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Three-Phased Heinrich Stadial 4 recorded in NE Brazil Stalagmites

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Abstract

The growth intervals of stalagmites from Northeast (NE) Brazil provide precise information on the timing of pluvial periods associated with the southward shift of the Intertropical Convergence Zone (ITCZ) during Heinrich Stadials (HS). Using ²³⁰Th dating and annual band counting, we constrained the timing of the pluvial period associated with HS4 to occur between 40.06 ±0.06 and 38.38 ±0.10 thousand years (kyr) B.P., coinciding with the interval between the end of Greenland Interstadial (GIS)/Chinese Interstadial (CIS) 9 and GIS/CIS 8. Oxygen isotope analysis shows a close anti-correlation between NE Brazil wet periods and East Asian monsoon intensity recorded in Hulu Cave, supporting a southerly migration of the global ITCZ during HS4. The pluvial anomaly can be divided into three phases, starting with a precursor, less intense pluvial interval (phase 1) between 40.06 ±0.06

and 39.59 ± 0.04 kyr B.P., likely correlative to the cool phase of the North Atlantic immediately before the partial collapse of the Laurentide Ice Sheet (LIS). This phase ends abruptly (<30 years) and is followed by an intense pluvial phase (phase 2) that spans approximately 5 centuries. Luminescent couplets are identified in all samples between 39.50 ± 0.04 and 39.41 ± 0.03 kyr, and are interpreted as a period of two rainy seasons per year during which the southernmost extent of the inland West Atlantic ITCZ reached south of our study site (10°S). Following the end of phase 2 at 39.09 ± 0.1 kyr B.P., intermittent speleothem growth suggests intermittent rainfall over NE Brazil (phase 3) until the abrupt onset of GIS/CIS 8 at 38.38 ± 0.1 kyr B.P. The phases identified in NE Brazilian stalagmites agree with the three-phased variation in low-latitude proxies registered in Northern Greenland, and are consistent with changes in methane concentrations recorded in the West Antarctic Ice Sheet (WAIS) Divide. The synchronicity of these distant records supports a multi-phased response of tropical atmospheric circulation during HS4. The timescales surrounding the LIS collapse, as inferred from our precisely dated stalagmites, are on the same order as recent predictions for the impending collapse of the WAIS and may therefore serve as a past analogue.

1. Introduction

The last glacial period was punctuated by a series of Heinrich Events (HE) during which a partial collapse of the LIS released massive volumes of ice and freshwater into the North Atlantic (Heinrich 1988). Although the underlying mechanisms remain unclear (Hemming, 2004), evidence suggests that a gradual reduction in the North Atlantic Meridional Ocean Circulation (AMOC) prior to HES (McManus et al., 2004) prompted extreme cooling of North Atlantic sea surface temperatures (SST) (Bond and Lotti, 1995; Barker et al., 2015) and subsurface warming (Marcott et al., 2011) that ultimately triggered a rapid breakdown of the expanding Laurentide ice shelf (Alvarez-Solas et al., 2010). The time period representing both precursor cooling and sustained cooling following the discharge event will be thus forward referred to as a Heinrich Stadial (HS). Emphasis on the study of

HEs and their associated HSs has increased in recent years, as they may serve as an imperfect analogue to the timescales surrounding the predicted collapse of the West Antarctic Ice Sheet (WAIS) (Alley et al., 2015; DeConto and Pollard, 2016).

Climate anomalies linked to HSs have been recognized in low latitude paleo-precipitation records worldwide. Broadly, proxy networks indicate a drying of the Northern Hemisphere subtropics (Deplazes et al., 2013; Cheng et al., 2016) and a wetting of the Southern Hemisphere tropics and subtropics (Arz et al., 1998; Wang et al., 2004; Jaeschke et al., 2007; Cruz et al., 2009; Kanner et al., 2012; Mosblech et al., 2012; Cheng et al., 2013; Strikis et al., 2015; Wang et al., 2017; Zhang et al., 2017) coinciding with HSs. Widespread changes in the distribution of subtropical precipitation is attributed to decreased interhemispheric heat transport under weakened AMOC conditions (McManus et al., 2004; Henry et al., 2016; Multiza et al., 2017) thereby expanding the northern Hadley cell and displacing its ascending branch (the ITCZ) southward (Chiang and Friedman, 2012; Alvez-Solas et al., 2010). Continental precipitation over NE Brazil is exceptionally sensitive to meridional shifts of the West Atlantic ITCZ (see section 2). Proxy evidence indicates a tight coupling between past variations in AMOC strength, Atlantic SSTs, and NE Brazil rainfall (Arz et al., 1998; Jaeschke et al., 2007; Cruz et al., 2009; Multiza et al., 2017), pointing to a rapid and proportional adjustment of the Atlantic ITCZ's latitudinal position to variations in interhemispheric heat transport. Past migrations of the Atlantic ITCZ may therefore provide insight into the timing of North Atlantic ocean-climate anomalies linked to HSs and HEs, as investigating the precise timing of these high-latitude events is often complicated by large uncertainties associated with Greenland ice and North Atlantic sediment records (Hemming, 2004). Ice rafted debris (IRD) evidence suggests that HE4 was the largest of the six HEs in terms of ice volume released into the North Atlantic during the last glacial period (Hemming, 2004), and therefore represents an ideal time period to study. Here, we provide a multi-stalagmite precipitation record of NE Brazil in order to better constrain the timing and structure of HS4.

