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A 2000-year record of Caribbean and tropical North Atlantic hydrographic variability

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[1] Here we present near-annually resolved oxygen isotope records from two species of planktic foraminifera from the Cariaco Basin that reflect sea surface temperature (SST) and Intertropical Convergence Zone (ITCZ) precipitation-related salinity variations over the Caribbean and tropical North Atlantic spanning the last 2000 years. A strong, broad spatial pattern of correlation exists between foraminiferal δ^{18}O and SSTs over the period of instrumental overlap, but the correlations weaken as they are extended back in time and instrumental SST records become discontinuous. A long-term trend in the *Globigerinoides ruber* δ^{18}O record can be explained by two different but equally plausible scenarios. First, the increase in δ^{18}O may indicate that tropical summer-fall SSTs have cooled by as much as 2°C over the last 2000 years, possibly as a result of a long-term increase in upwelling intensity. Alternately, comparisons to other studies of ITCZ and regional evaporation/precipitation variability suggest that much of the δ^{18}O record is influenced by decadal- to centennial-scale variations in the mean annual position of the ITCZ and associated rainfall patterns. Similarities between the *G. bulloides* δ^{18}O record and the 11-year sunspot cycle support prior studies that suggest solar variability plays a role in influencing the hydrologic balance of the circum-Caribbean. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1650 Global Change: Solar variability; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4267 Oceanography: General: Paleoceanography; 4215 Oceanography: General: Climate and interannual variability (3309); *KEYWORDS:* tropical paleoceanography, Late Holocene climate variability, oxygen isotopes

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1. Introduction

[2] Much attention is currently focused on the role of the tropics with regard to climate change, particularly on decadal to subcentennial timescales. Although improved in recent years, the number and diversity of high-resolution paleoclimate reconstructions for the tropics lags their middle- and high-latitude counterparts. In light of the climate variability observed over the last century and predictions for future climate change there is an increased need to understand the natural rates and ranges (i.e., preanthropogenic) of climate fluctuations, especially in the tropics.

[3] Tropical paleoclimate reconstructions with subdecadal to decadal-scale resolution are primarily based on relatively short coral records [e.g., *Cole and Fairbanks*, 1990; *Dunbar et al.*, 1994; *Swart et al.*, 1996] and high-altitude ice cores [e.g., *Thompson et al.*, 1986, 2000]. While marine sediments potentially provide longer continuous records representative of sea surface and low-altitude climate conditions, in most cases bioturbation and/or low sedimentation rates effectively bar their use in creating records with subdecadal to decadal resolution [*Anderson et al.*, 2002]. In this study, we present 2000 yearlong δ^{18}O records with near-annual resolution from two species of planktic foraminifera that correlate well with historical tropical Atlantic sea surface temperature (SST) variability over the interval of instrumental overlap (A.D. 1950–1990). Generated from laminated sediments collected from the anoxic Cariaco Basin (Venezuela), this record avoids the problems that plague many other marine records and has the potential to be extended back through the complete Holocene at annual to near-annual resolution.

2. Study Area

[4] The Cariaco Basin (Figure 1) is well-positioned to record a detailed history of surface ocean changes along the southern margin of the Caribbean [*Overpeck et al.*, 1989; *Hughen et al.*, 1996; *Lin et al.*, 1997; *Black et al.*, 1999; *Peterson et al.*, 2000; *Haug et al.*, 2001, 2003]. Varved, high deposition rate sediments (up to >100 cm per thousand years) 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. Between January and March, when the ITCZ lies close to the equator, strong easterly

