PALEOCEANOGRAPHY, VOL. 22, PA4204, doi:10.1029/2007PA001427, 2007

An 8-century tropical Atlantic SST record from the Cariaco Basin: Baseline variability, twentieth-century warming, and Atlantic hurricane frequency

David E. Black,[1] Matthew A. Abahazi,[2] Robert C. Thunell,[3] Alexey Kaplan,[4]
Eric J. Tappa,[3] and Larry C. Peterson[5]

Received 29 January 2007; revised 15 June 2007; accepted 14 August 2007; published 25 October 2007.

[1] We present the first direct comparison and calibration of a downcore foraminiferal Mg/Ca record to historical instrumental sea surface temperature (SST). Mg/Ca measured on the planktic foraminifer *Globigerina bulloides* from a Cariaco Basin sediment core strongly correlate with spring (March–May) instrumental SSTs between A.D. 1870 and 1990. A Mg/Ca SST equation is derived and a paleo-SST record is presented spanning the last 8 centuries, an interval that includes the end of the Medieval Warm Period and the Little Ice Age. The long-term record displays a surprising amount of variability. The temperature swings are not necessarily related to local upwelling variability but instead represent wider conditions in the Caribbean and western tropical Atlantic. The Mg/Ca SST record also captures the decadal and multidecadal variability observed in records of global land and sea surface temperature anomalies and Atlantic tropical storm and hurricane frequency over the late nineteenth and twentieth centuries. A divergence between the SST proxy record and Atlantic storm frequency around 1970 appears to reflect a fundamental change in Atlantic hurricane behavior noted in historical data. On average, twentieth-century temperatures are not the warmest in the entire record, but they do show the largest increase in magnitude and fastest rate of SST change over the last 800 a.

Citation: Black, D. E., M. A. Abahazi, R. C. Thunell, A. Kaplan, E. J. Tappa, and L. C. Peterson (2007), An 8-century tropical Atlantic SST record from the Cariaco Basin: Baseline variability, twentieth-century warming, and Atlantic hurricane frequency, *Paleoceanography*, *22*, PA4204, doi:10.1029/2007PA001427.

1. Introduction

[2] The likelihood of anthropogenic warming [e.g., *Overpeck et al.*, 1997; *Mann et al.*, 1999; *Crowley*, 2000] and the growing recognition of the role of the tropics in global climate change [e.g., *Schmittner and Clement*, 2002; *Grassi et al.*, 2006; *Peterson and Haug*, 2006] have spurred the need for long continuous high-resolution records of tropical climate variability. The Cariaco Basin (Figure 1) is well positioned to record a detailed history of surface ocean changes along the southern margin of the Caribbean and the tropical Atlantic [*Hughen et al.*, 1996; *Lin et al.*, 1997; *Black et al.*, 1999; *Peterson et al.*, 2000; *Haug et al.*, 2001, 2003; *Lea et al.*, 2003; *Tedesco and Thunell*, 2003a]. Varved, high deposition rate sediments deposited under anoxic conditions and an abundance of well-preserved microfossils result in one of the few marine records capable of preserving evidence of interannual- to decadal-scale climate variability in the tropical Atlantic. Here we present an 8-century Mg/Ca-derived SST record that is the first downcore record to be directly calibrated against instrumental SSTs.

2. Materials and Methods

[3] Box core PL07-73 BC (10°45.98′N, 64°46.20′W, 450-m water depth) was collected in 1990 from the northeastern slope of the Cariaco Basin. Consecutive 1-mm samples (565 in all) from the core were freeze-dried, weighed, and wet-sieved through a 63-μm screen. Samples were first analyzed for planktic foraminiferal census counts, and then 100 *Globigerina bulloides* (212- to 250-μm fraction) were picked from each sample for Mg/Ca analyses. Although *Globigerinoides ruber* is probably more representative of annual average conditions in the Cariaco Basin [*Tedesco and Thunell*, 2003b], *G. bulloides* was chosen for this study because of its greater abundance and hence sufficient material from each 1-mm sample for Mg/Ca analyses.

[4] Each sample was cleaned using a procedure modified from *Boyle* [1981] to remove possible contamination from clays and organic matter. The samples were gently crushed between two clean glass slides to break open the chambers and then repeatedly washed and sonicated with deionized water and methanol to remove clays. An oxidizing solution was added, and then the samples were boiled for 10 min with periodic sonication. This step was repeated to ensure

---

[1] School of Marine and Atmospheric Sciences, State University of New York at Stony Brook, Stony Brook, New York, USA.

[2] Department of Geology and Environmental Science, University of Akron, Akron, Ohio, USA.

[3] Department of Geological Sciences, University of South Carolina, Columbia, South Carolina, USA.

[4] Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, USA.

[5] Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida, USA.

0883-8305/07/2007PA001427$12.00

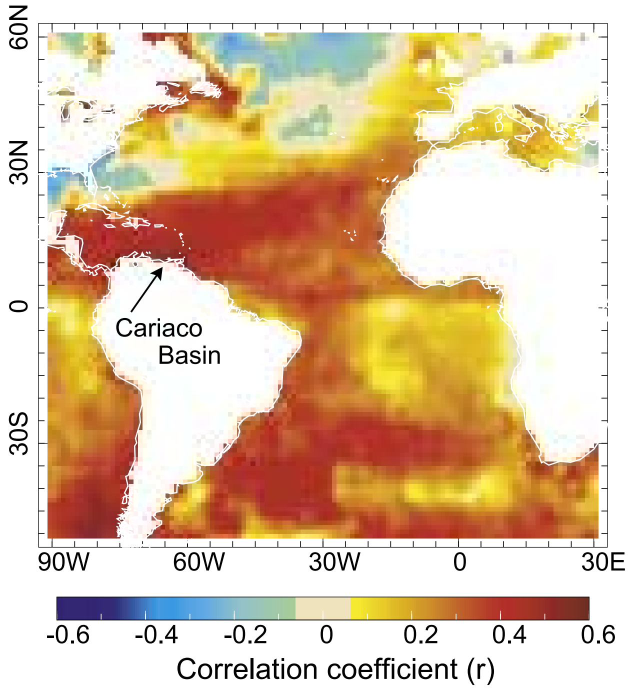

Figure 1. Map showing the location of the Cariaco Basin and spatial correlation coefficients between *G. bulloides* Mg/Ca and Hadley Centre SSTs for the period 1870–1990. Warmer colors indicate stronger correlations. Correlations are statistically significant ($p < 0.1$) for all of the Caribbean and much of the western tropical Atlantic, as they exceed the critical value $r = 0.31$ for the effective sample length $N_{\mathrm{eff}} = 30$.

removal of all organic material. The samples were then rinsed with deionized water, mildly acid-leached with a 0.001 M HNO_3 solution, rinsed again with deionized water, and then finally dried. The cleaned samples were then dissolved in 5% HNO_3 in a volume sufficient to yield a Ca concentration of 80 ppm.

[5] Magnesium and calcium were simultaneously measured on a Jobin Yvon Ultima Inductively Coupled Plasma Atomic Emission Spectrophotometer. Mg/Ca was corrected relative to a standard solution [*Schrag*, 1999] run between every sample, and 10% of the samples were replicated as well. Reproducibility of the standard and replicate samples in this study is ±0.06 and ±0.08 mmol/mol, respectively. The Mg/Ca for *G. bulloides* measured for this study vary between 3.82 and 5.86 mmol/mol, well within the range of other reported *G. bulloides* Mg/Ca [*Lea et al.*, 1999; *Mashiotta et al.*, 1999; *Elderfield and Ganssen*, 2000; *McConnell and Thunell*, 2005].

