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Millennial-scale climate variability during the last 12.5 ka recorded in a Caribbean speleothem

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ABSTRACT

We present a speleothem stable oxygen isotope record for the last 12.5 ka based on two stalagmites from western Cuba. The $\delta^{18}O$ signal is interpreted to represent past precipitation variability.

Both stalagmites show a pronounced transition from higher $\delta^{18}O$ values (indicating drier conditions) to more negative $\delta^{18}O$ values (suggesting wetter conditions) between 10 and 6 ka. This transition is also visible in a planktonic $\delta^{18}O$ record off Haiti. On orbital timescales, the $\delta^{18}O$ value of Caribbean precipitation, thus, strongly resembles the oxygen isotope composition of Caribbean surface water.

On millenial timescales, the speleothem $\delta^{18}O$ record shows a high correlation to a North Atlantic sea surface temperature (SST) record off West Africa as well as a similarity with the Bond events. Periods of lower North Atlantic SST correspond to less precipitation in the Caribbean and vice versa. The potential teleconnection to the Caribbean may reflect the position of the Intertropical Convergence Zone because a further southward position of the ITCZ leads to reduced precipitation in the northern Caribbean.
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1. Introduction

Tropical and subtropical Atlantic climate and hydrological conditions play an important role in the global climate system either as a feedback to changes in the Northern Hemisphere or as a driving mechanism for global climate conditions (Chiang, 2009).

Present-day climate variability in the Caribbean is influenced by atmospheric and oceanic processes in both the Pacific and the Atlantic Oceans (Giannini et al., 2001a, 2001b, Jury et al., 2007). Sea surface temperature (SST) anomalies in the North Atlantic may influence the meridional movement of the Intertropical Convergence Zone (ITCZ) and precipitation in the Caribbean (Knight et al., 2006). On multi-decadal timescales, for instance, the ITCZ is located further north during periods of higher SSTs in the North Atlantic (Sutton and Hodson, 2005). Higher evaporation rates during phases of warm North Atlantic SSTs lead to more precipitation in the Caribbean including Cuba (Lachniet, 2009a; Poveda et al., 2006). The ITCZ reaches Cuba, which is in close proximity to Mesoamerica, in September (Haug et al., 2003).

On millennial timescales, Caribbean climate anomalies have been suggested to be in phase with climate change in Europe (Haug et al., 2001; Hillesheim et al., 2005). Similarly, for the period between 9 and 11.5 ka, a connection between Caribbean precipitation anomalies and the Bond events (Bond et al., 2001) has been suggested (Hillesheim et al., 2005). The Bond events represent basin-wide North Atlantic cold events occurring every ~1500 a (Bond et al., 1997, 2001), which were also observed in sediment records off West Africa (deMenocal et al., 2000). They are thought to be related to a weakening of North Atlantic Deep Water (NADW) formation (Bond et al., 1997, 2001), which may result in a weakening of the Thermohaline Circulation (THC) and a southward shift of the ITCZ (Knight et al., 2006).

Climate change in the Caribbean area has also played an important role in local human history. For instance, episodes of severe drought on the Yucatan peninsula are thought to have caused the collapse of the Maya civilization (Hodell et al., 1995; Haug et al., 2003; Curtis et al., 1996). It is, therefore, important to investigate the processes controlling climate variability in the Caribbean (Jury et al., 2007).

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Proxy archives of past precipitation variability provide important information in order to understand the processes influencing Caribbean precipitation anomalies on decadal to millennial timescales. Stable isotope and trace element signals in speleothems have shown to be sensitive, high-resolution proxies for past precipitation (Fairchild and Treble, 2009; Lachniet, 2009b) and can be dated very precisely by U-series methods (Scholz and Hoffmann, 2008). In the Caribbean area, speleothem studies are still sparse. Fensterer et al. (2012) present high-resolution stalagmite data from Cuba covering the last millennium. Other stalagmite studies from the Caribbean include Mangini et al. (2007a), Medina-Elizalde et al. (2010), Lachniet et al. (2004a,b) and Winter et al. (2011). Most of these studies cover a few millennia only.

Here we present high-resolution oxygen isotope records from two stalagmites from north-western Cuba, which provide proxy data for past precipitation changes covering most of the last 12 ka. We investigate the relationship to North Atlantic SST anomalies on millennial timescales as well as to salinity changes on orbital timescales.

2. Sample location and analytical methods

Stalagmite Cuba Pequeño (CP) was collected in the Dos Anas cave system (14 km length), which is located in the Sierra de los Organos (Province of Pinar del Rio, Cuba, Fig. 1). The 420 mm-long stalagmite grew ~1.5 km from the cave entrance at an elevation of 120 m. The thickness of the rock overburden at this location is ~130 m. The upper 240 mm of the stalagmite consist of aragonite as confirmed by XRD. Below 240 mm the stalagmite consists of calcite.

Stalagmite Cuba Medio (CM) was collected in the Santo Tomas cave system, which is in close vicinity to the Dos Anas cave (~20 km, Fig. 1). Stalagmite CM grew in Torch cave, approximately at a height of 170 m above sea level with ~60 m of rock overburden. The stalagmite has a length of 520 mm.

^{230}Th/U-dating of stalagmite CP was performed using two instruments, thermal ionization mass spectrometry (TIMS, performed at the Heidelberg Academy of Sciences) and multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS, performed at the Bristol Isotope Group, Bristol University). Stalagmite CM has been solely dated using the TIMS method. Chemical preparation of the samples and analytical details are described in Hoffmann et al. (2007) and Hoffmann (2008) for MC-ICPMS and Scholz et al. (2004) for TIMS.

