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Key Points:

- Speleothem and other paleoclimate records confirm a wet climate in tropical South America within the Younger Dryas
- Precise speleothem multiproxy records reflect a bipartition of the Younger Dryas precipitation in northeastern Brazil
- Gradual South-North climate transition in the Atlantic responded to a gradual increase in atmospheric CO₂ within the YD

Supporting Information:

Supporting Information may be found in the online version of this article.

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Gradual South-North Climate Transition in the Atlantic Realm Within the Younger Dryas

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Abstract The abrupt climate event Younger Dryas (YD) has been extensively studied; however, its structure is still poorly understood. Climate in northeastern Brazil is very sensitive to the latitudinal position of the intertropical convergence zone (ITCZ) associated with abrupt climate change in the Atlantic. Here, we report changes in the ITCZ position within the YD by using precise speleothem multiproxy records from northeastern Brazil. We provide evidence for a gradual northward migration of the ITCZ preceding poleward shifts of the westerlies and the polar front in northern high latitudes within the YD. This can be attributed to gradual increase in atmospheric CO₂ concentration as a consequence of the weakening Atlantic Meridional Overturning Circulation (AMOC). We suggest that a persistent increase in atmospheric CO₂ might have triggered a resumption of the AMOC and reorganization of the atmosphere circulation in the Atlantic during the mid-YD.

Plain Language Summary The Younger Dryas (YD) is the most recent millennial-scale abrupt climate event in Earth history. Although its origin has been extensively studied, its structure is still poorly understood. Climate in northeastern Brazil is very sensitive to the latitudinal position of the intertropical convergence zone (ITCZ) responds to abrupt climate change in the Atlantic (e.g., YD). By using stable isotope and trace element proxy records of speleothem from Toca da Boa Vista Cave, northeastern Brazil, together with other paleoclimatic records in the Atlantic realm, we provide evidence for a gradual northward migration of the ITCZ preceding poleward shifts of the westerlies and the polar front in northern high latitudes within the YD. This can be attributed to a gradual increase in atmospheric CO₂ concentration under the situation of weakening Atlantic Meridional Overturning Circulation (AMOC). A persistent increase in atmospheric CO₂ concentration might have triggered a resumption of the AMOC and reorganization of the atmosphere circulation in the Atlantic during the mid-YD.

1. Introduction

The Younger Dryas (YD; 12,846–11,653 years before 1950 CE based on the NGRIP GICC05 chronology [Rasmussen et al., 2006]) is the most intensively studied climatic event during the transition from the last glacial period to the Holocene, especially with respect to its trigger mechanisms (Broecker, 2006; Clark et al., 2002). This event has been generally attributed to the disruption of the Atlantic Meridional Overturning Circulation (AMOC; Clark et al., 2002) resulting from a large freshwater influx into the North Atlantic or to the Arctic Ocean causing massive sea-ice expansion during winter (Broecker, 2006; Condon & Winsor, 2012; Keigwin et al., 2018; Murton et al., 2010; Not & Hillaire-Marcel, 2012; Tarasov & Peltier, 2005). Recently, the timing of the YD was significantly improved using speleothem data (12,870 ± 30 to 11,700 ± 40 years CE) and the mechanisms of its trigger, propagation, and termination were refined by a comprehensive and global comparison of high-resolution records

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Figure 1. Geographic context for this study showing locations of selected records from different climate regimes. Ice cores: NGRIP and GISP2 (Rasmussen et al., 2006) and WDC (Sigl et al., 2016); Marine cores: MD99-2284 (Faeroe–Shetland passage) (Bakke et al., 2009), HU90031-044 (St. Lawrence River) (Carlson et al., 2007), KNR166-2-26JPC (Florida Straits) (Schmidt & Lynch-Stieglitz, 2011), and PL07-39PC and PL07-58PC (Cariaco Basin) (Hughen et al., 2000); Lake sediments: Kråkenes (KR, Norway) (Bakke et al., 2009), Meerfelder Maar (MFM, Germany) (Lane et al., 2013), and Laguna de Los Anteos (Venezuela) (Stansell et al., 2010); Stalagmites: Chauvet Cave (France) (Genty et al., 2006), Seso Cave (Spain) (Bartolomé et al., 2015; Cheng et al., 2020), Fort Stanton Cave (FS, USA) (Asmerom et al., 2017), and Toca da Boa Vista Cave (TBV, NE Brazil, this study).