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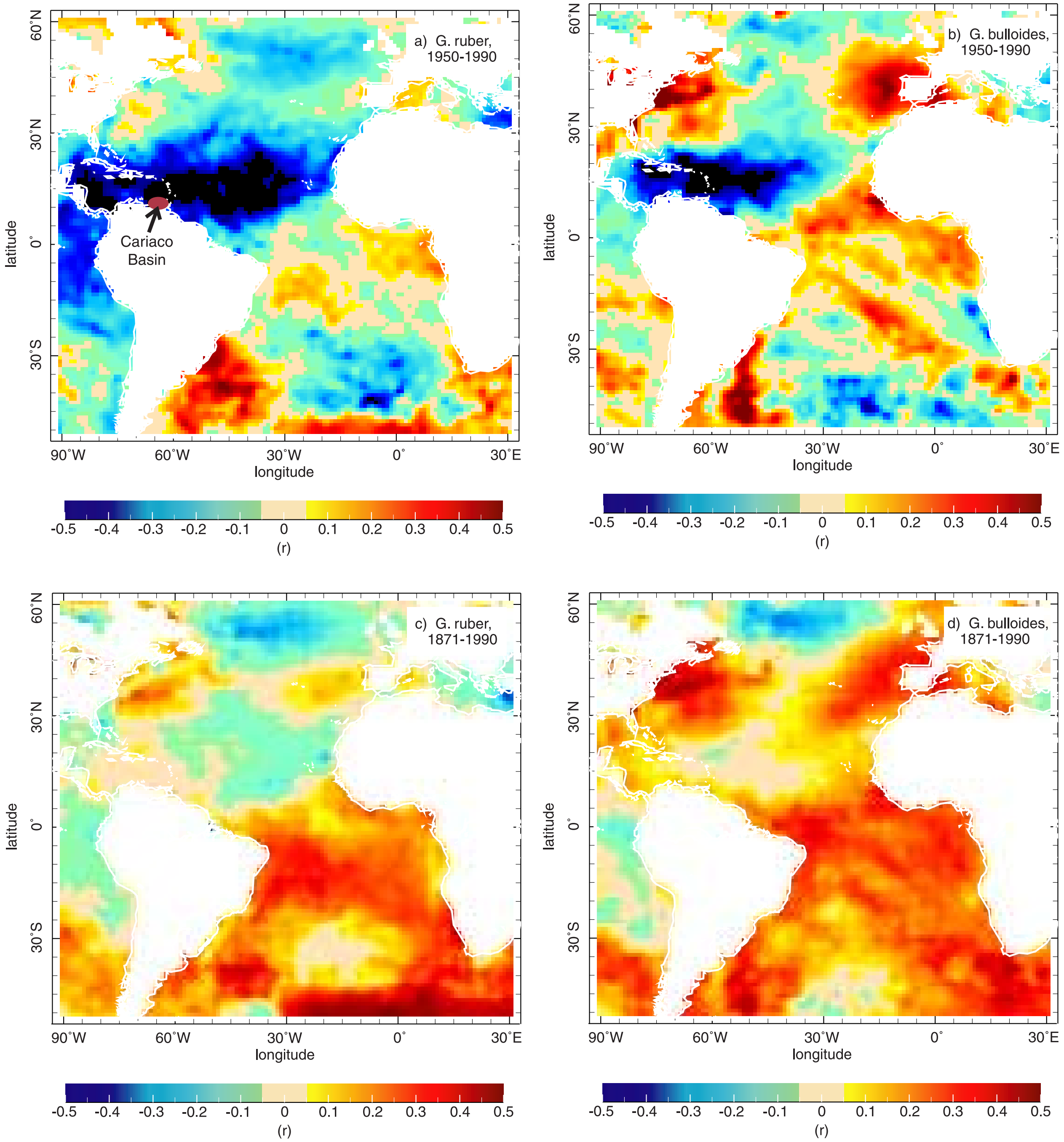

Figure 1. Spatial correlation patterns between Cariaco Basin (red ellipse) foraminiferal $\delta^{18}O$ and Hadley SSTs. Cooler colors represent stronger negative correlations. Each 2° × 2° grid square represents the correlation coefficient for a year-by-year comparison between instrumental SSTs for that particular grid square and our isotope data. (a and b) *G. ruber* and *G. bulloides* $\delta^{18}O$-SST correlations, A.D. 1950–1990, respectively. (c and d) *G. ruber* and *G. bulloides* $\delta^{18}O$-SST correlations, A.D. 1871–1990, respectively. Temporal resolution of the $\delta^{18}O$ records is nearly annual over both intervals.

trade winds along the northern coast of Venezuela create strong Ekman transport, intense upwelling, and peak primary productivity over the Cariaco Basin and the continental margin [*Richards*, 1975; *Peterson et al.*, 2000; *Muller-Karger et al.*, 2001]. Beginning in June or July, when the ITCZ migrates north to a position near the Venezuelan coast, the trade winds diminish, and upwelling over the basin weakens or is largely shut off. Studies of the Cariaco Basin microplankton have shown that the local planktic foraminifera population undergoes seasonal assemblage changes with *Globigerina bulloides* dominating during the winter/spring upwelling months, and *Globigerinoides ruber* during summer/fall months [*de Miró*, 1971; *Tedesco and Thunell*, 2003a].

