AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2013GL058846

Key Points:
- Rapid climate change in the tropics is not dependent solely on ice volume

Supporting Information:
- Readme
- Figure S1
- Figure S2
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- Supplementary info

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Citation:
Gibson, K. A., and L. C. Peterson (2014), A 0.6 million year record of millennial-scale climate variability in the tropics, *Geophys. Res. Lett.*, *41*, 969–975, doi:10.1002/2013GL058846.

Received 26 NOV 2013
Accepted 22 JAN 2014
Accepted article online 27 JAN 2014
Published online 14 FEB 2014

A 0.6 million year record of millennial-scale climate variability in the tropics

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Abstract A ~600 kyr long scanning X-ray fluorescence record of redox variability from the Cariaco Basin, Venezuela, provides insight into rapid climate change in the tropics over the past five glacial-interglacial cycles. Variations in the sediment accumulation of the redox-sensitive element molybdenum (Mo) can be linked to changes in Intertropical Convergence Zone migration and reveal that millennial-scale variability is a persistent feature of tropical climate over the past 600 kyr, including during periods of interglacial warmth. This new record supports the idea that high-frequency tropical climate variability is not controlled solely by ice volume changes, with implications for the role of high-latitude forcing of Intertropical Convergence Zone position and tropical hydrology on millennial timescales.

1. Introduction

Dansgaard-Oeschger (D/O) cycles—the abrupt, millennial-scale temperature excursions first discovered in Greenland ice cores spanning the last glacial period [*Dansgaard et al.*, 1993; *Grootes et al.*, 1993]—are now known to have a global footprint, with changes seen in records of temperature, tropical hydrology, atmospheric methane concentrations, and atmospheric and oceanic circulation [*Voelker*, 2002; *Clement and Peterson*, 2008]. A growing number of studies indicate that millennial-scale variability has been a persistent feature of global climate for hundreds of thousands to millions of years [*Oppo et al.*, 1998; *McManus et al.*, 1999; *Weirauch et al.*, 2008; *Bolton et al.*, 2010]. Some studies find that millennial-scale variability occurs only above certain continental ice volumes [*Oppo et al.*, 1998; *McManus et al.*, 1999; *Grutzner and Higgins*, 2010]; however, others note its presence at varying levels of ice sheet size [*Weirauch et al.*, 2008; *Bolton et al.*, 2010; *Billups et al.*, 2011]. While the cited records can be linked to processes operating in the high Northern latitudes and to Northern Hemisphere ice sheets, direct comparisons to past Greenland temperatures are presently limited to the last ~123 kyr [*North Greenland Ice Core Project Members*, 2004] and few paleoclimate records have the resolution to truly rival the Greenland ice core standard.

One location that can enhance our understanding of millennial-scale climate variability beyond the Greenland record is the Cariaco Basin in the southern Caribbean Sea. Here high sedimentation rates (≥ 30 cm/kyr) and extended periods of deep water anoxia have led to the generation of well-preserved sediment sequences and records that show a remarkably tight linkage to the abrupt, high-latitude climate changes preserved in Greenland ice. In particular, proxies for paleoproductivity, such as sediment laminae thickness and color [*Hughen et al.*, 1996; *Peterson et al.*, 2000a; *Deplazes et al.*, 2013], covary strongly with $\delta^{18}O$ records from Greenland ice cores on millennial timescales. Previous studies have implicated shifts in the position of the Atlantic Intertropical Convergence Zone (ITCZ) as responsible for variations in upwelling/productivity and precipitation/terrigenous input to the basin that are captured in its sedimentary record [*Peterson et al.*, 2000a; *Haug et al.*, 2001; *Deplazes et al.*, 2013].

