GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L21703, doi:10.1029/2009GL040445, 2009

Regionally coherent Little Ice Age cooling in the Atlantic Warm Pool

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Received 11 August 2009; revised 23 September 2009; accepted 30 September 2009; published 5 November 2009.

[1] We present 2 new decadal-resolution foraminiferal Mg/Ca-SST records covering the past 6–8 centuries from the northern Gulf of Mexico (GOM). These records provide evidence for a Little Ice Age (LIA) cooling of 2°C, consistent with a published Mg/Ca record from Pigmy Basin. Comparison of these 3 records with existing SST proxy records from the GOM-Caribbean region show that the magnitude of LIA cooling in the Atlantic Warm Pool (AWP) was significantly larger than the mean hemispheric cooling of <1°C. We propose that a reduction in the intensity and spatial extent of the AWP during the LIA, combined with associated changes in atmospheric circulation may account for the regional SST patterns observed in the GOM-Caribbean region during the LIA.
Citation: Richey, J. N., R. Z. Poore, B. P. Flower, T. M. Quinn, and D. J. Hollander (2009), Regionally coherent Little Ice Age cooling in the Atlantic Warm Pool, *Geophys. Res. Lett.*, *36*, L21703, doi:10.1029/2009GL040445.

1. Introduction

[2] Accurate reconstruction of high-resolution sea surface temperature (SST) records during time intervals of societal importance, such as the Little Ice Age (LIA), and through the 20th century, is important in determining the magnitude of pre-industrial climate variability. Given the uncertainties inherent to most SST proxies, as well as the influence of local climatology, replication of SST records is critical to understanding regional responses to climate forcing. The LIA generally spans the time interval from 1400–1850 AD, although the timing and magnitude of cooling varies widely throughout the Northern Hemisphere (NH). Temperature reconstructions (primarily based on extratropical terrestrial proxy records) suggest that the NH experienced modest cooling of 0.6–0.8°C during the 15th–19th centuries [*Mann et al.*, 1999; *Esper et al.*, 2002; *Moberg et al.*, 2005]. Here we show that SST proxy records from the GOM-Caribbean region experienced significantly larger cooling than the hemispheric average, and may be have been particularly sensitive to climate perturbations on multi-decadal to centennial timescales during the LIA.

[3] The Atlantic Warm Pool (AWP), defined by the >28.5°C SST isotherm, develops annually in the northern Caribbean during early summer (June) and expands into the GOM and western tropical North Atlantic through the late summer (July–October) [cf. *Wang et al.*, 2008a]. Multi-decadal variability in the size of the AWP is correlated with rainfall anomalies in the Caribbean region, formation and intensification of North Atlantic hurricanes, and variability in moisture transport to the North American continent via interactions with atmospheric circulation [*Wang et al.*, 2008a]. A number of geochemical proxy records from corals, sclerosponges and foraminifera in the region encompassed by the AWP show a large (2–3°C) cooling during the LIA [*Winter et al.*, 2000; *Watanabe et al.*, 2001; *Nyberg et al.*, 2002; *Haase-Schramm et al.*, 2003; *Richey et al.*, 2007; *Black et al.*, 2007; *Kilbourne et al.*, 2008] (Figure 1).

[4] Assessing the fidelity of SST proxy records is especially critical for the interpretation of decadal to sub-decadal resolution, low-latitude records covering critical time intervals such as the LIA-20th century. The uncertainties inherent to foraminiferal Mg/Ca-based SST estimates can exceed the environmental signal in some cases, and include factors such as Mg/Ca-SST calibration error, diagenetic overgrowths, salinity and dissolution. The relative influence of these factors is variable and often basin-specific. Thus, replication among regional cores is essential to developing a coherent record of regional climate variability. In this paper we present 2 new foraminiferal Mg/Ca-SST records spanning the past 6–8 centuries from the northern GOM, that replicate the magnitude and pattern of SST variability recorded in a published Mg/Ca record from the Pigmy Basin [*Richey et al.*, 2007], and further corroborate a large magnitude (2–3°C) cooling in the GOM-Caribbean region during the LIA.

