Mechanisms of southern Caribbean SST variability over the last two millennia

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[1] We present a high-resolution Mg/Ca reconstruction of tropical Atlantic sea surface temperatures (SSTs) spanning the last 2000 years using seasonally representative foraminifera from the Cariaco Basin. The range of summer/fall SST over this interval is restricted to 1.5°C, while winter/spring SST varies by 4.5°C over the same time period suggesting that boreal winter variations control interannual SST variability in the tropical North Atlantic. Antiphasing between the two data sets, including a large divergence in the seasonal records circa 900 Common Era, can be explained by changes in Atlantic meridional overturning circulation and associated changes in surface/subsurface temperatures in the tropical North Atlantic as well as resultant changes in trade wind belt location and intensity. A statistically significant but nonlinear relation exists between reconstructed winter/spring temperatures and solar variability. **Citation:** Wurtzel, J. B., D. E. Black, R. C. Thunell, L. C. Peterson, E. J. Tappa, and S. Rahman (2013), Mechanisms of southern Caribbean SST variability over the last two millennia, *Geophys. Res. Lett.*, *40*, 5954–5958, doi:10.1002/2013GL058458.

1. Introduction

[2] There are distinct gaps in our understanding of tropical Atlantic climate variability on subdecadal to centennial timescales for the past two millennia. These gaps are due in part to the limited spatial and temporal extent of the instrumental record and a lack of tropical proxy records of sufficient length and resolution to establish a baseline range of variability. Several studies have suggested a link between Atlantic meridional overturning circulation (AMOC) and climatic variations of the last two millennia [e.g., *Broecker*, 2000; *Lund and Curry*, 2006; *Saenger et al.*, 2011]; however, the role of AMOC in the tropics is not well understood. High-resolution proxy records from the Cariaco Basin can be used to address some of these uncertainties. The Cariaco Basin, located on the southern margin of the Caribbean Sea, is an anoxic basin characterized by varved sediments, high accumulation rates, an abundance of well-preserved microfossils, and a strong seasonal climatology that is driven by the annual migration of the Intertropical Convergence Zone (ITCZ) [*Peterson et al.*, 1991]. The Cariaco Basin has been shown to be consistently representative of a wide region of the Atlantic through the correlation of Cariaco-derived geochemical proxies to Atlantic instrumental data [*Black et al.*, 2004; *Black et al.*, 2007]. Collectively, these features produce one of the few marine records in the tropical Atlantic capable of preserving long continuous histories of climate variability on timescales ranging from the interannual to the interglacial.

[3] The seasonal hydrographic changes that occur in the Cariaco Basin as a result of the migration of the ITCZ also drive a seasonally varying plankton community. Biweekly sediment trap data collected over a 3 year period in the basin showed distinct patterns of seasonal flux in nine planktonic foraminiferal species [*Tedesco and Thunell*, 2003]. While all species reached their peak flux during the upwelling season, maximum and minimum relative abundances for different species vary seasonally. *Globigerina bulloides* reflects local upwelling conditions and dominates the Cariaco foraminifera assemblage during winter and spring such that proxy reconstructions using *G. bulloides* are unequivocally biased toward upwelling season (winter/spring) conditions. Proxies based on *G. bulloides* are often calibrated and compared to surface data because of limited instrumental subsurface data [*Black et al.*, 2007], though several studies from other locations have noted that *G. bulloides* Mg/Ca is in best agreement with water temperatures at ~30 m depth [*Pak et al.*, 2004; *Mekik et al.*, 2007]. Although observed in the basin year round, *G. bulloides* reaches its minimum relative abundance during the summer and fall months, at which time the highest relative abundances of *Globigerinoides ruber* (pink), a subtropical to tropical species [*Tedesco and Thunell*, 2003], occur. The dominance of *G. bulloides* during the upwelling season and the relative increase in *G. ruber* (pink (p)) in summer/fall are consistent annual responses to the local seasonal climate cycle, and we have used that relationship to generate a high-resolution, seasonal Mg/Ca-SST reconstruction.

