1400 yr multiproxy record of climate variability from the northern Gulf of Mexico

J.N. Richey College of Marine Science, University of South Florida, St. Petersburg, Florida 33701, USA
R.Z. Poore U.S. Geological Survey, 600 Fourth Street South, St. Petersburg, Florida 33701, USA
B.P. Flower College of Marine Science, University of South Florida, St. Petersburg, Florida 33701, USA
T.M. Quinn Jackson School of Geosciences, University of Texas at Austin, Austin, Texas 78759, USA

ABSTRACT

A continuous decadal-scale resolution record of climate variability over the past 1400 yr in the northern Gulf of Mexico was constructed from a box core recovered in the Pigmy Basin, northern Gulf of Mexico. Proxies include paired analyses of Mg/Ca and $\delta^{18}O$ in the white variety of the planktic foraminifer *Globigerinoides ruber* and relative abundance variations of *G. sacculifer* in the foraminifer assemblages. Two multidecadal intervals of sustained high Mg/Ca indicate that Gulf of Mexico sea surface temperatures (SSTs) were as warm or warmer than near-modern conditions between 1000 and 1400 yr B.P. Foraminiferal Mg/Ca during the coolest interval of the Little Ice Age (ca. 250 yr B.P.) indicate that SST was 2–2.5 °C below modern SST. Four minima in the Mg/Ca record between 900 and 250 yr B.P. correspond with the Maunder, Spörer, Wolf, and Oort sunspot minima, suggesting a link between changes in solar insolation and SST variability in the Gulf of Mexico. An abrupt shift recorded in both $\delta^{18}O_{calcite}$ and relative abundance of *G. sacculifer* occurred ca. 600 yr B.P. The shift in the Pigmy Basin record corresponds with a shift in the sea-salt-sodium (ssNa) record from the Greenland Ice Sheet Project 2 ice core, linking changes in high-latitude atmospheric circulation with the subtropical Atlantic Ocean.

Keywords: Little Ice Age, Medieval Warm Period, Mg/Ca, Pigmy Basin, Gulf of Mexico, Holocene.

INTRODUCTION

Establishing the geographic pattern and magnitude of natural climate variability in the late Holocene is important for anticipating and understanding the likely patterns of future climate change. A number of detailed climate records spanning the past 1–2 k.y. demonstrate that climate data of the late Holocene contain high-amplitude variability. Regional patterns and individual records during recent cold and warm extreme climate states, i.e., the Little Ice Age (LIA) and the Medieval Warm Period (MWP), are complex and highly variable. Cooling and/or warming in one region may be associated with warming and/or cooling or no change in another region, and individual proxy records may represent local climate phenomena, and are not necessarily representative of hemispheric patterns (e.g., see summary in Crowley and Lowery, 2000).

Hemispheric temperature reconstructions (e.g., Mann and Jones, 2003) that are based on a large number of temperature-sensitive proxy records with variable spatial and temporal resolution result in a record in which variability over the past 1 k.y., prior to A.D. 1900, is subdued (≤0.5 °C). The resulting low-amplitude reconstruction contrasts with several individual marine records that indicate that centennial-scale sea surface temperature (SST) oscillations of 2–3 °C occurred during the past 1–2 k.y. (i.e., Keigwin, 1996; Watanabe et al., 2001; Lund and Curry, 2006; Newton et al., 2006). Tree-ring and multiproxy reconstructions designed to capture multicentennial-scale variability (e.g., Esper et al., 2002; Moberg et al., 2005) also suggest that the amplitude of natural climate variability over the past 1 k.y. is >0.5 °C. Thus there is conflicting evidence on the amplitude of late Holocene decadal to century-scale climate variability. Resolving these discrepancies requires the continued development of quality high-resolution late Holocene climate records.