2. Modern climate

In order to investigate the spatial and temporal variability of past ITCZ migrations, we focus on the semi-arid region of NE Brazil located near the southernmost seasonal extent of the West Atlantic ITCZ (Fig. 1). The interior of NE Brazil is characterized by high evapotranspiration rates ($>1,400$ mm) and mean annual temperatures of 28°C with seasonal variations $<2^{\circ}\text{C}$. Modern vegetation is comprised of shrub-like, drought-resistant caatinga. The distribution and amount of rainfall at our study site (490 mm annually) is largely dependent on the latitudinal position of the near-equatorial confluence axis and associated low pressure trough that define the West Atlantic ITCZ, which transports moisture inland from the subtropical South Atlantic (Hastenrath and Lamb 1977; Hastenrath 1990; Hounsou-Gbo et al. 2015). During boreal summers, weakened Northern Hemisphere trade winds, warm North Atlantic subtropical sea surface temperatures (SSTs), and an intensified equatorial flank of the South Atlantic high pressure system contribute to a northward migration of the West Atlantic ITCZ, resulting in minimal rainfall over NE Brazil. During austral summers, an acceleration of the Northern Hemisphere trades and weakening of the South Atlantic equatorial pressure gradient contribute to a southward migration of the West Atlantic ITCZ, while warm South Atlantic subtropical SSTs serve to enhance the instability and moisture content of the boundary-layer flow directed into the interior of NE Brazil (Fig. S7; Hastenrath, 1990).

The isotopic composition of rainfall over northern and central NE Brazil (Fig. 1b), including our study site (40.86°W , 10.16°S), is predominantly controlled by rainfall amount (Vuille et al., 2003; Lee et al., 2009) which in turn is linked to the proximity to the West Atlantic ITCZ. Rainfall collected from 1965 to 1987 at GNIP stations in this region (Fig. 1b) reveals a broad spatial pattern of increasing weighted mean annual $\delta^{18}\text{O}$ values with increasing distance from the mean annual position of the West Atlantic ITCZ (IAEA/WMO 2018). The GNIP station closest to our study site, Floresta Fig. 1c; (38.34°W , 8.36°S), reports an anti-correlation ($R^2=0.64$) between modern mean monthly $\delta^{18}\text{O}$ values and rainfall amount. Maximum rainfall in Floresta centers on the month of March (IAEA/WMO 2018) when the West Atlantic ITCZ axis reaches its furthest seasonal southerly extent directly north of the NE Brazilian state Ceará (Hastenrath and Lamb 1977).

No current evidence suggests that rainfall from the South American Monsoon (SAM), which is isotopically depleted relative to tropical Atlantic-sourced vapor (Vuille et al., 2003; Lee et al., 2009), significantly contributes to total moisture content at our study site today. This is in contrast to southern NE Brazil, where maximum rainfall occurs during the month of December when the South Atlantic Convergence Zone (SACZ), a distinctive feature of SAM, is in its full expression (see supplementary materials in Strikis et al., 2015). Paleo-precipitation reconstructions in southern NE Brazil indicate that enhanced SACZ activity contributed to increased monsoon rainfall amount in southern NE Brazil during HSs (Strikis et al., 2015). However, $\delta^{18}\text{O}$ -proxy and modeling evidence suggests that SAM did not expand to northern and central NE Brazil during HSs or under maximum glacial conditions (Cruz et al., 2009; Lee et al., 2009). Instead, speleothem growth phases and $\delta^{18}\text{O}$ recorded in the northern and central NE Brazil indicate a direct coupling of regional rainfall amount to the mean latitudinal position of the ITCZ over millennial timescales (Wang et al. 2004; Cruz et al., 2009). Secondary factors that may influence isotopic composition of rainfall, such as changes in evapotranspiration (ET) rates, have not been studied but are largely expected to act as positive feedbacks (lower ET rates during wet periods would inhibit the enrichment of infiltrating surface waters).

3. *Study site*

Our study area consists of a well-developed underground karst system with shallow cave passages located in Precambrian dolomite bedrock. Toca da Boa Vista (TBV) and Toca da Barriguda (TBR) caves (40.86°W, 10.16°S; 600m above sea level) are located near the Salitre river valley approximately 500 km west of the tropical Atlantic (Fig. 1b). The two caves are separated by 500 m and are therefore unaffected by one another's internal temperature, humidity, or ventilation changes. Today, high potential evapotranspiration rates coupled with low annual precipitation amount (see section 2) greatly restricts surface infiltration, resulting in an absence of modern speleothem growth. Speleothems found within TBV and TBR caves are therefore relics of past wet periods. Stalagmite growth phases likely correspond to past periods of higher rainfall, as precipitation levels must exceed soil and bedrock

thresholds to initiate speleothem growth (Auler et al., 2004; Wang et al., 2004). Previous studies indicate that speleothem growth phases from TBV/TBR are strictly limited to past NE Brazil pluvial periods (Auler et al 2004), including growth phases associated with HS1, HS4, HS5, and HS6 (Wang et al., 2004). Here, we present the first $\delta^{18}\text{O}$ and luminescent band analysis of TBV/TBR stalagmites associated with HS4.