2. Samples and Methods

[4] Three cores were used for this study. Box core PL07-73BC and gravity core PL07-72GGC were collected in 1990 from the northeastern slope of the Cariaco Basin (10°45.98′N, 64°46.20′W, 450 m water depth and 10°45.77′N, 64°42.25′W, 390 m water depth, respectively). Box core CAR25-1 was collected from near the locations of PL07-73BC

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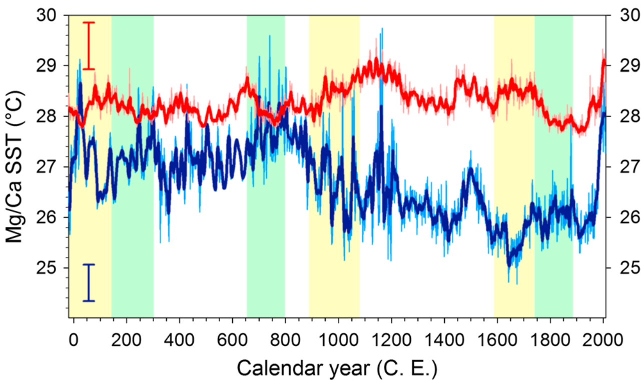

Figure 1. Mg/Ca SSTs for the period −20–2008 C.E. *Globigerinoides ruber* summer/fall Mg/Ca SSTs (light red) with overlapping nine-point running mean (dark red). *Globigerina bulloides* winter/spring Mg/Ca SSTs (light blue) with overlapping nine-point running mean (dark blue). Red and blue bars on the left side of the plot represent the error range for the respective reconstructions. Shaded areas demark intervals of antiphasing between the *G. ruber* and *G. bulloides* records—yellow boxes indicate periods of divergence; green boxes indicate periods of convergence.

and PL07-72GGC in 2008 (10°40.05′N, 64°39.01′W, 503 m water depth). Overlapping points from CAR25-1 and PL07-73BC between 1984 and 1990 Common Era (C.E.) were averaged to create a composite record. The youngest layer of PL07-72GGC is 1280 C.E. In the composite record, PL07-72GGC data picks up in 1226 C.E., where PL07-73BC ends. In all cores, samples of *G. ruber* (p) and *G. bulloides* were picked at 1.0 mm intervals (1–2 year resolution) for Mg/Ca analysis and cleaned using standard methods [*Boyle*, 1981], not including the reductive cleaning step. Age models for PL07-73-BC and PL07-72GGC were created by correlating foraminiferal census counts from these cores to nearby previously studied cores with published age models [*Black et al*., 2007]. The upper few centimeters of CAR25-1 were dated using ^{210}Pb.

[5] An 800 year record of winter/spring SSTs from the Cariaco Basin based on *G. bulloides* Mg/Ca values was previously generated and calibrated to Hadley instrumental SSTs [*Black et al*., 2007]. We employ similar methods here to extend the *G. bulloides* record back 1200 years and to generate a new 2000 year record of summer/fall SSTs based on *G. ruber* (p). However, *G. ruber* (p), like all foraminifera species in Cariaco Basin, has a flux peak during the winter/spring upwelling season in addition to its flux peak in late summer (Figure S1 in the supporting information), resulting in reconstructed Mg/Ca-based SSTs that exhibited a greater range of variability and lower mean SST than instrumental data indicated for the Cariaco Basin over the calibration period (1870–1990 A.D.) when published *G. ruber* (p) Mg/Ca-SST equations were applied. An alternative weighted calibration was therefore created (supporting information) to isolate the summer/fall SST signal ($r = 0.40$, $p < 0.0001$, $N = 120$, two-tailed). The in-sample estimate of predictive error for the *G. bulloides* and *G. ruber* reconstructions are 0.35°C and 0.45°C, respectively.

3. Sea Surface Temperature Reconstructions

[6] The Mg/Ca-SST data for *G. ruber* indicate that summer/fall SST variations fluctuated consistently around a mean of approximately 28.2°C between −20 and 900 C.E (Figure 1, red line). Summer/fall temperatures increased by over 1.2°C between 900 and 1150 C.E. and then cooled by approximately 1.3°C between 1150 and 1900 C.E., reaching a minimum of 27.7°C in the late nineteenth century. Summer/fall SSTs as indicated by the proxy data have risen abruptly by 1.3°C over the twentieth century, in good agreement with the 1.1°C rise observed in the instrumental record over the same interval. In general, summer/fall SST variations were restricted to a range of 1.5°C over the last two millennia, reaching a maximum of 29.5°C during the twelfth century coincident with the Medieval Climate Anomaly (MCA; circa 900–1280 C.E.), and a two-stage minima interval associated with the Little Ice Age (LIA; circa 1300–1890 C.E.). Twentieth century summer/fall temperatures increased by a rate of 0.12°C per decade, although a similar rate of warming is seen during a 40 year interval between 1405 and 1447 C.E.