While the last glacial and deglaciation have been well studied in Cariaco sediments, longer sedimentary sequences from the basin have thus far been largely unexploited at resolutions sufficient to capture millennial-scale climate variability. We present here new scanning X-ray fluorescence (XRF) records of sedimentary molybdenum (Mo) from IMAGES Calypso core MD03-2622 (10°42.37′N, 065°10.15′W, 877 m water depth) and Ocean Drilling Program (ODP) Site 1002 (10°42.73′N, 65°10.18′W; 893 m water depth) (Figure S1 in the supporting information) that together yield a composite, decadally resolved record of paleoenvironmental change from Cariaco Basin that spans nearly the last 600 kyr. Molybdenum is an

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element that is widely used to reconstruct changing redox conditions because it is enriched in sediments that accumulate under anoxic conditions [*Crusius et al.*, 1996; *Tribovillard et al.*, 2006].

2. Study Area, Setting, and Methods

The Cariaco Basin is located on the north central coast of Venezuela at approximately 10°N, the northernmost limit of the seasonal migration of the Atlantic ITCZ. The basin is separated from the open Caribbean by a series of shallow (<150 m deep) sills and is presently anoxic below ~ 275 m water depth. Previous studies have demonstrated that during warm interstadial (IS) periods of the last glacial, dark, organic-rich, typically laminated sediments were deposited under anoxic or near-anoxic conditions in the Cariaco Basin [*Peterson et al.*, 2000a; *Deplazes et al.*, 2013]. In contrast, during the cold stadials (S) of the last glacial, the sediments are light colored and predominantly bioturbated, indicating deep water oxygenation. Alternating intervals of laminated and bioturbated sediments over the full 170 m long sequence from Site 1002 [*Peterson et al.*, 2000b] suggest a long history of oscillation between oxygenated and anoxic conditions in the deep basin. Previous low-resolution studies of discrete samples from a Cariaco piston core and Site 1002 [*Dean et al.*, 1999; *Yarincik et al.*, 2000] have shown that Mo is ideally suited to capture these changes in redox state. The nondestructive, high-resolution (0.5 cm measurement interval) scanning-XRF method used here should therefore provide a tropical analog to the high-frequency climate records from Greenland, with the advantage that the Cariaco record spans multiple glacial-interglacial cycles.

Core sections from MD03-2622 and Site 1002 were run on an Avaatech XRF core scanner at the University of Miami for bulk elemental analysis. Core sections were scanned at a 0.5 cm resolution downcore step resulting in an average measurement spacing time of ~16 years. The age model for MD03-2622 and the upper ~123 kyr of Hole 1002C was made by matching the reflectance records of the two cores to that of nearby core MD03-2621 on the timescale of *Deplazes et al.* [2013]. The age model for the remainder of Hole 1002C was made by correlating a new planktic foraminiferal $\delta^{18}O$ record of *Globigerinoides ruber* (white morphotype) with the [*Lisiecki and Raymo*, 2005] benthic $\delta^{18}O$ stack using the program AnalySeries [*Paillard et al.*, 1996]. The prevalence of anoxic conditions in Cariaco precludes generation of a continuous benthic record. The Mo record presented here is a composite of data from core MD03-2622 (covering the last 115 kyr) spliced onto the longer record from Site 1002 (115 to ~600 kyr). Wavelet analyses were performed using software for MATLAB provided by Grinstead et al. (available at http://www.pol.ac.uk/home/research/waveletcoherence/). Before analysis, each time series was linearly interpolated at a constant 20 year time step, with a 95% confidence interval set assuming a red noise model. Further details on the age model and of methods and materials can be found in the supporting information.