[6] The age model for the last 130 a of PL07-73 BC is based on correlations of its foraminiferal census counts to the faunal data of nearby cores with a previously published well-established varve and ^{210}Pb stratigraphy, while the older parts of the core are constrained by a correlative chronology based on 17 accelerator mass spectrometry ^{14}C dates [*Black et al.*, 1999; *Goñi et al.*, 2003; *Black et al.*, 2004]. The resulting 8-century data set has a sample resolution of approximately 1 a per sample near the top of the record and approximately 1.5 a per sample near the bottom of the record. The data were then interpolated linearly onto the uniform monthly temporal grid, from March 1221 to May 1990. March–April–May (MAM) averages were then computed for each year to produce an annual resolution record which consequently was used in all further analyses presented in this paper.

3. Comparing the Cariaco Basin Mg/Ca Record to Instrumental Sea Surface Temperature Data, A.D. 1870–1990

[7] Previous studies examining the relationship between foraminiferal calcite Mg/Ca and sea surface temperature (SST) have used laboratory culture experiments [*Nürnberg et al.*, 1996; *Lea et al.*, 1999; *Mashiotta et al.*, 1999; *Toyofuku et al.*, 2000], sediment trap studies [*Anand et al.*, 2003; *McConnell and Thunell*, 2005], and core top calibrations [*Elderfield and Ganssen*, 2000; *Dekens et al.*, 2002]. No one to date has directly compared a downcore Mg/Ca record to historical instrumental data because there are very few areas with sufficiently high sedimentation rates where one can recover nonbioturbated sediments and high fossil foraminifera abundances. Long-term sedimentation rates in the Cariaco Basin are as much 1 m/ka, and sediments have been deposited under anoxic, nonbioturbated conditions for the last 12.6 ka, thus allowing one to compare and calibrate a suite of paleoceanographic proxies against historical instrumental data.

[8] The *G. bulloides* Mg/Ca data were compared to the Hadley SST data set [*Rayner et al.*, 2003] Cariaco Basin grid square (1° × 1°, centered on 10.5°N, 64.5°W) for the period of A.D. 1870–1990. The Mg/Ca record was initially compared to individual monthly SST series between 1870 and 1990. That is, correlation coefficients were calculated between the Mg/Ca record and 1870–1990 January SSTs, then February SSTs, then March SSTs, etc. (Figure 2). Correlations were highest for the months of March, April, May, and June (r of 0.49, 0.54, 0.57, and 0.52, significant for $p < 0.007$, 0.002, 0.001, and 0.002, respectively), strongly agreeing with recent Cariaco Basin sediment trap data indicating that *G. bulloides* fluxes are highest during March, April, and May [*Tedesco and Thunell*, 2003b]. Correlation significance (p value) was determined using the two-sided approximate Student's t test for correlation coefficients [*von Storch and Zwiers*, 1999]. In performing these tests the nominal sample length $N = 121$ was reduced to the effective number of independent values: $N_{\mathrm{eff}} = N/\tau$, where τ, the number of years between independent samples, was computed according to the *Davis* [1976] formula, adopted by *Trenberth* [1984] and found to be about 4 a for the months of March–June in our series.

[9] Having established the strongest monthly correlations, the Mg/Ca data were then compared to March–April–May average SSTs over the period of instrumental overlap (Figure 3a). We use the traditional exponential form of the relationship between Mg/Ca and temperature [e.g., *Lea et*

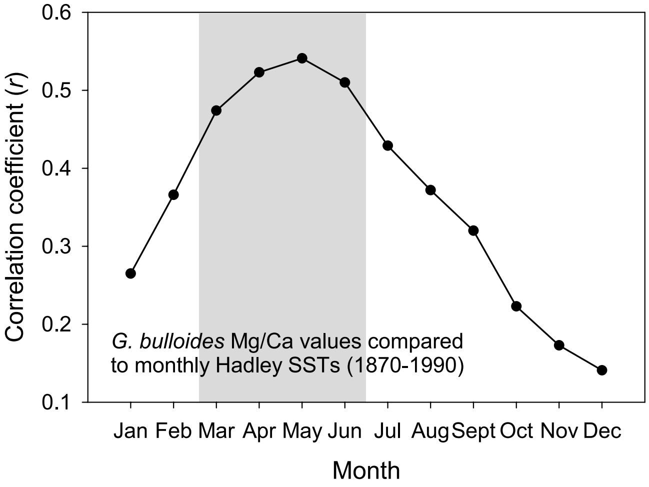

Figure 2. Correlation coefficients between the Mg/Ca data and monthly instrumental SSTs for the period 1870–1990. Highest correlations occur between the Mg/Ca data and March, April, May, and June SSTs, similar to sediment trap data indicating maximum *G. bulloides* fluxes during the same months [*Tedesco and Thunell*, 2003b].

al., 1999; *Elderfield and Ganssen*, 2000; *McConnell and Thunell*, 2005]:

$$\mathrm{Mg/Ca} = A\exp(BT). \tag{1}$$

By taking the logarithm of both sides and solving for T we obtain

$$T = 1/B \times \ln(\mathrm{Mg/Ca}) - \ln(A)/B. \tag{2}$$

Equation (2) is essentially a formula for the linear regression of T on ln(Mg/Ca). We used the standard formalism of linear regression [*von Storch and Zwiers*, 1999] to determine coefficients in equation (1) in a way that minimized the error in temperature predictions. This resulted in the predictive relationship:

$$T = 5.78 \times \ln(\mathrm{Mg/Ca}) + 17.56, \tag{3}$$

which corresponds to the parameters $A = 0.048$ and $B = 0.173$ in equation (1). The in-sample estimate of predictive error standard deviation in equation (3) is σ_ε = 0.35°C and is smaller than that for any other choice of parameters A and B.

[10] The errors of individual predictions depend on the value of predicted ln(Mg/Ca) because of sampling uncertainty in the parameters of equation (3) [*von Storch and Zwiers*, 1999]. These errors are large (Figure 3b) and the reconstructed signal standard deviation σ_r = standard deviation [$T_\mathrm{predicted}$] = 0.235°C is actually smaller than the σ_ε. This is expected since in linear regression formalism the total variance of the signal ($\sigma_\tau^2 = 0.42^2$ °C^2) is partitioned between the variance of predictive regression line (σ_r^2) and error variance (σ_ε^2): $\sigma_\tau^2 = \sigma_\mathrm{r}^2 + \sigma_\varepsilon^2$, with the coefficient of determination $r^2 = \sigma_r^2/\sigma_\tau^2 = 0.313 = 0.559^2$ being equal to the squared correlation coefficient. Even though our prediction reconstructs only 31.3% of the total signal variance, it is undoubtedly skillful according to the F test [*von Storch and Zwiers*, 1999], taking into account the effective sample size (N_eff). Using $N_\mathrm{eff} = 28$, we compute the F statistics value $F = (N_\mathrm{eff} - 2)\ \sigma_r^2/\sigma_\varepsilon^2 = (28 - 2)(0.235)^2/(0.347)^2 = 11.92$ that comes from the distribution $F(1, N_\mathrm{eff} - 2)$ and thus corresponds to the p value of 0.0019 in the one-sided F test. This small p value signifies a prediction skill well beyond what could normally occur by chance.