Stable isotopes (oxygen and carbon) were sampled and analyzed at Innsbruck University at a resolution of 0.2 mm for CP corresponding to a temporal resolution of ~4–10 a. The resolution for CM is 0.1 mm corresponding to a temporal resolution of ~15 a. All stable isotope values are reported relative to the VPDB standard. Long-term precision of the δ^{13}C and δ^{18}O values, estimated as the 1σ-standard deviation of replicate analyses, is 0.06‰ and 0.08‰, respectively (Spötl and Vennemann, 2003).

Minor element concentrations were measured along the growth axis of CP by ICP-OES at Heidelberg University in order to confirm the transition from aragonite to calcite at 240 mm distance from top. The internal 1σ-standard deviation is $<1\%$ for Ca, Mg and Sr. NIST 1643e is used as a standard, and its 1σ-standard deviation of replicate analyses is 1 mg/l for Ca, 0.4 mg/l for Mg, and 6 μg/l for Sr.

3. Results

18 TIMS and 20 MC-ICPMS ^{230}Th/U-ages were determined for CP (Fig. 2, black circles represent ICP-MS ages, red triangles are TIMS ages, see also supplementary Tables 1–3). All ages are corrected for detrital contamination assuming a bulk Earth ^{238}U/^{232}Th activity ratio of 0.8 ± 0.4. Stalagmite CP has a high U content of up to 6 μg/g (supplementary Tables 1 and 2), which is probably due to its aragonitic structure (see below). Thus, despite of the relatively high ^{232}Th content of up to 90 ng/g (supplementary Tables 1 and 2), the detrital correction is only significant for two samples. Detailed investigation of another stalagmite from the same cave has revealed that detrital correction using a bulk Earth ^{238}U/^{232}Th activity ratio is not appropriate for this sample and that a higher ^{238}U/^{232}Th ratio must be used (Fensterer et al., 2010, 2012). However, this speleothem comes from a different part of the cave, consists of calcite and has a very low U content. Therefore, the two samples are not directly comparable, and we refrain from applying this correction to CP. The age model for the top 240 mm of CP (Fig. 2, grey line) has been determined using the StalAge algorithm (Scholz and Hoffmann, 2011). In general, CP shows a relatively slow growth rate of 8 μm/a during the last 2.5 ka. Between 2.5 and 3.3 ka, the age model indicates a hiatus

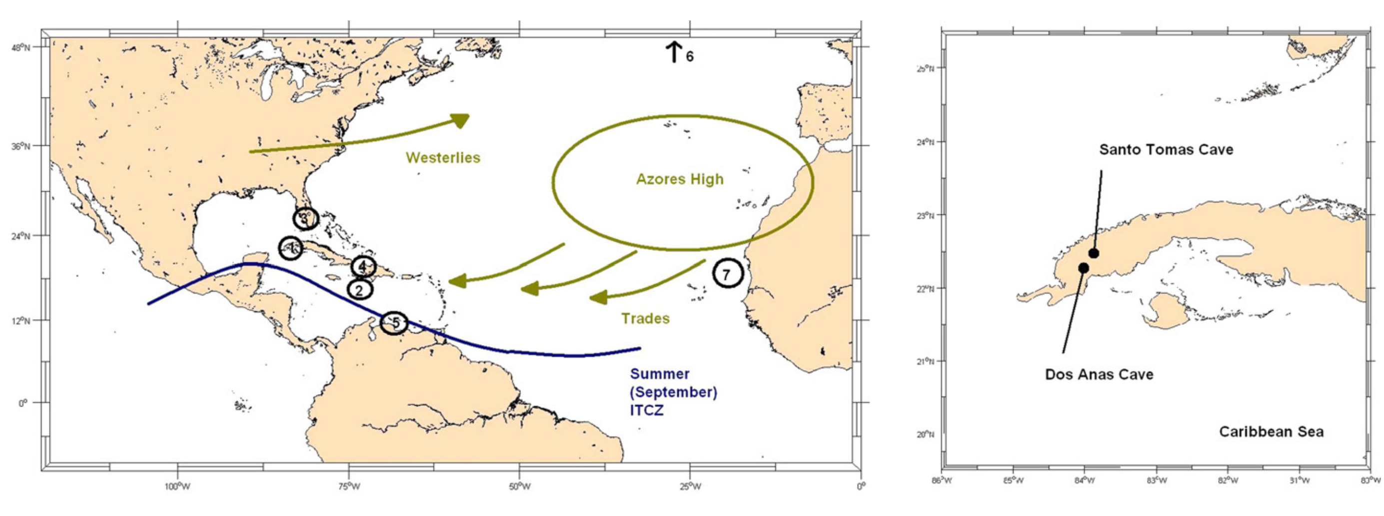

Fig. 1. Left: Location of the records discussed in this study. (1) Cuba, two stalagmite δ^{18}O records, this study; (2) south of Haiti, planktonic δ^{18}O sediment record (Horn, 2011); (3) Florida, lake pollen records (Grimm et al., 1993); (4) Haiti, lake sediment δ^{18}O record (Hodell et al., 1991); (5) Cariaco basin, sediment Titanium content (Haug et al., 2001); (6) south of Greenland, hematite-stained grains sediment record (Bond et al., 2001); (7) off West Africa, sediment SST record (deMenocal et al., 2000); also shown are the major Atlantic climate patterns, such as the Azores High, the trade winds, the Westerlies and the September ITCZ from Haug et al. (2003). Right: Location of the two speleothem sampling sites: Dos Anas cave (stalagmite Cuba Pequeño) and Santo Tomas cave system (stalagmite Cuba Medio) located in western Cuba.