3. Materials and Methods

[5] We sampled sediments from a box core (PL07-71 BC; 10°45.46′N, 64°41.86′W, 395 m water depth) and a gravity core (CAR7-2; 10°39.06′N, 64°39.60 W, 449 m water depth) recovered from the gentle northeastern slope of the Cariaco Basin. In order to obtain as high a resolution record as possible, the sediments were sampled at consecutive 1-mm intervals (see *Black et al.* [1999] for sampling procedure). Samples were freeze-dried, weighed, and wet-sieved through a 63 μm screen, and specimens of both *G. bulloides* (212–250 μm fraction) and the pink pigmented morphotype of *G. ruber* (212–425 μm fraction) were picked for oxygen and carbon isotopic analyses. We used sixteen to twenty *G. bulloides* tests and six to eight *G. ruber* tests per analysis due to the limited sample size of millimeter intervals and specific size fractions. These two species of planktic foraminifera were chosen as their annual population succession best represent the end-members of the annual hydrographic and SST cycle in the Cariaco Basin [*Lin et al.*, 1997; *Tedesco and Thunell*, 2003a]. All isotopic analyses were performed on a VG Optima isotope ratio mass spectrometer equipped with an automated carousel. Samples were reacted at 90°C in phosphoric acid, and all isotope data are reported relative to Vienna Peedee belemnite (VPDB) via our working standard, NBS-19. Replicate analyses of this standard yielded an analytical precision (1σ) of ±0.08‰ during the period of data generation for this study. Replicate analyses were performed on approximately ten percent of the total samples; reproducibility of individual samples was ±0.10‰ for *G. bulloides* and ±0.15‰ for *G. ruber*.

[6] The age models for cores PL07-71 BC and CAR7-2 have been previously published [*Black et al.*, 1999; *Goñi et al.*, 2003]. Sediment ages for these cores were derived from a combination of varve counts (PL07-71 BC), ^{210}Pb dating (PL07-71 BC), and accelerator mass spectrometry (AMS) ^{14}C dates (PL07-71 BC and CAR7-2). There is approximately 400 years of overlap between the two cores, which were spliced together using a combination of the AMS ^{14}C dates and detailed multiple species population correlations between each core. The resultant 2000-year record has a sample resolution of approximately one year per sample near the top of the record, and decreases in resolution to approximately 2.5 years per sample at the base.

4. Results and Discussion

4.1. Comparing the Cariaco Basin Record to Instrumental Data, 1950–1990 and 1871–1990 A.D.

[7] The δ^{18}O of planktonic foraminiferal calcite is a function of two independent variables, the temperature at the time of calcification and the oxygen isotopic composition of seawater, with the latter variable being a measure of local salinity. Thus both temperature and salinity must be considered when interpreting foraminiferal δ^{18}O records. A temperature calibration of the δ^{18}O records was carried out by correlating the δ^{18}O records of *G. ruber* and *G. bulloides* from core PL07-71 BC to Cariaco Basin and Atlantic SSTs from the Hadley SST data set [*Rayner et al.*, 2003] for the period A.D. 1950 to 1990 (Figures 1a and 1b). Each 2° × 2° grid square represents the resultant correlation coefficient for a year-by-year comparison between our isotope data and the respective grid square's instrumental SST record. The 1950–1990 time period was chosen because historical temperature data is relatively continuous both geographically and temporally over this interval. Regional instrumental SST records become discontinuous prior to 1950 making a longer year-by-year comparison rely in part on statistically interpolated SSTs, discussed further below. A strong inverse correlation (due to the δ^{18}O/SST relationship) between *G. ruber* and *G. bulloides* δ^{18}O and tropical Atlantic SSTs is observed, with correlation coefficients as strong as -0.61 ($\rho < 0.01$) for both species. *Globigerinoides ruber*'s δ^{18}O values correlate best with late summer/early fall SSTs (August, September, and October) as expected based on previous studies of seasonal planktic foraminiferal distributions in the Cariaco Basin. The *G.* ruber δ^{18}O-SST correlations are strong over the entire Caribbean Sea and across both sides of the tropical North Atlantic. Surprisingly, *G. bulloides*' δ^{18}O correlates best to SSTs during October through December. Previous plankton tow [*de Miró*, 1971] and sediment trap studies [*Tedesco and Thunell*, 2003a] of the Cariaco Basin foraminifera population indicate that the *G. bulloides* population is typically greatest during the months of December through April. However, correlations coefficients between *G. bulloides* δ^{18}O and December-April SSTs are poor. The *G. bulloides* temporal correlation pattern may be explained by isotopic modeling of Cariaco Basin sediment trap samples. *Tedesco and Thunell* [2003a] suggest that *G. bulloides* prefers subsurface water depths (<50 m) during most of the year, and is only found in surface waters during the spring upwelling season. Still, *G. bulloides* δ^{18}O-SST correlation coefficients exhibit a similar strength and spatial pattern to those of *G. ruber*, although the extent of the *G. bulloides* correlations is less, encompassing the Caribbean and just the western tropical North Atlantic.