2. Core Locations

[5] The Fisk Basin (PE07-5I; 817 m depth; 27°33.0′N, 92°10.1′W) and Garrison Basin (PE07-2; 1570 m depth; 26°40.5′N, 93°55.5′W) box cores were collected onboard the R/V Pelican in 2007, and are located on the continental slope in the northern GOM. They have relatively high sediment accumulation rates (20–40 cm/kyr) due to large inputs of terrigenous material via the Mississippi River. For each of the box cores the sediment-water interface was recovered, and AMS ^{14}C dates with bomb radiocarbon confirm that the core-top samples include the most recently deposited sediments (see auxiliary material for age models).[4] Core-top age was set to 2000 AD for each of these GOM records for ease of comparison with other regional, absolutely dated records.

3. Gulf of Mexico Mg/Ca Records

[6] In order to test the reproducibility of the Pigmy Basin Mg/Ca record [*Richey et al.*, 2007], we generated Mg/Ca

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0094-8276/09/2009GL040445$05.00

[4]Auxiliary materials are available in the HTML. doi:10.1029/2009GL040445.

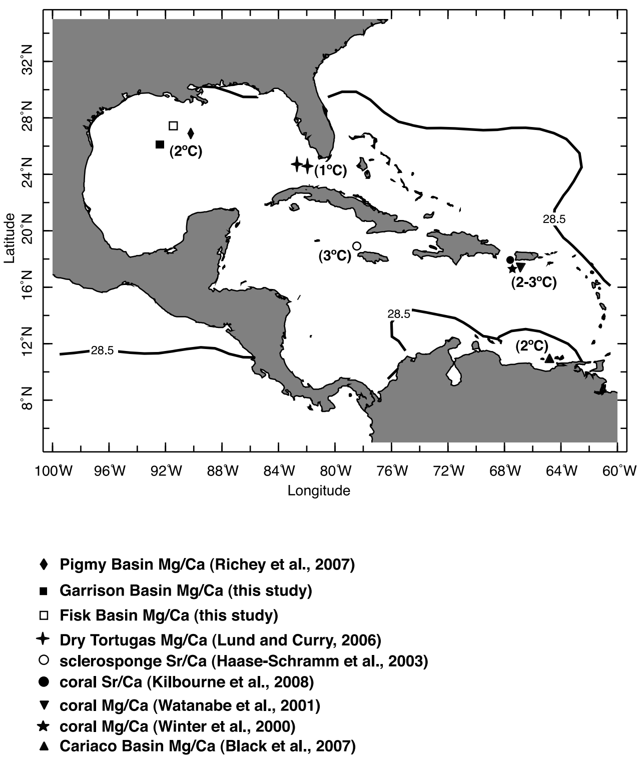

Figure 1. Map of proxy records in the GOM-Caribbean region exhibiting 1–3°C cooling during the LIA. The Fisk (open square) and Garrison (closed square) basins are the 2 new Mg/Ca-SST records presented in this study. The September (maximum seasonal geographic extent) AWP (28.5°C isotherm) is plotted using the Reynolds and Smith OISST V2.0 dataset (1° × 1° grid, averaged from 1981–2009). Mean LIA cooling is indicated in parentheses for each region.

records from the *G. ruber* (white) in 2 additional GOM basins: Garrison Basin (box core PE07-2) and Fisk Basin (box core PE07-5I). The upper 13 cm of the Garrison Basin box core covers the past ~600 yrs. The core-top Mg/Ca value is 4.43 mmol/mol (±0.16 mmol/mol), based on 2 replicate measurements, and corresponds to an SST of 25.4°C (Mg/Ca = 0.449 * exp(0.09 * SST) [from *Anand et al.*, 2003]), the modern annual average for the GOM [*Levitus*, 2003]. This is equivalent to the core-top Mg/Ca value of 4.43 (±0.03 mmol/mol) that was generated from replicate measurements of 3 different sub-cores from the Pigmy Basin box core [*Richey et al.*, 2007]. The mean precision for replicate analyses of the Garrison Basin downcore record is ±0.14 mmol/mol (±0.3°C), with 60% of the samples run in duplicate. The major features of this record include 3 distinct SST minima (ca. 1450–1550, 1700–1750, and 1900 AD), that are ~2°C cooler than the core-top SST (Figure 2).