3. Results

The Mo record for the 48.3 m long sediment sequence from MD03-2622 shows good correlation to both MD03-2622 lightness (L*) and NGRIP $\delta^{18}O$ over the ~123 kyr length of the Greenland record (Figure 1). Each warm IS in Greenland is matched by a peak in sedimentary Mo, indicating anoxic conditions, and low L* values, corresponding to darker sediment color (high organic carbon content). Millennial-scale temperature shifts in Greenland are thought to be linked to productivity and oxygenation changes in Cariaco Basin via shifts in the mean annual position of the ITCZ, with warm IS (cold S) in Greenland associated with a northerly (southerly) shifted ITCZ, high (low) productivity, and anoxic (oxygenated) conditions in Cariaco [*Peterson et al.*, 2000a; *Deplazes et al.*, 2013]. Some decoupling is observed between the L* record and the Mo record when sedimentary Mo is depleted, such as during the coldest portions of Marine Isotope Stage (MIS) 2 and MIS 4 (Figure 1). This behavior reflects the fact that Mo will only accumulate in sediments under fully anoxic conditions, whereas sediment color may be responding more continuously to productivity changes. In spite of this redox "threshold" behavior, under anoxic conditions the Mo proxy is sensitive enough that even relatively brief IS such as IS 3, 4, and 18 have counterparts in the Cariaco record, giving confidence in its ability to record low-latitude responses to high-latitude climate shifts. If this close relationship between Cariaco Mo and Greenland temperature persists over time, patterns of earlier millennial-scale variability at high northern latitudes can be inferred.

The long composite record of Cariaco Mo (Figure 2) terminates in sediments deposited during MIS 15, capturing four additional glacial periods (MIS 6, 8, 10, and 12) and five full interglacial periods (MIS 5, 7, 9, 11, and 13). Due

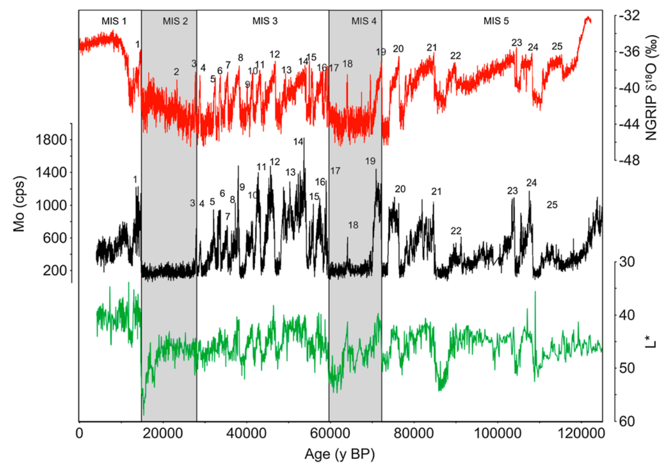

Figure 1. Cariaco reflectance and sedimentary Mo compared to Greenland ice core $\delta^{18}O$ during the last ~123 kyr. Sediment lightness (L*) and scanning-XRF record of Mo (10 point running smooth) (black) from MD03-2622 compared to NGRIP $\delta^{18}O$ (red), a proxy for Greenland air temperature [*NGRIP Members*, 2004]. Interstadials (IS) and marine isotope stages (MIS) are labeled with boundaries from *Wolff et al.* [2010]. Correlation between the Cariaco records and NGRIP $\delta^{18}O$ is excellent on the millennial scale. Low L* values (dark sediment color) and peaks in Mo coincide with Greenland interstadials, indicating that warm IS in the Northern Hemisphere are paralleled by accumulation of dark, organic-rich sediments under anoxic deep water conditions in the Cariaco Basin.

to less certainty in the age model prior to MIS 13, caution is exercised in interpretation of patterns in MIS 14 and 15. Upon examination of the full Mo record, the most apparent observations are that there is a clear correlation to local summer insolation and that the entire ~600 kyr is dominated by suborbital-scale variability, consistent with previous observations from records in the high latitudes [*Oppo et al*., 1998; *McManus et al*., 1999; *Weirauch et al*., 2008; *Bolton et al*., 2010]. Out of the four additional glacial periods captured in the Mo record, however, MIS 10 is the only interval that appears to follow the pattern of variability observed during the last glacial, with intervals of prolonged oxygenation (i.e., stability) at the onset and maximum of each interval bracketing a period of rapidly changing ventilation (instability) (Figure 2). In contrast, MIS 6, 8, and 12 exhibit different patterns of variability. During MIS 8, millennial-scale variability is seen at the onset of ice sheet buildup and also during the time of maximum ice volume extent. The Mo record from MIS 6 shows instability only in the first half of the glacial while MIS 12 shows rapid redox excursions throughout its duration.