[11] Equation (3) minimizes error in SST predictions from Mg/Ca and, when the error is included, accurately captures the full range of instrumental SSTs over the calibration interval. One could derive an equation that preserves the instrumental SST range, but the predictive error would be much larger.

[12] One additional complicating factor is that *G. bulloides* is a subsurface dweller (30–50 m typically) but the temperature calibration for this study was done using actual surface temperature data rather than laboratory culture or sediment trap preferred in situ temperatures. Recent hydrographic studies of the Cariaco Basin noted that the average vertical temperature gradient between 50 m and the surface was just under 3°C during the upwelling season between 1995 and 1998 [*Muller-Karger et al.*, 2001; *Astor et al.*, 2003]. A direct subsurface temperature calibration was not possible because long-term subsurface temperature data for this region are not available, and as such, this equation may not be valid for other study areas.

[13] The Mg/Ca record reflects SST beyond the Cariaco Basin as shown by significant correlations with SSTs over much of the southern Caribbean and tropical North Atlantic over the period of instrumental overlap (Figure 1). Our proxy data also capture a significant portion of the global combined land and sea temperature anomaly record variability (Figure 3c) [*Jones et al.*, 1999].

4. Full 8-Century Record

[14] The complete 8-century Mg/Ca-derived SST record (Figure 4a) shows an unexpectedly large amount of variability for a tropical location during the late Holocene. The base of the record captures the latter part of the Medieval Warm Period (MWP), approximately A.D. 1200 and 1425, during which spring SSTs gradually cooled by 0.75°C. This cooling was followed by more than 1.0°C warming between A.D. 1425 and 1500. The Little Ice Age (LIA) is characterized by a pronounced 1.5°C SST decrease between A.D. 1500 and 1640, with a particularly steep drop between approximately 1630 and 1640, almost exactly coincident with the beginning of the Maunder Minimum in 1645 [*Eddy*, 1976]. SSTs gradually rose again until about A.D. 1800, after which temperatures fluctuate around a mean that is slightly cooler than SSTs observed for the late Medieval Warm Period. A brief 0.5°C cooling occurred in the late 1800s and early 1900s followed by a strong 1°C warming during the twentieth century. The resolution of this data set is sufficient to capture even short transient events such as the brief but notable cooling that occurred in the Atlantic

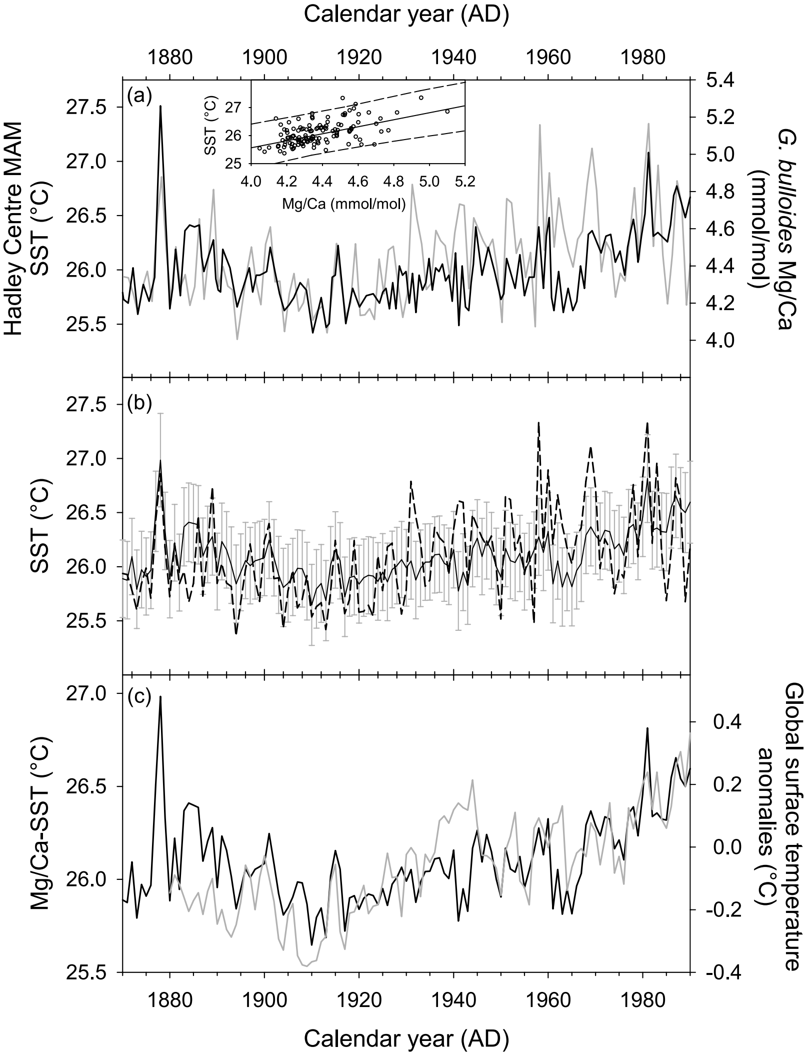

Figure 3. (a) Comparison of *G. bulloides* Mg/Ca (black line) to MAM instrumental SSTs (gray line) over the period of overlap. Inset shows Mg/Ca SST scatterplot regression with 95% confidence lines. (b) Mg/Ca SST (solid line) with 1-σ error bars compared to instrumental SST (dashed line). (c) Comparison of Mg/Ca SST (black line) to global land and sea surface temperature anomalies (gray line) [*Jones et al.*, 1999].

during the Great Salinity Anomaly of the late 1960s [*Dickson et al.*, 1988; *Levitus*, 1989].

[15] On average, twentieth-century Mg/Ca SSTs are not the warmest of the entire record. Rather, the 100 a spanning approximately A.D. 1450–1550 are the warmest. However, the twentieth century contains the largest magnitude temperature increase for any 100-a interval and, correspondingly, the largest rate of temperature change over the entire record. Mg/Ca SSTs increased by ~1.1°C over 70 a during the twentieth century (most of that since the mid-1960s) compared to 1.0°C increases that occurred over 88 a during the 1400s and mid-1600s.

[16] Comparable Caribbean/tropical Atlantic SST records are rare, but those that do exist show generally similar trends to the Cariaco reconstruction. A high-resolution sclerosponge Sr/Ca-derived SST study from Jamaica (20 m below sea level) [*Haase-Schramm et al.*, 2005] shows similar long-term trends (Figure 4b) but almost always estimates warmer SSTs over equivalent intervals, and the temperature offset between the two records is not constant. The pronounced SST rise and fall across the MWP/LIA transition in the Mg/Ca data are not as strongly reflected in the sclerosponge data. The observed warming in the latter part of both records is also different, both in terms of onset and magnitude; the Mg/Ca SSTs suggest a warming of about 1°C between 1910 and 1990, while the sclerosponge SSTs suggest an average warming of about 4°C between 1840 and 1990.

[17] Planktic foraminiferal Mg/Ca SST records from just south of the Dry Tortugas in the northern Caribbean [*Lund and Curry*, 2006] show similar twentieth-century warming as the Cariaco data (Figure 4c), but a well-defined Medieval Warm Period and Little Ice Age are not apparent. Interestingly, the δ^{18}O data from the same cores do show equivalent MWP and LIA events.

