina-Elizalde et al., 2017) suggested that local precipitation varied between +200% and −100% between 26 and 23 ka BP (including Heinrich stadial 2), while speleothem $\delta^{18}O$ values ranged from -6 to 0‰, which translates in a similar slope as observed in this study. This confirms that our inferences are reasonable.

In contrast, the most negative $\delta^{18}O$ values in PR-LA-1 of approximately -1.9 to -2.4‰ were reached during Greenland Interstadials (GI) 7c (35.4 - 35.0 ka) and 11 (43.3 – 42.2 ka). Similarly, GIs 2, 3, 5, 6, 12a and 12c are characterized by $\delta^{18}O$ values of about -1.2 to -1.6‰, whereas during GI 4 and 4.1, the values stay around -1‰ (Figure 5). Taking into account only the global ice volume and salinity changes in the tropical Atlantic surface waters during Marine Isotope Stage (MIS) 3, which account for about 0.5-1‰ (Hagen & Keigwin, 2002; Schmidt & Spero, 2011), peak values during GI7c and 11 nearly reach modern values in the cave. Keeping in mind that speleothem records from Puerto Rico and other Caribbean sites exhibit $\delta^{18}O$ variations of up to ± 1‰ during the Holocene (e.g., Fensterer et al. (2013); Medina-Elizalde et al. (2010); Winter et al. (2011)), we conjecture that the environmental conditions could have been comparable to the present-day. During the other interstadials, $\delta^{18}O$ values suggest at most only slightly drier and/or cooler conditions.

### 4.1.3 Persistent link of multi-decadal to millennial-scale rainfall to ocean circulation

A remarkable feature of the PR-LA-1 record is that speleothem $\delta^{18}O$ values closely track changes in the reconstructed strength of the AMOC (Figure 5) on centennial to millennial scales. Major events of freshwater input into the North Atlantic and subsequent slowdown of ocean circulation, such as Heinrich stadials HS1 (17.2 - 15.5 ka), HS2 (24.3 - 23.8 ka) and HS3 (30 – 29 ka), are recorded by elevated speleothem $\delta^{18}O$ values (Figure 5 and Figure 6), indicating pronounced transitions to drier and cooler conditions on Puerto Rico (section 4.1.2). Similar observations were made in other studies. A cooling by about 4°C during HS 1 to 3 was observed in speleothems from the Bahamas (Arienzo et al., 2017; 2015). Lacustrine sediments from Central America show increased aridity and a 4-10°C cooling associated with HS1 (Correa-Metrio et al., 2012; Escobar et al., 2012; Hodell et al., 2008), and a speleothem record from south-western Mexico demonstrates a reduction of the North American Monsoon (Lachniet et al., 2013).

The Larga $\delta^{18}O$ record strikingly agrees with sedimentary $^{231}Pa/Th$ from the Bermuda Rise, not only during Heinrich stadials, but also in the course of millennial to centennial variations associated with D/O main- and sub-stages (Figure 5). This suggests a strong and persistent link between Puerto Rican precipitation and the AMOC, which we therefore regard as the dominant regional control of abrupt rainfall changes in the subtropical Caribbean (Burckel et al., 2015; Henry et al., 2016; Waelbroeck et al., 2018). In agreement with recent modelling studies suggesting that asymmetric extratropical forcing, such as ice sheets or freshwater input into the North Atlantic, produce meridional shifts in the zonal mean rain belt, these observations indicate a southward shift of the ITCZ associated with abrupt decreases of AMOC strength (Broccoli et al., 2006; Clark et al., 2001; Singarayer et al., 2017).

Variations in the strength of the AMOC are linked to meridional redistribution of ocean heat within the North Atlantic, whose spatial SST pattern is superimposed on that of the Atlantic Multi-Decadal Oscillation (AMO) (Winter et al., 2020; Zanchettin et al., 2014; Zhang & Zhang, 2015). In particular, this Atlantic multi-decadal variability also involves surface warming and cooling of the inter-American Seas (del Monte-Luna et al., 2015; Enfield et al., 2001). Spectral analysis of the speleothem PR-LA-1 $\delta^{18}O$ data indicates relatively high power on multi-decadal to centennial periods during Greenland Stadials and Interstadials as well as the LGM. Instrumental, paleoclimate and modelling data support a positive correlation between the AMO and the hydro-climate over the western tropical Atlantic including Puerto Rico during the Late Holocene as well as on millennial and longer time scales (e.g., Bhattacharya et al. (2017); Fensterer et al. (2012); Winter et al. (2011)).