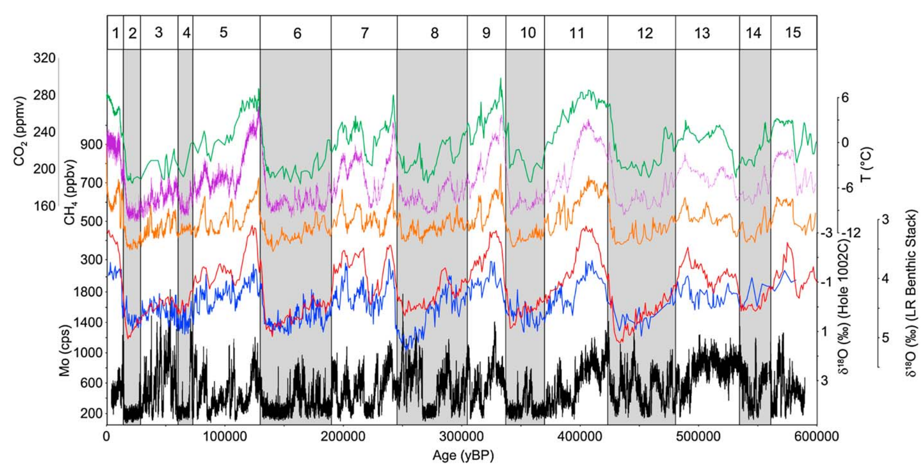

Figure 2. Variations in the spliced MD-2622 (0 to 115 kyr) and ODP Site 1002 (115 to ~600 kyr) Cariaco Mo record (10 point running average) (black) compared to CO_2 (green) [*Luthi et al*., 2008], CH_4 (orange) [*Loulergue et al*., 2008], and temperature (purple) [*Jouzel et al*., 2007] from the EPICA Dome C (EDC) ice core in Antarctica. Also shown is the $\delta^{18}O$ record of the planktic foraminifer *G. ruber* from ODP Site 1002 (blue) and the Lisiecki-Raymo benthic $\delta^{18}O$ stack (red), a proxy for global ice volume [*Lisiecki and Raymo*, 2005]. Marine isotope stages are labeled across the top, with glacial periods highlighted by gray bars.