[18] A lower-resolution SST history based on planktic foraminifera abundances from a core taken near Puerto Rico

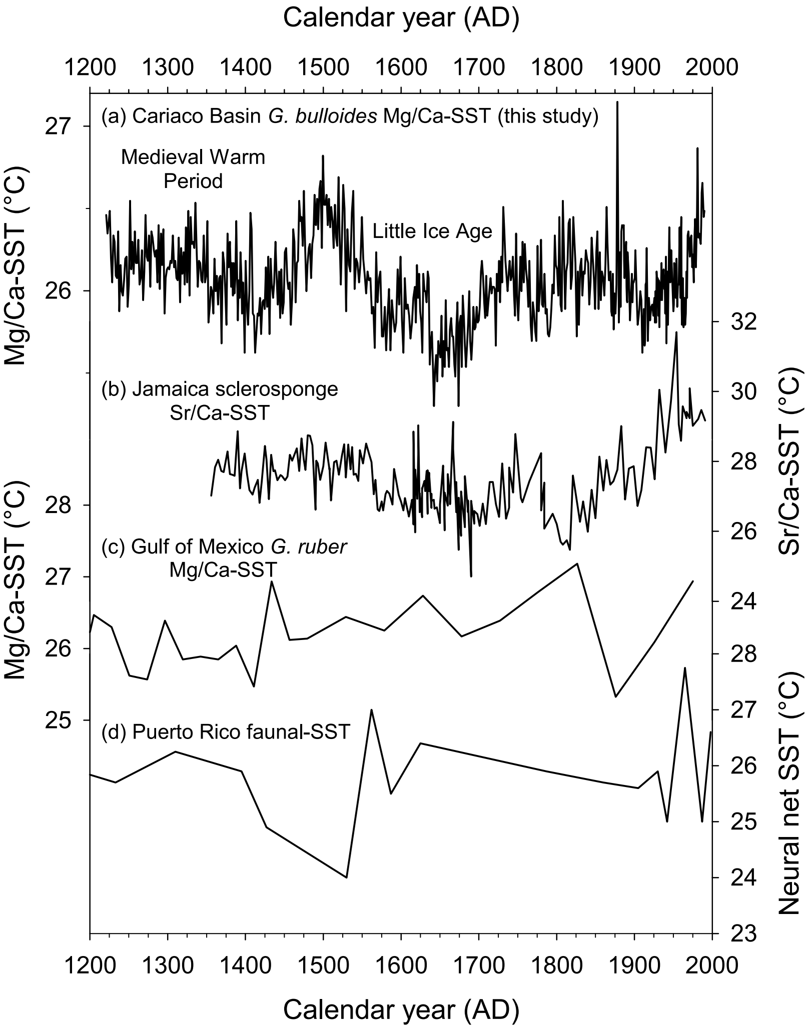

Figure 4. (a) Full core Mg/Ca SST record compared to other circumtropical Atlantic reconstructions from south to north (temperature scales are not identical between individual records). (b) Sclerosponge Sr/Ca data from Jamaica [*Haase-Schramm et al.*, 2005] converted to SST after *Rosenheim et al.* [2004]. (c) *G. ruber* Mg/Ca SST from the Gulf of Mexico [*Lund and Curry*, 2006]. (d) Foraminiferal abundance SSTs from Puerto Rico [*Nyberg et al.*, 2002].

[*Nyberg et al.*, 2002] shows the same general pattern as the Mg/Ca data (Figure 4d), but there is a temporal offset between the two records that cannot be explained by age model differences alone.

[19] Farther to the north near Bermuda, a shorter but high-resolution coral Sr/Ca record [*Goodkin et al.*, 2005] contains some of the same early twentieth-century variability as our Mg/Ca record but is generally dissimilar to the Cariaco record overall. The lack of similarity is not surprising, as previous Cariaco Basin studies have not correlated well with instrumental or proxy data from the Bermuda area [*Black et al.*, 1999, 2004], and the spatial correlation pattern in Figure 1 again suggests that these two regions do not share a strong teleconnection.

[20] Regional precipitation/aridity paleoclimate data sets show some similarity to the Cariaco Mg/Ca SST data (Figure 5). Percent titanium data from Cariaco Basin sediments [*Haug et al.*, 2001] show a similar pattern to Mg/Ca SSTs during the LIA but are distinctly different during the MWP. A terrestrial lake record of gastropod $\delta^{18}O$ from the Yucatan Peninsula shows a nearly identical LIA pattern, including a large drop in values at the beginning of the Maunder Minimum and a subsequent increase, but the records do not show the same trends during the MWP or the twentieth century [*Hodell et al.*, 2005]. The variable correlations suggest that the relationship between cold/dry and warm/wet conditions in the tropical Atlantic and Caribbean may be too simplistic.

5. The $\delta^{18}O$ Water Reconstruction

[21] It was originally hoped that the $\delta^{18}O$ water component of the classic calcite $\delta^{18}O$ paleotemperature relationship could be reconstructed with the development of the Mg/Ca temperature proxy. Paired Mg/Ca-$\delta^{18}O$ measurements in theory allow one to solve for the $\delta^{18}O$ water

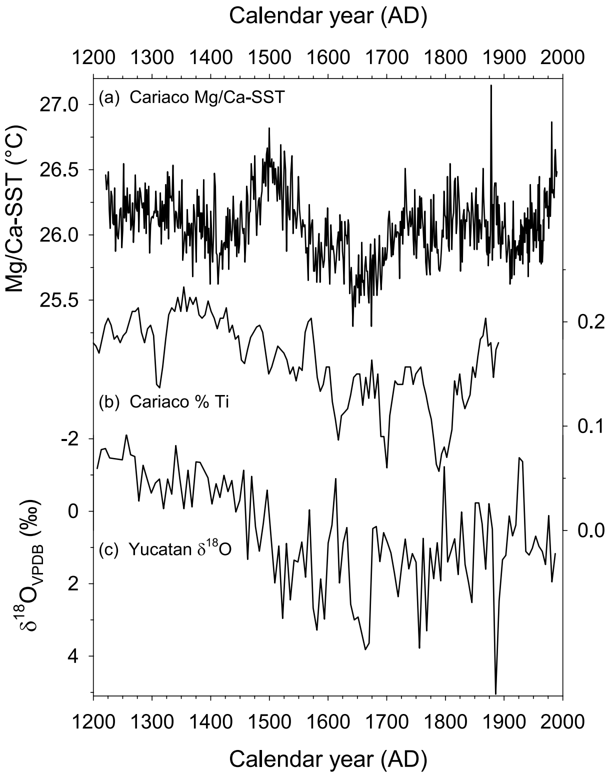

Figure 5. (a) *Globigerina bulloides* Mg/Ca SST compared to (b) Cariaco Basin sediment percent titanium data (three-point smooth) [*Haug et al.*, 2001], and (c) gastropod δ^{18}O from the Yucatan Peninsula [*Hodell et al.*, 2005].

variable and, in principle, to reconstruct paleosalinity. In practice, this has not proven to be simple because of the combined effects of analytical precision errors in both the Mg/Ca and δ^{18}O measurements and temporal averaging within individual samples themselves. Our very high resolution, well-calibrated Mg/Ca record is no exception.