(Cheng et al., 2020). In contrast to the intensively studied onset of the YD, its structure (variability and long-term trend within the YD) has not yet received much attention (Bakke et al., 2009; Bartolomé et al., 2015; Pearce et al., 2013). Recently, several paleoclimatic records (Bakke et al., 2009; Bartolomé et al., 2015; Lane et al., 2013; Schlolaut et al., 2017) from the Northern Hemisphere (NH) indicated that the AMOC regained some of its strength during the mid-YD, resulting in an initial cold phase followed by a climatic amelioration between the mid-YD and the end of the YD. The progressive warming of the subtropical Atlantic Ocean and the concomitant gradual resumption of the AMOC in the mid-YD were accompanied by the northward retreat of both the polar front and the latitudinal position of the westerlies, as confirmed by paleoclimatic records from NH midlatitudes (Baldini et al., 2015; Bartolomé et al., 2015; Belli et al., 2017; Schmidt & Lynch-Stieglitz, 2011). In contrast, this “bipartition” feature of the YD has not been reported in the Southern Hemisphere (SH) climate archives, limiting our understanding about the structure of the YD on a global scale.

Here, we present multiproxy data from a precisely dated and partly annual lamina-counted stalagmite (TBV13; Figure S1) from Toca da Boa Vista (TBV) Cave (40°51′39″W, 10°9′36″S; 600 m above sea level;

Figure 1) in northeastern (NE) Brazil in order to examine the structure of the YD in the tropical SH. Today, NE Brazil is semiarid, located immediately south of the intertropical convergence zone (ITCZ; Hastenrath, 2000). Precipitation in this region varies as a function of the latitudinal position and seasonal fluctuations of the Atlantic ITCZ, with the majority of rainfall occurring when the ITCZ is at its southernmost seasonal extent during austral spring (Marengo et al., 2012; Novello et al., 2017; Wang et al., 2004). A previous study has demonstrated that speleothem and travertine growth pulses in the TBV Cave correspond to short wet periods which resulted from a southward migration of the ITCZ during the cold periods in the NH associated with Heinrich stadials in the last glacial period (Wang et al., 2004). Therefore, this site is ideal to explore the structure and mechanism of the YD. Our new data document a gradual northward migration of the ITCZ preceding changes in atmospheric circulation in the northern high latitudes within the YD. Together with other paleoclimatic records, we suggest that the reorganization of atmosphere circulation in the Atlantic and a resumption of the AMOC during the mid-YD might be triggered by the persistent increase in atmospheric CO₂ concentration.

2. Methods

Samples for ²³⁰Th-dating were hand-drilled along the growth axis of halved stalagmite TBV13 and spiked with a mixed ²³⁵U–²³³U–²²⁹Th spike similar to that described in Edwards et al. (1987). Separate uranium and thorium liquid extracts were measured using a multicollector-inductively coupled plasma-mass spectrometer (MC-ICP-MS) at the Institute of Global Environmental Change, Xi'an Jiaotong University. Details about the instrumental setup are provided in Cheng et al. (2000) and Cheng, Edwards, et al. (2013).

Stable isotope subsamples were micromilled along the growth axis of TBV13 and measured on a Thermo Fisher Delta V isotope ratio mass spectrometer equipped with a Gasbench II at the Institute of Geology, University of Innsbruck (Spötl, 2011). Results are reported relative to the Vienna Pee Dee Belemnite (VPDB) standard and the analytical precision is 0.08‰ and 0.06‰ for δ¹⁸O and δ¹³C, respectively (1σ).

Measurements of Sr/Ca and Ba/Ca ratios were performed by a multielemental scanning method using laser-induced breakdown spectroscopy (LIBS) at the Institute of Global Environmental Change, Xi'an Jiaotong University. LIBS is a fast analytical technique for obtaining long series of geochemical data including many trace elements (Fortes et al., 2012). Sample preparation, parameter setting, and data processing followed those described in Cáceres et al. (2017). Data were obtained by averaging 20 laser shots at each sample position following three laser shots used for cleaning the sample surface. Mg/Ca values in the aragonite section are too low to reach the LIBS detection line, thus Mg/Ca proxy was not used in this study. Detailed technology and settings are described in Li et al. (2018).