4. *Materials and methods*

Stalagmites TBV40, TBV63, and TBR14 were collected from cave galleries located approximately 15, 20, and 30 meters below surface (m.b.s.), respectively. Stalagmites were selected for this study due to their growth location, cleanliness, and straight geometry (see Fig. S1). Subsamples for ^{230}Th dates ($n=39$) were hand drilled along the growth axis of halved stalagmites and spiked with a mixed ^{233}U - ^{236}U - ^{229}Th spike similar to that described in Edwards et al. (1987) (table S1). Separate uranium and thorium liquid extracts were measured using a Thermo Neptune ICP- Mass Spectrometer following the methods described in Shen et al. (2012) and Cheng et al. (2013). Age models were calculated using the Bayesian statistical software OxCal version 4.2 under sequence “P” with k-parameter set to 0.1 (Bronk Ramsey, 2009, Fig. S5). Micro X-Ray diffraction (XRD) powder subsamples ($n=6$) were hand drilled and measured using a Bruker-AXS Microdiffractometer with a 2.2 kW sealed Cu X-ray source. Oxygen isotope samples ($n=818$) were continuously micro-milled at 0.5-0.1mm intervals along the growth axis of HS4 phases. Samples were measured using a Finnigan Delta V Advantage Mass Spectrometer at the Institute of Geological Sciences of the University of Bern. Results are reported relative to the Vienna Pee Dee Belemnite (VPDB) standard with analytical errors of 0.07 ‰ VPDB (1σ).

Confocal laser fluorescent microscopy (CLFM) techniques were conducted to identify individual growth bands in the HS4 calcitic portion of each stalagmite using a Nikon A1R Multi-Photon instrument operating with a 488nm argon-sourced laser line at the University of Minnesota Imaging Center. The methodology for CLFM imaging and identification of growth bands was adapted from Orland et al. (2009). A series of overlapping images (1.22 mm in width, pixel size 1.23 μm), were collected along

the growth axis of each stalagmite using an emission filter for wavelengths between 505 and 539 nm. The widths of bands were measured and counted using the Nikon Elements Viewer software. Each clearly visible light band was given a count of one. When two bands were not clearly distinguishable, the unclear couplet was given a count of 1.5 and assigned an error of 0.5. This method was adopted after the ice core layer-counting procedure described by Alley et al. (1997). Growth hiatuses are identified as intrusions of abnormally bright, unstructured material between distinct growth layers (see Fig. S4 for example), indicating the presence of accumulated detritus commonly observed on the “rind” of modern, non-growing speleothems. When possible, growth hiatuses were verified using ^{230}Th dating (table S1). In addition, CLFM imaging was utilized to identify the precise location of aragonite-calcite boundaries in stalagmites TBV40 and TBV63 (Fig. S1) as confirmed by XRD analysis.

5. Results

Resulting ^{230}Th dates and their respective replicates are in stratigraphic order within 2σ uncertainties (table S1). In total, we present evidence for the timing of four growth intervals, each associated with a HS period, summarized in table 1. Growth intervals 17.07 ± 0.04 to 16.09 ± 0.07 kyr B.P. (HS1 period) and 48.88 ± 0.10 to 47.80 ± 0.17 kyr B.P. (HS5 period) were calculated by subtracting the top (minimum sampling depth) ^{230}Th age from bottom (maximum sampling depth) ^{230}Th age of associated growth phases on stalagmite TBR14 (Fig. S1). Growth interval 66.7 ± 0.10 to 65.56 ± 0.11 kyr B.P. (HS6b period) was calculated by subtracting the top from the bottom ^{230}Th ages of associated growth phase on stalagmite TBV40 (Fig. S1). Growth interval 40.06 ± 0.06 to 38.38 ± 0.10 kyr B.P. (HS4 period) is the focus of this study, and was calculated from the OxCal age model of stalagmite TBV40.

$\delta^{18}\text{O}$ values for all three samples are similar in range, trend, and absolute values (Fig. 3). A high degree of replication in $\delta^{18}\text{O}$ profiles between TBV and TBR caves argues against any substantial kinetic effect. In corroboration with modern-day observations (IAEA/WMO 2018), we interpret variations in speleothem $\delta^{18}\text{O}$ (ranging from -2‰ to -9‰) to largely represent variations in rainfall

amount, with minor (~10%) variation attributable to change in mineralogy (see section 5.1.2). XRD analyses suggest the presence of unaltered aragonite in the HS4 growth phase of TBV40 and TBV63 (table S2). At 40.06 ± 0.1 kyr B.P., TBV40 commences HS4 period growth (Phase I) as aragonite. An aragonite-to-calcite transition in TBV40, the exact depth determined using CLFM imaging and mineralogy confirmed with XRD analysis, occurs at 39.59 ± 0.1 kyr B.P (beginning of HS4 period, Phase II). The TBV40 aragonite-to-calcite transition is within age uncertainties of the aragonite-to-calcite transition in TBV63 (boundary also determined using CLFM imaging), thus providing independent evidence for the precise timing of this event. Calcite was then deposited in TBV40 and TBV63 between 39.59 and 39.09 ± 0.1 kyr B.P. (HS4 period, Phase II). TBR14 has HS4 growth, which is entirely calcite, only from 39.59 to 39.07 kyr B.P. (± 0.2), thus corresponding to the calcite growth phases of TBV40 and TBV63, within uncertainties (HS4 period, Phase II). All age uncertainties are determined using the OxCal age model uncertainties at the specific depth in question (mm from top of stalagmite). Thin (<100 microns) hiatuses identified within the top <4mm of TBV63 and TBV40 suggesting intermittent growth at this time. Speleothem growth ceased immediately following 38.4 ± 0.1 kyr B.P. (top ^{230}Th date from TBV40).