Here we present a continuous, decadal-scale–resolution marine record from the Pigmy Basin, located on the continental slope in the northern Gulf of Mexico (27°11.61 N, 91°24.54 W, water depth 2259 m). During the boreal summer the Western Hemisphere Warm Pool (WHWP) extends into the Gulf of Mexico, with SSTs exceeding 28.5 °C throughout. The WHWP, which extends from the eastern North Pacific Ocean through the Gulf of Mexico and Caribbean and into the tropical Atlantic, is the dominant heat source for the Western Hemisphere extratropics during the summer, and is the primary moisture source driving the North American Monsoon (Wang and Enfield, 2001). The Gulf of Mexico is closely linked to the Caribbean and tropical Atlantic via the Loop Current, a surface-ocean current that brings warm waters from the Caribbean Sea through the Yucatan Strait into the Gulf of Mexico before exiting through the Florida Straits to be incorporated into the Gulf Stream.

METHODS

Age control for Pigmy Basin box core PBBC-1 is based on seven accelerator mass spectrometer ^{14}C dates (see GSA Data Repository supplementary materials[1]). Raw radiocarbon dates were converted to calendar years using the CALIB 5.0 program with a 400 yr reservoir correction (Stuiver et al., 1998). Calibrated ages were plotted against core depth, and a least squares regression ($r^2 = 0.995$) indicates a linear sedimentation rate of 43 cm/k.y. (within the errors of the calibrated dates) and a core-top age of 0 yr B.P. The youngest radiocarbon date indicates a post-A.D. 1950 age for the upper 2 cm of core PBBC-1; therefore we infer that the data from the core top in our record represent near-modern conditions. The age model with a sampling interval of 0.5 cm results in an average sample resolution of 12 yr throughout the record.

Sediment samples were processed for faunal, isotopic, and elemental analyses using standard procedures (see footnote 1). Isotopic and elemental analyses were performed on the 250–300 µm size fraction of the white variety of *Globigerinoides ruber*. Oxygen isotope ratios were measured on a ThermoFinnigan Delta Plus XL light stable isotope ratio mass spectrometer at the College of Marine Science, University of South Florida (CMSUSF). The average precision for $\delta^{18}O_{calcite}$ is ±0.09‰, based on replication of 15% of the samples (n = 20 replicates). Samples for Mg/Ca analysis were cleaned according to the procedure outlined in Appendix 1 of Barker et al. (2003). Elemental analyses were performed on a Perkin Elmer Optima 4300 dual view inductively coupled plasma–optical emission spectrometer at the CMSUSF. The average precision for Mg/Ca values is ±0.16 mmol/mol, based on 40% duplicate and triplicate samples (n = 45 replicated samples).

We determined a mean Mg/Ca core-top value of 4.43 mmol/mol (±0.03) for the Pigmy Basin from analyses of 0–0.5 cm samples from three subcores of PBBC-1. Converting Mg/Ca to an SST estimate is not straightforward because there are significant differences between existing calibration equations used to derive SST estimates from Mg/Ca.

[1]GSA Data Repository item 2007101, age model, silicate contamination for magnesium/calcium, and the data set, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

For example, the Pigmy Basin core-top Mg/Ca value of 4.43 mmol/mol results in a temperature estimate of 25.4 °C using the *G. ruber* equation of Anand et al. (2003), and 27.2 °C using the equation of Dekens et al. (2002). However, both equations yield temperature records with identical amplitudes because they use the same exponential constant of 0.09. We chose to calculate SST using the *G. ruber*–specific equation with a fixed exponential constant [$Mg/Ca = 0.449 \times \exp(0.09 \cdot SST)$] from Anand et al. (2003), because it yielded a core-top SST value of 25.4 °C, equivalent to the modern annual average for the Gulf of Mexico (NOAA/OAR/ESRL, 1994). Due to the discrepancy in absolute SST values between calibration equations, we focus on comparison of the PBBC-1 record to Pigmy Basin core-top Mg/Ca, and highlight the amplitude of temperature change but not the absolute SST estimates.