[7] Mg/Ca-estimated winter/spring SSTs from *G. bulloides* average approximately 27°C between −20 and 900 C.E., but there are frequent and large deviations of as much as 2°C around the mean over the same time period (Figure 1, blue line). Winter/spring SSTs cooled by 2.5°C between 780 and 1640 C.E., punctuated by two small 200 year warming intervals of 1.5°C and 1°C, centered at 1160 and 1500 C.E., respectively. A particularly sharp drop in winter/spring SST (0.6°C) occurred coincident with the onset of the Maunder Minimum between 1630 and 1640 C.E. Winter/spring temperatures rose by about 1°C between 1700 and 1890 C.E., followed by a nearly 2.5°C warming over the twentieth century. Similar to the *G. ruber* data in trend but larger in overall magnitude, the *G. bulloides* record indicates relatively cooler temperatures prior to 700 C.E., warmer temperatures during the MCA, and significantly cooler temperatures during the LIA. Likewise, the rate of winter/spring warming during the twentieth century is unusually fast compared to the rest of the record (0.2°C per decade) but not unprecedented. A 40 year interval at the beginning of the record exhibits an increase of 0.5°C per decade, rising from 26.4°C to 28.1°C between −20 and 20 C.E.

[8] Analyses of instrumental SSTs spanning 1950–1999 indicate that variations in winter SST drive interannual variability across the tropical North Atlantic [*Czaja*, 2004]. Our data show significantly greater interannual variability in winter/spring SST than in summer/fall, confirming that the conclusion based on instrumental data is valid for at least the last two millennia. This observation likely explains differences in various temperature estimates of past climate events in the tropical North Atlantic and circum-Caribbean. For example, LIA cooling in this region has been reported to be as little as ~1°C to as much as 3°C [*Richey et al*., 2009 and references therein]. Studies using proxies that are representative of annual SST [*Lund and Curry*, 2006; *Saenger et al*., 2009] may result in reduced estimates of past change relative to those with more of a winter bias. Similar seasonal proxy bias discrepancies for the region have also been noted in the Gulf of Mexico [*Richey et al*., 2011; *Spear et al*., 2011].

[9] The respective SST reconstructions are characterized by similar temporal patterns of variability. Multitaper

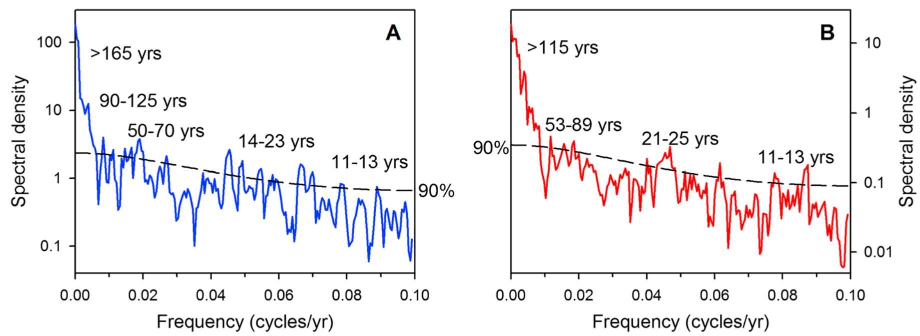

Figure 2. Multitaper spectral analyses of the (a) *G. bulloides* and (b) *G. ruber* proxy SST data. The dashed line in both figures represents the 90% confidence interval. Both SST data sets display spectral power in bands associated with the Atlantic's cross-equatorial SST gradient (~11–13 years), the Atlantic Multidecadal Oscillation (50–90 years), and AMOC variability (50–90 years and longer).

spectral analysis of both records indicates spectral power on decadal to subcentennial timescales (Figure 2). At the higher-frequency range of the spectrum, both the winter/spring and summer/fall data contain variance at 11–13 years, a period previously noted in a record of Cariaco Basin upwelling variability [*Black et al.*, 1999] and associated with fluctuations in the Atlantic's cross-equatorial surface temperature gradient [*Chang et al.*, 1997]. Both records also show power in multidecadal bands (50–90 years) comparable to those noted for the Atlantic Multidecadal Oscillation [*Schlesinger and Ramankutty*, 1994] and AMOC variability [*MacMartin et al.*, 2013 and references therein]. While our reconstruction does not significantly correlate with the Atlantic Multidecadal Oscillation, we believe that AMOC fluctuations can explain some of the variability in our data, as described below.