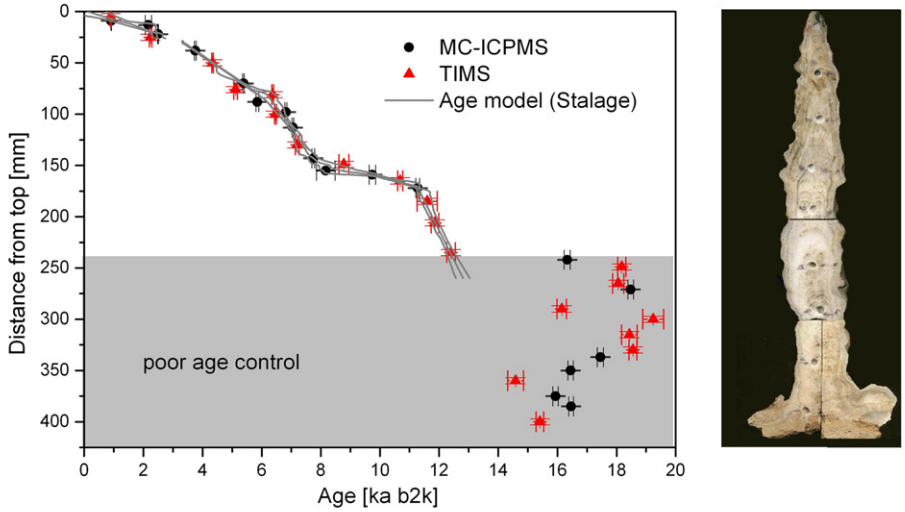

Fig. 2. ^{230}Th/U-chronology and longitudinal section of stalagmite CP. MC-ICPMS ages are shown as black circles, TIMS ages as red triangles. The age model calculated using StalAge (Scholz and Hoffmann, 2011) and the corresponding 95%-confidence limits are shown in grey. CP shows a slow growth rate of 8 μm/a during the last 2.5 ka, a hiatus between 2.5 and 3.3 ka and higher growth rates between 3.3 and 8 ka (between 19 and 29 μm/a). Between 8 and 11.5 ka, the growth rate was ~10 μm/a and 58 μm/a between 11.5 and 12.5 ka. Note the loss of age control below 240 mm distance from top, which is due to recrystallization of aragonite to calcite. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

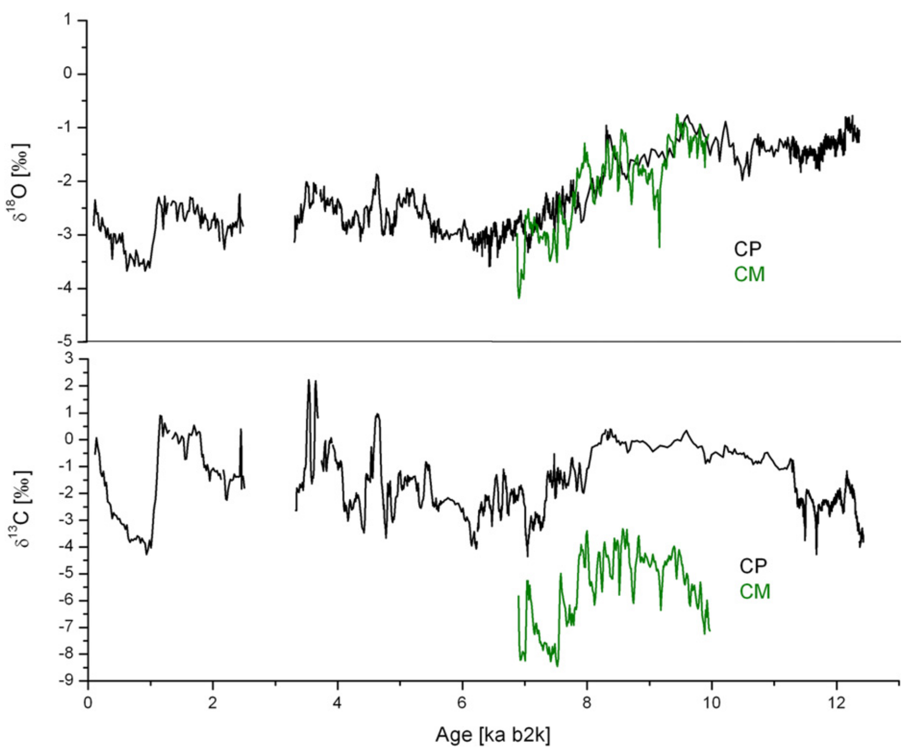

Fig. 3. δ^{18}O and δ^{13}C records of stalagmites CP, which grew during the last 12 ka, and CM, which grew between 7 and 10 ka. The upper panel shows the δ^{18}O records (black: CP; green: CM), the bottom panel shows the δ^{13}C data of the two stalagmites. From 12.5 to 9 ka, the δ^{18}O signal of CP shows values around −1.5‰. Between 9 and 6 ka, the values decrease to mean values around −3‰ during the last 6 ka. The δ^{18}O signal of CM shows similar absolute values and the same decreasing trend as CP between 10 and 7 ka. The δ^{13}C signal of CP shows values around −2‰, the δ^{13}C signal of CM is lower (~5‰). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Fig. 2). The growth phase between 3.3 and 8 ka shows higher growth rates (i.e., between 19 and 29 μm/a). Between 8 and 11.5 ka, the growth rate is slower with a value of 10 μm/a. Finally, CP shows a rather high growth rate of 58 μm/a between 11.5 and 12.5 ka.