PIGMY BASIN SST RECORD

Seasonal flux data from the Sargasso Sea indicate that the white variety of *G. ruber* is abundant in surface waters throughout the year (Deuser, 1987), and our Mg/Ca-derived core-top SST value is equivalent to the mean annual SST for the Gulf of Mexico. Therefore we follow previous work (Flower et al., 2004; LoDico et al., 2006) and interpret variation in Mg/Ca of *G. ruber* (white variety) as a proxy for mean annual SST. The main features of the Mg/Ca record from PBBC-1 (Fig. 1A) include two multidecadal intervals of sustained high Mg/Ca (>4.4 mmol/mol) between 1000 and 1400 yr B.P. that are separated by a multidecadal interval of lower Mg/Ca. A shift to lower mean Mg/Ca occurred ca. 1000 yr B.P., and lower but variable mean Mg/Ca occurred between 900 and 300 yr B.P. After 250 yr B.P., mean Mg/Ca increased toward the core-top value of 4.4 mmol/mol.

The total amplitude of variability in mean Mg/Ca (~1.4 mmol/mol) indicates a temperature range of ~3 °C from the maxima between 1000 and 1400 yr B.P. to the SST minima occurring between 900 and 300 yr B.P. This range is 75% of the glacial-interglacial range of 4 °C in the Gulf of Mexico (Flower et al., 2004). The sustained multidecadal-long intervals of high Mg/Ca between 1000 and 1400 yr B.P. are at the beginning of the time range associated with the MWP (ca. 800–1200 yr B.P.; Broecker, 2001). The mean Mg/Ca in the Pigmy basin record from 1000 to 1400 yr B.P. exceeds core-top values by ~0.4 mmol/mol, while 11 individual measurements exceed the core-top value by >0.6 mmol/mol. Thus our data provide evidence for mean annual SST in the northern Gulf of Mexico as being warm or warmer than near-modern SST during the early part of the MWP.

Minima in Mg/Ca, defined by intervals lasting >50 yr in which the Mg/Ca is more than 0.6 mmol/mol lower than the core-top value (>1.5 °C cooler), are present ca. 850 yr B.P., 700 yr B.P., 450 yr B.P., and 250 yr B.P. The youngest three minima are within the age range associated with the LIA (Crowley and Lowery, 2000). Multiple individual Mg/Ca measurements between 850 and 250 yr B.P. are >1 mmol/mol lower than the core-top value, indicating that SST in the northern Gulf of Mexico was as much as 2.0–2.5 °C cooler than near-modern SST during several intervals of the LIA. The four Mg/Ca minima coincide with the Oort, Wolf, Spörer, and Maunder minima in the sunspot record. Thus it is likely that the variability in the Pigmy Basin SST record is linked to centennial-scale variability in solar insolation.

IMPLICATIONS FOR LATE HOLOCENE CLIMATE EXTREMES

The magnitude of cooling indicated by Pigmy Basin Mg/Ca during cold extremes of the LIA near 250 and 450 yr B.P. is ~2.0–2.5 °C, coinciding in general with the cold intervals of the LIA centered at A.D. 1800 and 1600 (Crowley and Lowery, 2000). Oxygen isotopic and Mg/Ca temperature estimates from coral records from Puerto Rico indicate LIA cooling of 1.5 °C ca. A.D. 1800 and 2 °C ca. A.D. 1700 (Winter et al., 2000; Watanabe et al., 2001). The Sr/Ca temperature estimates from Bermuda coral ca. A.D. 1850 indicate a cooling of at least 1.0 °C (Goodkin et al., 2005). SST estimates based on $\delta^{18}O$ in the planktonic foraminifer

