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Combined records from a stalagmite from Barbados and from lake sediments in Haiti reveal variable seasonality in the Caribbean between 6.7 and 3 ka BP

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Abstract

The growth of a well-dated stalagmite from Barbados records high infiltration rates into the karst aquifer and hence increased rainfall intensity between 6.7 and 3 ka BP in agreement with records from Lake Miragoane, Haiti [Hodell et al., 1991. Reconstruction of the Caribbean climate change over the past 10,500 years. Nature 352, 790–793], mainly reflecting the insolation maximum of the Northern Hemisphere. Both the lake record and the stable isotope record of the stalagmite reveal additional centennial variability of recharge. High oxygen isotope values in stalagmite calcite, corresponding to reduced recharge, are synchronous with periods of lower stable isotope values recorded in Lake Miragoane ostracods, previously attributed to enhanced precipitation. Accordingly, periods of increased recharge in Barbados correspond to ^{18}O-enriched isotope values of ostracods, which were attributed to higher evaporation/precipitation ratios in the lakes. We ascribe this apparent discrepancy to changes in seasonality, i.e., winter periods of reduced temperature and relative humidity following summer months of increased precipitation. At present, such climate conditions occur during periods of enhanced Northern Atlantic Oscillation (NAO$^+$). If enhanced seasonality is a consequence of a NAO$^+$ situation, the apparent discrepancy of high isotope values in lakes (previously attributed to droughts) can be reconciled with lower winter temperatures in the lakes. Further, the correlation of solar intensity (derived from ^{14}C and ^{10}Be) with the isotopic signals recorded in the lacustrine sediments suggests a solar forcing of the NAO during the mid Holocene.

1. Introduction

The Intertropical Convergence Zone (ITCZ) is one of the most important climatic phenomena affecting the distribution and timing of rainfall around the equatorial region.

The ITCZ is an area of low pressure that forms where the northeast and southeast trade winds meet near the Earth's equator. When these winds converge, moist air is forced upward causing water vapour to condense as the air rises and cools, resulting in a band of heavy precipitation around the globe. This band moves seasonally, as it is drawn towards the area of most intense solar heating, or warmest surface temperatures. It moves towards the southern hemisphere from September to February and reverses direction during the northern hemisphere in summer. The ITCZ is less mobile over the oceanic longitudes, where it holds a stationary position just north of the equator. In these areas, the rain simply intensifies with increased solar heating and diminishes as the sun moves away. An exception to this rule occurs during ENSO events, during which the ITCZ is deflected towards unusually warm sea surface temperatures (SSTs) in the tropical Pacific. Summaries of recent advances in tropical climate prediction, as well as in observational and theoretical studies of ENSO are given by Hastenrath (1995); Trenberth et al. (1998); Chiang et al. (2000); Fedorov and Philander (2000).

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But how has the ITCZ behaved in the past and what factors influenced its behaviour? Palaeoclimatic records from sensitive equatorial areas, such as the region surrounding the Caribbean Sea, can help to shed light on this question.

Studies from the Mexican peninsula (Hodell et al., 2001), the north coast of South America (Haug et al., 2001) and various Caribbean islands (Higuera-Gundy et al., 1990) have investigated the Holocene activity of the ITCZ and its palaeoclimatic signal. Because these regions lie on the boundary of the (present) northern summer ITCZ, they therefore present climatically sensitive locations where this phenomenon can be studied.

Hodell et al. (1991) reconstructed lake levels from Lake Miragoane, Haiti, using $^{18}O/^{16}O$ ratios in ostracod shells. Lake levels were shown to have risen at the end of the last deglaciation (ca. 10–7 ka BP), and wetter conditions prevailed in the mid-Holocene between ~7 and 3.2 ^{14}C ka BP, with climatic drying and a subsequent fall in lake levels only occurring after this period. These results were corroborated by a vegetation reconstruction from the same lake, which identified the mid-Holocene as a period characterised by a greater relative abundance of moist forest taxa (Higuera-Gundy et al., 1990).

Banner et al. (1996) also identified this wet period during the mid-Holocene through strontium-isotope analysis of precisely dated calcite layers from Barbados speleothems. A ground-water flow route model predicts that the compositional balance of cave drip waters gives rise to lower $^{87}Sr/^{86}Sr$ ratios during periods of elevated recharge (i.e., low evaporation/precipitation ratio—E/P), whilst $^{87}Sr/^{86}Sr$ ratios will be higher during periods of diminished recharge. From 6 to 4 ka, $^{87}Sr/^{86}Sr$ values decreased, and then increased from 4 to 1 ka, after which values dropped again. This implies that the period from 6 to 4 ka BP represented a time of maximum recharge, and thus a potentially wet period during the Holocene.

However, not all reconstructions from the Caribbean region identify a wet period during this time. For instance, Haug et al. (2001) suggested that since the Holocene 'thermal maximum' (since ca 5.4 ka BP) there has been a trend towards drier conditions due to a southward shift in the mean latitude of the ITCZ. Because the Cariaco Basin records exhibit strong correlations with records from non-proximal regions, it is of interest to investigate whether or not the Cariaco palaeoclimate data tallies with other more regional data from the Caribbean. The position of the ITCZ over northern South America is also thought to be influenced by a number of other factors, including Atlantic and Pacific sea surface conditions, and with regard to the latter, the resultant interaction of the ITCZ with the ENSO phenomenon (Haug et al., 2001). The Ti-data from the Cariaco Basin suggest, for example, that the ITCZ is located southernmost during warm ENSO events and further north during the cold ENSO (La Niña) events. The analysis of meteorological data of the last 120 years demonstrates the influence of the cold La Niña events on the state of the atmospheric circulation in the North Atlantic region and on the state of the North Atlantic Oscillation (NAO), with a statistically significant pattern of North Hemisphere sea level pressure resembling the positive phase of the NAO (Pozo-Vazquez et al., 2001). However, the physical basis for the influence of ENSO on both the position of the ITCZ and on the state of the NAO is difficult to assess.

The variation of the position of the ITCZ throughout the Holocene is also reflected by the stable isotopes from stalagmite Q5 from southern Oman (Fleitmann et al., 2003; Fleitmann et al., 2007). This record of the intensity of precipitation in Oman, displaying a long southward trend of the ITCZ that was overlapped by numerous centennial shifts in both directions, resembles very much that of the Ti-content in the Cariaco sediments.

It is still debatable what the climate forcing mechanisms and elements are for the position of the ITCZ, but several authors have suggested that solar forcing is one potential candidate for variable precipitation and droughts in the Caribbean. Haug et al. (2001) suggest that the general southward shift of the ITCZ they identified over the Holocene may be the result of changes in insolation seasonality related to the ~21 ka precession component of Milankovitch forcing.

The influence of solar forcing as a climatic driver in the region was also identified by Hodell et al. (2001). Lake cores from the Yucatan Peninsula, Mexico, presented a 2.6 ka BP Holocene record where solar forcing was postulated to be the cause of a recurrent drought pattern (with a dominant periodicity of 208 years), as this cycle is similar to the 206-year cycle of cosmogenic nuclide production (Hodell et al., 2001).

We analysed a stalagmite from Barbados, West Indies (13°N), that lies close to the Cariaco Basin (ca. 10°N), around the currently northernmost threshold of the ITCZ. We expect the $\delta^{18}O$ signal in the stalagmite to be sensitive to the intensity of the ITCZ and compare the stalagmite data with the paleoclimatic records from the lakes.