[7] The upper 20 cm of the Fisk Basin box core span the past ~800 years, which has a sedimentation rate of ~26.5cm/kyr (~18 yrs per 0.5 cm sample). The core-top Mg/Ca value is 4.75 mmol/mol (±0.17 mmol/mol), based on 3 measurements, which corresponds to an SST of 26.2°C (±0.4°C), and is slightly higher (by 0.8 ± 0.4°C) than the core-top Mg/Ca-SST for the Pigmy and Garrison basins. The Fisk Basin Mg/Ca record shows a similar pattern of variability to the other 2 GOM records over the past 6 centuries, with SST minima ca. 1550 and 1750–1850 AD that are ~3°C cooler than the core-top SST (Figure 2).

[8] LIA cooling in all 3 GOM Mg/Ca records is preceded by an interval of warmth in which Mg/Ca is as high or higher than the mean GOM core-top value of 4.4 mmol/mol ± 0.12 mmol/mol (based on 7 GOM core-tops). The timing of the warm interval in the Pigmy and Fisk basins is similar (ca. 1500 and 1450 AD, respectively), while it is slightly later in Garrison Basin (~1600 AD). All 3 basins reach maximum cooling ca. 1750 AD. The linear warming trend from maximum LIA cooling (1750 AD) to the core-top is similar in the Pigmy and Garrison basins (~0.007°C/yr), while the slope of the warming trend is slightly steeper in Fisk Basin (Figure 2). In actuality however, given the uncertainty of the age models and Mg/Ca-SST estimates, the timing of the onset as well as the magnitude of LIA cooling is consistent among these 3 GOM sites.

4. Regional Comparisons

[9] We have generated a 600-year stacked ΔSST record for the northern GOM based on the Fisk, Garrison and Pigmy Basin Mg/Ca-SST records (Figure 3d) (see auxiliary