Fluorescent banding was discovered in all three stalagmites along the entire traverse of calcite growth phases. Fluorescent banding is aligned perpendicular to the vertical growth axis and displays a saw tooth pattern (Fig. 3b). The existence of fluorescence indicates that organic acids were present in drip water during calcite precipitation (Orland et al., 2009). The observed fluorescent band pattern is typical for stalagmites from subtropical regions with distinct seasonal changes in rainfall (e.g. Orland et al., 2014), in which a single band is defined by the sharp onset of fluorescence (likely onset of rainy season) followed by a more gradual transition to low fluorescence (likely onset of dry season). Individual growth layers with this bright-to-dark fluorescent gradient pattern are identified as “single-bright bands.” Individual growth layers that include a sharp onset of high fluorescence immediately followed by a second, yet distinct, sharp onset of high fluorescence followed by a gradual transition to low fluorescence (bright-bright-dark) are identified as “double-bright bands” (see Fig. S3 for example).

Total band counts (single-bright + double-bright bands) for the calcitic portion of each stalagmite are within the uncertainties ^{230}Th dating (table 2) and are therefore considered annual.

6. Discussion

Growth phases of TBV40, TBV63 and TBR14 correlate within age uncertainties of the timing of HS1, HS4, HS5 (Bond and Lotti, 2009) and the Greenland stadial between GIS 19/18 (NGRIP Members, 2004) associated with HS6b. Pluvial periods recorded in NE Brazilian stalagmites corresponds to periods of decreased runoff in the Cariaco Basin (Deplazes et al., 2013), increased SAM intensity (Wang et al., 2006; Kanner et al., 2012; Mosblech et al., 2012; Cheng et al., 2013; Strikis et al., 2016; Wang et al., 2017; Zhang et al., 2017), increased runoff to the NE Brazil margin (Arz et al., 1998; Jaeschke et al., 2007), slowing of the AMOC (McManus et al., 2004; Henry et al., 2016; Multiza et al., 2017), and decreased East Asian monsoon strength (Cheng et al., 2016) (Fig. 2, Fig. S4). The synchronicity of these events supports a southward migration of the ITCZ during HSs. In order to assess the precise timing of ITCZ migrations from a global perspective, we compare the NE Brazil pluvial phases associated with HS4 to East Asian monsoon intensity recorded in Hulu cave (stalagmites MSL and MSD; Cheng et al., 2016) located immediately north of the modern-day West Pacific ITCZ (Fig. 4). The precision of ^{230}Th dates of Hulu cave stalagmites is comparable to those from NE Brazil (0.1 kyr 2σ errors) and thus can be examined in detail. In both Chinese and Brazilian speleothems, HS4 can be divided into the following 3-phased structure.

6.1 Three-phased HS4

6.1.1 Phase I

The onset of NE Brazil speleothem growth at 40.06 ± 0.06 (TBV40 age model) marks the start of phase 1. Phase 1 is characterized by an aragonite growth phase in NE Brazilian stalagmites TBV40 and TBV 63 that persisted for 470 ± 70 years (TBV40 age model). The presence of cave aragonite is

commonly used as an indicator of aridity (e.g. Frisia et al., 2002), as seasonal dryness promotes evaporation, dry soil conditions, slower drip rate, more extensive degassing of CO₂ in the vadose zone above the cave, and enhanced prior-calcite precipitation, thereby leading to an increase in magnesium content in drip water. As a result, calcite precipitation is inhibited and aragonite may form (Fairchild et al., 2000). We therefore interpret phase 1 as a period of increased precipitation over NE Brazil relative to today, sufficient to initiate the growth of stalagmites while still maintaining semi-arid conditions as indicated by the presence of aragonite. High $\delta^{18}\text{O}$ values over this time interval also supports this scenario. The timing and duration of NE Brazilian phase 1 correlates in detail to the period of weak East Asian monsoon immediately following CIS 9, occurring in both records at 40.06 kyr B.P. within age uncertainties (Fig. 4). The synchronicity of both records suggest a global migration of the ITCZ southwards at this time, thereby weakening the East Asian monsoon while providing NE Brazil with enough rainfall to prompt the growth of aragonite speleothems.