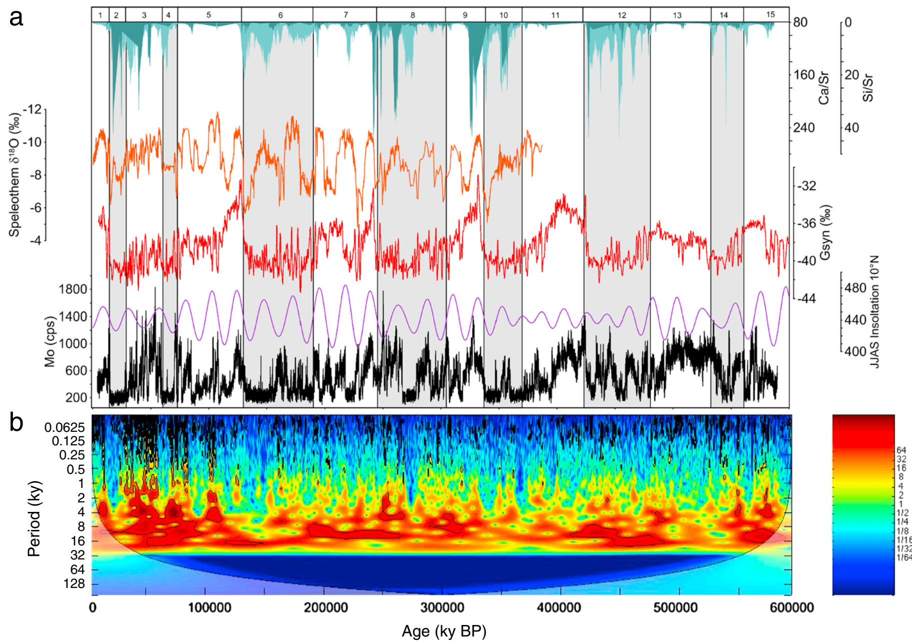

Figure 3. (a) Cariaco scanning-XRF Mo record (10 point running average; black) compared to summer (JJAS) insolation at 10°N [*Laskar et al*., 2004], a composite speleothem δ^{18}O record from East Asia [*Wang et al*., 2008; *Cheng et al*., 2009], the synthetic Greenland ice core record of *Barker et al*. [2011] (red), and scanning-XRF records of Ca/Sr and Si/Sr from North Atlantic Integrated Ocean Drilling Program Site U1308 [*Hodell et al*., 2008] (dark and light green, respectively), which serve as proxies for ice-rafted debris (IRD). Marine isotope stages are labeled across the top, with glacial periods highlighted by gray bars. (b) Wavelet analysis of the scanning-XRF Mo record. The Mo data were resampled at an even 20 year time step (linearly interpolated), detrended, prewhitened to heighten high-frequency variability, and high-pass filtered (bw = 0.4) to remove variability at periods > 20 kyr. Black lines indicate the Cone of Influence, outside of which estimates may be influenced by edge effects, and 95% confidence intervals for the wavelet analysis.

Interglacial periods are similarly characterized by variable patterns of basin ventilation (Figure 2). The oldest interglacial periods covered in entirety in this record, MIS 13 and 11, show prolonged periods of Mo enrichment that last for nearly the full duration of both interglacials. Although the records display some variability, oxygenated conditions were never achieved during the peaks of MIS 13 or MIS 11. Sediments representing MIS 9 show an extended interval of high Mo values corresponding to peak interglacial conditions as indicated by the lowest δ^{18}O values, followed by a transition to more pronounced Mo variability and intermittent ventilation toward the end of the interglacial that extends into MIS 8. In contrast, distinct oscillations between periods of full bottom water oxygenation and anoxia occur throughout MIS 7 and MIS 5, although the intervals of Mo enrichment are, on average, longer than those observed during the glacial periods.

In summary, while millennial-scale variability does indeed appear to be a persistent feature of tropical Atlantic climate over the past ~600 kyr, the patterns and distribution of that variability are not consistent between or among glacial and interglacial periods. This is reinforced by results of a wavelet analysis of the Mo record (Figure 3) which reveals strong power at periods less than 10 kyr throughout the Mo record, but more importantly, that the distribution of this high-frequency variability is not restricted to any particular ice volume state. Since the patterns of suborbital variability presented here do not appear intrinsically linked to a specific ice sheet size or threshold, this suggests that either some component of the variability observed in the Mo record is restricted to the tropics and not seen at high latitudes or that ice sheet extent is not the primary control of millennial-scale variability.

4. Mechanisms for Millennial-Scale ITCZ Migration

As previously noted, the mechanism most likely responsible for the connection between high latitude and tropical millennial-scale climate variability during the last glacial is thought to be shifts in the mean position of the ITCZ, which migrates in response to changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC). Specifically, reductions in the strength of the AMOC lead to a decrease in northward heat transport, an increased meridional sea surface temperature (SST) gradient, and a southward shift of the ITCZ

[*Clark et al*., 2001; *Vellinga and Wood*, 2002; *Broccoli et al*., 2006] which, in turn, impacts productivity, local hydrography, and deep water ventilation in Cariaco Basin.