Confocal laser fluorescence microscopy (CLFM) was used to identify banding in the calcitic portion of stalagmite TBV13 (30–60 mm distance from the top) using a Nikon A1+ Multi-Photon operating with a 488-nm Ar-sourced laser line at the State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University. Detailed technology and settings are described in Zhao & Cheng (2017). A single band is defined by the sharp onset of fluorescence (wet season) followed by a more gradual transition toward non-fluorescent calcite (dry season) (Orland et al., 2012). Each clearly visible bright band was given a count of one. When banding was not clear and/or two bands were not clearly distinguishable, each band was given a count of 1.5 and assigned an error of 0.5.

3. Results

3.1. Chronology and Mineralogy

The chronology of this record is based on five ²³⁰Th dates and lamina counting, covering the interval from 12,500 ± 39 to 11,742 ± 76 years BP (Figure S2 and Table S1). X-ray diffraction analyses indicate calcite between 60 and 30 mm from the top deposited between 12,500 ± 39 and 12,168 ± 26 years BP, followed by aragonite between 30 and 0 mm from the top from 12,168 ± 26 to 11,742 ± 76 years BP (Figure S2). Aragonite formation is favored in water with a high Mg/Ca ratio and a low saturation level with respect to

Figure 2. Comparison between speleothem TBV13 and ice core records from Greenland between 13.2 and 11.2 ka BP. (a) Greenland ice core $\delta^{18}\text{O}$ record NGRIP (Rasmussen et al., 2006). (b) $\delta^{18}\text{O}$, (c) Sr/Ca, and (d) Ba/Ca records of speleothem TBV13 (this study). (e) Cariaco Basin sediment total reflectance (L^*) (Deplaze et al., 2013). (f) Ca^{2+} concentration in the GISP2 ice core record (Rasmussen et al., 2014). The Sr/Ca and Ba/Ca data of the aragonite and calcite sections are shown on different scales, because the aragonite values are 10 times higher than the calcite ones. Black dashed lines mark the duration of the YD stadial. Red dashed line indicates the mid-YD transition from wet to dry climate at 12,168 years BP documented by TBV $\delta^{18}\text{O}$ record. Blue and red columns indicate the periods of calcite (12,500–12,168 years BP) and aragonite (12,168–11,742 years BP) in TBV13. YD, Younger Dryas; TBV, Toca da Boa Vista.

the sharp transition from calcite to aragonite at $12,168 \pm 26$ years BP (Figures 2b–2d). Changes in speleothem $\delta^{13}\text{C}$ are generally controlled by the density and composition (C3/C4) of the vegetation above cave, which vary according to the hydroclimate, leading to higher $\delta^{13}\text{C}$ values during drier conditions (Cruz et al., 2006; Genty et al., 2006). The modern vegetation above the TBV Cave comprises shrub-like drought-resistant Caatinga (Wang et al., 2004). Both density and composition of vegetation (especially C3/C4 ratio) may have changed from a dry climate (between 12,500 and 16,116 years BP) to an extremely wet climate between 12,500 and 12,168 years BP, causing $\delta^{13}\text{C}$ variability on centennial–decadal time scales different from that of $\delta^{18}\text{O}$, Sr/Ca, and Ba/Ca in the calcite section (wet period) (Figure S3). Thus, in this study, we use the $\delta^{18}\text{O}$, Sr/Ca, and Ba/Ca as precipitation proxies. Of note is that raw $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data in the aragonite section have been corrected to calcite values by using -0.8‰ and -1.1‰ offset, respectively, based on different isotope fractionation factors between aragonite/calcite–water at cave temperatures (Figure S3) (Kim et al., 2007; H. Zhang et al., 2014, 2015).

CaCO_3 (De Choudens-Sánchez & González, 2009) during dry climate episodes and/or during the dry season (Railsback et al., 1994). Fluorescent bands were identified in the calcitic portion using CLFM, showing similar characteristics of growth band as observed in other studies (Wendt et al., 2019). A total of 332 ± 13 lamina counted in the calcitic portion are within the error of the ^{230}Th dates and these regular lamina are therefore regarded as annual (Figure S2 and Table S2). A hiatus can be observed at 60 mm from the top, the ^{230}Th age below the hiatus (66 mm from the top) is $16,116 \pm 183$ years BP (during Heinrich 1 event) (Figure S1 and Table S1), suggesting the stalagmite TBV13 resumed grow at $\sim 12,500$ years BP after the growth during the Heinrich 1 event. Thus, the material below 60 mm was not used in this study.