6.1.2 Phase II (a-c)

The aragonite-to-calcite boundary in stalagmites TBV40 and TBV63 marks the onset of phase 2 (Fig. 3b). The boundary occurs at 39.59 ± 0.04 kyr B.P. (TBV40 age model) and corresponds to a drop of 5.9 ‰ in $\delta^{18}\text{O}$ in both stalagmites over a time span of less than 30 years. The duration of the observed $\delta^{18}\text{O}$ drop was calculated by counting the number of annual CFLM bands across the calcitic portion of the drop and extrapolating this growth rate across the aragonitic portion of the drop (<1.5mm), yielding 29 and 24 years from samples TBV63 and TBV40, respectively. A transition from aragonite to calcite in speleothems is estimated to induce a 0.6‰ decrease in $\delta^{18}\text{O}$ values under equilibrium conditions (Tarutani et al., 1969). Thus the observed shift of 5.9‰ in $\delta^{18}\text{O}$ in NE Brazil stalagmites at the aragonite-calcite boundaries is largely the result of an abrupt and significant shift in the isotopic composition of rainfall, with only ~10% of the shift attributable to change in mineralogy. The switch from aragonite to calcite and the abrupt lowering of NE Brazil $\delta^{18}\text{O}$ values at 39.59 kyr B.P. (± 0.04) occurs synchronously with the abrupt shift of Hulu Cave $\delta^{18}\text{O}$ to its highest value (Fig. 4), suggesting

a secondary ITCZ shift further south during this time. Immediately following the shift, lower $\delta^{18}\text{O}$ values and calcite growth are consistent with increased rainfall relative to phase 1. Therefore, much of the calcite growth phase of all three samples (phase 2a-c) likely represents the period of maximum rainfall over NE Brazil during this time interval, spanning a cumulative period of 520 ± 160 years (TBV40 age model).

CFLM bands identified in the calcitic growth phases of all three stalagmites provide detailed insight into seasonal precipitation patterns during this period of high rainfall. Bright (wet) and dark (dry) sections of annual CFLM bands immediately following the abrupt shift in oxygen isotope values suggest that the period of high rainfall was initially characterized by a single rainy season (phase 2a). Remarkably, all three stalagmites exhibit CFLM bands with consecutive bright couplets instead of single bright bands between 39.50 ± 0.04 and 39.41 ± 0.03 kyr B.P (TBV40 age model; Fig. 2). We interpret this “double-bright” structure to indicate that our cave site experienced two distinct periods of heavy rainfall per year during phase 2b, analogous to the modern day Guyanese coast region located at 6°N . From the double-bright structure, we infer that the southernmost extent of the South American inland section of the West Atlantic ITCZ reached a few to several hundred km south of our study site. As the West Atlantic ITCZ oscillated north-south seasonally, it would pass over TBV and TBR caves twice annually, providing two distinct periods of intense rainfall ultimately recorded in NE Brazil stalagmites as two bright sections at the end of each annual growth band. Immediately after the “double-bright” century, the CFLM bands remain well-defined, but return to the more common single band structure, implying a single rainy season (phase 2c). The single-band structure is consistent throughout the remaining ~ 4 centuries of phase 2 (phase 2c). Over these same centuries, NE Brazil $\delta^{18}\text{O}$ values gradually increase implying continual drying, during which a gradual recovery of the East Asian monsoon is also observed. We interpret phase 2c as the start of a gradual northward recovery of the global ITCZ.

6.1.3 Phase III

The onset of Phase 3 at 39.09 ± 0.1 kyr B.P. (TBR14 OxCal age model) is determined by the end of TBR14 growth and start of intermittent calcite growth identified within the last <4mm of TBV63 and TBV40 (Fig. S4). Why TBR14 ceased growing while TBV63 and TBV40 continued intermittent growth during phase 3 is likely due to differing collection depths: stalagmites TBV40 and TBV63 grew at shallower depths (~15 and ~20 m.b.s. respectively) than TBR14 (~30 m.b.s.) and are presumed to be more susceptible to surface infiltration. The presence of intermittent growth is interpreted as a period of intermittent rainfall over NE Brazil. Intermittent rainfall may be due to a gradual northward recovery of the ITCZ during this time, as supported by a simultaneous gradual recovery of the East Asian monsoon intensity towards interstadial conditions (Cheng et al., 2016). Intermittent growth of shallow NE Brazil speleothems may also be linked to a gradual increase in local vegetation density and soil profile development throughout the HS4 pluvial period, thereby restricting surface infiltration. The lack of aragonite deposition during phase 3 is likely due to limitations in prior calcite precipitation, either through increasing vegetation cover (decreasing surface evaporation) and/or the development of a vadose zone water buffer, thereby generating environmental conditions that are unfavorable for aragonite deposition. Intermittent calcite growth continues until approximately 38.38 ± 0.10 kyr B.P. (TBV40 ^{230}Th date), coinciding with the abrupt onset of GIS/CIS 8.