Lake Miragoane and the Yucatan lakes, from which the records are derived, lie further north (ca 20°N) and east (73°W and 88°W) of Barbados. Although this may result in large differences regarding the influence of the ITCZ in the region, we may expect that the solar forcing at both sites could be similar. When comparing lake levels with the speleothem record, it is important to realise that these are two different types of records, which deliver complementary results. Whilst lake levels record gross precipitation amounts (precipitation minus evapotranspiration and possible runoff over the whole year), stalagmites record recharge, which is a measure of both the precipitation amount and distribution over the summer. However, it is also important to note that the Yucatan lake records are late Holocene in age, whilst our Barbados record covers the mid-holocene period. It is possible that predominant forcing factors could have differed over this period.

2. Study area

Barbados is located on the outer-arc of the eastern chain of the Caribbean islands at 13°N 59°W. The total area of the island is ca. 430 km^2, and most of the island is covered by a cap of coral limestone (Fig. 1).

Barbados has a tropical climate, with the wet season extending from June to December and the maximum rainfall occurring between August and October. The average annual rainfall varies from ca 1000 mm yr^{-1} at the northern and southeastern margins to over 2000 mm yr^{-1} at the island's centre (Jones and Banner, 2003a,b). Daytime temperatures range from 28 to 32 °C whilst night time temperatures are only slightly lower (23–27 °C). In the winter, night time temperatures can drop to values between 15 and 22 °C. Monthly average relative humidity ranges from 71% in the winter months to 86% in summer.

Harrison's Cave, from where speleothem HC-1 was retrieved, is located towards the centre of the island, and near to its highest point at about 300 m above sea level. Observations have shown that interior cave air temperatures are usually very near to the average annual temperature of the area where the cave is situated (Wigley and Brown, 1976). A surface temperature between 29 and 31 °C is related to a cave temperature ranging from 24 °C near the (artificial) cave entrance to 26 °C in the deepest parts of the cave. Relative cave air humidity ranges from 97.5% to 100%. Besides the earlier studies on speleothems (Banner et al., 1996), more recent work on the speleothems in this cave has been reported (Mickler et al., 2004, 2006). In this new approach, they compared stable isotopes of modern speleothems with drip waters to assess the degree to which equilibrium is achieved during calcite precipitation. Stalagmite HC-1 was sampled from a chamber close to the natural entrance of the cave. This area was defined as Spur 1 (Mickler et al., 2004). During our visit to the cave in the month of February 2002 we could not discern if the stalagmite was actively growing or not.

3. Methods and results

3.1. U/^{230}Th dating

Eighteen ages were obtained from the ca 80 cm long stalagmite using the Th/U method (TIMS) as described earlier (Frank et al., 2000; Neff et al., 2001) (Table 1, see Appendix A). The depth profile reveals that the stalagmite started to grow at about 7 ka. Three sections of faster growth occurred at about 3.7 and 5.3 ka BP (Fig. 2). The youngest age at 5 cm is 3135 ± 67 years. Applying a growth rate model, we converted the depth profile into an age profile. In this study we only discuss the sections with better time resolution deposited between 6 and 3 ka.

3.2. Stable isotopes

A total of 356 subsamples for stable isotope analysis were microdrilled at 2 mm intervals. The stable C and O isotope composition was measured on a Delta$^{\text{plus}}$XL mass spectrometer equipped with an automated carbonate preparation system (Gasbench II). Results are reported relative to the VPDB standard and standardisation was accomplished using NBS 19. The long-term precision of δ^{13}C and δ^{18}O values expressed as the 1-sigma standard deviation is 0.065% and 0.075%, respectively (Spötl and Vennemann, 2003). Fig. 3

The δ^{18}O record shows variable isotope composition along the profile with values ranging from −4‰ to −2.2‰. Mickler reported values for modern carbonate between −5‰ and −3‰. The lower values correspond to calcite formed in equilibrium with rainfall of about −2‰

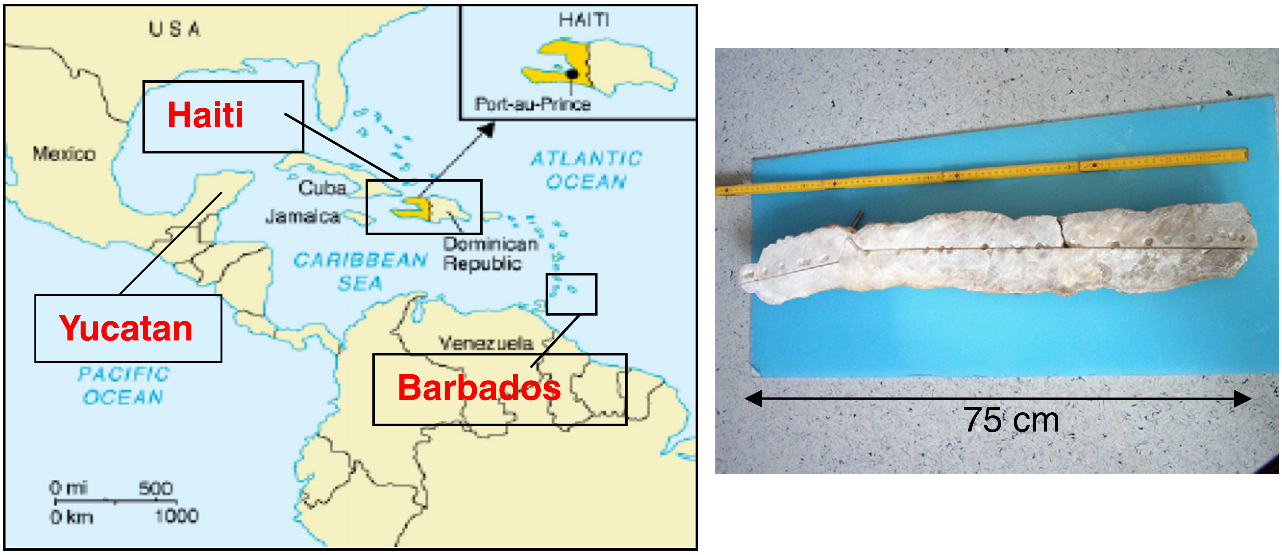


Fig. 1. Location of Barbados and Haiti (Lake Miragoane), as well as photograph of the stalagmite HC-1. The holes along the transect show the position of samples for Th/U dating. The profile for isotope analyses was taken along the central axial zone. The stalagmite is 80 cm high.