3.2. Speleothem Records and Their Climatic Implications

Records of $\delta^{18}\text{O}$, Sr/Ca, Ba/Ca (Figure 2), and $\delta^{13}\text{C}$ (Figure S3) from TBV13 indicate a two-phase variation within the YD stadial, showing lower values with a gradually increasing trend in the calcite section between 12,500 and 12,168 years BP and higher values in the aragonite section between 12,168 and 11,742 years BP. “Hendy tests” (Hendy, 1971) suggest that both the calcite and the aragonite part of TBV13 were deposited close to isotopic equilibrium (Figure S4), indicating that speleothem $\delta^{18}\text{O}$ largely reflects $\delta^{18}\text{O}$ of meteoric precipitation. Instrumental (Hastenrath, 2000) and paleoclimatic (Vuille et al., 2003) studies have convincingly shown that the $\delta^{18}\text{O}$ values of tropical Brazilian speleothems are primarily controlled by rainfall amount, though the degree of upstream rainfall might also have a significant influence, indicating that high $\delta^{18}\text{O}$ values correspond to reduced precipitation, and vice versa. Previous studies also suggest that higher Sr/Ca and Ba/Ca ratios in speleothems reflect decreased infiltration into the karst because of a lower precipitation minus evaporation balance (Cruz et al., 2007; Fairchild & Treble, 2009; Stoll et al., 2012). A dry climate gives rise to a longer residence time of the seepage water in the vadose zone, resulting in higher Sr/Ca and Ba/Ca ratios in the drip water, and consequently higher Sr/Ca and Ba/Ca ratios in the speleothems (Fairchild & Treble, 2009; Stoll et al., 2012).

The strong correlation between $\delta^{18}\text{O}$, Sr/Ca, and Ba/Ca in TBV13 argues for common controlling factors, with dry conditions corresponding to higher $\delta^{18}\text{O}$, Sr/Ca, and Ba/Ca values, and vice versa (Figures 2b–2d). It is notable that $\delta^{18}\text{O}$, Sr/Ca, and Ba/Ca show a gradual decrease before

4. Discussion

4.1. Pluvial Conditions in NE Brazil During the YD Stadial

In a previous study, Wang et al. (2004) reported a large number of speleothem deposition in TBV Cave during the Heinrich events, in contrast, no speleothem deposition occurred during the YD in TBV Cave, although some travertine formations were found during the YD in the nearby Salitre and Jacaré River Valleys. This was attributed to insufficient rainfall to promote speleothem formation during the YD (Wang et al., 2004). However, our new data of TBV13 are indeed a complement and partly question this interpretation, implying a humid climate during the YD but presumably drier than that during the Heinrich events. The growth period of speleothem TBV13 between 12,500 and 11,742 years BP is synchronous within error with the pluvial period documented in ocean sediment core GB3910 off the continental margin of NE Brazil (Strikis et al., 2015) and speleothem records from tropical South America (Figure S5) (Cheng, Sinha, et al., 2013; Mosblech et al., 2012; Novello et al., 2017; Strikis et al., 2018) and also correlates with a dry interval recorded by marine sediments in the Cariaco Basin (Deplazes et al., 2013; Haug et al., 2001) (Figure 2e) and the YD cold period documented in NGRIP $\delta^{18}\text{O}$ (GICC05) (Rasmussen et al., 2006) in Greenland (Figures 2a and 2f). This supports the hypothesis that a southward migration of the ITCZ in response to a reduction of the AMOC and sea-ice expansion in the North Atlantic dramatically increased precipitation in NE Brazil (Broecker, 2006). Of note is that both TBV13 multiproxy records and sediment total reflectance from the Cariaco Basin show a “bipartition” feature of the ITCZ during the YD (Figures 2e and 2f), with a gradual northward migration of the ITCZ before the sharp transition from calcite to aragonite at $12,168 \pm 26$ years BP.