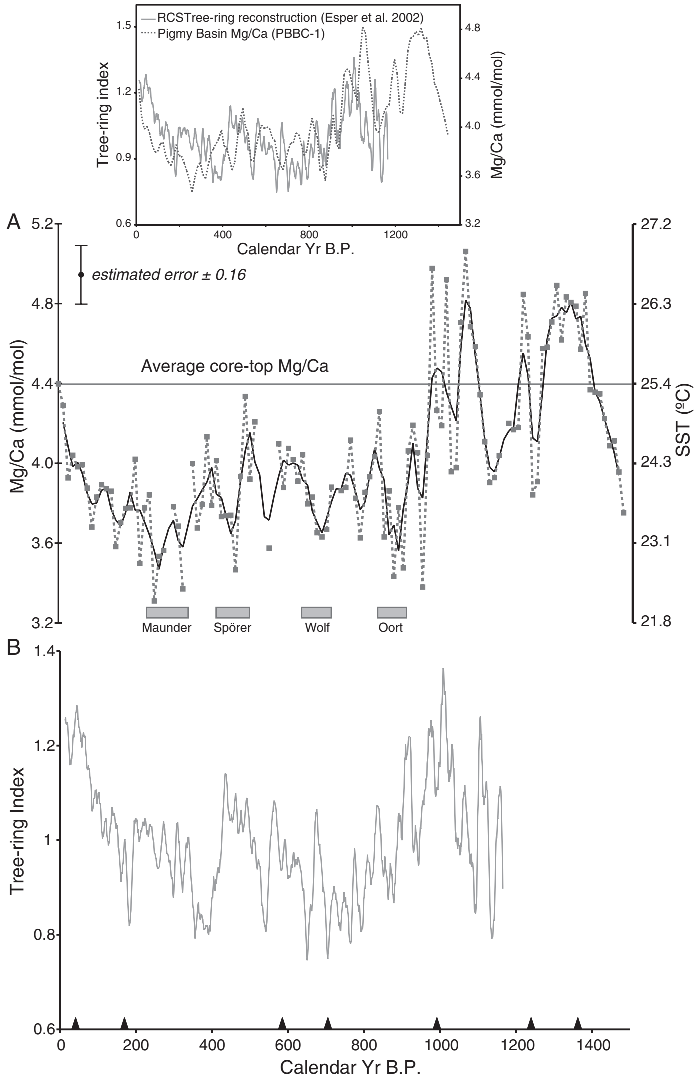

Figure 1. A: Mg/Ca of *Globigerinoides ruber* (white variety) from core PBBC 1. Mg/Ca record is plotted with corresponding sea surface temperature (SST, °C) values on secondary axis. Markers indicate individual Mg/Ca measurements, and solid line is three-point running mean. Overall precision of Mg/Ca data is ±0.16 mmol/mol. B: Regional curve standardization (RCS) curve from Esper et al. (2002). Inset shows Mg/Ca curve from PBBC-1 and RCS curve from Esper et al. (2002). Pigmy Basin and RCS records are plotted against their independent time scales.

G. ruber (white) from the Sargasso Sea suggest cooling of ~1–2 °C 300–400 yr B.P. (Keigwin, 1996). Thus the ~2.0–2.5 °C LIA cooling derived from the Pigmy Basin is consistent with published LIA cooling estimates from the Caribbean and subtropical western Atlantic.

Lund and Curry (2006) obtained 4 Mg/Ca SST records from the Dry Tortugas and the Great Bahama Bank in the subtropical western Atlantic that show very different patterns of variability over the past ~1400 yr. However, all four records indicate that SST during parts of the LIA was ~1.0 °C cooler than modern. In addition, Great Bahama Bank core 125 MC indicates that SST ca. 1200–1300 yr B.P. was similar to modern SST. Newton et al. (2006) developed a subdecadal resolution Mg/Ca SST record from the western tropical Pacific that is consistent with the Pigmy Basin SST record. Temperature maxima ca. 1000 yr B.P. are similar to modern SST, and temperature minima during the LIA were 1.0 °C to 1.5 °C below modern. Thus, the near-modern or slightly warmer than modern Pigmy Basin SST estimates for ca. 1000 yr B.P. are supported in part by published estimates from the subtropical western Atlantic and the western tropical Pacific.