At present, the favored explanation for AMOC disruptions centers on freshwater input to the high-latitude North Atlantic from periodic releases of meltwater derived from surrounding ice sheets [*Vidal et al*., 1997; *Ganopolski and Rahmstorf*, 2001]. Paleo and modeling studies [*Vidal et al*., 1997; *Hemming*, 2004] indicate that significant reductions in the strength of the AMOC occur in response to freshwater input during Heinrich Events (HEs), stratigraphic intervals in North Atlantic sediments characterized by an abundance of ice-rafted debris (IRD) derived from melting icebergs, specifically those shed from the Laurentide Ice Sheet (LIS) [*Hemming*, 2004]. Invoking AMOC changes to explain the variability seen in the Cariaco Mo record falls short for several reasons, however. The first is that HEs are only observed during some D/O stadials [*Hemming*, 2004], while changes in Cariaco Basin deep water ventilation are observed with each S-IS transition (Figure 1). Furthermore, compelling evidence for AMOC reductions during each and every D/O stadial is generally lacking. This discrepancy can be at least partially reconciled by incorporating non-HE-like ice rafting events into the picture. Evidence for IRD derived from sources other than the LIS (for example, from Icelandic or European sources) exists for each cold stadial during the last glacial [*Bond and Lotti*, 1995] and during stadial-like periods over the past 600 kyr [*Hodell et al*., 2008] (Figure 3). The consideration of non-LIS ice rafting events as additional sources of meltwater to the North Atlantic potentially provides a mechanism for producing more modest AMOC reductions than during HEs that would lead to commensurately smaller shifts in ITCZ position. The Cariaco Basin today sits near the northernmost limit of the seasonal Atlantic ITCZ migration, making its location especially sensitive to southward displacements of a smaller magnitude than those that accompany HEs. To the south, speleothem records from Northeastern Brazil [*Wang et al*., 2004] document intervals of increased regional precipitation only during HEs, an observation consistent with more extreme excursions of the tropical rain belt during HEs when evidence for more dramatic AMOC reductions is available [*Ganopolski and Rahmstorf*, 2001; *McManus et al*., 2004].

A second shortcoming of an ice rafting-dependent explanation is the implication that there is a critical ice volume threshold only above which climate over Greenland becomes unstable [*McManus et al*., 1999]. In Cariaco Basin, ventilation changes are clearly observed during interglacials at times where long IRD records show little to no ice rafting occurring (Figure 3). In particular, during MIS 5 and 7, the frequent occurrence of bioturbated, Mo-depleted intervals similar to those observed during glacials implies repeated southward excursions of the Atlantic ITCZ during at least some interglacial periods as well. Thus, the lack of North Atlantic IRD during interglacial periods makes it difficult to invoke a similar meltwater/AMOC coupling as the sole or primary control on millennial-scale variability within the warm periods of the last 600 kyr.

An alternative explanation to the traditional iceberg-derived freshwater input for forcing millennial-scale variability during the last glacial involves the growth and decay of sea ice in the North Atlantic [*Li et al*., 2005; *Siddall et al*., 2010; *Petersen et al*., 2013]. In models, the position of the ITCZ has been shown to be sensitive to North Atlantic sea ice extent [*Chiang et al*., 2003], thereby preserving the mechanistic link between high- and low-latitude rapid climate change. Changes in sea ice extent do not necessarily explain the Mo variability during interglacials, however, as there may be a feedback between sea ice extent and ice sheet volume that amplifies millennial-scale variability in glacial periods [*Siddall et al*., 2010].