[22] Paired Mg/Ca and stable oxygen isotope analyses were performed on *G. bulloides* samples for the period spanning the twentieth century, the time when age control is tightest for the entire core. The δ^{18}O and Mg/Ca SSTs were then entered into the *Bemis et al.* [1998] δ^{18}O paleotemperature equation for *G. bulloides*. The resulting calculated δ^{18}O water are, on average, approximately 0.8‰ higher than recently measured δ^{18}O water for the Cariaco Basin [*McConnell et al.*, 2005] and 1.0‰ higher than Cariaco Basin salinity-derived δ^{18}O water estimates [*Tedesco et al.*, 2007].

[23] A recent 3-a Cariaco Basin sediment trap-based study found that *G. bulloides* δ^{18}O-derived temperatures using the *Bemis et al.* [1998] equation were consistently cooler than instrumental SSTs, except during the spring upwelling season in each year when the instrumental and derived temperatures were similar [*Tedesco et al.*, 2007]. We tested to see if this seasonal bias might be affecting our δ^{18}O water reconstructions by substituting average March–April–May Hadley instrumental SSTs for the Mg/Ca SSTs into the *G. bulloides* δ^{18}O paleotemperature equation. Similar to the Mg/Ca SST results, calculated δ^{18}O water using the seasonal instrumental SST data also produced values that are approximately 0.8‰ heavier than measured. Like the Mg/Ca SST equation derivation, the δ^{18}O water calculation may be complicated by the fact that *G. bulloides* does not live right at the surface yet we are using surface temperatures for the calculation.

6. Forcing Mechanisms

[24] An immediate question is to what extent does upwelling variability influence the temperature record, particularly since maximum *G. bulloides* fluxes occur during the local upwelling season [*Tedesco and Thunell*, 2003b]. A comparison of the Mg/Ca SST record to *G. bulloides* abundance, a proxy for upwelling and trade wind variability in the Cariaco Basin [*Peterson et al.*, 1991; *Black et al.*, 1999], reveals very little similarity between the two records. In particular, the large SST changes during the end of the MWP, the beginning of the LIA, and the mid to late twentieth century are not associated with corresponding changes in *G. bulloides* abundance in either PL07-71BC or PL07-73BC. However, *Black et al.* [1999] noted a near-zero correlation (r = 0.03) between *G. bulloides* abundance from a different Cariaco Basin core and local SSTs. A comparison of the *G. bulloides* abundance record from the core used for this study (PL07-73 BC) to instrumental SSTs over the period of instrumental overlap results in a weak, although statistically significant, correlation (r = 0.18, $p <$ 0.1). Given the overall weak correlation between *G. bulloides* abundance and instrumental SSTs, any attempt to interpret the Mg/Ca SST record in terms of local upwelling variability should be treated with caution.

[25] Multitaper method spectral analysis [*Ghil et al.*, 2002] of the Mg/Ca SST record results in peaks primarily in the 3- to 6-a range, no significant power in the decadal and multidecadal range, and some power at multicentury scales that are poorly characterized relative to the length of the proxy record (Figure 6). There are no decadal-scale peaks that exceed the 90% confidence limit, and it is not until periods longer than approximately 63 a do we see

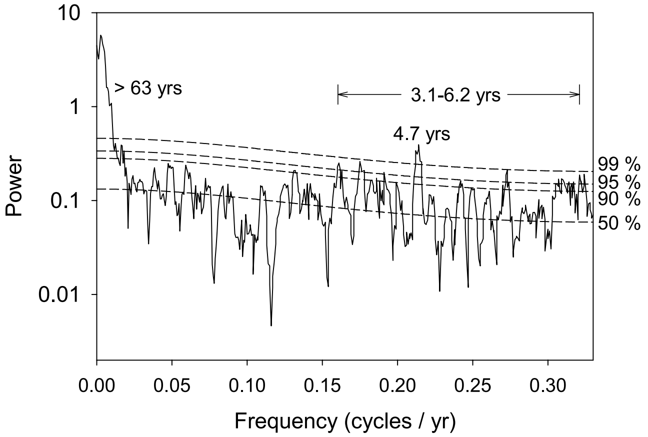

Figure 6. Multitaper method spectral analysis of the Mg/Ca-derived SST data.

spectral power that exceeds the 95% confidence limit. This is surprising as studies of the much shorter instrumental tropical Atlantic SST record have noted decadal-scale periodicities [e.g., *Mehta and Delworth*, 1995; *Carton et al.*, 1996; *Chang et al.*, 1997]. Prior analysis of *G. bulloides* abundance, a proxy for trade wind variability, also noted decadal-scale variability [*Black et al.*, 1999].

[26] Power in the 3- to 6-a band initially suggests an El Niño–Southern Oscillation (ENSO) influence on the Cariaco Basin SST record. However, the correlation coefficient between the Niño 3.4 index and the derived SST record is very weak ($r = 0.11$; statistically insignificant), and historically strong warm or cold phase ENSO events are unremarkable in the Mg/Ca record. Still, a number of studies have found a relationship between ENSO and interannual climate variability in the Caribbean. An analysis of instrumental SSTs for the period 1950–1992 demonstrated that tropical Atlantic and Caribbean SST variability is correlated with ENSO variability [*Enfield and Mayer*, 1997]. Anomalous warming in the Atlantic typically occurred during the boreal spring following the maximum ENSO anomalies, the same season with the highest correlation between *G. bulloides* Mg/Ca and instrumental SST. *Giannini et al.* [2000] also noted anomalous warming in the Caribbean–western Atlantic basin following the mature phase of an ENSO event. However, lagging our Mg/Ca SST record relative to the Niño 3.4 index lowers the correlation even further ($r = 0.09$).

[27] The geographically closest paleo-SST record to ours found spectral peaks in the 2- to 7-a range which were attributed to ENSO variability [*Haase-Schramm et al.*, 2005], but processes in the Atlantic may also play a role in generating subdecadal-scale variability. *Carton et al.* [1996] noted variability in tropical Atlantic SST anomaly patterns on 2- to 5-a timescales related to processes similar to ENSO, where the western Atlantic trade winds weaken and eastern equatorial Atlantic thermocline waters shift westward. However, this equatorial Atlantic mode appears to have more of an effect on eastern tropical Atlantic SST distributions than western Atlantic SSTs [*Carton et al.*, 1996; *Kayano et al.*, 2005].

[28] Another possible forcing mechanism is the North Atlantic Oscillation (NAO), even though the spectral analysis does not initially suggest it. Maximum covariance analyses (MCA) of the Hadley Centre SST data set [*King and Kucharski*, 2006] indicate an inverse correlation between the NAO and tropical Atlantic SSTs, with r values between -0.16 and -0.20 for regions just east of the Cariaco Basin. The MCA data also indicate that the influence of the NAO on tropical Atlantic SSTs weakens post-1960. When our Mg/Ca SST record is compared to the NAO index [*Hurell*, 1995], there is a weak but statistically significant correlation of the correct sign and magnitude ($r = -0.20$, $p < 0.05$), and the correlation improves to -0.31 ($p < 0.01$) if the A.D. 1960–1990 data are removed.