The Pigmy Basin Mg/Ca record is compared in Figure 1 to a regional curve standardization (RCS) climate reconstruction derived from tree-ring records at 14 sites in the Northern Hemisphere (Esper et al., 2002). The RCS record is developed from middle- to high-latitude (30–70 °N) and high-elevation sites in the Northern Hemisphere. We chose to compare our record to the Esper et al. (2002) reconstruction because they utilized statistical techniques that preserve multicentennial climate variability after the data are processed. The Pigmy Basin Mg/Ca record and the RCS climate reconstruction show similar patterns of variability. For example, both indicate maximum cooling ca. 200 and 400 yr B.P. Both records contain a multidecadal warm interval ca. 1000 yr B.P., indicating temperature as warm or warmer than near modern temperature. Results of Blackman-Tukey cross-spectral analysis between the two records indicate a significant coherence (at the 95% significance level) for periods >200 yr. The similarity of the Pigmy Basin Mg/Ca and RCS records indicates a link between extratropical continental temperature variability and northern Gulf of Mexico SST on multicentennial time scales. Small differences in the timing of climate extremes between the two records are within the errors of the independent age models.

OXYGEN ISOTOPE AND FAUNAL RECORDS

The relative abundance of *G. sacculifer* in the planktic foraminifer assemblages and the $\delta^{18}O$ of *G. ruber* from core PBBC 1 are plotted with the ssNa record from the Greenland Ice Sheet Project 2 (GISP2) ice core in Figure 2. *G. sacculifer* (Fig. 2A) is abundant in the Caribbean, and variations in the *G. sacculifer* abundance in the Gulf of Mexico sediments are related to the influx of Caribbean surface waters into the Gulf of Mexico and the average position of the Intertropical Convergence Zone (Poore et al., 2004). The most prominent feature in the *G. sacculifer* record is an abrupt shift to lower relative abundance at 600 yr B.P.

Interpretation of the $\delta^{18}O$ record is complicated because the $\delta^{18}O$ is influenced by changes in SST and the isotopic composition of seawater. The major feature of the mean $\delta^{18}O$ *G. ruber* record (Fig. 2B) is a rapid shift to more positive values ca. 600 yr B.P. The mean record prior to 600 yr B.P. is fairly stable with the exception of a decadal-scale excursion to more positive values ca. 1050 yr B.P. After the shift at 600 yr B.P., the $\delta^{18}O$ record contains several well-defined oscillations that culminate in a trend to more negative values over the past 100 yr.

Paired Mg/Ca and $\delta^{18}O$ measurements can be used to calculate seawater $\delta^{18}O$ ($\delta^{18}O_{seawater}$). The $\delta^{18}O_{seawater}$ may then be interpreted in terms of salinity variations. Given the unresolved uncertainties in the absolute Mg/Ca-SST estimates that are used as an input into the equation for deriving $\delta^{18}O_{seawater}$, we present the PBBC-1 $\delta^{18}O_{seawater}$ curve in Figure 3 to illustrate major trends in $\delta^{18}O_{seawater}$ variability, but do not attach significance to minor fluctuations or absolute numerical $\delta^{18}O_{seawater}$. The major features of the $\delta^{18}O_{seawater}$ curve include two maxima centered near 500 and 1050 yr B.P. The older excursion coincides with the sustained interval of high SST centered at 1050 yr B.P. (see Fig. 1), as well as a multidecadal excursion of higher $\delta^{18}O_{calcite}$ (see Fig. 2). The younger excursion coincides with the mean shift observed in both the *G. sacculifer* and $\delta^{18}O_{calcite}$ records (see Fig. 2).

LINKS TO HIGH-LATITUDE CIRCULATION

Analysis of a glacio-chemical series of major ions in an ice core from Greenland (GISP2) has revealed a distinct shift in ssNa concentrations at 600 yr B.P. (Meeker and Mayewski, 2002). When the most recent 100 yr of the ssNa series is compared to the instrumental record of sea-level pressure (SLP) in the North Atlantic, a strong positive relationship between ssNa concentration and intensity of the Icelandic Low (IL) is revealed (Meeker and Mayewski, 2002). A more pronounced (deeper) IL results in increased winter winds blowing from the North Atlantic onto Greenland, increasing the ssNa content of the ice. Thus the long-term ssNa record (Fig. 2C) is considered a proxy for variability in the IL.