Table 1
Results of Th- and U-isotope analyses on HC-1

From top (cm)	dU (‰)	2 sigma (abso.)	^{238}U (μg/g)	2 sigma (abso.)	^{232}Th (ng/g)	2 sigma (abso.)	^{230}Th (pg/g)	2 sigma (abso.)	Age(corr.) (ka)	2 sigma (ka)	Age(uncorr.) (ka)	From top (cm)
5.0 + 0.3	60.7	4.6	0.40861	0.00082	0.32665	0.00203	0.2021	0.0042	3.135	0.067	3.156	5.0 + 0.3
8.0 ± 0.3	53.3	4.0	0.29672	0.00059	< 0.1		0.1452	0.0027	3.137	0.061	3.144	8.0 ± 0.3
12.1 ± 0.3	56.2	3.6	0.29006	0.00058	0.20828	0.00067	0.1476	0.0037	3.242	0.082	3.262	12.1 ± 0.3
15.0 ± 0.3	47.9	3.2	0.27501	0.00055	< 0.1	–	0.1616	0.0087	3.799	0.209	3.807	15.0 ± 0.3
15.7 ± 0.3	54.6	3.6	0.27205	0.00054	0.12592	0.00064	0.1602	0.0025	3.778	0.060	3.791	15.7 ± 0.3
22.0 ± 0.3	59.2	3.7	0.37791	0.00076	0.16944	0.00090	0.2257	0.0060	3.815	0.106	3.828	22.0 ± 0.3
27.0 ± 0.3	56.5	3.1	0.37955	0.00076	0.10952	0.00056	0.2263	0.0063	3.823	0.109	3.831	27.0 ± 0.3
31.0 ± 0.3	53.0	5.0	0.34727	0.00069	0.16130	0.00171	0.2331	0.0100	4.324	0.187	4.336	31.0 ± 0.3
33.3 ± 0.3	49.4	3.2	0.49580	0.00099	0.66775	0.00414	0.3444	0.0069	4.470	0.092	4.507	33.3 ± 0.3
34.5 ± 0.3	57.6	3.1	0.44796	0.00090	0.52210	0.00277	0.3406	0.0054	4.872	0.080	4.904	34.5 ± 0.3
39.5 ± 0.3	54.2	3.2	0.58199	0.00116	1.12309	0.00348	0.4461	0.0057	4.908	0.066	4.961	39.5 ± 0.3
44.5 ± 0.3	51.2	4.9	0.24044	0.00048	0.44452	0.00156	0.1951	0.0024	5.224	0.070	5.274	44.5 ± 0.3
47.0 ± 0.3	56.0	3.0	0.34837	0.00070	0.16496	0.00092	0.2835	0.0062	5.253	0.117	5.265	47.0 ± 0.3
51.2 ± 0.3	52.3	5.6	0.36251	0.00073	0.28940	0.00159	0.2985	0.0066	5.327	0.123	5.349	51.2 ± 0.3
56.8 ± 0.3	53.6	3.5	0.34231	0.00068	0.30480	0.00155	0.2851	0.0041	5.380	0.082	5.404	56.8 ± 0.3
63.3 ± 0.3	56.6	4.4	0.35082	0.00070	0.56344	0.00563	0.2927	0.0138	5.354	0.256	5.397	63.3 ± 0.3
68.0 ± 0.3	47.3	6.5	0.34622	0.00069	0.39627	0.00313	0.3164	0.0102	5.949	0.198	5.981	68.0 ± 0.3
71.0 ± 0.3	49.8	3.9	0.33435	0.00067	1.48855	0.00759	0.3601	0.0083	6.946	0.167	7.067	71.0 ± 0.3

The ages are from 2003 AD.

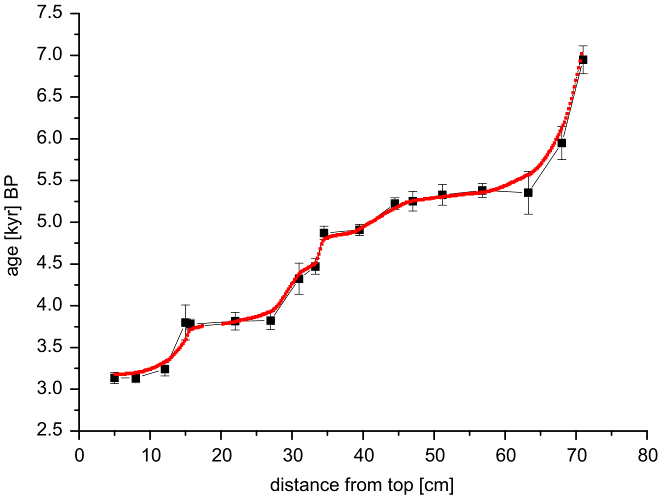


Fig. 2. Depth–age relationship derived from the Th/U dating of HC-1. The red line shows the age model (Akima-fit) applied to the data.

VSMOW, a value slightly higher than the present day drip water values in the cave, between −3.5‰ and −3.0‰ VSMOW (Mickler et al., 2004). These differences could be attributed either to a different composition of precipitation during the last 3,000 yr or to kinetic effects.

The lower δ^{13}C values of about −13‰ lie within the range expected for carbonate formed from a mixture of biogenic (−25‰) and marine carbonate (~0‰), and are within the range reported (Mickler et al., 2004).

We find a high variability of both δ^{18}O and δ^{13}C with depth. The good correlation between δ^{18}O and δ^{13}C isotopes (Fig. 4) suggests that strong kinetic processes occurred during periodically drier periods (Hendy, 1971; Mickler et al., 2007; Wiedner et al., 2007). Consequently,

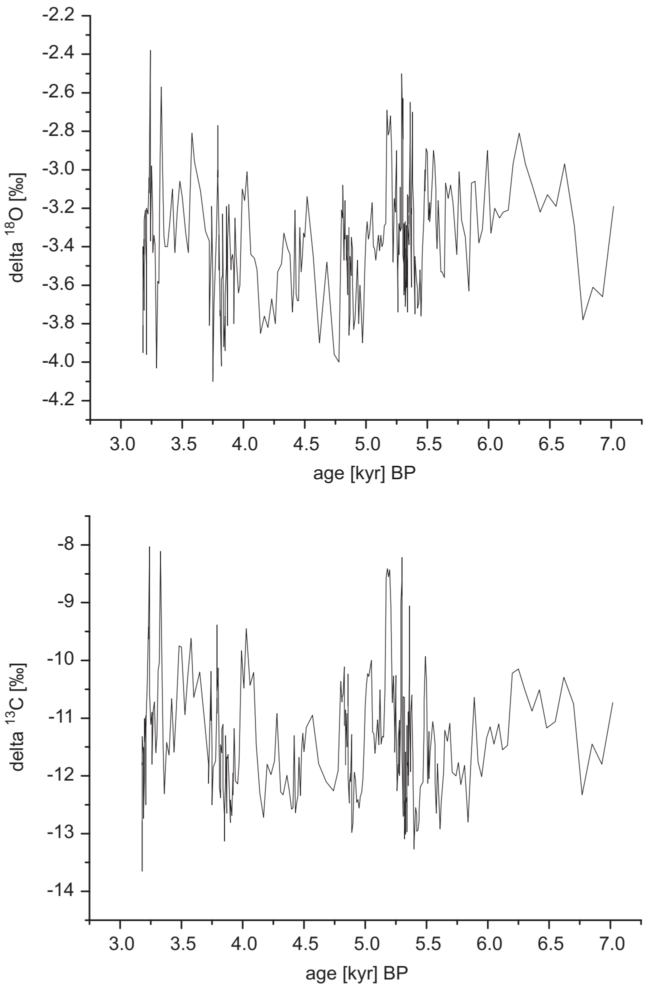


Fig. 3. Records of δ^{18}O and δ^{13}C of HC-1 derived by applying the age–depth relationship shown in Fig. 2. The present-day δ^{18}O-values of the drip water of the cave in Spur 1 range between −3‰ and −3.5‰ (Mickler et al., 2004).

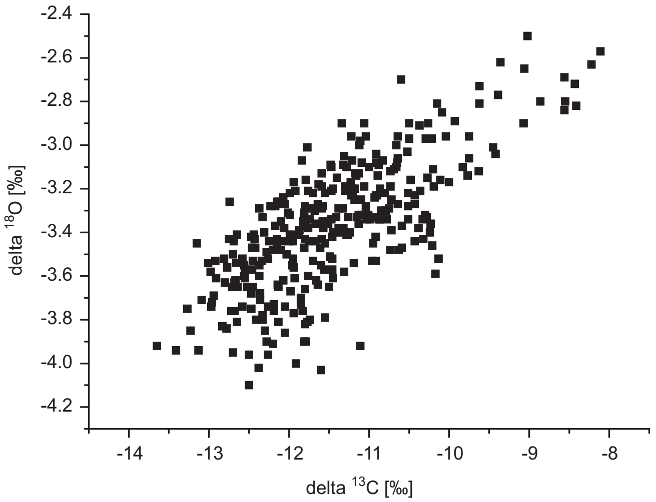


Fig. 4. Correlation between $\delta^{13}C$ and $\delta^{18}O$ in HC-1, suggesting strong kinetic processes during formation of the stalagmite (Mickler et al., 2006). The linear relationship is given by $\delta^{18}O = -0.83 + \delta^{13}C*0.22$, with a correlation coefficient of 0.75.