Below 240 mm distance from top, the ages show large scatter and several age inversions (Fig. 2). This clearly shows that at least some of the ages determined for this section are not accurate. The aragonite and calcite content, respectively, of the stalagmite was determined by XRD, which revealed that the upper part of the stalagmite consists of aragonite, whereas the part below 240 mm is calcite. This is confirmed by the results of trace element analysis, which are shown in supplemental Fig. S1. In the section above 240 mm, Mg/Ca ratios are relatively low (~0.002), whereas Sr/Ca weight ratios are rather high (~0.0013). Below 240 mm distance from top, the stalagmite reveals relatively high Mg/Ca ratios (~0.012) and low Sr/Ca ratios (~0.0003). Considering the different partition coefficients of Mg and Sr for aragonite respectively calcite (Morse and MacKenzie, 1990; Huang and Fairchild, 2001), these trace element patterns confirm the sharp transition from calcite to aragonite at 240 mm distance from top. A similar trace element pattern has been found in aragonitic layers within a calcitic stalagmite from the western Mediterranean (McMillan et al., 2005). Post-depositional recrystallization of aragonite to calcite is accompanied by remobilization (i.e., loss and/or addition) of U. This represents a violation of one of the basic assumptions of ^{230}Th/U-dating and has a large effect on the ^{230}Th/U-ages (Holzkämper et al., 2009; Scholz and Mangini, 2007).

The ages in the upper section do not show the large scatter observed for the lower section (Fig. 2). However, not all ages are in stratigraphic order within their uncertainty. Based on the XRD and trace element data, we consider post-depositional recrystallization of aragonite to calcite unlikely as the reason for these age inversions. StalAge (Scholz and Hoffmann, 2011) takes into account such problems for age model construction and appropriately increases the uncertainty of the final age model. Thus, the uncertainty of the age model of CP is, at least for some sections of the stalagmite, relatively large (up to 800 a, Fig. 2, compare also Fig. 10 in Scholz et al. (in press)). A detailed discussion of the CP record and a comparison with other methods for age model construction is given in Scholz et al. (in press).

Stalagmite CM has only been dated at low resolution by three TIMS ages (Fig. S2). The age model has also been obtained by application of StalAge. The slope of the fit is 0.135 ka/mm, which corresponds to a slow growth rate of 7 μm/a.

The stable isotope records of both stalagmites are shown in Fig. 3. For CP, only the part above 240 mm is shown due to poor age control in the bottom part. The δ^{18}O signal of CP shows three different phases. In the oldest part, from 12.5 to 9 ka, the δ^{18}O signal shows relatively high values around −1.5‰. Between 9 and 6 ka, the δ^{18}O values progressively decrease, and during the last 6 ka, the δ^{18}O signal shows mean values around −3‰. The δ^{18}O signal of CM shows similar absolute values and the same decreasing trend as CP between 10 and 7 ka. Since the age control of CM is relatively poor, we focus on millennial-scale climate variability here. The δ^{13}C signal of CP shows values around −2‰ with a relatively high peak-to-peak variability of 6‰. The δ^{13}C signal of CM is generally lower (~5‰) than that of CP and shows a variability of up to 2‰.

The correlation between the raw δ^{18}O and δ^{13}C signals of CP is shown in Fig. S3. Two different slopes are visible. Whereas the correlation is rather high (r^2=0.58) for the data from the last 8 ka, it is much lower (r^2=0.18) for the older time interval.

Some sections of the aragonitic part of CP show distinct growth layers and two Hendy (1971) tests could be performed. The results of these tests are shown in Fig. S4. All Hendy tests show a relatively stable δ^{18}O signal with a maximum peak-to-peak variability of 0.5‰. The correlation between δ^{18}O and δ^{13}C is not significant for both Hendy tests (r_1^2=0.13 and r_2^2=0.10) indicating a low degree of kinetic isotope fractionation (McDermott, 2004).

4. Discussion

4.1. Climatic interpretation of stalagmite δ^{18}O

For the circum-Caribbean area, the amount effect has been suggested as one of the most important drivers of the δ^{18}O values of precipitation (e.g., Vuille et al., 2003). On seasonal to inter-annual timescales, values between −1.60 and −2.85‰/100 mm were established for the relationship between δ^{18}O and the amount of precipitation in Panama (Lachniet and Patterson 2006; Lachniet et al., 2004b). Values between −2.20 and −2.75‰/100 mm were found for Barbados (Jones et al., 2000), and −1.24‰/100 mm for Belize (Lachniet and Patterson, 2009).

However, other effects may also influence the δ^{18}O signals in speleothems, such as changes in cave temperature or drip rate (Mühlinghaus et al., 2009; Lachniet, 2009b). For instance, higher δ^{18}O values are expected during periods of drier climate and decreasing drip rate (Mühlinghaus et al., 2009). In the tropics, higher temperatures are usually related to more precipitation and lower δ^{18}O values (Vuille et al., 2003). Higher cave temperatures would result in lower δ^{18}O values in speleothem calcite (Mühlinghaus et al., 2009) and, therefore, amplify the negative relationship between rainfall amount and speleothem δ^{18}O. In summary, all potential effects should influence the δ^{18}O signature in the same direction, and we interpret lower speleothem δ^{18}O values as a proxy for more rainfall and vice versa.