Determining if the variability observed in the Cariaco Mo record is restricted to the tropics or is also seen at high latitudes is hampered by the paucity of high-resolution records of this length. One exception at present is the EPICA Dome C (EDC) record from Antarctica [*Jouzel et al*., 2007; *Loulergue et al*., 2008; *Luthi et al*., 2008]. Although plotted on their independent age models (Figure 2), Mo peaks in Cariaco agree reasonably well with CH_4 peaks from the EDC record, adding further support to the idea that Mo-rich, anoxic intervals occur during times of increased warmth and humidity in the northern tropics that would facilitate expansion of tropical wetlands and CH_4 increases in the atmosphere. In contrast, intervals of depleted Mo during interglacial periods in Cariaco Basin (e.g., MIS 5, 7, and 9) align closely with lows in the EPICA CH_4 record, consistent with a linkage between oxygenated deep basin conditions (southward ITCZ) and dry and/or cool conditions in the major methane producing wetlands of the northern tropics at these times.

Reduced heat transport into the North Atlantic during times of weakened or collapsed AMOC leads to an accumulation of heat in the Southern Hemisphere, a mechanism that has come to be known as the "bipolar thermal seesaw" [*Broecker*, 1998]. *Barker et al*. [2011] used this concept along with the Antarctic EDC temperature record to create a synthetic record of Greenland temperature variability over the last 800 kyr, an approach that relies on the assumption that Antarctica and Greenland remained out of phase with respect to millennial-scale temperature variations over the pre-NGRIP time interval. Comparison of the Cariaco and synthetic Greenland records (Figure 3) reveals that large-scale features are in good agreement, particularly after MIS 13. For example, the beginning of MIS 6 in both records appears to have more variability than the latter portion, and the period of reduced variability in mid MIS 8 relative to the onset and end of the glacial period also features in both. In general, the synthetic record shows more high-frequency variability during the coldest intervals, which is not unexpected since Mo displays a threshold behavior and does not accumulate in sediments during periods of deep water oxygenation. Overall, there is also good agreement between the two records in the interglacial periods, which suggests that, in spite of reduced ice volume during warm interglacials, changes in the strength of the AMOC and reductions in northward heat transport did indeed occur.

5. Conclusions

Regardless of the forcing mechanism, the presence of fully oxygenated intervals during interglacials in the Cariaco record indicates that stadial-like southward excursions of the ITCZ can occur during times of reduced ice sheet extent. This has important implications for changes in tropical hydrology during periods of interglacial warmth. Southward migrations of the ITCZ during stadial portions of the last glacial have been linked to arid conditions in northern South America [*Peterson et al*., 2000a; *Wang et al*., 2007] and Africa [*Weldeab et al*., 2007], as well as to reductions in Asian Summer Monsoon strength [*Wang et al*., 2008; *Cheng et al*., 2009] (Figure 3). The ITCZ migrations inferred from the ventilated portions of the Cariaco Mo record, and the similarity between the Cariaco record and a composite record of speleothem $\delta^{18}O$ variability from East Asia (Figure 3), indicate that periods of aridity in the low latitudes and midlatitudes that have traditionally been associated with cold conditions in the high northern latitudes are not restricted to glacial periods.

The ~600 kyr record of deep water ventilation from the Cariaco Basin presented here indicates that millennial-scale climate change has been a dominant feature of tropical climate for the past half million years. Comparison of the Cariaco Mo record to the synthetic Greenland record of *Barker et al*. [2011] supports the idea that the bipolar seesaw has been in general operation over the past 600 kyr, although evidence for periods of deep water oxygenation in the basin during interglacials raises questions regarding the importance of ice volume in the forcing of rapid climate change. Stadial-like southward migrations of the ITCZ during periods of interglacial warmth carry important implications for hydrology in the tropical Atlantic.

Acknowledgments

Support for this study was provided by NSF grants OCE-0602392 and OCE-1003364. Archive halves of core sections from ODP Hole 1002C and 1002D were generously provided for XRF scanning by the Integrated Ocean Drilling Program Gulf Coast Repository. Core MD03-2622 was collected as part of the IMAGES PICASSO campaign. We thank S. Barker for providing data for comparison and R. Thunell, G. Haug, and two anonymous reviewers for helpful comments that greatly improved the quality of this manuscript.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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