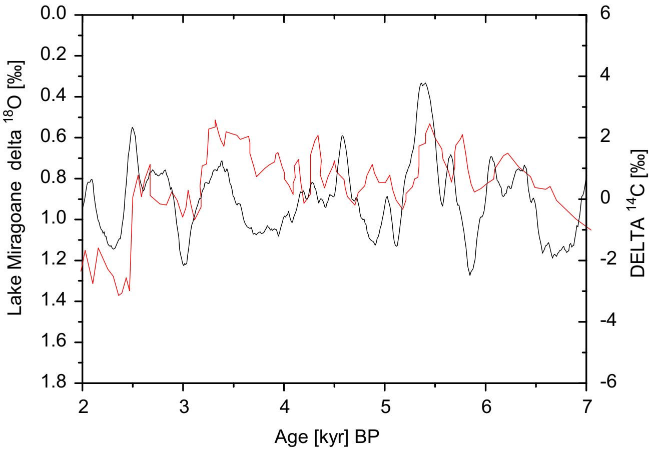


Fig. 5. Comparison of the $\delta^{18}O$ in ostracods from Lake Miragoane (red curve) (Hodell et al., 1991) and $\Delta^{14}C$ (black curve, before 1950). Because Lake Miragoane is a hard water lake, radiocarbon ages are susceptible to error due to contribution from the dissolution of old carbonate rock. To estimate this effect, a paired wood and ostracod sample gave an age difference of 1025 years. The correction with a hard water age through the entire core yielded good agreement between ^{210}Pb, organic and carbonate ^{14}C dates at all levels. For better comparison with $\Delta^{14}C$ we detrended the record of Lake Miragoane applying a linear function (+0.15‰/ka). The correlation coefficient between $\delta^{18}O$ and $\Delta^{14}C$ is -0.42 (see Appendix A).

higher isotope values correspond to periods of reduced recharge of the karst aquifer.

In a hydrological survey of Barbados during the last 40 years, Jones and Banner (2003a,b) have shown that recharge is higher when rainfall is concentrated in a few months of the year than when rainfall is more evenly distributed throughout the year. Recharge also shows a general inverse relationship with ENSO. In Barbados, conditions conducive of recharge usually occur during one month of the year but may occur during as many as 3 months (Jones and Banner, 2003b).

3.3. *The record of Lake Miragoane, Haiti*

The generally accepted opinion is that rainfall in the Caribbean region is intensified by increased solar heating. The lake level in Miragoane is in agreement with this rule as it tracks the insolation in the N. Hemisphere that has a maximum between 9 and 6 ka and describes a slow decrease which is also seen in the percentage of fluvially transported Ti in Cariaco Basin sediments (Haug et al., 2001). Orbital forcing varies on a millennial time scale, and the $\delta^{18}O$ data of ostracods from both lakes in Mexico and in Haiti suggest an additional solar forcing on a centennial scale.

Hodell et al. (2001) found a very good correlation between $\Delta^{14}C$ and the ostracod $\delta^{18}O$ record from a Mexican lake. Peaks of $\delta^{18}O$ were suggested to indicate increased evaporation/precipitation (E/P). These peaks coincide with minima in ^{14}C production, which are caused in part by increased solar activity (Hodell et al., 2001). The ostracod record in Lake Miragoane shows the same trend: peaks of $\Delta^{14}C$ coincide with minima of ^{18}O (Fig. 5, and Appendix A). As shown in Fig. 5, we determined a correlation coefficient of -0.42.

However, if the rule is that rainfall is intensified by increased solar heating, we then have to explain why the peaks of $\delta^{18}O$ in Lake Miragoane, which may be ascribed to droughts, coincide with periods of stronger solar activity as deduced from the minima of $\Delta^{14}C$ and ^{10}Be records. To solve this contradiction, we need to find a mechanism that enhances evaporation at a larger degree than precipitation during periods of stronger solar heating. The record in stalagmites, which traces mainly recharge, yields additional information that helps to solve this apparent disagreement.

4. Discussion

4.1. *Comparison of the stalagmite record in Barbados with the $\delta^{18}O$ record in Lake Miragoane*

HC-1 growth marks the most humid period in Barbados, in good agreement with earlier results derived from Sr-isotope records on speleothems from Barbados (Banner et al., 1996) and with the record in Lake Miragoane (Hodell et al., 1991). The second order Sr isotope oscillations appear to record periodic variations in the relative variations in the Sr flux to the aquifer. Sr-isotope values decreased from 6 to 4 ka and increased again from 4 to 1 ka. This decrease indicates the transition from a relatively dry to a wet climate. This humid period coincided with the lake level high stand in Miragoane between 6.7 and 3.2 ka.

The $\delta^{18}O$ signal in stalagmites is mainly a record of recharge, and drier periods with less recharge go along with an enrichment of $\delta^{18}O$. Because the kinetic effect also

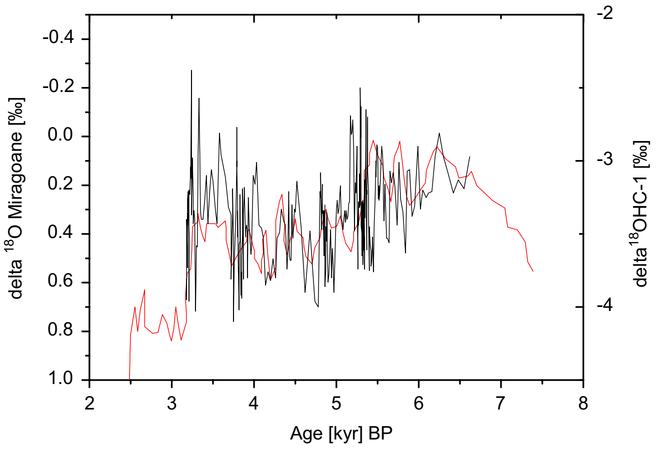


Fig. 6. Comparison of $\delta^{18}O$ in HC-1 (black) and $\delta^{18}O$ in ostracods (red) from Lake Miragoane. Note inverted left-hand axis. The correlation coefficient is -0.59 (see Appendix A).

dominates the isotopic composition of HC-1, we relate peaks of $\delta^{18}O$ to periods of less recharge.

The comparison of the record of HC-1 with that of Lake Miragoane (Fig. 6, and Appendix A) shows anticorrelation between the high-frequency variations of $\delta^{18}O$ in stalagmite HC-1 and in the ostracods from Lake Miragoane, with a correlation coefficient of -0.59. Lower $\delta^{18}O$ values in HC-1 coincide with higher ostracod $\delta^{18}O$ values in Lake Miragoane. This suggests that periods of maximum recharge (HC-1) correspond to periods of increased E/P in Miragoane, that have been interpreted as droughts by Hodell et al. (2001). What is the reason for this apparent contradiction? One possible explanation is that the meteorological conditions at Haiti and Barbados are different. We prefer another explanation that takes into account that stalagmites in Barbados record only summer precipitation, whereas $\delta^{18}O$ in ostracods record the whole year average water budget and the average isotopic composition during ostracod growth in lakes. Indeed, ostracods molt their shells eight to nine times before reaching maturity, resulting in overlapping generations that attain maturity at different times especially in the tropics. A large number of specimens were analyzed in each sample in the isotope study of Lake Miragoane. Analysis of these many specimens average out any seasonal noise, and in addition each sample represents deposition over many years (20 years on average given the sedimentation rate in Lake Miragoane (Curtis and Hodell, 1993)).