The interpretation of speleothem δ^{13}C signals is non-trivial since δ^{13}C is influenced by a complex interplay of various processes occurring in the soil and karst above the cave, inside the cave and on the stalagmite surface (McDermott, 2004; Fairchild et al., 2006; Scholz et al., 2009; Dreybrodt and Scholz, 2011). Robust interpretation of speleothem δ^{13}C values largely benefits from a cave monitoring program (e.g., Frisia et al., 2011; Mattey et al., 2008), which is currently not available for the two caves on Cuba. As a consequence, we do not use the speleothem δ^{13}C signals as a climate proxy here.

4.2. Holocene transition (10–6 ka)

The most pronounced feature of the δ^{18}O record is the transition from higher δ^{18}O values (indicating drier conditions) to more negative δ^{18}O values (suggesting wetter conditions) between 10 and 6 ka (Fig. 4a, black). Superimposed on this transition are millennial-scale dry/wet events, which will be discussed separately. The CM δ^{18}O record (Fig. 4a, green) confirms the transition phase recorded in CP in both magnitude and timing. This transition to wetter conditions is also recorded by several other climate proxies in the Caribbean region. For instance, a lake sediment record from Haiti (Hodell et al., 1991, Fig. 4d, olive) shows a very similar trend to wetter conditions. This trend was interpreted to reflect a change in lake level due to increasing precipitation and was attributed to orbital forcing (Fig. 4d, orange, Berger, 1978). In contrast to this record, the CP δ^{18}O record does not show a pronounced return to drier conditions after 5 ka. Two pollen records from Florida (Grimm et al., 1993, Fig. 4c, cyan) also show a trend towards wetter climate in the Caribbean area with a similar timing indicated by the abundance of pine. Peros et al. (2007) argue that increasing humidity in the Caribbean was caused by both decreasing insolation and increasing sea level. Finally, the Cariaco basin sediment record (Fig. 4e, blue) shows a trend towards wetter conditions that started after the Younger Dryas and peaked between 10.5 and 5.5 ka (Haug et al., 2001) during the Holocene thermal maximum. Although the transition to wetter conditions is pronounced in all records, the timing of the transition is not exactly the same in all records. This may, at least in part, be related to the dating uncertainties of the individual records. For instance, the age model of stalagmite CP is associated with uncertainties of up to 1.6 ka at the 95%-confidence level in the section including the transition, which is mainly due to the change in growth rate at ca. 150 mm distance from top (Fig. 2, see also Scholz et al. (in press), for a detailed discussion). Similarly, a large hard water effect of 1000 a has been assumed for the calculation of the ^{14}C ages of the lake sediment record from Haiti (Hodell et al., 1991). Finally, the chronology of the pollen record from Florida is only based on a single calibrated