4.2. Bipartition of the YD Stadial in Tropical South America

The bipartition of the YD, that is, an initial cold phase followed by a second phase of climatic amelioration associated with a first resumption of the AMOC, is captured by several records from the northern midlatitudes and high latitudes (Baldini et al., 2015; Bartolomé et al., 2015; Genty et al., 2006; Lane et al., 2013; Scholaut et al., 2017). Until now, however, there was no report of such a bipartition of the YD in the SH, although it is suggested by some paleoclimatic records from tropical America, but these records are of low resolution and/or show rather large dating uncertainties (Figure S5). Precisely dated and high-resolution data of TBV13 provide the first record of such an intra-YD change in the SH (Figures 2b–2d), consistent with sediment total reflectance from the Cariaco Basin (Figure 2e). The data indicate a gradual decrease in precipitation from 12,500 to 12,168 years BP, followed by relatively drier conditions until the beginning of the YD termination at 11,742 years BP. Taking these records together (Figure 2), we conceive two stages for the YD in tropical South America: (1) the reduction of the AMOC intensity at the beginning of the stadial led to a southerly migration of the ITCZ, resulting in dramatically increased precipitation in the study area around 12,500 years BP initiating growth of TBV13. Precipitation gradually decreased between 12,500 and 12,168 years BP due to the gradual northward migration of the ITCZ. (2) Between 12,168 and 11,742 years BP, the ITCZ remained at a northerly position (but still south of the present-day position) resulting in relatively less precipitation in the study area. A rapid northward migration of the ITCZ in response to the full recovery of the AMOC at $11,742 \pm 76$ years BP is consistent with the abrupt termination of the YD in the northern high latitudes (Figure 2).

4.3. Interhemispheric Atlantic Seesaw During the YD Stadial

A comparison with other high-resolution records shows that this gradual intra-YD climate transition was spatially variable from the tropical SH to the northern high latitudes (Figure 3). Our TBV13 records (Figure 3i), together with a lacustrine Ti record from Venezuela (Figure 3h) (Stansell et al., 2010) and a sediment reflectance record from the Cariaco Basin (Figure 3e) (Deplazes et al., 2013), indicate a gradual northward migration of the ITCZ at $12,500 \pm 39$ years BP. This was synchronous with the northward migration of the westerlies across northern Spain and southern France, reflected by the gradually increased humidity documented by speleothem $\delta^{13}\text{C}$ records from Spain (Figure 3g) and speleothem $\delta^{18}\text{O}$ records from France (Figure 3f) at $12,450 \pm 50$ years BP (Baldini et al., 2015; Bartolomé et al., 2015; Rossi et al., 2018). TBV13 multiproxy records indicate that the ITCZ migrated significantly

Figure 3. Comparison of high-resolution climate records between 13.2 and 11.2 ka BP from different climate regimes. (a) NGRIP $\delta^{18}\text{O}$ record from Greenland (Rasmussen et al., 2006). (b) SST record from marine core MD99-2284 located in the Faeroe–Shetland passage (Bakke et al., 2009). (c) Ti record from Lake Kråkenes, Norway (Bakke et al., 2009). (d) Ti record from Meerfelder Maar, Germany (Lane et al., 2013). (e) Cariaco Basin sediment total reflectance (L^*) (Deplaze et al., 2013). (f) Stalagmite $\delta^{18}\text{O}$ record from Chauvet Cave, France (Genty et al., 2006). (g) Stalagmite $\delta^{13}\text{C}$ record from Seco Cave, NE Spain (Bartolomé et al., 2015). (h) Ti record of lacustrine sediment from Laguna de Los Anteojos, Venezuela (Stansell et al., 2010). (i) Stalagmite $\delta^{18}\text{O}$ record from TBV Cave (this study). The black and red dashed lines and the blue and red columns are similar to those in Figure 2. The yellow zone highlights the gradual climate transition from the tropical SH to the high-latitude North Atlantic. SST, sea surface temperature; TBV, Toca da Boa Vista; SH, Southern Hemisphere.

northward at $12,168 \pm 26$ years BP (Figure 2), consistent with the timing ($12,196$ years BP) in the Cariaco Basin sediment reflectance record within error (red dashed line in Figure 3). A precise correlation based on lacustrine sediments in Europe shows that the poleward shifts of the westerlies and polar front across Meerfelder Maar (MFM) in Germany to Kråkenes (KR) in Norway (Figures 3c and 3d) occurred at $12,190 \pm 40$ and $12,070 \pm 40$ years BP, respectively (Lane et al., 2013). This is further supported by a significant northward shift of the westerlies across southern France (Genty et al., 2006) (Figure 3f) and 3NE Italy (Belli et al., 2017), southern Germany (Brauer et al., 2008; von Grafenstein et al., 1999), southwestern Turkey (Fleitmann et al., 2009), and New Mexico, USA (Fort Stanton Cave in Figure 1) (Asmerom et al., 2017) during the mid-YD (Figure S6), despite their limited sampling resolution and less well-constrained chronology. The first and largest sea surface temperature (SST) peak in core MD99-2284 (Bakke et al., 2009) (Figure 3b) from the Faeroe–Shetland passage occurred ~ 100 years after the retreat of the polar front in KR, Norway, which is ~ 150 years earlier than the temperature increase on the NGRIP (Figure 3a). These records indicate that the northward migration of the ITCZ and the poleward shifts of the westerlies and the polar front was time transgressive. Besides the time-transgressive transition of climate change from the tropical to the northern Atlantic, the transitional duration also became shorter toward NH high latitudes (yellow zone in Figure 3).