4.2. *Increased summer evaporation or lower winter temperatures?*

In summary:

(1) The growth of HC-1 corresponds to a wet period, and coeval high levels in Lake Miragoane coincide with maximum N. H. summer insolation.
(2) Maxima of short-term solar activity correspond to maximum recharge and precipitation (Barbados), but also to even stronger evaporation, as recorded in Mexican and Haiti lakes.
(3) Recharge in Barbados occurs only in summer.

From points (1)–(3) we conclude that the periods of heavier isotopic composition of Caribbean lakes, coincident with the maxima of short-term solar activity, should be related to drier or colder winters. Both mechanisms would shift the isotopic value of the water towards heavier values. But which mechanism may enhance winter evaporation and lower SSTs in the Caribbean during periods of elevated solar activity? We ascribe this finding to enhanced colder trade winds in Caribbean winters during periods of a high phase of the Northern Oscillation index.

The dominant pattern of SST variability in the Caribbean has been studied in detail (Czaja, 2002). Based on a spring SST index of the Northern Tropical Atlantic (NTA) (5°N–25°N), Czaja et al. (2002) showed that almost all SST extreme events from 1950 to present can be related to either ENSO or NAO, and lower SST correspond to ENSO^{-} and NAO^{+} phases, respectively. The study of Czaja et al. on the longer SST record (1856–1992) suggests that ENSO dominates over NAO at interannual time scales but NAO dominates over ENSO on time scales longer than decadal. This finding corroborates that of Pozo-Vazquez et al. (2001), who reported that statistically significant anomalies in the North Atlantic (NAO^{+}) area are highly related to cold ENSO (La Niña) events.

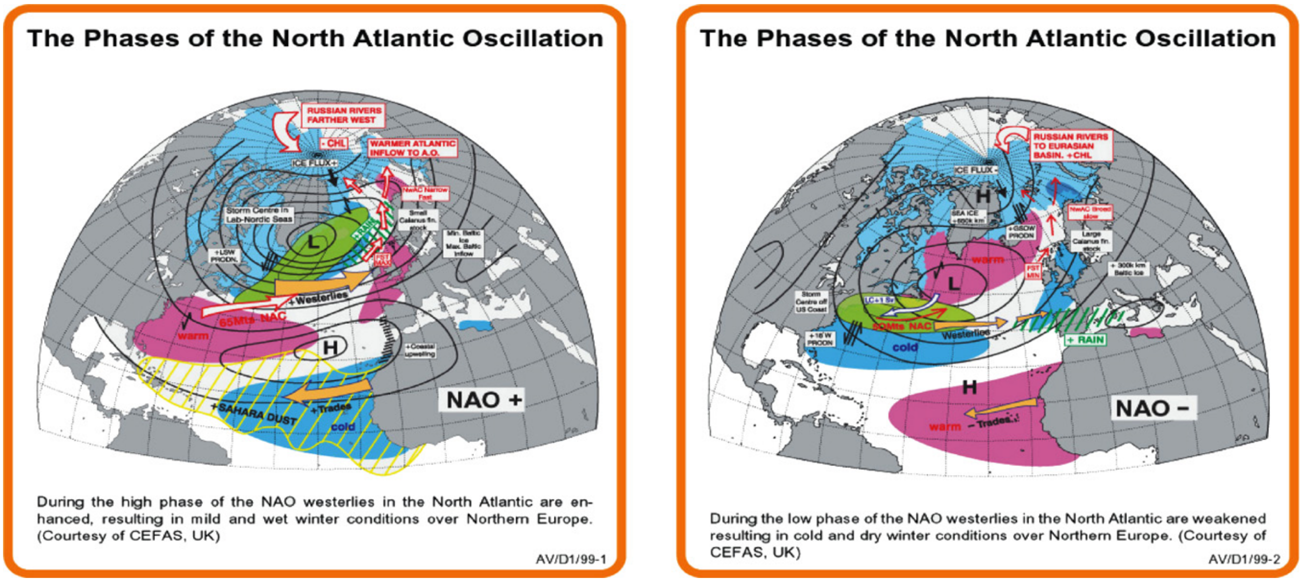
The predominant wind directions during the two different modes of NAO are shown in Fig. 7.

During the low phase of the NAO, the Westerlies in the North Atlantic are weakened resulting in cold and dry winter conditions over northern Europe and weaker, warm trade winds. On the contrary, the high phase of the NAO is accompanied by enhanced Westerlies, wet and mild winter conditions over northern Europe but enhanced, cold trade winds. The intensity of the trade winds, being colder and relatively drier air flowing towards the Caribbean, parallels that of the westerlies. During high NAO^{+} phases trade winds are stronger.

We hypothesise that the drier phases recorded in the Caribbean ostracods and the stalagmite might be induced by the enhanced supply of drier and colder trade winds during periods of NAO^{+} phase and or due to colder temperatures associated with the La Niña events.

A first test of this hypothesis is to check if summers with enhanced recharge in Barbados correspond to periods of lowest winter temperatures in Haiti in the records of the last 40 years. We use the data set for the recharge in Barbados (Jones and Banner, 2003b) together with the Multivariate Enso Index (MEI) (Wolter and Timlin, 1993). For the January temperature, we use the data set from NCEP.

The two graphs in Fig. 8 show that the lowest January temperatures in Haiti as well as the highest recharge in



During the high phase of the NAO westerlies in the North Atlantic are enhanced, resulting in mild and wet winter conditions over Northern Europe. (Courtesy of CEFAS, UK)

AV/D1/99-1

During the low phase of the NAO westerlies in the North Atlantic are weakened resulting in cold and dry winter conditions over Northern Europe. (Courtesy of CEFAS, UK)

AV/D1/99-2

Fig. 7. Diagram showing the two different phases of the North Atlantic Oscillation. (Copyright: Dr. David B. Stephenson, Department of Meteorology, P.O. Box 243 Reading RG6 6BB, U.K.).

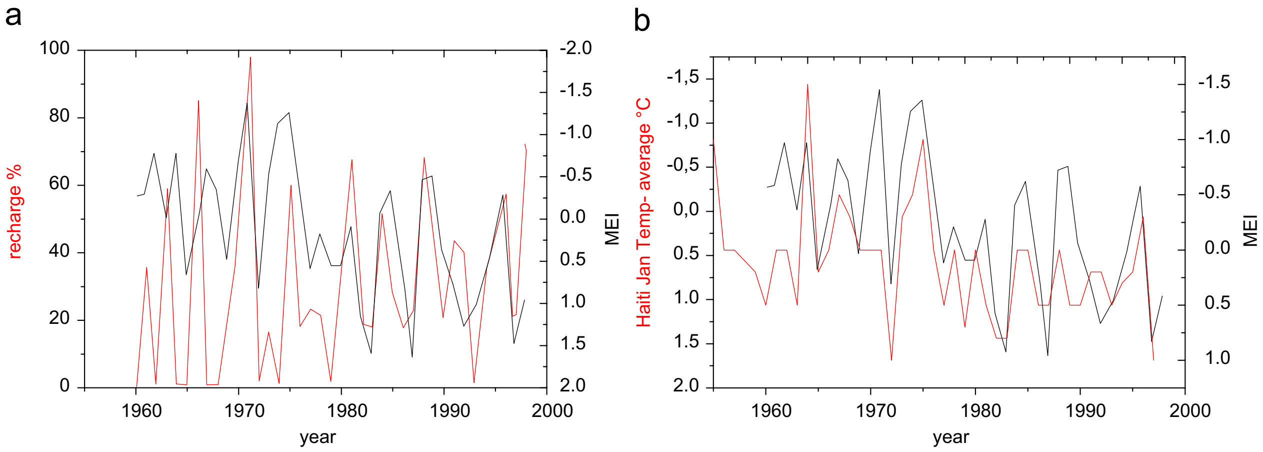


Fig. 8. (a) Comparison of ENSO intensity with the amount of recharge in Barbados (Jones and Banner, 2003a). The correlation coefficient for the period between 1960 and 2000 is −0.31. Between 1970 and 2000 it is −0.49. (b) Comparison of ENSO intensity with the January temperature in Haiti (location of Lake Miragoane). The temperature is plotted as deviation from the average of the years 1956–1998. The January temperature is compared with the yearly averaged ENSO index of the previous year (e.g., 1956 January with 1955 MEI). The correlation coefficient is 0.71.