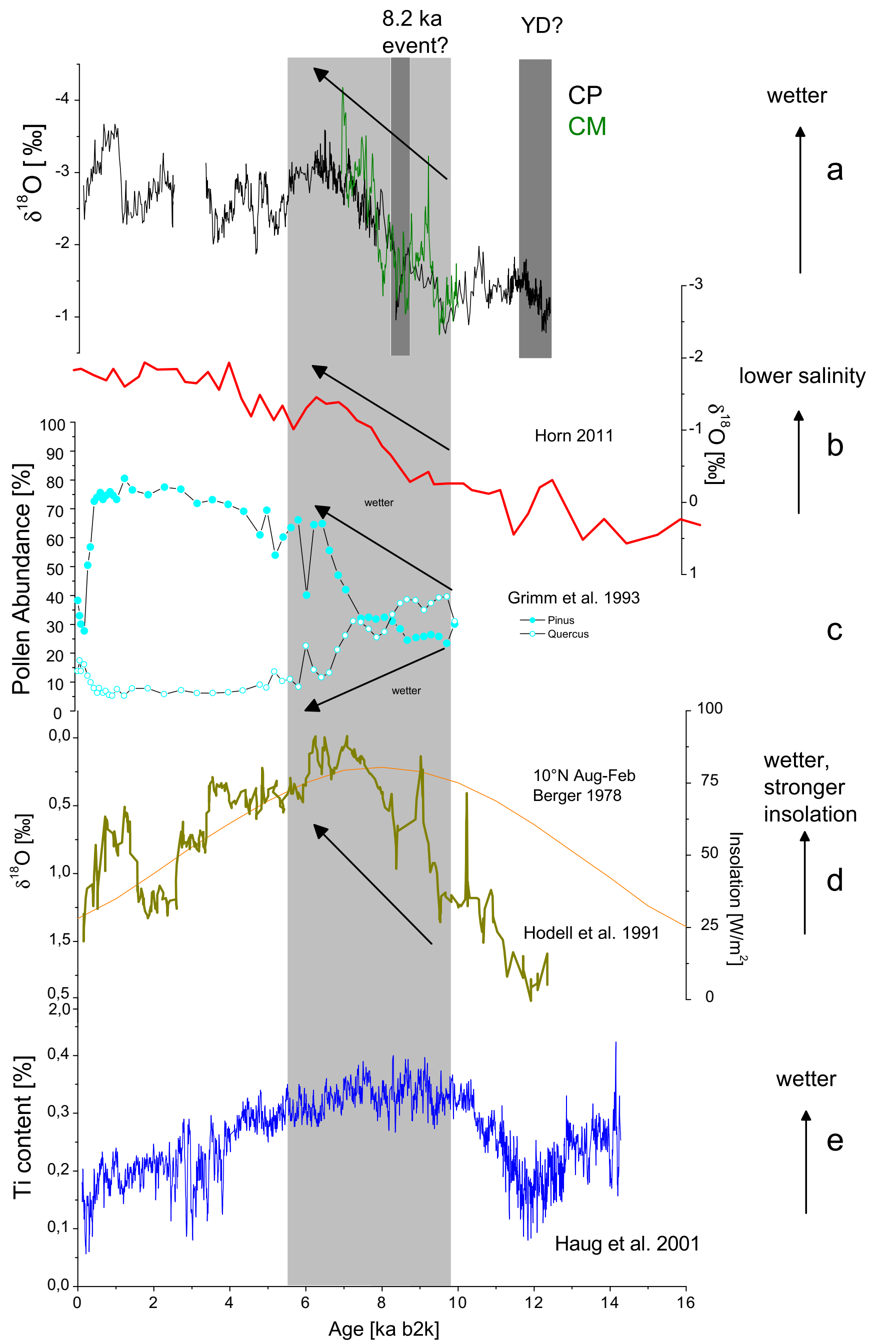

Fig. 4. Stalagmite δ^{18}O values in comparison with other Holocene Caribbean climate proxy records for the last 16 ka. (a) Stalagmite δ^{18}O records of CP and CM, Cuba, this study; (b) planktonic δ^{18}O values from a sediment core off Haiti (Horn, 2011); (c) pollen abundance in a record from Florida, USA (Grimm et al., 1993; note that here the calibrated ^{14}C chronology from Peros et al. (2007) is shown); (d) lake sediment δ^{18}O record from Haiti (Hodell et al., 1991) together with the insolation curve for 10°N (orange) (Berger, 1978). The ^{14}C ages of Hodell et al. (1991) were calibrated using the algorithm of Danzeglocke et al. (2011); (e) Titanium content of the sediment record from the Cariaco basin (Haug et al., 2001). The light grey bar highlights the transition towards more negative δ^{18}O values between 10 and 6 ka, which is visible in all δ^{18}O records and was simultaneous with a transition to wetter conditions in Florida. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

^{14}C age (ca. 8200 a) in the section of the transition. Another option is that the observed discrepancies in the timing of the transition are due to local effects affecting the individual climate archives.

Despite of the chronological uncertainties discussed above, both the millennial-scale pattern and the orbital-scale trend of the CP δ^{18}O record do not correlate with the Cariaco basin record. A potential reason for this is that the CP record from Cuba might be more influenced by Atlantic SSTs, whereas the sediment record is more influenced by South American climate patterns.

The CP record also shows a good agreement with a planktonic δ^{18}O record off Haiti (Horn, 2011, Fig. 4b, red), which is interpreted as a gradual decrease in relative sea surface salinity at the core site from 10 to about 4 ka. Interestingly, the change in δ^{18}O values during the transition (i.e., ~2.5‰) is similar in both records. Since Cuba is relatively close to the major source of Caribbean precipitation (i.e., the North Atlantic and the Caribbean Sea), this indicates that the CP δ^{18}O signal reflects sea surface δ^{18}O on orbital timescales. On shorter time-scales, it is not possible to deduce the influence on the stalagmite $\delta^{18}O$ values due to the low resolution of sea surface $\delta^{18}O$ values.

4.3. The Younger Dryas and the 8.2 ka event

Previous studies have suggested a relationship between climate change in the Caribbean and the high-latitude North Atlantic on a variety of timescales (Hughen et al., 1996; Hillesheim et al., 2005). Major North Atlantic cold events such as the Younger Dryas or the 8.2 ka event were probably related to changes in the THC. This may have affected the latitudinal position of the ITCZ (Cheng et al., 2009). Furthermore, the accompanying reduction of North Atlantic SST is thought to have resulted in stronger trade winds over the tropical North Atlantic (Hughen et al., 1996). A strengthening of the trade winds and/or a southward displacement of the North Atlantic anticyclone may have led to a decreased strength and/or southward displacement of the ITCZ (Giannini et al., 2000). This could have resulted in drier conditions in the Caribbean area (Lachniet et al., 2004a).

In order to test this potential relationship, we examine the $\delta^{18}O$ signals of the Cuban stalagmites for the two most pronounced cold events in the North Atlantic realm in the last 13 ka, the Younger Dryas cold period (from 12.9 to 11.7 ka, Rasmussen et al. (2006)) and the 8.2 ka event (Alley et al., 1997).

For the Younger Dryas, Haug et al. (2001) reconstructed dry climate conditions in the Caribbean area on the basis of Ti content in the Cariaco basin sediment record. Unfortunately, the YD is not fully represented in our record, which starts at 12.4 ka. Furthermore, the chronology at the boundary to the lower section, which shows evidence for recrystallization, is poorly constrained and we cannot unambiguously infer climate conditions in the Caribbean for this important climate phase. However, around 12 ka, the $\delta^{18}O$ signal of CP shows up to 1‰ higher values than during the Preboreal (Fig. 4a). This may indicate drier climate in the northern Caribbean during the YD.

Several authors reported climatic change in the Caribbean area around 8 ka and suggested a relation with the 8.2 ka event. Hughen et al. (1996) proposed enhanced trade winds during this period, and Hillesheim et al. (2005) related drier conditions in Guatemala to the 8.2 ka event. In addition, Lachniet et al. (2004a) reported drier conditions and a weaker Central American Monsoon in Costa Rica on the basis of stalagmite $\delta^{18}O$ values, and Hodell et al. (1995) reconstructed drier conditions in Mexico using $\delta^{18}O$ values of lacustrine gastropods.