4. Tropical Atlantic SSTs, AMOC, and Cariaco Water Column Stratification

[10] The direct comparison of summer/fall and winter/spring proxy reconstructions in this study reveals features that suggest the winter/spring temperature signal as recorded by *G. bulloides* at 30 m depth may not always be indicative of surface temperatures as suggested by previous studies [*Black et al.*, 2007; *Tedesco et al.*, 2007]. Rather, subsurface temperatures appear to diverge from the surface temperature signal. Distinctly opposite trends in summer/fall and winter/spring SSTs occur frequently throughout the record, including large antiphasing from 20 B.C.–300 C.E., 650–1050 C.E., and 1600–1875 C.E. (Figure 1). Reductions in the summer/fall-winter/spring gradient are driven not just by a rise in *G. bulloides* temperatures but also a concurrent drop in *G. ruber* SSTs. It is possible that these reversals are a function of error within the calibration. There is, however, a scenario that lends credence to the antiphasing in our data, in which the tropical North Atlantic subsurface has anomalously warm temperatures while the surface cools as a function of variations in AMOC intensity. Models note that AMOC weakening is generally associated with cooler North Atlantic SSTs and warmer South Atlantic SSTs while AMOC intensification results in relatively warm North Atlantic SSTs and relatively cool South Atlantic SSTs—an oscillation commonly referred to as the "bipolar seesaw" [*Vellinga and Wu*, 2004; *Zhang and Delworth*, 2005]. Recent modeling and proxy studies indicate that the cross-equatorial temperature variations resulting from AMOC fluctuations are more complex than the bipolar seesaw model initially predicted. Tropical North Atlantic cooling during a reduction in AMOC is limited to a very thin surface layer (~30 m) and the pooling of heat in the South Atlantic extends into the subsurface tropical North Atlantic at depths ranging from as shallow as 30–50 m to as deep as 1000 m [*Chiang et al.*, 2008; *Zarriess et al.*, 2011]. *Zhang* [2007] showed that observed tropical North Atlantic SSTs are strongly anticorrelated with tropical North Atlantic subsurface temperatures on multidecadal timescales and argued that they are inextricably linked to AMOC such that subsurface temperature anomalies may be used as a proxy for AMOC variability. Interpreted from this perspective, AMOC intensifications occurred from −20 to 150 C.E., 900 to 1050 C.E., and 1600 to 1725 C.E., and AMOC weakening occurred from 150 to 300 C.E., 650 to 800 C.E., and 1725 to 1900 C.E.

[11] The few existing AMOC flow reconstructions are spatially distant from the Cariaco and focus on specific currents that exist as part of thermohaline circulation. Foraminiferal data from the Florida Straits were used by *Lund et al.* [2006] to reconstruct Gulf Stream density structure, from which the authors inferred a 10% decrease in AMOC strength in that region, during the LIA. Another study used grain size to reconstruct deep water flow in the northern North Atlantic and also found evidence of strengthened and reduced flow during the MCA and LIA, respectively [*Bianchi and McCave*, 1999]. The antiphasing in our data indicates not only increased AMOC intensity during the MCA but also increased AMOC intensity leading into the LIA and AMOC weakening toward the end of the LIA, a pattern opposite of what one might expect.

[12] An alternate explanation or one that may work in concert with AMOC variations is that the antiphasing may be a result of local upwelling-controlled changes in water column stratification. AMOC variations impact the position of the ITCZ and trade wind belts [*Chiang et al.*, 2008] and as such would lead to variations in Ekman-induced upwelling within the Cariaco. A sustained increase in upwelling intensity would decrease the *G. ruber*-*G. bulloides* gradient, while a long-term decrease in upwelling intensity would increase the temperature difference between the two species. However, the antiphased intervals do not correspond to changes in *G. bulloides* abundance, a proxy for local upwelling [*Black et al.*, 1999]. The one exception is the large temperature divergence beginning 900 C.E. that persists through today. A record of *G. bulloides* abundance spanning