Barbados coincide with low ENSO indices. Combining both results, obviously suggests that the years of highest recharge in Barbados are accompanied by lowest winter temperatures in Haiti. The correlation coefficient between recharge in Barbados and January temperature is −0.41 for the period between 1970 and 2000. However, for the period between 1960 and 2000 the correlation coefficient is lower (−0.15) due to a slight offset of the recharge as may be seen in Fig. 8a.

The record of the relative humidity in January (monthly average) in Haiti (Fig. 9) shows deviations of up to 5% from the average values that are in phase with the deviations of temperature. Low ENSO indices are accompanied by lower relative humidity in January. Fig. 10

In summary, our hypothesis that the records in Lake Miragoane and the stalagmites may be attributed to climate conditions with a larger seasonality, with wetter summers and colder winters, is corroborated by the findings of Czaja et al. (2002), who suggest that during the past 40 years NAO^+ and $ENSO^-$ conditions correspond to lower N. tropical temperatures in winter.

4.3. Testing the possible mechanisms

4.3.1. Evaporation

The second step is to evaluate whether the enhanced supply of colder, drier air into the Caribbean area in winter may result in higher oxygen isotope values in Lake Miragoane ostracods. To test the sensitivity of $\delta^{18}O$ to the relative humidity, we modelled the variation of the isotopic composition of a lake (without run off) as a function of the air moisture applying an equilibrium model

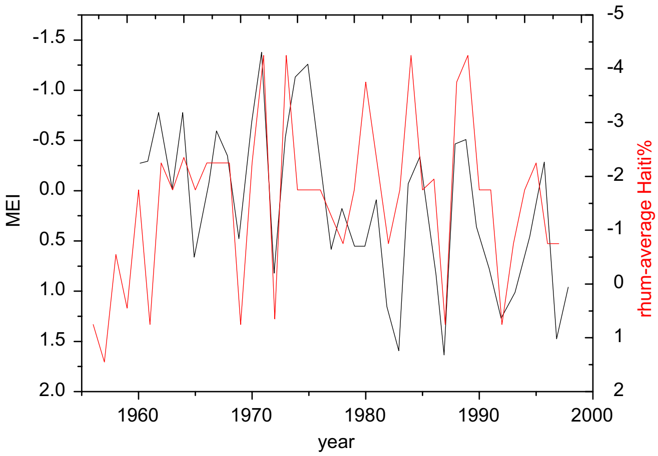


Fig. 9. Comparison of the relative humidity in January at Haiti with the intensity of ENSO. The relative humidity is plotted as deviation from the average of the years 1956–1998. The January relative humidity is compared with the yearly averaged ENSO index of the previous year (e.g., 1956 January with 1955 MEI). The correlation coefficient is 0.61.

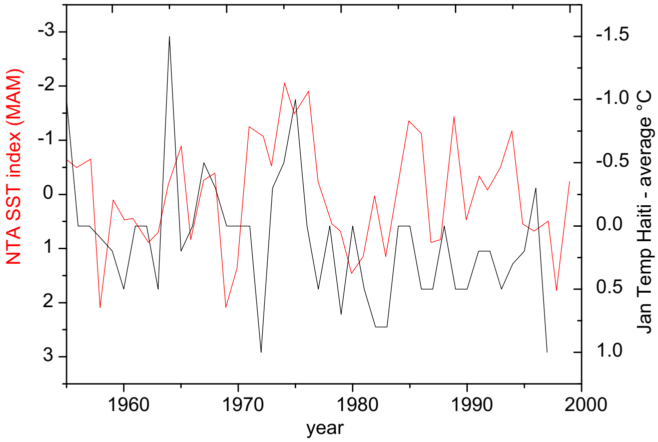


Fig. 10. The comparison of the spring SST index of the Northern Tropical Atlantic (NTA) with the departure of the January temperature in Haiti from the average. The correlation coefficient is 0.44.

(Gat, 1995). The results in Fig. 11 show that the observed variability in δ^{18}O of about several tenths per mille can be attained if the average relative humidity is lower by several percent.

The proposed explanation is in apparent agreement with the hypothesis that positive anomalies of the sea level pressure index reflect a strengthening of the trade winds, which yields enhanced evaporative loss over the northern tropical Atlantic region. However, the estimated increase of evaporation due to the reduction of humidity is probably too small to produce the observed enrichment of δ^{18}O. Applying the evaluated sensitivity of latent heating to SST of 10 W/m^2 K (Czaja et al., 2002), one may estimate that a variation of 2 °C during a period of 6 months will result in a lowering of the lake level of only 0.1 cm (evaluated as 259 W s m^{-2}/2.5 × 10^6 J kg^{-1}). Thus, evaporative lowering of the lake level during winter months should not affect the isotopic composition of the lake. As we a priori excluded that the δ^{18}O in Lake Miragoane was driven by the variations of the ratio of evaporation to precipitation, we reject the hypothesis of droughts being the cause of the observed variability of δ^{18}O in Lake Miragoane and also in Mexico in the past. However, the relationship applied in Fig. 11 is very simplistic and more realistic models are required to exclude hydrological changes as drivers of the δ^{18}O record in the Caribbean lakes.

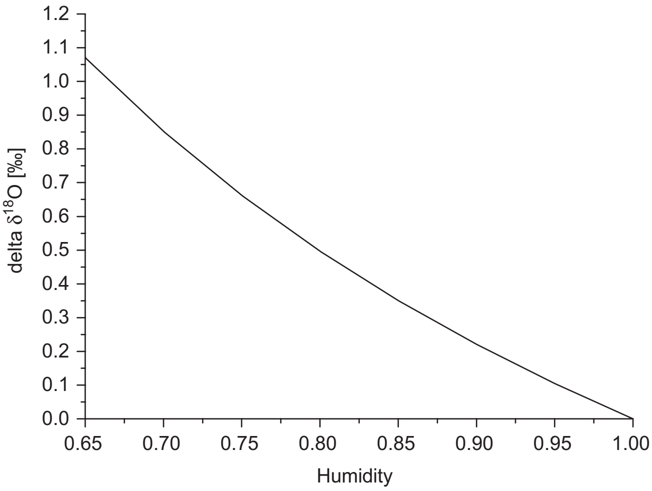


Fig. 11. Change of δ^{18}O in a lake, which is in equilibrium with the atmosphere (no recharge and outflow), as a function of atmospheric moisture. Assuming that precipitation occurs only during the summer months, the curve shows how the equilibrium value changes as a function of the moisture content. A change of 5% in the moisture content corresponds to 0.3‰ change in δ^{18}O. The values were calculated using case 1 from Gat (1995), applying $e^* = 0.996$‰ and $C_k = 0.9903$.