In our record, the 8.2 ka event falls within the Holocene transition, which dominates the $\delta^{18}O$ record of CP. Although the $\delta^{18}O$ values decrease by 2‰ between 10 and 6 ka, we identify a short peak of relatively high values around 8.3 ka, which might reflect drier conditions and may be attributed to the 8.2 ka event. The precise timing of this event recorded in Greenland ice cores is 8240 a (Vinther et al., 2006), and its duration has been determined to 160 a (Thomas et al., 2007). The 'dry phase' in the CP record falls in the time range between 8.7 ($\pm$0.6) and 8.2 ($\pm$0.4) ka. The CM record shows similar features between 8.7 ($\pm$0.2) and 8.1 ($\pm$0.1) ka (Fig. 4). This event may be related to the 8.2 ka event. However, considering the relatively low magnitude of the event recorded in the two Cuban speleothem records and that the record shows several other events of similar magnitude, a detailed statement on the impact of the 8.2 ka event in the northern Caribbean is not possible.

4.4. Holocene millennial-scale variability

The Bond events are cold events that occurred in the North Atlantic during the Holocene with an approximate time spacing of 1500 a (Bond et al., 1997, 2001). Several other authors found that these millennial-scale Holocene SST variations appear to have involved the entire North Atlantic basin (O'Brien et al., 1995; Bianchi and McCave, 1999; Keigwin, 1996; Mangini et al., 2007b) and involved large-scale oceanic and atmospheric reorganizations with a duration from decades to centuries. deMenocal et al. (2000) also found periods of cold SST with a similar timing off West Africa and, thus, suggested a relationship with the Bond events.

Fig. 5 shows a comparison of the $\delta^{18}O$ record of CP (Fig. 5c, black) with the percentage of hematite-stained grains (HSG, Fig. 5a, green) in sub-polar North Atlantic deep-sea sediments, which record the Bond events (Bond et al., 1997, 2001). HSG are transported by drift ice, and higher amounts of HSG are interpreted as reflecting colder temperatures. Also shown is the SST record off West Africa (deMenocal et al., 2000, Fig. 5b, red and blue). Other SST reconstructions for the Caribbean (e.g., Lea et al., 2003) have a relatively low temporal resolution, which is why we focus on the record of deMenocal et al. (2000) here.

The numbers in Fig. 5a identify the different Bond events, and the lines highlight the coincidence of these periods of cold conditions in the North Atlantic with low SSTs off West Africa (Fig. 5b). Bond event 6 is an exception in this context as it is not clearly reflected in the SST record (Fig. 5b). The CP stalagmite record shows higher $\delta^{18}O$ values during most of these phases suggesting drier conditions in the Caribbean (Fig. 5c). These phases of elevated $\delta^{18}O$ are centered at 11.3, 10.3, 9.7, 5.2, 4.6 and 1.5 ka as well as at the top of the stalagmite. These dry phases may reflect Bond events 8, 7, 6, 4, 3 and 1. For Bond event 8, the $\delta^{18}O$ values do not show such a clear positive excursion as for Bond events 6 or 7. Bond event 4 seems to have started ~500 a later in the CP record, but in agreement within the dating uncertainties. A counterpart for Bond event 5 is not visible, but this may be related to the large change in $\delta^{18}O$ values during the transition between 10 and 6 ka, which is also visible in the SST record off West Africa. This large transition may mask Bond event 5. The hiatus between 2.5 and 3.3 ka may reflect dry climate conditions during Bond event 2 (Fig. 5c). However, this hiatus may also be due to local processes in the aquifer above the cave and, thus, does not necessarily reflect drier conditions. A positive excursion in $\delta^{18}O$ around 3.5 ka does not have a counterpart in the HSG record. This dry phase is close to Bond event 2. However, the uncertainty of the age model in this section of the stalagmite is rather low (ca. $\pm$30 a, Fig. 2, see also the detailed discussion in Scholz et al. (in press)). Consequently, this phase is unlikely to correspond to Bond event 2.

The overall good agreement of the timing of these phases with the timing of the Bond events suggests a general relationship between North Atlantic climate and precipitation intensity in the northern Caribbean during the Holocene, with drier conditions in the Caribbean corresponding to cooler phases in the North Atlantic. So far, only one study has suggested a relationship between climate variability in the Caribbean and the Bond events (Hillesheim et al., 2005). A speleothem record from central-eastern Brazil also suggests a relationship to the Bond events (Strikis et al., 2011) during the last 10 ka. The main finding of this study is a potential relationship between the Bond events and millennial-scale variability in the South American Monsoon System (SAMS). Colder conditions in the North Atlantic are related to wetter conditions in Brazil, which is the opposite pattern as observed here for the northern Caribbean. Strikis et al. (2011) suggest an intrinsic control on SAMS precipitation through the mean latitudinal position of the ITCZ, which generally confirms the hypothesis of a relationship between Caribbean precipitation anomalies and North Atlantic SSTs through the meridional movement of the ITCZ on millennial timescales.