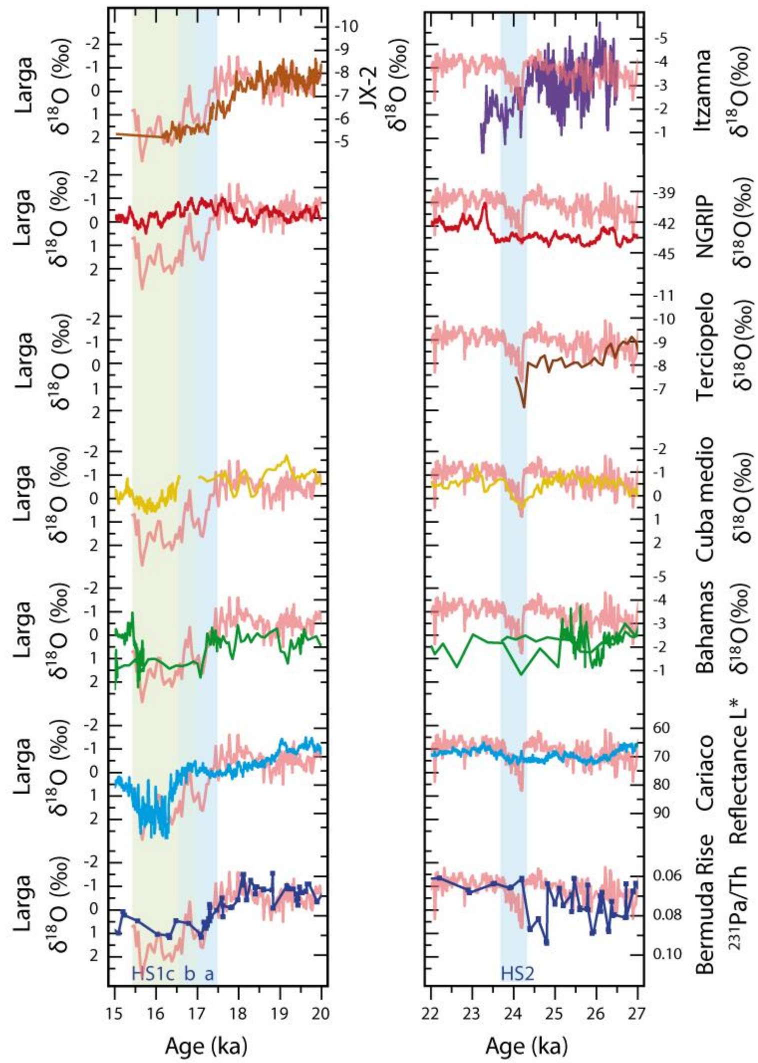


**Figure 6: PR-LA-1 $\delta^{18}O$ record for Heinrich stadials 1 (left) and 2 (right) in comparison with: $\delta^{18}O$ values from the NGRIP ice core using the GICC05 timescale (Svensson et al., 2008).; speleothem Cuba Medio $\delta^{18}O$ values from Santo Tomas Cave, Cuba (Warken et al., 2019); $\delta^{18}O$ values from Abaco Island, Bahamas (Arienzo et al., 2017); reflectance record from the Cariaco Basin (Deplazes et al., 2013) and $^{231}Pa/^{230}Th$ compilation from the Bermuda Rise (Böhm et al., 2015; Henry et al., 2016; Lippold et al., 2009; McManus et al., 2004). Also shown in the top left panel are speleothem $\delta^{18}O$ values from Juxtlahuaca, Mexico (Lachniet et al., 2013). On the top right panel, $\delta^{18}O$ values from Río Sécreto, Yucatán Peninsula, Mexico (Medina-Elizalde et al., 2017) and speleothem $\delta^{18}O$ values from Terciopelo cave, Costa Rica (Lachniet et al., 2009) are presented. Vertical blue and green bars indicate the (sub-) stages HS1 (left) and HS2 (right) as registeredd in the PR-LA-1 $\delta^{18}O$ record.**

For the Last Glacial, the lacustrine record from Lake Petén Itzá also suggests inter-annual and multi-decadal variability (Correa-Metrio et al., 2012; Escobar et al., 2012; Hodell et al., 2008), and Medina-Elizalde et al. (2017) reported multi-decadal variability in a high-resolution speleothem $\delta^{18}O$ record from the Yucatan Peninsula spanning 26 to 24 ka BP (Figure 6).