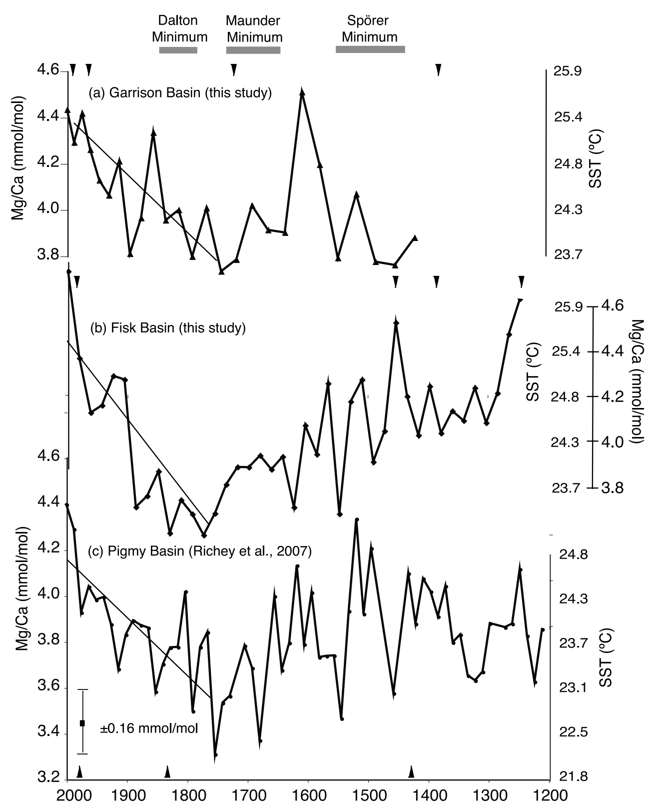

Figure 2. Mg/Ca records from (a) Garrison Basin (b) Fisk Basin and (c) Pigmy Basin [from *Richey et al.*, 2007] are plotted on the same Mg/Ca scale, with age control points indicated by arrows. Corresponding SST scale is given on a secondary y-axis, using the relationship [Mg/Ca = 0.449 * exp(0.09 * SST)], from *Anand et al.* [2003]. Lines are plotted on each curve representing the linear warming trend over the past 250 years.

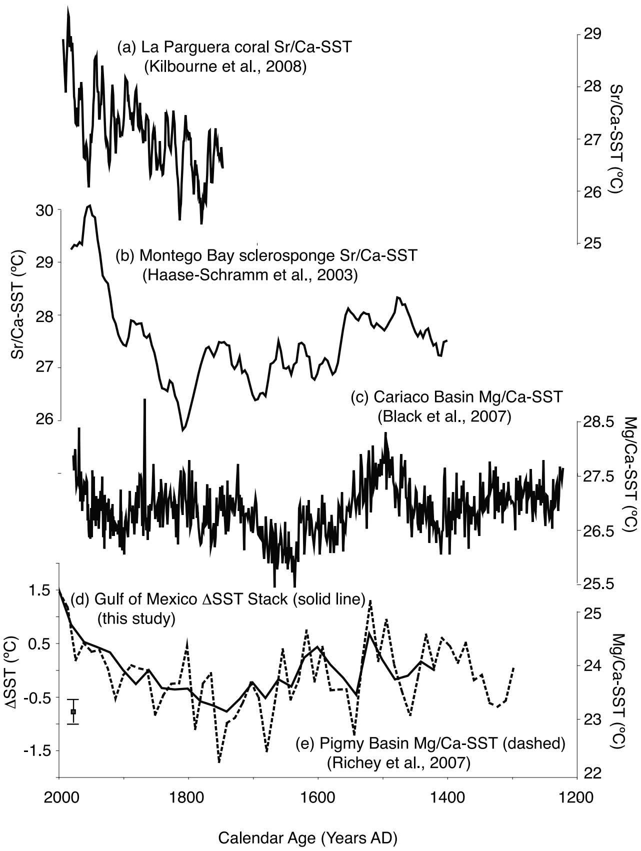

Figure 3. Regional Comparison of (a) La Parguera, Puerto Rico coral Sr/Ca-SST [*Kilbourne et al.*, 2008], (b) Montego Bay, Jamaica sclerosponge Sr/Ca-SST [*Haase-Schramm et al.*, 2003], (c) Cariaco Basin *G. bulloides* Mg/Ca-SST calibrated to SST using the equation Mg/Ca = 0.368 exp(0.092 * T), (d) Gulf of Mexico ΔSST stack (solid line) and (e) Pigmy Basin, GOM foraminiferal Mg/Ca-SST (dashed line) [*Richey et al.*, 2007]. Each record is plotted on its own independent timescale, and SST is scaled identically in each plot. The error bar in Figure 3d indicates the uncertainty in the GOM ΔSST stack of ±0.4°C. See auxiliary material for details of SST calibrations and mathematical treatment of records.

material for statistical methods). This stack represents the multi-centennial trend that is common to the 3 independent GOM SST records, and is used here to draw regional comparisons. We compare the GOM ΔSST stack to a 250-year continuous coral Sr/Ca-SST record from the species *Montastraea faveolata* from La Parguera, Puerto Rico [*Kilbourne et al.*, 2008]. Both records (plotted their own independent timescale, and calibration to SST) show that it was ~2°C cooler ca. 1750 AD than modern, and they also can both be described by a linear warming trend of 0.007°C/yr from the LIA toward the present (Figures 3a and 3d). There are 2 additional coral-based SST records from Puerto Rico that compare brief time intervals during the LIA to late 20th century SSTs. *Winter et al.* [2000] infer that LIA SSTs were 2–3°C cooler than modern, while *Watanabe et al.* [2001] suggest that LIA SSTs were 2°C cooler than modern (from $\delta^{18}O$ and Mg/Ca data in *M. faveolata*, respectively). In summary, these 3 different Puerto Rico coral-based geochemical proxies agree that early 18th century SSTs were 2–3°C cooler than modern.