[29] The observed spectral power at lower frequencies is more difficult to explain because the peak is not well defined (encompasses periodicities between 63 and 800 a at the 95% confidence level). Climate models suggest that significant multidecadal- to century-scale variability can result from processes internal to the Earth's climate system alone (thermohaline circulation, for example), but the models suggest different dominant timescales of variability [e.g., *Manabe and Stouffer*, 1996; *Delworth et al.*, 1997; *Timmerman et al.*, 1998]. While the spectral analysis indicates that a multidecadal to multicentury mode must be important, the cause of this scale of variability is not clear at this time.

7. Tropical Atlantic SSTs and Hurricanes

[30] A variety of consequences have been suggested as a result of global warming, including sea level rise, shifts in precipitation patterns, changes in drought frequency and severity, outbreaks of tropical disease, geographic shifts in ecologic zones, and much more. One possible consequence that has received a great deal of attention recently is the potential for a more active hurricane season and stronger storms [e.g., *Goldenberg et al.*, 2001; *Emanuel*, 2005; *Trenberth*, 2005; *Trenberth and Shea*, 2006; *Mann and Emanuel*, 2006]. Our study location lies in the heart of the tropical Atlantic/Caribbean, and given that SST is a critical component to hurricane formation, we compared our Mg/Ca-derived SST record to the number of hurricanes and tropical storms in the Atlantic for the period A.D. 1886–1990 (Figure 7a). The year-to-year correlation between the two records is significant ($r = 0.27$, $p < 0.07$), and the Mg/Ca SST record visually captures the decadal- and multidecadal-scale Atlantic storm variability.

[31] Nine-year moving averages of the number of hurricanes/tropical storms and Mg/Ca SST data sets were compared to determine how well the decadal-scale variability was characterized. The general trend is what one would expect: more tropical storms and hurricanes when SSTs are warmer (Figures 7b and 7c). The correlation is strong until approximately 1970 when the two records diverge, a pattern seen in a scatterplot of the data sets (Figure 7c). The cluster of outlying points represents post-1970 data only; none of the outliers are from earlier parts of the record. The divergence appears to reflect a fundamental change in Atlantic hurricane behavior. Recent analyses of instrumental data indicate that Atlantic hurricanes have formed increasingly to the east and south since approximately 1970, associated with a spread of the Atlantic Warm Pool [*Holland and Webster*, 2007; *Andronache and Phillips*, 2007]. The spatial pattern of Mg/Ca SST correlation decreases toward the eastern and southern tropical Atlantic, and hence the correlation divergence at this time. Additionally, the number of major hurricanes was reduced during the 1970s and 1980s relative to earlier parts of the record [*Nyberg et al.*, 2007]. If the post-1970 data are removed, the Mg/Ca SST record is strongly correlated to the number of hurricanes and tropical storms ($r = 0.83$, $p < 0.082$ after accounting for the reduced degrees of freedom resulting from smoothing the data sets).

[32] We also attempted to correlate the previously discussed tropical Atlantic paleo-SST records to Atlantic storm frequency, but with one exception, none of these records have the temporal resolution to provide a meaningful correlation. The Jamaican sclerosponge data [*Haase-Schramm et al.*, 2005] contain 20 data points within the interval of interest, but the correlation between its paleo-

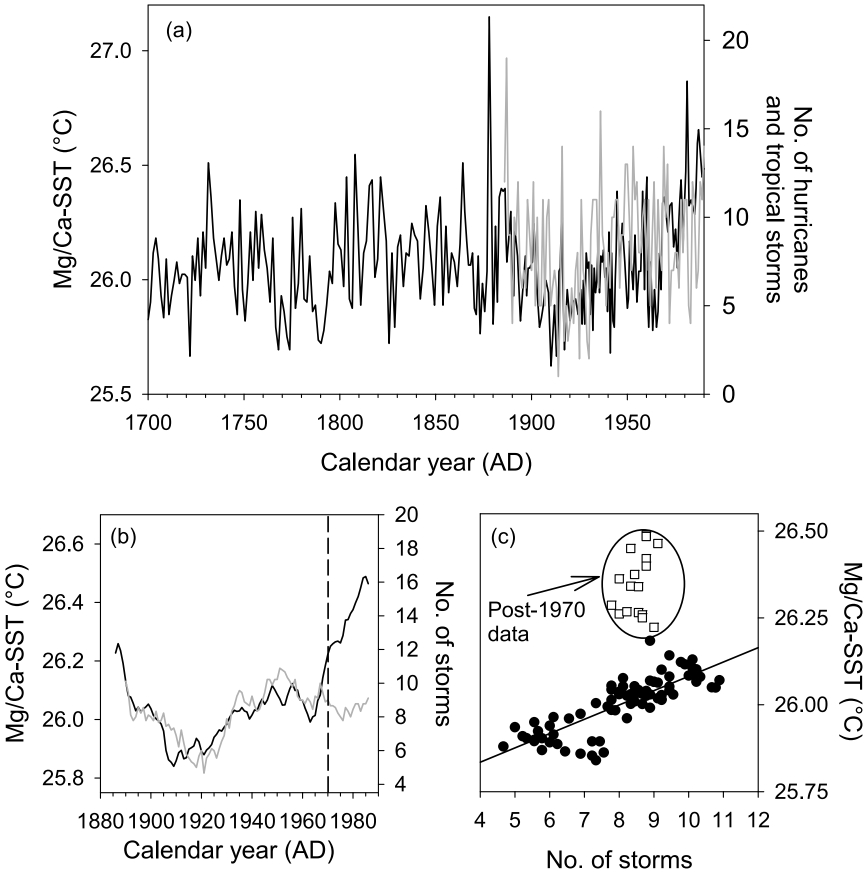

Figure 7. (a) Mg/Ca SSTs (black line) compared to the combined number of Atlantic tropical storms and hurricanes in a given year (gray line). (b) Nine-year moving averages of Mg/Ca SST (black line) and number of Atlantic tropical storms and hurricanes (gray line). Correlation between the two records changes around 1970 (vertical dashed line). (c) Scatterplot of the series in (Figure 7b) (1880–1969 data, solid circles; 1970–1990 data, open squares).

SSTs and Atlantic storm frequency was nearly zero. The lack of correlation is likely because Jamaica lies well outside the "main development region" [*Goldenberg et al.*, 2001] for Atlantic tropical storms and hurricanes.

8. Conclusions

[33] We present the first downcore Mg/Ca record that has been directly calibrated to instrumental SSTs. The sediment record supports sediment trap studies indicating that *G. bulloides* is representative of spring conditions in the Cariaco Basin, but correlation to the wider Atlantic basin instrumental SST record demonstrates that Cariaco Basin Mg/Ca SSTs can be used to characterize SST variability for the Caribbean and western tropical Atlantic.

[34] The full 8-century record reveals that tropical SSTs during the last millennia are more variable than previously thought, with some MWP warmth, significant LIA cooling, and abrupt twentieth-century warming. Unlike recent instrumental data analyses, spectral analysis of the Mg/Ca SST data does not indicate decadal-scale variability. Instead, an interannual to subdecadal mode dominates the record, with possible ties to ENSO, the NAO, and tropical Atlantic ocean-atmosphere dynamics.

[35] **Acknowledgments.** We thank D. Lea, J. Carton, S. Hameed, T. Cronin, and one anonymous reviewer for their discussion and valuable comments. This research was supported by NSF grants ATM-0417909, EAR-0320898, OCE-0326313, OCE-0315234, and OCE0317941.