A significant migration of the ITCZ at $12,168 \pm 26$ years BP (Figure 3i), which resulted in the change in the stalagmite's mineralogy corresponding to a change toward dry conditions in NE Brazil, was synchronous with the poleward shift of the westerlies across the southern Germany and a resumption of the AMOC. Although the mid-YD transition occurred synchronously in the southern and the northern subtropical Atlantic, unstable climate occurred earlier in the subtropical Atlantic (Figures 3e–3i) than in the northern high-latitude Atlantic (Figures 3a–3d) during the early YD ($12,500$ – $12,168$ years BP). Some lacustrine and marine sediment studies presented evidence of a gradual increase of the AMOC preceding the rapid decline of the sea-ice cover at the end of the YD, suggesting that the SH (Talbot et al., 2007) or the ocean circulation (Pearce et al., 2013) may have played a significant role in the termination of the YD. Using a fully coupled atmosphere–ocean model, X. Zhang et al. (2017) proposed that the atmospheric moisture transport across Central America, driven by a gradual increase in atmospheric CO_2 (~ 15 ppm), triggered the AMOC recovery from cold Heinrich stadial conditions by increasing the salinity in the subtropical North Atlantic (Leduc et al., 2007). A comparison of paleoclimate records from the low and high latitudes sheds light on the ocean–atmospheric interactions during the YD. After the onset

of the YD at $12,846$ years BP possibly caused by freshwater injection (Figures 4a and 4b), cooling in Greenland and the North Atlantic resulted in a gradual warming in Antarctic (Figures 4h and 4i) and an increase in atmospheric CO_2 concentration (Figure 4j) via the “interhemispheric Atlantic seesaw” (Barker et al., 2009, 2011; Broecker, 1998; Cheng et al., 2020; Denton et al., 2010). Gradually rising atmospheric CO_2 concentrations (Bereiter et al., 2015; Hughen et al., 2000) (Figure 4j) led to increasing SSTs in the Cariaco Basin (Lea et al., 2003) (Figure 4d) and the Florida Straits (Schmidt & Lynch-Stieglitz, 2011) (Figure 4g) during the early YD. Moisture transport from the Atlantic to the Pacific Ocean across Central America led to relatively high salinities in the North Atlantic Ocean and contributed to the formation of North Atlantic Deep Water (Leduc et al., 2007; Peterson et al., 2000), resulting in

Figure 4. Mechanism of the resumption at mid-YD linked to possible factors. (a) NGRIP $\delta^{18}\text{O}$ record. (b) U/Ca ratio from HU90031-044 in the mouth of the St. Lawrence estuary (Carlson et al., 2007). (c) $^{231}\text{Pa}/^{230}\text{Th}$ profiles of core GGC5 from the Bermuda Rise (McManus et al., 2004). (d) Mg/Ca-derived SST record from sediment core PL-07-39PC located in Cariaco Basin (Hughen et al., 2000). (e) Detrended $\Delta^{14}\text{C}$ record from sediment core PL-07-58PC in the Cariaco Basin (Hughen et al., 2000). (f) TBV13 $\delta^{18}\text{O}$ record (this study). (g) Mg/Ca-based SST record from core KNRI66-2-26JPC in the Florida Straits (Schmidt & Lynch-Stieglitz, 2011); (h) Antarctic WDC $\delta^{18}\text{O}$ record on the WD2014 chronology (Sigl et al., 2016). (i) Antarctic Temperature Stack (ATS) changes from five Antarctic ice cores on the EPICA Dome C (EDC) chronology (Parrenin et al., 2013). (j) CO_2 concentration from EDC (Bereiter et al., 2015). The black and red dashed lines and the blue and red columns are similar to those in Figure 2. YD, Younger Dryas; SST, sea surface temperature.