6.2 High- to low-latitude reconciliation

In order to investigate the three NE Brazil phases in the context of high-latitude events during HS4, we compare our record to the Northern Greenland Eemian Ice Drilling (NEEM) ice core record (Fig. 5) of both high-latitude ($\delta^{18}\text{O}_{\text{ice}}$) and low-latitude ($\delta^{18}\text{O}_{\text{atm}}$) proxies (Fig. 5). $\delta^{18}\text{O}_{\text{atm}}$ reflects the $\delta^{18}\text{O}$ of atmospheric oxygen (O_2), a major source of which is produced in the Northern Hemisphere lower latitudes via photosynthesis. On millennial timescales, variations in $\delta^{18}\text{O}_{\text{atm}}$ are interpreted as changes in the water cycle and biosphere productivity in the Northern Hemisphere low-latitudes (Severinghaus et al., 2009). We additionally compare the timing of NEEM and WAIS methane (CH_4) variations, which

reflect the activation/deactivation of CH₄ sources in response to changes in low-latitude rainfall patterns (Chappellaz et al., 2013).

NEEM $\delta^{18}\text{O}_{\text{ice}}$ values decrease at the onset of HS4 stadial conditions (~39.9 kyr BP) and remain uniformly low throughout HS4 (Guillevic et al., 2013). This observation is supported by firn gas fractionation ($\delta^{15}\text{N}$) indicating cold and stable temperatures over the entirety of Greenland Stadial (GS) 9 (Guillevic et al., 2013). Conversely, shifts in low-latitude proxies recorded in NEEM can be broken down into three phases, referred to here as NEEM Phases 1-3 (Guillevic et al., 2014). NEEM Phase 1 (39.9 to 39.3 kyr B.P., GICC05 chronology) is defined by decreases in both NEEM and WAIS CH₄ concentrations (Chappellaz et al., 2013; Rhodes et al., 2015) likely due to the drying of the North Hemisphere subtropics (deactivation of CH₄ sources) during the initial displacement of the global ITCZ in response to the start of North Atlantic stadial conditions (e.g. Deplazes et al., 2013). NEEM Phase 2 (39.3 to 38.50 kyr B.P., GICC05 chronology) is characterized by (1) an abrupt increase in NEEM and WAIS CH₄ concentrations (Rhodes et al., 2015; Chappellaz et al., 2013) and (2) an enrichment of $\delta^{18}\text{O}_{\text{atm}}$ values (Guillevic et al., 2014). A rise in global CH₄ is attributed to a wetting of the Southern Hemisphere subtropics (activation of CH₄ sources) (Chappellaz et al., 2013; Rhodes et al., 2015). The enrichment of $\delta^{18}\text{O}_{\text{atm}}$ values signals an enrichment of meteoric waters feeding the terrestrial biosphere in the Northern Hemisphere low-latitudes and overall decrease in bio-productivity, both of which are attributed to a drying of the northern subtropics and weakening of monsoon systems in the Northern Hemisphere (Severinghaus et al., 2009). Rises in global CH₄ and $\delta^{18}\text{O}_{\text{atm}}$ during NEEM Phase 2 are interpreted to reflect a period of maximum southerly displacement of the ITCZ (Guillevic et al., 2014; Chappellaz et al., 2013; Rhodes et al., 2015). The delayed shift in NEEM low-latitude proxies (approximately 550 ±60 years after the onset of stadial conditions) is in agreement with SST reconstructions at the Iberian Margin, suggesting an onset of cooling at approximately 40.18 kyr B.P. that lasted ~500 years prior to peak North Atlantic C_{37:4} alkenone percentages (indicative of an ice rafting event) within the same sediment core (Martrat et al., 2007). These observations support the hypothesis that ice rafting events occurred several centuries after North Atlantic surface

cooling/subsurface warming under a weakened AMOC state (Bond and Lotti 1995; McManus et al., 2004; Henry et al., 2016; Barker et al., 2015). In total, NEEM Phase 2 is interpreted as a period of maximum reorganization of ocean and atmospheric circulation. NEEM Phase 3 (38.50 to 38.20 kyr B.P.; GICC05 chronology) is characterized by a stabilization of global $\delta^{18}\text{O}_{\text{atm}}$ and CH_4 concentrations (Guillevic et al., 2014; Chappellaz et al., 2013; Rhodes et al., 2015), which is interpreted as a period of recovery towards interstadial conditions prior to the onset of GIS 8. A more gradual rate of change in $\delta^{18}\text{O}_{\text{atm}}$ values during NEEM Phase 2 the onset of GIS 8 is expected due to the long residence time of O_2 in the atmosphere (1000–2000 years) relative to CH_4 (10 years).

Although the uncertainty of the GICC05 and WD2014 timescales during HS4 limits the ability to assess the precise synchronicity of these distant records, the timing of shifts and duration of phases presented here, which are precisely dated, are in agreement with the timing of shifts and duration of phases registered in the polar ice core records. Building off of Guillevic et al. (2014), we propose the following series of events: (1) ~5 centuries of low Greenland temperatures, North Atlantic surface cooling, and weakened AMOC conditions prior to HE4 facilitated an initial southward migration of the global ITCZ, which prompted aragonite growth in NE Brazil speleothems (phase 1), decreased East Asian monsoon intensity, and initial drying in the Northern Hemisphere subtropics which triggered decreased global CH_4 concentrations. (2) An additional southerly shift of the ITCZ at 39.59 ± 0.04 kyr B.P., likely triggered by the initiation of HE4 ice rafting, prompted calcite growth in NE Brazil (phase 2) and an additional decrease in East Asian monsoon intensity. Between 39.50 ± 0.04 and 39.41 ± 0.03 kyr B.P, maximum displacement of the inland West Atlantic ITCZ provided NE Brazil with two rainy seasons (double-bright bands). During this period of maximum HS4 expression, the activation of new Southern Hemisphere subtropical CH_4 sources facilitated an increase in global CH_4 concentrations while a drying of the Northern Hemisphere subtropics enriched global $\delta^{18}\text{O}_{\text{atm}}$ values. (3) Intermittent rainfall in NE Brazil (phase 3), recovery of East Asian monsoon intensity, resumption of AMOC, and stabilization of CH_4 and $\delta^{18}\text{O}_{\text{atm}}$ suggest a gradual recovery of the ITCZ prior to the onset of GIS/CIS 8.