Our dataset indicates that multi-decadal variability is indeed a persistent feature of the tropical hydro-climate during both interstadials and stadials as well as across the LGM. This supports the hypothesis that the Atlantic low-latitude regions responded to internal modes of climate variability on these timescales regardless of the global climate state (Medina-Elizalde et al., 2017; Winter et al., 2020). The appearance of multi-decadal, centennial and millennial scale precipitation variability in the same archive further suggests a common mechanism of heat redistribution in an AMO-analogue mode on all these timescales (Bhattacharya et al., 2017; Ting et al., 2009; Zhang & Zhang, 2015). This argues for a dominant role of the strength of ocean circulation in tropical Atlantic precipitation and adds support to the hypothesis that the AMOC is a key element for the link between northern high latitudes and tropical climate - not only during Heinrich stadials but also for D/O events.

## 4.2 Spatio-temporal patterns of western tropical Atlantic precipitation

### 4.2.1 Spatio-temporal patterns on orbital timescales

The compilation of existing reconstructions of past precipitation in the western tropical Atlantic realm provides the opportunity to explore spatio-temporal rainfall patterns and to reconstruct past regional ITCZ variations on millennial to orbital timescales. Figure 5 shows that the long-term variability in PR-LA-1 $\delta^{18}O$ values generally appears to be inversely related with summer insolation. This observation agrees with long speleothem records from Cuba and Costa Rica, which also document an inverse relationship of regional rainfall and summer insolation during MIS 4 to 2 (Lachniet et al., 2009; Warken et al., 2019). This relationship is unexpected since previous studies have documented a positive link between rainfall intensity and summer insolation in the Americas (Cruz et al., 2009; Poveda et al., 2006). However, model studies also demonstrated that the seasonal northern limit of the American rain belt during the Last Glacial varied not only in response to local insolation, but also responded to ice-sheet forcing due to the regional land-ocean configuration (Singarayer et al., 2017). During times of an extensive Northern Hemisphere ice cover, the maximum northward extent of the ITCZ occurs earlier in the year, when most local land is to the south (Singarayer et al., 2017). When local summer insolation is high, the land-sea temperature contrast increases and the ITCZ rain belt moves south, apparently away from the warmer hemisphere, but in fact towards the locally warmed land (Singarayer et al., 2017). This implies that orbital variations produce expansions and contractions of the global zonal mean of the ITCZ. We further evaluate this process here by comparing the speleothem records from the northern limit of the tropical rain belt to the reflectance record from the Cariaco basin, which mirrors the meridional position of the mean position of the ITCZ (Deplazes et al., 2013). During periods of reduced summer insolation, e.g., MIS2, $\delta^{18}O$ values of speleothems north of the Cariaco basin as well as central American lacustrine sediments (e.g., Hodell et al. (2008)) indicate relatively wet conditions. In contrast, the Cariaco reflectance record remains relatively constant, which may suggest that the tropical rain belt indeed expanded northward during this interval in response to orbital forcing.

#### 4.2.2 Spatio-temporal patterns on millennial timescales

Of all the Heinrich stadials recorded in PR-LA-1, HS1 (17.2 - 15.4 ka) stands out as the most pronounced, suggesting that it was the severest stadial in the region (Arienzo et al., 2015; Escobar et al., 2012). This observation is supported by reconstructions of AMOC strength showing that HS1 was accompanied by a near shutdown of the AMOC and an abrupt and synchronous response of the ITCZ to changes in ocean circulation (Lachniet et al., 2013; Stríkis et al., 2015). In contrast, there were only muted changes during HS2 and 3 (Böhm et al., 2015; Lynch-Stieglitz et al., 2014). The onset of HS1 in PR-LA-1 occurred at about 17.5 ka with a gradual increase in $\delta^{18}O$ values indicating a decrease of rainfall amount and temperature, interrupted by a short warm and wet period at about ~17 ka (Figure 6). Comparing PR-LA-1 $\delta^{18}O$ values with the speleothem record from Juxtlahuaca Cave, Mexico (Lachniet et al., 2013), and Abaco Island, Bahamas (Arienzo et al., 2017), shows that the timing of the increase in the $\delta^{18}O$ values during the sub-stages of HS1 was nearly synchronous (Figure 6). A three-stage structure of HS1 is also recorded by lacustrine sediments in Guatemala (Escobar et al., 2012), supporting its region-wide impact.