a weak increase in the AMOC intensity (McManus et al., 2004) (Figures 4e and 4c). Carlson et al. (2008) demonstrated increased salinity in the subtropical Atlantic during periods of weakened AMOC and a possible resumption of a shallow overturning circulation that leads a full resumption of the AMOC at the end of the Younger Dryas. The gradual increase in atmospheric CO_2 led to warming in the subtropical North Atlantic faster than its southern counterpart, promoting a northward shift in position of the ITCZ (Hastenrath, 2000; Nobre & Shukla, 1996) (Figure 4f). This atmospheric–ocean interaction between the northern and southern Atlantic during the YD is consistent with Cheng et al. (2020). However, cold and dry conditions still dominated in the northern high latitudes with extensive winter sea ice in the North Atlantic during the early YD (Figures 3a–3d). In response to persistently increasing CO_2 concentration of ~ 15 ppm during the early YD between 12,500 and 12,168 years BP (Figure 4j), gradual warming in the North Atlantic pushed the sea-ice edge further northward (Figure S7 and Figure 5a) and increased salinity in the subtropical Atlantic led to a possible resumption of a shallow overturning circulation (Carlson et al., 2008), resulting in a resumption of the AMOC at 12,168 years BP before its full recovery at the end of the YD (Figures 4c, 4e and 5a), and the reorganization of the atmosphere circulation in the Atlantic (including a significant northward movement of the ITCZ, and the poleward shifts of the westerlies and the polar front in the northern high latitudes) (Figures 3 and 5a and Figure S7). After that, the AMOC regained more strength under the sustained increase of atmospheric CO_2 during the late YD (Figures 4c and 4j) although a subsequent smaller freshwater injection can be observed (Figure 4b), the ITCZ and the westerlies stayed further northward than those during the early YD (Figures 3c–3h and 5b) and the SST in the Faeroe–Shetland Channel and the temperature in the Greenland increased (Figures 3a, 3b and 5b and Figure S7). The final recovery of the AMOC occurred after additional increase in atmospheric CO_2 at the end of the YD (Figures 4c and 4j). This, in addition to the relative stable and intermediate-sized global ice volume during the YD (Carlson & Clark, 2012; Fairbanks, 1989), supports the assertion that AMOC resumption and recovery can be triggered by gradual increase in atmospheric CO_2 under intermediate glacial conditions (X. Zhang et al., 2017).

5. Conclusions

Our TBV13 record documents a bipartition of the YD stadial in northeastern Brazil with a wet climate during the early YD between $12,500 \pm 39$ and $12,168 \pm 26$ years BP and a drier condition during the late YD between $12,168 \pm 26$ and $11,742 \pm 76$ years BP. A comparison with other paleoclimate records supports a gradual northward migration of the ITCZ preceding the variations in the atmospheric circulation in the northern mid to high latitudes (i.e., the poleward shift of the westerlies and the polar front) during the early YD, related to an

increase in atmospheric CO_2 as a consequence of the weakening AMOC. We propose that an increase in atmospheric CO_2 concentration during the early YD might have triggered a resumption of the AMOC and the reorganization of the atmosphere circulation in the Atlantic during the mid-YD, corroborating previous paleodata and model results.

Figure 5. Summary cartoon of the mechanism proposed in this study. (a) Early YD stadial with a weak AMOC. (b) Late YD stadial with an enhanced AMOC. The study site is marked by the red star (TBV Cave) and the black dots show the locations of other climate records (KR, Kråkenes Lake [Bakke et al., 2009]; MFM, Meerfelder Maar [Lane et al., 2013]; Seso Cave [Bartolomé et al., 2015; Cheng et al., 2020]; FS, Fort Stanton Cave [Asmerom et al., 2017]). Purple and green dashed lines represent the ITCZ and the westerlies, respectively, and gray arrows indicate the polar front. Red and blue belts/arrows indicate the upper northward and deeper southward AMOC branch, respectively. Modified from X. Zhang et al. (2017). YD, Younger Dryas; AMOC, Atlantic Meridional Overturning Circulation; TBV, Toca da Boa Vista; ITCZ, intertropical convergence zone.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data presented in this study can be found in supplementary information and in the public paleoclimate databases of NOAA (<https://www.ncdc.noaa.gov/paleo/study/33013>).

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