[10] A Sr/Ca-SST record spanning the past 650 years from a Jamaican sclerosponge shows mean LIA conditions that were ~3°C cooler than modern [*Haase-Schramm et al.*, 2003]. Although the magnitude of cooling inferred from this sclerosponge record is slightly larger than that observed in other circum-Caribbean SST records, the general pattern of variability is very similar to other regional records (Figure 3b).

[11] A Cariaco Basin foraminiferal Mg/Ca-SST record shows a similar pattern of centennial-scale variability to the GOM Mg/Ca-SST records over the past 8 centuries [*Black et al.*, 2007]. Both show a period of warmth ca. 1500 AD., during which SSTs are similar to core-top SSTs, followed by a period of significant cooling during the LIA, and a rapid warming over the past 100 years (Figure 3c). The amplitude of SST variability reported by *Black et al.* [2007] is muted relative to GOM SST variability; however, the use of an alternate Mg/Ca-SST calibration equation yields an SST record that exhibits a ~2°C LIA cooling, and an amplitude of variability that is similar to that of the GOM SST records (see auxiliary material).

[12] The similarities between the SST proxy records that span the GOM-Caribbean region, in spite of the uncertainties in both the Mg/Ca and Sr/Ca temperature proxies, suggests that the trends recorded in the northern GOM over that past 6 centuries are representative of a regional climate signal.

5. Discussion

[13] There are important implications of a regionally coherent 2–3°C cooling in the GOM-Caribbean region during the LIA. NH temperature reconstructions suggest a <1°C hemispheric cooling [*Mann et al.*, 1999; *Esper et al.*, 2002; *Moberg et al.*, 2005], and model results using both medium and high solar radiative forcing estimate NH LIA cooling of <1°C [*Ammann et al.*, 2007]. Simulated NH temperature response to volcanic forcing shows cooling of 0.2–0.5°C, and is in good agreement with NH temperature reconstructions [*Gao et al.*, 2008]. While model simulations and terrestrial temperature reconstructions suggest a modest (<1°C) LIA cooling for the NH, proxy records estimate that cooling in the high northern latitudes is on the order of 1–3°C [*Overpeck et al.*, 1997]. Based on the concept of polar amplification, one would predict much more subtle temperature changes in the subtropical Atlantic Ocean than at the high northern latitudes. Based on the weight of evidence, however, we suggest that there was a large cooling (2–3°C) in the GOM-Caribbean region during the LIA.

[14] Timing of local SST minima in existing high-resolution continuous records from the GOM-Caribbean correspond roughly (within the error of age models) to minima in solar insolation associated with sunspot minima (The Dalton, Maunder and Spörer Minima). The reduction in solar irradiance (0.25–0.65%) attributed to these sunspot minima indicates a very small change in radiative forcing [*Bard et al.*, 2000], and a model simulation by *Ammann et al.* [2007] shows that the low-latitude North Atlantic has a relatively low sensitivity to solar forcing (<0.05°C/watt m^{-2})

compared with the mid to high latitudes. Modeled surface air temperature response to irradiance changes, similar to the decrease in irradiance associated with the Maunder Minimum, show a ΔT of $\sim 0.3°C$ in the GOM-Caribbean region [*Shindell et al.*, 2006], much smaller than the observed SST variability from proxy records in this region during these solar minima. Thus direct solar forcing alone is not likely responsible for the large LIA cooling in the GOM-Caribbean region, but perhaps positive feedbacks (e.g., intensification of the subtropical high) amplified cooling during periods of reduced solar irradiance.