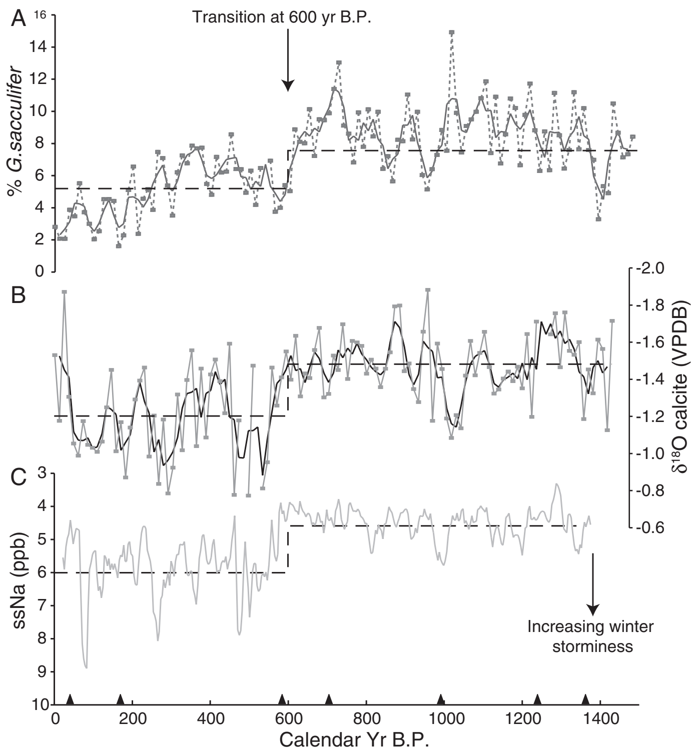

Figure 2. A: Relative abundance variations of planktic foraminifer *Globigerinoides sacculifer* (B) and *G. ruber* (white variety) $\delta^{18}O$ measured in core PBBC-1 plotted against calibrated calendar yr B.P. Markers show individual measurements; solid lines are three-point running means. C: Sea-salt-sodium (ssNa) record from Greenland Ice Sheet Project 2 (GISP2) ice core. Record of ssNa is 20 yr smoothed version, resampled at 6 yr resolution, and is plotted against time scale for GISP2 (from Meeker and Mayewski, 2002). VPDB—Vienna Peedee belemnite.

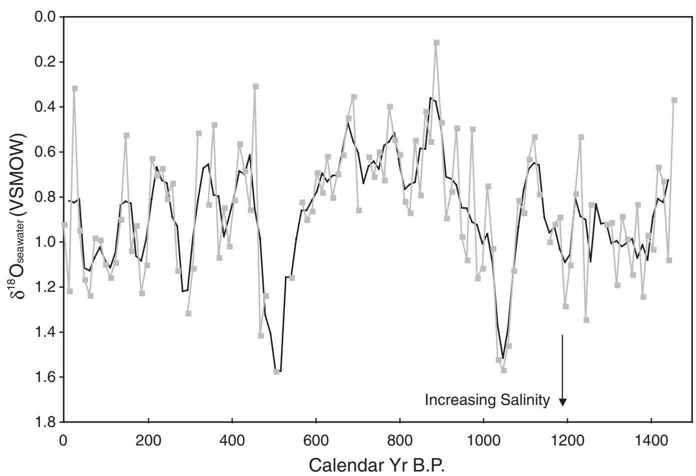

Figure 3. Calculated $\delta^{18}O_{seawater}$. Markers indicate individual values, and three-point running mean is shown in bold. $\delta^{18}O_{seawater}$ was calculated from paired Mg/Ca–sea surface temperature (SST) estimates and $\delta^{18}O_{calcite}$ measurements using equation for planktonic foraminifer *Orbulina universa* (high light) [SST(°C) = 14.9 – 4.8(δc – δw)] from Bemis et al. (1998). Resulting $\delta^{18}O_{seawater}$ is converted from Vienna Peedee belemnite to Vienna standard mean ocean water (VSMOW) by adding 0.27‰.