References

Anand, P., H. Elderfield, and M. H. Conte (2003), Calibration of Mg/Ca thermometry in planktonic foraminifera from a sediment trap time series, *Paleoceanography*, *18*(2), 1050, doi:10.1029/2002PA000846.

Andronache, C., and V. Phillips (2007), Statistical characteristics of Atlantic hurricanes from time series observations, *Eos Trans. AGU*, *88*(23), Jt. Assem. Suppl., Abstract A4B203.

Astor, Y., F. Muller-Karger, and M. I. Scranton (2003), Seasonal and interannual variation in the hydrography of the Cariaco Basin: Implications for basin ventilation, *Cont. Shelf Res.*, *23*, 125–144.

Bemis, B. E., H. J. Spero, J. Bijma, and D. W. Lea (1998), Reevaluation of the oxygen isotopic composition of planktonic foraminifera: Experimental results and revised paleotemperature equations, *Paleoceanography*, *13*, 150–160.

Black, D. E., L. C. Peterson, J. T. Overpeck, A. Kaplan, M. N. Evans, and M. Kashgarian (1999), Eight centuries of Atlantic Ocean atmosphere variability, *Science*, *286*, 1709–1713.

Black, D. E., R. C. Thunell, A. Kaplan, L. C. Peterson, and E. J. Tappa (2004), A 2000-year record of Caribbean and tropical North Atlantic hydrographic variability, *Paleoceanography*, *19*, PA2022, doi:10.1029/2003PA000982.

Boyle, E. A. (1981), Cadmium, zinc, copper, and barium in foraminifera tests, *Earth Planet. Sci. Lett.*, *53*, 11–35.

Carton, J. A., X. Cao, B. S. Giese, and A. M. Da Silva (1996), Decadal and interannual SST variability in the tropical Atlantic Ocean, *J. Phys. Oceanogr.*, *26*, 1165–1175.

Chang, P., L. Ji, and H. Li (1997), A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions, *Nature*, *385*, 516–518.

Crowley, T. J. (2000), Causes of climate change over the past 1000 years, *Science*, *289*, 270–277.

Davis, R. E. (1976), Predictability of sea surface temperature and sea level pressure anomalies over North Pacific Ocean, *J. Phys. Oceanogr.*, *6*, 249–266.

Dekens, P. S., D. W. Lea, D. K. Pak, and H. J. Spero (2002), Core top calibration of Mg/Ca in tropical foraminifera: Refining paleotemperature estimation, *Geochem. Geophys. Geosyst.*, *3*(4), 1022, doi:10.1029/2001GC000200.

Delworth, T. L., S. Manabe, and R. J. Stouffer (1997), Multidecadal climate variability in the Greenland Sea and surrounding regions: A coupled model simulation, *Geophys. Res. Lett.*, *24*, 257–260.

Dickson, R. R., J. Meincke, S. A. Malmberg, and A. J. Lee (1988), The "great salinity anomaly" in the northern Atlantic 1968–1982, *Prog. Oceanogr.*, *20*, 103–151.

Eddy, J. A. (1976), The Maunder Minimum, *Science*, *192*, 1189–1202.

Elderfield, H., and G. Ganssen (2000), Past temperature and δ^{18}O of surface ocean waters inferred from foraminiferal Mg/Ca ratios, *Nature*, *405*, 442–445.

Emanuel, K. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, *436*, 686–688.

Enfield, D. B., and D. A. Mayer (1997), Tropical Atlantic sea surface temperature variability and its relation to El Niño-Southern Oscillation, *J. Geophys. Res.*, *102*, 929–945.

Ghil, M., et al. (2002), Advanced spectral methods for climatic time series, *Rev. Geophys.*, *40*(1), 1003, doi:10.1029/2000RG000092.

Giannini, A., Y. Kushnir, and M. A. Cane (2000), Interannual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean, *J. Clim.*, *13*, 297–309.

Goldenberg, S. B., C. W. Landsea, A. M. Mestas-Nuñez, and W. M. Gray (2001), The recent increase in Atlantic hurricane activity: Causes and implications, *Science*, *293*, 474–479.

Goñi, M. A., H. L. Aceves, R. C. Thunell, E. Tappa, D. Black, Y. Astor, R. Varela, and F. Muller-Karger (2003), Biogenic fluxes in the Cariaco Basin: A combined study of sinking particulates and underlying sediments, *Deep Sea Res., Part I*, *50*, 781–807.

Goodkin, N. F., K. A. Hughen, A. L. Cohen, and S. R. Smith (2005), Record of Little Ice Age sea surface temperatures at Bermuda using a growth-dependent calibration of coral Sr/Ca, *Paleoceanography*, *20*, PA4016, doi:10.1029/2005PA001140.

Grassi, B., G. Redaelli, and G. Visconti (2006), A physical mechanism of the atmospheric response over Antarctica to decadal trends in tropical SST, *Geophys. Res. Lett.*, *33*, L17814, doi:10.1029/2006GL026509.

Haase-Schramm, A., F. Böhm, A. Eisenhauer, D. Garbe-Schönberg, W.-C. Dullo, and J. Reitner (2005), Annual to interannual temperature variability in the Caribbean during the Maunder sunspot minimum, *Paleoceanography*, *20*, PA4015, doi:10.1029/2005PA001137.

Haug, G. H., K. A. Hughen, D. M. Sigman, L. C. Peterson, and U. Rohl (2001), Southward migration of the Intertropical Convergence Zone through the Holocene, *Science*, *293*, 1304–1308.

Haug, G. H., D. Günther, L. C. Peterson, D. M. Sigman, K. A. Hughen, and B. Aeschlimann (2003), Climate and the collapse of Maya civilization, *Science*, *299*, 1731–1735.

Hodell, D. A., M. Brenner, J. H. Curtis, R. Medina-Gonzalez, E. I.-C. Can, A. Albornaz-Pat, and T. P. Guilderson (2005), Climate change on the Yucatan Peninsula during the Little Ice Age, *Quat. Res.*, *63*, 109–121.

Holland, G. J., and P. J. Webster (2007), Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend?, *Philos. Trans. R. Soc., Ser. A*, doi:10.1098/rsta.2007.2083, in press.

Hughen, K. A., J. T. Overpeck, L. C. Peterson, and S. Trumbore (1996), Rapid climate changes in the tropical Atlantic region during the last deglaciation, *Nature*, *380*, 51–54.

Hurell, J. (1995), NAO station based (annual), Natl. Cent. Atmos. Res., Boulder, Colo.

Jones, P. D., M. New, D. E. Parker, S. Martin, and I. G. Rigor (1999), Surface air temperature and its changes over the past 150 years, *Rev. Geophys.*, *37*, 173–199.

Kayano, M. T., V. B. Rao, and R. V. Andreoli (2005), A review of short-term climate variability mechanisms, *Adv. Space Res.*, *35*, 843–851.

King, M. P., and F. Kucharski (2006), Observed low-frequency covariabilities between the tropical oceans and the North Atlantic Oscillation in the twentieth century, *J. Clim.*, *19*, 1032–1041.

Lea, D. W., T. A. Mashiotta, and H. J. Spero (1999), Controls on magnesium and strontium uptake in planktonic foraminifera determined by live culturing, *Geochim. Cosmochim. Acta*, *63*, 2369–2379.