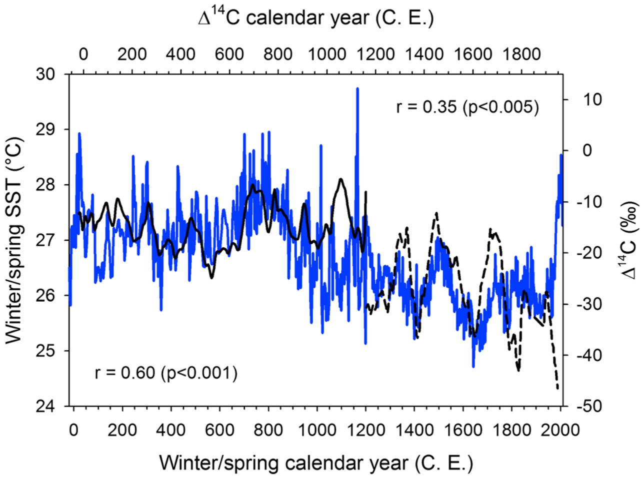

Figure 3. Comparison of the *G. bulloides* SST data (blue line) to $\Delta^{14}C$ (black lines) [*Reimer et al*., 2009; *Stuiver and Quay*, 1980], a measure of past solar variability. The $\Delta^{14}C$ is plotted with a 40 year lead of SST as described in the text. Winter/spring temperatures warm during times of reduced solar variability, but the response is nonlinear between the first half (−20 to 1050 C.E.) and second half (1230–2008 C.E.) of the record. The $\Delta^{14}C$ data between 1230 and 2008 C.E. (dashed black line) have been shifted −25‰ relative to the pre-1230 C.E. data to show the visual correlation. Correlation coefficients represent the *r* value between $\Delta^{14}C$ and winter/spring SST for the intervals −20–1050 C.E. and 1230–1950 C.E., respectively.

the last 2000 years notes a 50% decrease in abundance beginning approximately 1200 C.E. that also persists through the present [*Black et al*., 2001]. The abundance drop indicates a substantial decrease in Cariaco productivity. While not precisely coincident in time, the increased *G. ruber-G. bulloides* gradient between 1200 and 2008 C.E. suggests an increase in local water column stratification resulting from a long-term decrease in trade wind-induced upwelling intensity, in turn driving the drop in Cariaco Basin productivity.

5. Link to Solar Variability

[13] Several studies of circumtropical Atlantic climate variability have suggested links to solar variability [e.g., *Peterson et al*., 1991; *Black et al*., 1999; *Verschuren et al*., 2000; *Hodell et al*., 2001]. A comparison between the winter/spring SST record and one of past solar variability [*Reimer et al*., 2009; *Stuiver and Quay*, 1980] reveals an inverse, nonlinear correlation with periods of warmer tropical North Atlantic winter/spring temperatures corresponding to times of reduced solar activity (Figure 3). While initially counterintuitive, the relationship is plausible when considered in the context of AMOC variations. *Stuiver and Braziunas* [1993] suggest that a minor reduction in the solar constant over an extended period of time produces AMOC weakening, which would in turn increase tropical North Atlantic subsurface temperatures as described earlier. Other models indicate that solar fluctuations can induce changes in the Hadley circulation that affect tropical SSTs through the trade winds and latent heat flux [*Rind and Overpeck*, 1993]. However, solar variability consistently leads the Cariaco temperature record by 25–40 years, as determined by maximum correlation using different offsets, suggesting the link between solar variability and tropical SSTs is driven by relatively slow marine processes rather than faster atmospheric ones.

[14] The relationship between solar variability and proxy temperature is nonlinear over the length of the record. A strong statistically significant correlation on multidecadal and longer timescales is present in both the earlier and later halves of the record (for −20–1050 C.E., $r = 0.0.60$, $p < 0.001$; for 1230–1950 C.E., $r = 0.35$, $p < 0.005$; 70 year low-pass filter applied to both intervals). However, the solar data after 1200 C.E. need to be offset by −25‰ to show the correlation visually in Figure 3. It is not clear why the relationship changes midrecord. The data strongly diverge in 1950, possibly as a result of anthropogenic influences dominating the recent tropical SST signal.

6. Conclusions

[15] We present a continuous seasonal temperature reconstruction for the southern Caribbean and tropical North Atlantic spanning the last two millennia. Summer/fall temperatures vary by no more than 1.5°C over the length of the record, ranging from 27.75 to 29.25°C, whereas winter/spring temperatures show 3 times as much variability (4.5°C), ranging from 24.75 to 29.25°C. Our data confirm instrumental-based studies that conclude boreal winter fluctuations dominate interannual tropical North Atlantic variability, and because our reconstruction extends much further into the past than instrumental records, we argue that boreal winter variability dominates tropical temperature patterns on longer timescales as well. On decadal timescales, both data sets confirm that variability in the 11–13 year band is an important component of tropical Atlantic climate. On longer timescales, intervals of antiphasing between the seasonal reconstructions, including a notable divergence starting circa 900 C.E., can be explained by surface and subsurface temperature changes resulting from weakening and strengthening of AMOC, but variations in local upwelling intensity could also produce the same patterns. Finally, there is a statistically significant correlation between winter/spring temperatures and past solar variability. While the correlation remains positive over the length of the record, the magnitude of the winter/spring temperature response changes midrecord.

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