The ssNa record contains an abrupt shift in mean values at 600 yr B.P. that is synchronous within dating errors with the abrupt shifts to lower values in the *G. sacculifer* and $\delta^{18}O$ record from PBBC-1. The shift in ssNa is interpreted as an atmospheric circulation change resulting in a deeper IL and more intense winter circulation over the North Atlantic at the beginning of the LIA (Meeker and Mayewski, 2002). Cross-spectral analysis (using the Blackman-Tukey method) between the Pigmy Basin $\delta^{18}O$ record and the GISP2 ssNa record indicate significant coherence (at the 95% confidence level) for periods >200 yr. The close correspondence at centennial time scales coupled with the synchronous mean shift observed in both records ca. 600 yr B.P. indicates a link between atmospheric circulation in the North Atlantic and the subtropical Atlantic. No change in Mg/Ca is associated with the shift in the $\delta^{18}O$ and *G. sacculifer* records, indicating that the change in regional hydrology ca. 600 yr B.P. is not linked with a major change in Gulf of Mexico SST.

Over the instrumental period, positive ssNa anomalies are highly correlated with an increased SLP gradient between the IL and the Bermuda High (BH) (Meeker and Mayewski, 2002). The intensification of winter trade winds associated with a larger IL-BH gradient could increase evaporation in the trade-wind belt, thus producing the positive $\delta^{18}O_{seawater}$ excursions in the Pigmy Basin record that coincide with increases in ssNa in the GISP2 record.

SUMMARY AND CONCLUSIONS

Close correspondence of the Pigmy Basin Mg/Ca record to the Northern Hemisphere climate reconstruction of Esper et al. (2002) demonstrates coherence between high-latitude terrestrial climate and subtropical Atlantic SST. Raw Mg/Ca during two multidecadal intervals between 1000 and 1400 yr B.P. suggest that SST was as warm or warmer than near-modern SST at that time. Pigmy Basin Mg/Ca data also suggest SST cooling during intervals of the LIA that was at least 2 °C below near-modern SST. The overall amplitude of SST variability in the Pigmy Basin record during the past 1400 yr is ~3 °C, 75% of the glacial-interglacial SST difference estimated in the Gulf of Mexico (Flower et al., 2004).

SST and hydrologic changes are decoupled on multidecadal to centennial time scales in the Gulf of Mexico. The abrupt shift in $\delta^{18}O_{calcite}$ and *G. sacculifer* abundance from the Pigmy Basin ca. 600 yr B.P. coincides with a rapid change in atmospheric circulation as inferred from the GISP2 ssNa record from Meeker and Mayewski (2002). The data suggest a strong link between atmospheric circulation changes in the high-latitude North Atlantic and the hydrologic changes in subtropical Atlantic ca. 600 yr B.P., but not with SST.

ACKNOWLEDGMENTS

We thank Ethan Goddard for technical assistance with instrumentation; Gary Mitchum, Nele Meckler, and Harunur Rashid for helpful insights and discussions; Lloyd Keigwin, David Hollander, and Debra Willard for constructive comments and reviews; and two anonymous reviewers for their comments.

REFERENCES CITED

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

Barker, S., Greaves, M., and Elderfield, H., 2003, A study of cleaning procedures used for foraminiferal Mg/Ca paleothermometry: Geochemistry, Geophysics, Geosystems, v. 4, doi: 10.1029/2003GC000559.

Bemis, B.E., Spero, H.J., Bijma, J., and Lea, D.W., 1998, Reevaluation of the oxygen isotopic composition of planktonic foraminifera: Experimental results and revised paleotemperature equations: Paleoceanography, v. 13, p. 150–160, doi: 10.1029/98PA00070.

Broecker, W.S., 2001, Paleoclimate—Was the medieval warm period global?: Science, v. 291, p. 1497–1499, doi: 10.1126/science.291.5508.1497.

Crowley, T.J., and Lowery, T., 2000, How warm was the Medieval Warm Period?: Ambio, v. 29, p. 51–54.