4.3.2. Temperature

The second explanation, which seems more probable, assumes a stronger cooling of the lake during winter in ENSO$^-$ phases that are accompanied by NAO$^+$ phases. Calcite formed in equilibrium at a temperature lower by 2 °C should be about 0.44‰ heavier in δ^{18}O. The response of the lake to a lowering of the ambient temperature is rather fast because the piston velocity (D/z) for the diffusive transport of heat across a boundary layer of thickness, z, lies in the range of some metres per day (evaluated as: 1 × 10^{-5} cm^2 s^{-1}/10^{-2}cm). Ostracods forming their calcite in spring obviously will record the lower temperature anomaly in the NTA during periods of high NAO phase. Due to their resolution, the two discussed Caribbean archives will only record the longer events on a decadal or centennial scale.

4.4. A variable intensity of the NAO in the past?

Both highly resolved records of the variation of the location of the ITCZ from the Cariaco Basin and from

Oman (Haug et al., 2001; Fleitmann et al., 2003) display significant variations of the position of the ITCZ, which are ascribed to changes of the intensity of ENSO in the past. As the intensity of the NAO$^+$ is found to be strongly related to the intensity of the cold ENSO events (Pozo-Vazquez et al., 2001), one should expect the timing of precipitation and temperature in the Caribbean also to be related to the variations observed in the records of the ITCZ. As shown in Fig. 12, the δ^{18}O of HC-1 has indeed a significant correlation to the intensity of the South Indian Monsoon recorded in stalagmite Q5 from Oman (Fleitmann et al., 2003, 2007) (Fig. 13).

But what are the causes for the multicentennial variations of the ITCZ?

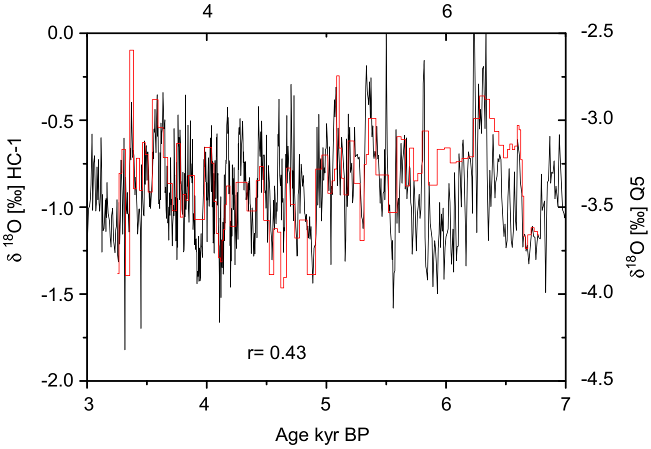


Fig. 12. Correlation between a smoothed version of the δ^{18}O record of HC-1 and the δ^{18}O of stalagmite Q5 from Oman. The correlation coefficient *r* is 0.43. Q5 was detrended with a linear function (1‰/4.000 years), and HC-1 was tuned to Q5. As suggested by this figure, lighter isotope values, corresponding to wetter and colder periods in the Caribbean, coincide with wetter periods in Oman.

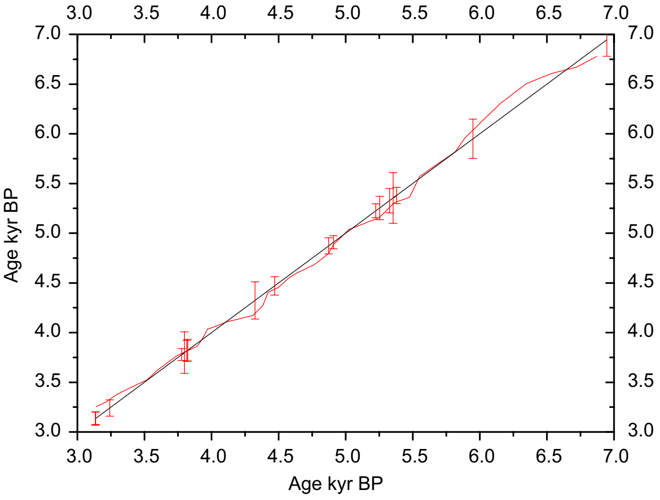


Fig. 13. The red curve shows the adjustment performed to match HC-1 to Q5. The error bars are two sigma errors of the dating of HC-1.

There is multiple evidence that the Northern Atlantic Oscillation index may be related to the intensity of solar irradiation, both on the longer precession time scale as well as on a centennial time scale (Kodera, 2002; Gimeno et al., 2003; Niggemann et al., 2003a,b; Andersen et al., 2004; Kodera and Kuroda, 2005). Gimeno et al. (2003) investigated the relationship between NAO and Northern Hemisphere Temperature (NHT) for the period between 1856 and 1999 and found that for solar maximum phases NAO and NHT are positively correlated. Their results are in agreement with a different extension of the NAO during different solar cycle phases (Kodera, 2002). High-resolution sediment cores from the Nordic Seas were used to reconstruct SST during the Holocene (Andersen et al., 2004). They indicate that climate development is in phase with the decreasing insolation in the N. Hemisphere. The climate development recorded in the cores resembles that of a steadily decreasing positive NAO signature. In addition, a persistent influence of North Atlantic hydrography on Central European winter temperature during the last 9,000 years has been observed (Vollweiler et al., 2006; Mangini et al., 2007). At present, the amount of winter precipitation in Northern Europe is related to the intensity of the Northern Hemisphere Annular Mode (NAM; Thompson and Wallace, 2001). Periodically stronger indexes of NAM enhance the intensity of the westerlies yielding milder and wetter winters in northern Europe. The good correlation between δ^{18}O and Δ^{14}C in stalagmites from central Europe suggests that periods of decreased winter precipitation have occurred synchronously with periods of maximum radiocarbon content in the atmosphere (Niggemann et al., 2003b) also during the past 6000 years. As the increase of atmospheric Δ^{14}C probably results from higher cosmic irradiation due to a weaker solar activity, these results could be interpreted such that periods of lower intensity of solar irradiation were accompanied by drier climate in northern Europe, and shifted the NAM indices towards lower values.

The observed correlation between cosmogenic isotopes and δ^{18}O in ostracods in the lakes from Yucatan (Hodell et al., 2001) and Miragoane, together with the opposite behaviour of recharge in Barbados and winter temperature support this hypothesis. Although the scenario proposed here makes intuitively sense, the topic remains widely controversial and debated.

5. Conclusions

The comparison of the δ^{18}O records from a stalagmite from Barbados and from Lake Miragoane in Haiti suggests that precipitation and temperature in the period from 6.7 to 3 ka BP were both affected by the variability of the intensity of the sun. Periods of enhanced recharge in Barbados are accompanied by periods of high oxygen isotope values in Lake Miragoane. We ascribe this apparent contradiction to increased seasonality during phases of NAO$^+$ (and a corresponding La Niña phase), which results in increased precipitation and recharge in summer together with cooler winters. Our conclusion, however, disagrees with an earlier interpretation, which ascribed the heavier $\delta^{18}O$ in the lake to droughts (Hodell et al., 1991; Haug et al., 2001). The good correlation of the stable isotopes from the Caribbean lakes with cosmogenic radioisotopes supports solar forcing of the NAO during the past 6000 years, but requires validation with a larger data base.

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Appendix A

A.1. Cross correlations

(a) *Records of the last 50 years*: In order to eliminate uninteresting long-term components, we first filtered the raw time series with a standard high-pass filter designed to remove all energy at periods longer than 40 years. Synchrony of two time series was then quantified as their Pearson correlation coefficient.