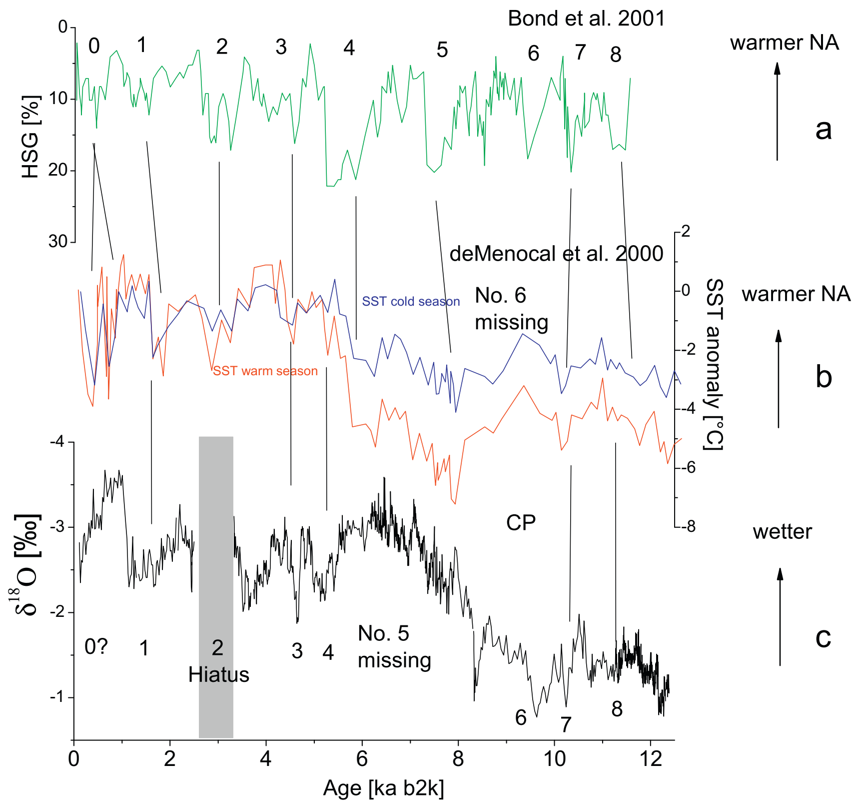

Fig. 5. Stalagmite CP $\delta^{18}O$ values (c) in comparison with the percentage of hematite-stained grains (HSG) in sub-polar North Atlantic deep-sea sediments (a), which record the Bond events (Bond et al., 1997, 2001). (b) Two SST records off West Africa (red: reconstructed temperature during warm season, blue: cold season) (deMenocal et al., 2000). The numbers identify the different Bond events, which are linked to cold SSTs in West Africa (deMenocal et al., 2000). During most Bond events, the stalagmite record suggests drier conditions on Cuba. Bond event 5 is an exception in this context. A hiatus occurred during Bond event 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In the older part of the record (i.e., >8.5 ka), the relationship between cool conditions in the North Atlantic and drier conditions on Cuba seems to be less pronounced. This may suggest that the connection between high northern latitudes and the tropics may have been weaker prior to 8.5 ka. A potential explanation for this observation has been provided by Debret et al. (2009), who studied millennial-scale variability in the Atlantic region and South America. They observed a strong transition during the mid-Holocene and noted that the records show a stronger relation to solar activity (i.e., a cyclicity of 1000 and 2500 a) during the early Holocene. Melt water pulses in combination with the progressively rising sea level may have prevented stabilization of the THC during the early Holocene. In the mid-Holocene, the 1000 a-cycle disappears at the expense of cyclic, internal (ocean) forcings (Debret et al., 2009).

Whether solar variability has a significant effect on climate change, is still a matter of debate (Wanner et al., 2008). However, Shindell et al. (1999) hypothesized that during times of reduced solar irradiance changes in stratospheric ozone may lead to a cooling of the high northern latitudes, a southward shift of the northern subtropical jet and a decrease in the northern Hadley circulation. These processes could potentially lead to an increase in North Atlantic drift ice, cooling of the ocean surface and reduced precipitation at low latitudes (Bond et al., 2001). Therefore, one potential explanation for the observed coincidence between dry conditions on Cuba and the Bond events may be that both are related to solar forcing. Another potential explanation involves the deep ocean's response to reduced solar irradiance. Deep water circulation proxies suggest reduced production of North Atlantic Deep Water (NADW) during at least some Bond events (Bond et al., 2001). A comparison with records from Greenland, Europe and the SST record off West Africa (deMenocal et al., 2000) resulted in temperature patterns that resemble those of phases of reduced NADW formation, such as during the Younger Dryas and the 8.2 ka cold event (Bond et al., 2001). In addition, sea surface salinity has been observed to decrease during the Bond events indicating fresher conditions, which may have the potential to reduce the formation of NADW (Bond et al., 2001; Dickson et al., 1996). Potentially, during the Bond events as well as the YD and the 8.2 ka event, the reduction in SST could have led to a further southward ITCZ and reduced precipitation in the Caribbean.

5. Conclusions

The $\delta^{18}O$ record of stalagmite CP from Cuba reflects precipitation variability in the Caribbean during the last 12.5 ka. The stalagmite record shows the same trend as a marine surface water $\delta^{18}O$ record off Haiti (Horn, 2011) suggesting that, on orbital timescales, the $\delta^{18}O$ value of precipitation mainly reflects the $\delta^{18}O$ value of the source of the water vapor (i.e., the North Atlantic and the Caribbean Sea).

On millennial timescales, the Cuban record exhibits a good agreement with an SST record off West Africa and the Bond events, which indicates a connection to North Atlantic SSTs. This may be related to the variability of the strength of the THC. Model results as well as observations suggest that during warm phases in the North Atlantic, the ITCZ was in a position further north leading to higher precipitation in the Caribbean and vice versa. During North Atlantic Bond events, the stalagmite record shows drier conditions and, thus, supports this teleconnection for the Holocene.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.epsl.2012.11.019.

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