Lea, D. W., D. K. Pak, L. C. Peterson, and K. A. Hughen (2003), Synchroneity of tropical and high-latitude Atlantic temperatures over the last glacial termination, *Science*, *301*, 1361–1364.

Levitus, S. (1989), Interpentadal variability of temperature and salinity at intermediate depths of the North Atlantic Ocean, 1970–1974 versus 1955–1959, *J. Geophys. Res.*, *94*, 6091–6131.

Lin, H.-L., L. C. Peterson, J. T. Overpeck, S. E. Trumbore, and D. W. Murray (1997), Late Quaternary climate change from δ^{18}O records of multiple species of planktonic foraminifera: High resolution records from the anoxic Cariaco Basin, Venezuela, *Paleoceanography*, *12*, 415–428.

Lund, D. C., and W. Curry (2006), Florida Current surface temperature and salinity variability during the last millennium, *Paleoceanography*, *21*, PA2009, doi:10.1029/2005PA001218.

Manabe, S., and R. J. Stouffer (1996), Low-frequency variability of surface air temperature in a 1000-year integration of a coupled atmosphere-ocean-land surface model, *J. Clim.*, *9*, 376–393.

Mann, M. E., and K. A. Emanuel (2006), Atlantic hurricane trends linked to climate change, *Eos Trans. AGU*, *87*, 233.

Mann, M. E., R. S. Bradley, and M. K. Hughes (1999), Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations, *Geophys. Res. Lett.*, *26*(6), 759–762.

Mashiotta, T. A., D. W. Lea, and H. J. Spero (1999), Glacial-interglacial changes in subantarctic sea surface temperature and δ^{18}O-water using foraminiferal Mg, *Earth Planet. Sci. Lett.*, *170*, 417–432.

McConnell, M. C., and R. C. Thunell (2005), Calibration of the planktonic foraminiferal Mg/Ca paleothermometer: Sediment trap results from the Guaymas Basin, Gulf of California, *Paleoceanography*, *20*, PA2016, doi:10.1029/2004PA001077.

McConnell, M. C., R. C. Thunell, E. J. Tappa, and J. D. Wright (2005), Seasonal variability of seawater salinity and the oxygen isotopic composition of seawater in the Cariaco Basin, Venezuela, *Eos Trans. AGU*, *86*(52), Fall Meet. Suppl., Abstract PP31B-1526.

Mehta, V. M., and T. Delworth (1995), Decadal variability of the tropical Atlantic Ocean surface temperature in shipboard measurements and in a global ocean-atmosphere climate model, *J. Clim.*, *8*, 172–190.

Muller-Karger, F., et al. (2001), Annual cycle of primary production in the Cariaco Basin: Response to upwelling and implications for vertical export, *J. Geophys. Res.*, *106*, 4527–4542.

Nürnberg, D., J. Bijma, and C. Hemleben (1996), Assessing the reliability of magnesium in foraminiferal calcite as a proxy for water mass temperature, *Geochim. Cosmochim. Acta*, *60*, 803–814.

Nyberg, J., B. A. Malmgren, A. Kuijpers, and A. Winter (2002), A centennial-scale variability of tropical North Atlantic surface hydrography during the late Holocene, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *183*, 25–41.

Nyberg, J., B. A. Malmgren, A. Winter, M. R. Jury, K. H. Kilbourne, and T. M. Quinn (2007), Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years, *Nature*, *447*, 698–701.

Overpeck, J. T., et al. (1997), Arctic environmental change of the last four centuries, *Science*, *278*, 1251–1256.

Peterson, L. C., and G. H. Haug (2006), Variability in the mean latitude of the Atlantic Intertropical Convergence Zone as recorded by riverine input of sediments to the Cariaco Basin (Venezuela), *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *234*, 97–113.

Peterson, L. C., J. T. Overpeck, N. G. Kipp, and J. Imbrie (1991), A high-resolution late Quaternary upwelling record from the anoxic Cariaco Basin, Venezuela, *Paleoceanography*, *6*, 99–119.

Peterson, L. C., G. H. Haug, K. A. Hughen, and U. Rohl (2000), Rapid changes in the hydrologic cycle of the tropical Atlantic during the last glacial, *Science*, *290*, 1947–1951.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *J. Geophys. Res.*, *108*(D14), 4407, doi:10.1029/2002JD002670.

Rosenheim, B. E., P. K. Swart, S. R. Thurrold, P. Willenz, L. Berry, and C. Latkoczy (2004), High resolution Sr/Ca records in sclerosponges calibrated to temperature in situ, *Geology*, *32*, 145–148.

Schmittner, A., and A. C. Clement (2002), Sensitivity of the thermohaline circulation to tropical and high latitude freshwater forcing during the last glacial-interglacial cycle, *Paleoceanography*, *17*(2), 1017, doi:10.1029/2000PA000591.

Schrag, D. P. (1999), Rapid analysis of high-precision Sr/Ca ratios in corals and other marine carbonates, *Paleoceanography*, *14*, 97–102.

Tedesco, K., and R. Thunell (2003a), High resolution tropical climate record for the last 6,000 years, *Geophys. Res. Lett.*, *30*(17), 1891, doi:10.1029/2003GL017959.

Tedesco, K. A., and R. C. Thunell (2003b), Seasonal and interannual variations in planktonic foraminiferal flux and assemblage composition in the Cariaco Basin, Venezuela, *J. Foraminiferal Res.*, *33*, 192–210.

Tedesco, K. A., R. Thunell, Y. Astor, and F. Muller-Karger (2007), The oxygen isotope composition of planktonic foraminifer from the Cariaco Basin, Venezuela: Seasonal and interannual variations, *Mar. Micropaleontol.*, *62*(3), 180–193, doi:10.1016/j.marmicro.2006.08.002.

Timmerman, A., M. Latif, R. Voss, and A. Grötzner (1998), Northern Hemispheric interdecadal variability: A coupled air–sea model, *J. Clim.*, *11*, 1906–1931.

Toyofuku, T., H. Kitazato, H. Kawahata, M. Tsuchiya, and M. Nohara (2000), Evaluation of Mg/Ca thermometry in foraminifera: Comparison of experimental results and measurements in nature, *Paleoceanography*, *15*, 456–464.

Trenberth, K. E. (1984), Signal versus noise in the Southern Oscillation, *Mon. Weather Rev.*, *112*, 326–332.

Trenberth, K. E. (2005), Uncertainty in hurricanes and global warming, *Science*, *308*, 1753–1754.

Trenberth, K. E., and D. J. Shea (2006), Atlantic hurricanes and natural variability in 2005, *Geophys. Res. Lett.*, *33*, L12704, doi:10.1029/2006GL026894.

von Storch, H., and F. W. Zwiers (1999), *Statistical Analysis in Climate Research*, 484 pp., Cambridge Univ. Press, Cambridge, U. K.

M. A. Abahazi, Department of Geology and Environmental Science, University of Akron, Akron, OH 44325, USA.

D. E. Black, School of Marine and Atmospheric Sciences, State University of New York at Stony Brook, Stony Brook, NY 11794, USA. (david.black@stonybrook.edu)

A. Kaplan, Lamont-Doherty Earth Observatory of Columbia University, 103 C Oceanography, Palisades, NY 10964, USA.

L. C. Peterson, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA.

E. J. Tappa and R. C. Thunell, Department of Geological Sciences, University of South Carolina, 712 South Main Street, Columbia, SC 29208, USA.