Dekens, P.S., Lea, D.W., Pak, D.K., and Spero, H.J., 2002, Core top calibration of Mg/Ca in tropical foraminifera: Refining paleotemperature estimation: Geochemistry, Geophysics, Geosystems, v. 3, doi: 10.129/2001GC000200.

Deuser, W.G., 1987, Seasonal variations in isotopic composition and deep-water fluxes of the tests of perennially abundant planktonic foraminifera of the Sargasso Sea: Results from sediment-trap collections and their paleoceanographic significance: Journal of Foraminiferal Research, v. 17, p. 14–27.

Esper, J., Cook, E.R., and Schweingruber, F.H., 2002, Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability: Science, v. 295, p. 2250–2254, doi: 10.1126/science.1066208.

Flower, B.P., Hastings, D.W., Hill, H.W., and Quinn, T.M., 2004, Phasing of deglacial warming and Laurentide Ice Sheet meltwater in the Gulf of Mexico: Geology, v. 32, p. 597–600, doi: 10.1130/G20604.1.

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

Keigwin, L.D., 1996, The Little Ice Age and Medieval Warm Period in the Sargasso Sea: Science, v. 274, p. 1504–1508, doi: 10.1126/science.274.5292.1504.

NOAA/OAR/ESRL (National Oceanic & Atmospheric Administration, Earth System Research Laboratory), 1994, NODC (Levitus) World Ocean Atlas Data 1994: http://www.cdc.noaa.gov/cdc/data.nodc.woa94.html (January 2006).

LoDico, J.M., Flower, B.P., and Quinn, T.M., 2006, Subcentennial-scale climatic and hydrologic variability in the Gulf of Mexico during the early Holocene: Paleoceanography, v. 21, p. PA3015, doi: 10.1029/2005PA001243.

Lund, D.C., and Curry, W., 2006, Florida current surface temperature and salinity variability during the last millennium: Paleoceanography, v. 21, p. PA2009, doi: 10.1029/2005PA001218.

Mann, M.E., and Jones, P.D., 2003, Global surface temperature over the past two millennia: Geophysical Research Letters, v. 30, p. 1820–1823, doi: 10.1029/2003GL017814.

Meeker, L.D., and Mayewski, P.A., 2002, A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia: Holocene, v. 12, p. 257–266, doi: 10.1191/0959683602hl542ft.

Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., and Karlén, W., 2005, Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data: Nature, v. 433, p. 613–617, doi: 10.1038/nature03265.

Newton, A., Thunell, R., and Stott, L., 2006, Climate and hydrographic variability in the Indo-Pacific Warm Pool during the last millennium: Geophysical Research Letters, v. 33, p. L19710, doi: 10.1029/2006GL027234.

Poore, R.Z., Quinn, T.M., and Verardo, S., 2004, Century-scale movement of the Atlantic Intertropical Convergence Zone linked to solar variability: Geophysical Research Letters, v. 31, p. L12214, doi: 10.1029/2004GL019940.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., Van Der Plicht, J., and Spurk, M., 1998, INTCAL98 radiocarbon age calibration 24,000–0 cal BP: Radiocarbon, v. 40, p. 1041–1083.

Wang, C., and Enfield, C.B., 2001, The tropical Western Hemisphere Warm Pool: Geophysical Research Letters, v. 28, p. 1635–1638, doi: 10.1029/2000GL011763.

Watanabe, T., Winter, A., and Oba, T., 2001, Seasonal changes in sea surface temperature and salinity during the Little Ice Age in the Caribbean Sea deduced from Mg/Ca and $^{18}O/^{16}O$ rations in corals: Marine Geology, v. 173, p. 21–35, doi: 10.1016/S0025–3227(00)00166–3.

Winter, A., Ishioroshi, H., Watanabe, T., Oba, T., and Christy, J., 2000, Caribbean Sea surface temperatures: Two-to-three degrees cooler than present during the Little Ice Age: Geophysical Research Letters, v. 27, p. 3365–3368, doi: 10.1029/2000GL011426.

Manuscript received 2 November 2006
Revised manuscript received 20 December 2006
Manuscript accepted 27 December 2006

Printed in USA