(b) *Records from Lake Miragoane and the Barbados stalagmite*: We have removed the fastest components off the records, as well as the slowest, by filtering the raw reconstructions with a standard band-pass mask. In Fig. A1 we compare the evolution of $\delta^{18}O$ in Lake Miragoane against solar intensity as measured by $\Delta^{14}C$. In this case, the filter is designed to remove all energy at periods shorter than 350 and longer than 1150 years. In panels (a) and (b) we can appreciate the effect of the applied band-pass filter on the raw time series from Haiti and $\Delta^{14}C$, respectively. For better comparison, in panel (c) we show only their filtered versions. The opposite inflexions of these curves are reflected by a Pearson correlation coefficient of −0.42 and suggest a solar forcing of the NAO during the mid-Holocene, as discussed in the main text.

In Fig. A2 we present a similar analysis for the evolution of $\delta^{18}O$ as recorded by Lake Miragoane and stalagmite HC-1. In this case, a strong anticorrelation is observable for the fastest modes but still also on much longer time scales (up to 4000 years). The corresponding correlation coefficient is −0.59, supporting the contention that epochs of enhanced recharge in Barbados are synchronous with periods of high oxygen isotope levels in Lake Miragoane in Haiti.

Finally, in Fig. A3 we compare the history of $\delta^{18}O$ in our stalagmite HC-1 in Barbados against the solar signal in $\Delta^{14}C$. As before, panels (a) and (b) allow a comparison between raw and filtered versions of these magnitudes, and the lowest panel (c) depicts only the smoothed versions for

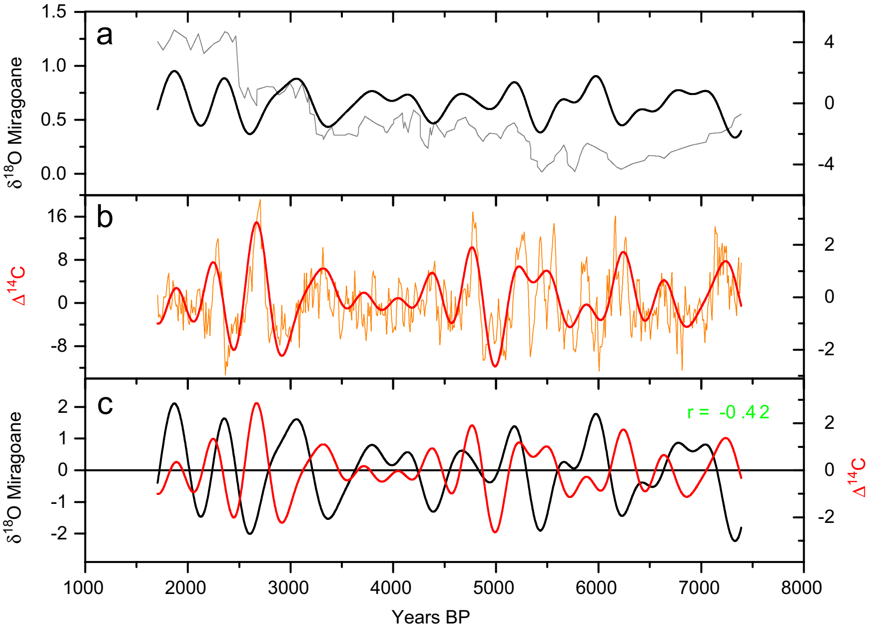

Fig. A1. Comparison between the isotopic variability of lacustrine sediments in Haiti and the solar signal. (a) Raw and filtered $\delta^{18}O$ time series from Lake Miragoane. (b) Raw and filtered $\Delta^{14}C$. (c) The smoothed series show a correlation coefficient of −0.42.

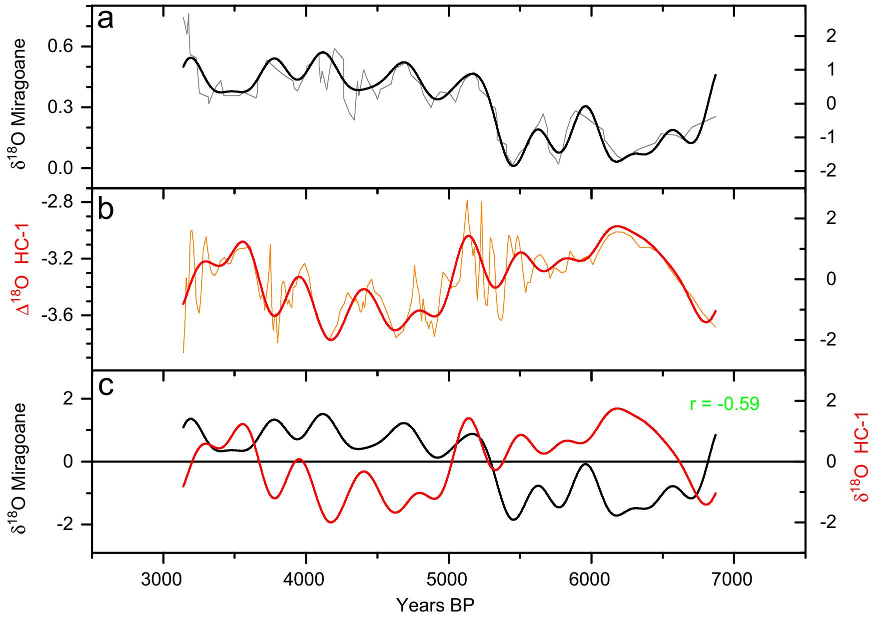

Fig. A2. Comparison between Lake Miragoane and HC-1. (a) Raw and filtered δ^{18}O time series from Lake Miragoane. (b) Raw and filtered δ^{18}O data from our stalagmite in Barbados. (c) The smoothed series show a correlation coefficient of -0.59. In this case the band-pass filter allows all energies at periods between 300 and 4000 years.

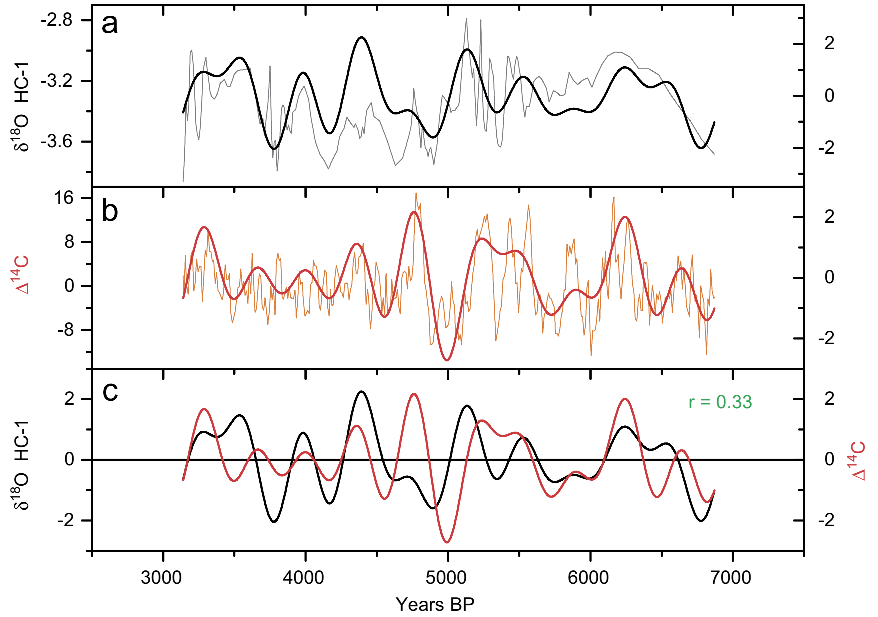

Fig. A3. Comparison between HC-1 and Δ^{14}C. (a) Raw and filtered δ^{18}O time series from Barbados. (b) Raw and filtered Δ^{14}C data. (c) The smoothed series show a correlation coefficient of 0.33. Band-pass filter: 350–1250 yr.

better comparison. In this case, the Pearson correlation coefficient is 0.33.

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