[15] The observed LIA cooling in the Caribbean and northern GOM may have been driven by changes in the size of the AWP (which can vary by ±50%) and the SST anomaly within the AWP (±0.4°C) on multidecadal timescales [*Wang et al.*, 2008b]. During the LIA, it is possible that there was a dramatic reduction in the geographic extent and intensity of the AWP, thus reducing summer SSTs in regions on the periphery of the AWP (e.g., Puerto Rico and the northern GOM) for prolonged time intervals. Model results of *Wang et al.* [2008a] suggest that an anomalously small AWP, coupled with associated changes in atmospheric circulation can lead to an increase in the mid-summer drought in the Central America/Yucatan region, and an increase in moisture transport from the GOM to the North American continent via a strengthening of the Caribbean low-level jet and the Great Plains low-level jet. Proxy records of hydrologic variability suggest that this was the likely regional climate scenario during the LIA. Records from the Yucatan Peninsula suggest drier conditions during the LIA [*Hodell et al.*, 2005], while bulk $\delta^{18}O$ from the Blue Hole in Belize suggest drier and/or cooler conditions in Central America [*Gischler et al.*, 2008]. An increase in salinity (inferred from an increase in the $\delta^{18}O$ of seawater) in the GOM [*Richey et al.*, 2007] and Florida Current [*Lund and Curry*, 2006] during the LIA further supports increased evaporation minus precipitation in the GOM-Caribbean.

[16] The LIA cooling in the GOM-Caribbean region is consistent with an increase in the north-south sea-level pressure (SLP) gradient associated with the positive phase of the North Atlantic Oscillation (NAO). Increased levels of Na^+ and K^+ in a glaciochemical series from the GISP2 ice core suggest multiple intervals of increased north Atlantic storminess during the LIA [*Meeker and Mayewski*, 2002], which suggests an increase in the pressure gradient between the Icelandic Low and the North Atlantic subtropical high. This positive NAO-like pattern is characterized by an increase in North Atlantic trade wind strength, and a cooling in northern hemisphere tropical and subtropical SSTs [*Marshall et al.*, 2001]. A centennial-scale strengthening of the trade winds is consistent with evidence for cooler and drier conditions observed throughout the GOM-Caribbean region. Although a recent reconstruction of the NAO suggests a shift to weaker NAO conditions during the LIA [*Trouet et al.*, 2009], evidence from the subtropical North Atlantic is consistent with a persistent, enhanced positive NAO pattern of SLP and SST during the LIA.

6. Conclusions

[17] Despite uncertainties in foraminiferal Mg/Ca-SST proxy data and radiocarbon dating, the 3 late Holocene Mg/Ca-SST records generated from the northern GOM show very similar variability over the past 6–8 centuries, corroborating observations from throughout the GOM-Caribbean region that there was a prominent LIA cooling of 2–3°C. This suggests that the tropical-subtropical North Atlantic may be more dynamic than previously thought during the late Holocene. A reduction of the AWP, coupled with reorganization of atmospheric circulation patterns during the LIA, may explain the observed cooling in this region. Additional high quality SST proxy records from the subtropical North Atlantic Ocean are needed to establish the spatial extent and timing of this LIA cooling. Additional proxy records of regional hydrologic variability will aid in understanding the ocean-atmosphere dynamics during this climatically important interval. Models including solar and volcanic forcing during the LIA have not been able produce a >1°C cooling in the GOM-Caribbean region, thus more work needs to be done to better understand the regional climate dynamics that could lead the observed cooling.

[18] **Acknowledgments.** We thank Lisa Osterman, the PI of the 2007 R/V Pelican cruise, Hali Kilbourne, Kristine DeLong and Chris Maupin for helpful insights and discussions, and 2 anonymous reviewers for their constructive comments and reviews.

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