Due to our unprecedented age control, the timing of NE Brazil pluvial phases may provide critical temporal constraints for polar ice records during HS4 and thus shed insight on the timing of North Atlantic events leading up to, during, and after HE4. We argue that the abrupt wetting over NE Brazil at 39.59 ± 0.04 kyr B.P. represents a time marker for the transition from precursor North Atlantic surface cooling to full HE4 expression. Moreover, the duration of the transition to maximum pluvial conditions in NE Brazil (30 years) suggests that the initiation of massive iceberg discharge associated with HE4 and extension of cold, polar waters southward occurred over the span of no more than 2 to 3 decades.

Understanding the timescales associated with multiple collapses of the LIS during the last glaciation has become increasingly important, as similarities between these past events and the predicted future collapse of the WAIS continue to be revealed (Alley et al., 2015). Although the authors acknowledge the different boundary conditions between the past LIS and present WAIS, we note that our inferred HS4 timescales (a century to centuries of favorable ocean-atmospheric conditions leading up to the collapse, and a few decades for the commencement of the main discharge event) are of the same order as those predicted by DeConto and Pollard (2016) for the future of the WAIS.

7. Conclusions

We present a multi-stalagmite precipitation record that constrains the timing of the NE Brazil pluvial period associated with HS4 to between 40.06 ± 0.06 and 38.38 ± 0.10 thousand years (kyr) B.P. Oxygen isotope analysis shows a detailed anti-correlation between NE Brazil wet periods and Hulu Cave Chinese monsoon intensity, with three distinct phases identifiable in both records. A precursor, less intense pluvial interval (phase 1) between 40.06 ± 0.06 and 39.59 ± 0.04 kyr B.P. likely corresponds to an initial migration of the ITCZ following GIS/CIS 9. Phase 1 ends abruptly (<30 years) at 39.59 ± 0.04 kyr B.P. and is followed by an intense pluvial phase (phase 2). Double-bright CLFM bands identified during phase 2 indicate a change in seasonality between 39.50 ± 0.04 and 39.41 ± 0.03 kyr B.P., and are interpreted to represent a period when the southernmost seasonal extent of the inland section of the West Atlantic ITCZ was south of our study site (10°S). Phase 3 is characterized as a

period of intermittent rainfall over NE Brazil and a gradual increase in East Asian monsoon intensity, likely corresponding to a gradual northward recovery of the ITCZ until the onset of GIS/CIS 8 at 38.38 ± 0.10 kyr B.P. In total, the pluvial anomaly associated with HS4 lasted for 1680 ± 110 years, including the last ~ 700 years of intermittent stalagmite growth (table 1). The phases identified in NE Brazil stalagmites agree, both in timing and duration, with the three phases identified in low-latitude proxies record in the NEEM and WAIS ice cores, thus supporting a multi-phased response of tropical atmospheric circulation during HS4. In particular, an abrupt increase in CH_4 concentrations recorded in NEEM and WAIS ice cores coincide with a period of maximum rainfall over NE Brazil (phase 2), suggesting the activation of Southern Hemisphere subtropical CH_4 sources during this period of maximum ITCZ displacement. The synchronicity of high-to low-latitude records allows the precisely dated NE Brazil pluvial phases to provide critical temporal constraints for polar ice records. We argue that the maximum southerly shift of the ITCZ, dated to 39.59 ± 0.04 kyr B.P., represents a time marker for the transition from precursor North Atlantic surface cooling to full HE4 expression. The timescales of favorable North Atlantic ocean-atmospheric conditions leading up to the partial LIS collapse (few centuries) and duration of the main discharge event (few decades) interpreted here on the same order as recent predictions for the collapse of the WAIS in the coming centuries.

FIGURE and TABLE CAPTIONS

Fig. 1: (A) Annual mean precipitation (mm/day) from 1979 to 2017 (GPCP 2016). Yellow arrows indicate prevailing wind direction. Purple dots indicate location of nearby GNIP stations. Orange dots indicate location of studies discussed in this text: 1–Cariaco Basin (Deplazes et al., 2013), 2–GeoB16224.1 (Zhang et al., 2017), 3–Paraíso cave (Wang et al., 2017), 4–GeoB16202.2 (Mulitza et al., 2017), 5–GeoB 3910.2 (Jaeschke et al., 2007), 6–Rio Grande do Nord (Cruz et al., 2009), 7 and 8–Paixão and Lapa Sem Fim caves (Strikis et al., 2015), 9–Botuverá cave (Wang et al., 2006), 10–Pacupahuain cave (Kanner et al., 2012), 11–El Condor cave (Cheng et al., 2013), 12–Santiago cave (Mosblech et al., 2012). (B) Dashed lines show the approximate mean and seasonal southerly extent of the modern West Atlantic ITCZ for illustration purposes (see text). Shaded region indicates the approximate extent of north and central NE Brazil, whose annual rainfall amount is predominately controlled by seasonal migrations of the ITCZ. Purple dots indicate GNIP stations with corresponding weighted mean annual $\delta^{18}\text{O}$ precipitation values (IAEA/WMO 2018). The GNIP station located near our study site (Floresta) is indicated by an asterisk. (C) Mean monthly rainfall amount and $\delta^{18}\text{O}$ data from GNIP station Floresta in the state of Pernambuco (IAEA/WMO 2018).