In contrast, HS2 on the other hand shows a slightly different picture in Puerto Rico characterized by an abrupt, one-stage increase in $\delta^{18}O$ between 24.2 and 23.8 ka (Figure 6), which is also clearly imprinted in the records from the Bahamas and Cuba. The records from the north-eastern Caribbean closely follow the pattern of $^{231}Pa/Th$ on the Bermuda Rise, indicating a temporary weakening of the AMOC and a synchronous reduction of regional rainfall. In contrast, the speleothem record from the Yucatan peninsula (Medina-Elizalde et al., 2017) is characterized by a continuous precipitation reduction after 23.8 ka (Figure 6), which was attributed to be synchronous and in-phase with precipitation records from South America. The difference in the climate response in the north-eastern Caribbean compared to reconstructions from further south-west most likely indicates a diminishing influence of the Atlantic from the east towards the south-west.

In addition, the amplitude of stadial and interstadial intervals is attenuated in the northernmost records from Cuba and the Bahamas (Arienzo et al., 2017; Warken et al., 2019), but also towards Costa Rica (Lachniet et al., 2009) compared to precipitation records in the Cariaco basin (Deplazes et al., 2013) and in Larga Cave (Figure 5). Warken et al. (2019) noted a weaker sensitivity of $\delta^{18}O$ values in a speleothem from Cuba to North Atlantic forcing during MIS 4 to 2 compared to MIS 5 and the Holocene. Similarly, PR-LA-1 shows decreasing amplitudes of centennial to millennial oscillations after 30 ka compared to NGRIP and Cariaco with weak or even absent excursions across GIs 2 to 5 (Figure 5). Oster et al. (2019) identified an east–west gradient in precipitation patterns based on late Holocene speleothem $\delta^{18}O$ records, with increasing Pacific influence when moving across the Caribbean towards the west. As the northern extent of the ITCZ moves further south, it causes a progressive weakening of the connection between Caribbean precipitation and North Atlantic forcing and affects the competing influence of the Atlantic and Pacific. This is also a likely explanation for the observed patterns in the Caribbean precipitation records on centennial to millennial scale during the last glacial period, highlighting the complex climatological patterns in this region.

## 5 Conclusions

The speleothem multi-proxy record from Larga Cave provides valuable insights into regional paleoclimate variability on multi-decadal to orbital timescales, whereby $\delta^{18}O$ values are the key proxy of past precipitation amount. This study highlights the close connection of western tropical Atlantic precipitation variability and Northern Hemisphere climate variability on millennial to centennial timescales. In particular, our record underlines the central and persistent role of the strength of the AMOC for abrupt glacial climate change, adding valuable information to recent debates and underscoring that a more complete understanding of the underlying mechanisms can only be achieved by integrating observations and models (Roberts & Hopcroft, 2020; Them Il et al., 2015). The compilation of regional records from speleothems and other archives suggests the existence of spatially and temporally varying precipitation patterns during the last glacial period. These observations argue for a complex ITCZ variability, with meridional shifts occurring along with expansions and contractions of the rain belt on different timescales and depending on the nature of the forcing. Thus, the concept of north-south shifts of the ITCZ causing wet-dry conditions in the region is insufficient to explain the observed tropical precipitation variability and requires further in-depth research on the variability and drivers of the western tropical Atlantic rain belt. As shown in this study, precisely dated speleothem records can provide important information towards this endeavour.

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## Data availability

The data presented in this paper were uploaded to the open PANGAEA data library (https://doi.pangaea.de/10.1594/PANGAEA.911486) and will be available after acceptance of this paper.

## Supporting information

**Supporting information S1:** Simulation of the observed proxy variability.

**Table S 1**: Results of the linear fit models for each Osmond isochron indicated in Figure S 2.

**Table S 2**: Activity ratios and final ages of stalagmite PR-LA-1.

**Figure S 1** Map of Larga Cave and location of stalagmite PR-LA-1, Puerto Rico

**Figure S 2:** Individual Osmond type I isochrones and $(^{230}Th/^{238}U)$ vs. $(^{232}Th/^{238}U)$ activity ratios of stalagmite PR-LA-1.

**Figure S 3**: Results of I-STAL simulations for speleothem PR-LA-1 compared to speleothem proxies.

**Figure S 4:** ISOLUTION simulations of the stable isotopic composition of calcite.

**Figure S 5**: Spectral power for different intervals of the PR-LA-1 $\delta^{13}C$ record**.**

**Figure S 6:** Spectral power for different intervals of the PR-LA-1 Mg/Ca record.

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