Fig. 2: Global records discussed in text from 80 to 10 kyr B.P. Grey bars indicated timing of HS 6 (a-b), 5, 4, and 1. (A) Ca/Sr ratios indicating the presence of North Atlantic IRD (Hodell et al., 2008). (B) Northern Greenland Ice Core project $\delta^{18}\text{O}$ (NGRIP members, 2004). (C) Iberian margin SST reconstructions (Martrat et al., 2007). (D) North Atlantic marine sediment Pa/Th ratios reflecting AMOC intensity (Henry et al., 2016). (E) East Asian monsoon intensity record (Cheng et al., 2016). (F) Cariaco basin runoff amount derived from sediment reflectance (L^*) (Deplazes et al., 2013). (G) NE Brazil stalagmite growth intervals indicating pluvial conditions in green (this study) and pink (Wang et al., 2004). (H) WAIS Divide ice core methane concentrations (Rhodes et al., 2015).

Fig. 3: (A) Stacked record of NE Brazil pluvial phase associated with HS4, including TBV63 (brown), TB40 (intermediate green), and TBR14 (dark green). Black circles represent ^{230}Th ages with 2σ uncertainties. Phases 1, 2, and 3 identified by dashed boxes. Phase 2b is highlighted with shaded bar. (B) Examples of fluorescent banding throughout phase 2. White bars represent approximately 250 μm . From bottom: phase 2a commences at the transition from acicular aragonite fabric to calcite fabric containing thin annual bright-to-dark couplets. Phase 2b contains large annual double-bright (or bright-bright-dark) couplets. Phase 2c returns to thin annual bright-to-dark couplets.

Fig. 4: Comparison of the NE Brazil pluvial period (this study) and East Asian monsoon weak interval (stalagmites MSL and MSD, Cheng et al., 2016) associated with HS4. ^{230}Th age location and associated 2σ uncertainties for both records are shown. Phases 1-3 are indicated with shaded boxes.

Fig. 5: Comparison of NE Brazil pluvial period (this study) with the NEEM and WAIS polar ice cores. Each record is plotted on its independently published timescale (GICC05 and WD2014 to kyr B.P.). From top: NEEM $\delta^{18}\text{O}_{\text{ice}}$ (Guilleveic et al., 2013), NEEM CH_4 (Chappellaz et al., 2013), NEEM $\delta^{18}\text{O}_{\text{atm}}$ (Guilleveic et al., 2014), NE Brazil pluvial period including ^{230}Th ages with 2σ uncertainties (this study), and WAIS ice core methane concentrations (Rhodes et al., 2015). Phases 1-3 are indicated with shaded boxes.

Table 1: Summary of ^{230}Th -dated growth periods of stalagmites TBV63, TBV40, and TBR14, ordered here by HS. Uncertainties reported to 2σ . *HS6b is defined here as the cool period between Greenland Interstadial 19 and 18 (NGRIP Members, 2004). The growth phases listed here are from this study, and do not include all NE Brazil stalagmite growth phases reported in Wang et al. (2004).

Table 2: Summary of CLFM bands vs ^{230}Th years in the calcite growth phase of each stalagmite. ^{230}Th years were calculated by subtracting the maximum and minimum years (derived by individual OxCal age models) for the calcite growth phase each stalagmite. ^{230}Th uncertainties are reported to 2σ . See methods for the

determination of band-counting uncertainties. CLFM are consistently less than total ^{230}Th years due to “missing” growth bands due to the presence of small growth hiatuses.

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475 Figure 3

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NE Brazil Pluvial Period (listed by associated HS)	Timing (kyr B.P.)	Duration (yr)
HS1	17.07±0.04 - 16.09±0.07	980±80
HS4		
Phase I	40.06±0.06 - 39.59±0.04	470±70
Phase II	39.59±0.04 - 39.07±0.16	520±160
Phase IIb	39.50±0.04 - 39.41±0.03	90± 50
Phase III	39.07±0.16 - 38.38±0.10	680±184
Full growth phase	40.06±0.06 - 38.38±0.10	1680± 110
HS5	48.88±0.10 - 47.80±0.17	1080± 200
HS6b (GIS 19/18)*	66.74±0.10 - 65.56±0.11	1180± 150

Stalagmite	CLFM bands	²³⁰ Th years
TBV40	373 ± 60	500 ± 80
TBV63	457 ± 228	470 ± 120
TBR14	423 ± 139	520 ± 200

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