[8] The respective δ^{18}O records were also compared to SSTs for the full length of the Hadley SST data set, spanning the period A.D. 1871–1990 (Figures 1c and 1d). Correlations over this longer interval to Caribbean and tropical North Atlantic SSTs have near-zero values for both *G. ruber* and *G. bulloides*. There are several possible explanations for the poor long-term isotope-SST correlations including variations in surface salinity, small errors in the core's age model, a shift in species' habitat depth, and the incompleteness of instrumental SST records prior to 1950.

[9] Given that the δ^{18}O value of foraminiferal calcite is a function of temperature and salinity, it is possible that either local or regional surface salinity varied sufficiently between A.D. 1871 and 1950 such that the δ^{18}O-temperature component was overwhelmed, and hence led to minimal SST correlations. Unfortunately, there are no long-term instrumental salinity records for this region of the Caribbean and Atlantic, and thus there is no direct way to test this hypothesis. Local rainfall and stream level records are

equally sparse making even an indirect test nearly impossible. The most extensive regional precipitation record available is for Fortaleza, Brazil (see http://dss.ucar.edu/datasets/ds570.0). Rainfall in the Nordeste of Brazil is similarly controlled by variations in the average annual position of the ITCZ, but no significant correlation (positive or negative) was found when compared to the δ^{18}O records for either the A.D. 1950–1990 or 1871–1990 periods.

[10] One approach to estimating the potential surface salinity changes necessary to produce the low 1871–1990 correlations is to calculate paleotemperatures using the isotope data and then vary the $\delta^{18}O_{water}$ component of the equations such that the isotope-derived SSTs match those of the instrumental record. One can then use the δ^{18}O/salinity relationship for the western equatorial Atlantic [*Fairbanks et al.*, 1992] to estimate the salinity variability over the instrumental interval. A variety of paleotemperature equations have been published for *G. bulloides* [*Spero and Lea*, 1996; *Bemis et al.*, 1998, 2002] and the white morphotype of *G. ruber* [*Thunell et al.*, 1999; *Spero et al.*, 2003]. However, when the respective equations were applied to the A.D. 1950–1990 interval, when correlations between foraminiferal δ^{18}O and SST are particularly strong, the resulting isotope-derived paleotemperatures consistently underestimated instrumental SST by 1–3°C. The correct SST trends were reproduced, but absolute values did not match. As such, we felt that attempting to estimate the exact magnitude of the potential salinity overprint using this method could result in spurious estimates.

[11] The low pre-1950 correlations could be a result of small errors in the age model for the upper section of box core PL07-71 BC. However, isotope-SST correlations were performed with a variety of lagged offsets (i.e., shifting the core's age model) of as much as ten years with no improvement in correlation pattern or values indicating that the age model for the uppermost part of the record is robust.

[12] A shift in the preferred depth habitats of *G. ruber* and *G. bulloides* prior to A.D. 1950 could take the species out of contact with surface waters (and hence SSTs) leading to low SST correlations. Sediment trap data indicates that *G. bulloides* is only found in surface waters (<10 m) during the spring upwelling season [*Tedesco and Thunell*, 2003a]. If upwelling was reduced prior to 1950, *G. bulloides* may have been sufficiently disconnected from the surface to lose any isotopic correlation with SST. However, instrumental wind stress, faunal abundance [*Black et al.*, 1999], and coral trace element data [*Reuer et al.*, 2003] do not support the notion of reduced upwelling between A.D. 1871–1950 relative to 1950–1990. *Globigerina bulloides* abundance values increase between the mid-1950s and early 1980s [*Black et al.*, 1999] suggesting that upwelling steadily intensified during this time. Interestingly, the strength of the *G. bulloides* isotope-SST correlation increases over the same interval. Upwelling variability should not affect the *G. ruber* correlations as it is a surface dweller and thus its isotopic values should always be representative of surface temperatures regardless of upwelling intensity.

[13] Inconsistent instrumental SST recordings prior to A.D. 1950 may also contribute to the weak correlations over the early part of the calibration period. The Hadley SST data set includes SSTs that are statistically interpolated for months/years when no instrumental measurement were made. There are gaps of decades (and longer) in the instrumental SST record for the waters immediately surrounding the Cariaco Basin prior to 1950, and the number of ship observations is significantly less before this time as well. Similar gaps presumably exist in the instrumental records for much of the tropical North Atlantic. It is possible that there were changes in SST in the Caribbean and tropical North Atlantic that the Hadley data does not interpolate as well as it does for more highly sampled areas. It is interesting to note that some of the correlations observed for the A.D. 1950–1990 interval with areas possessing longer instrumental SST records maintain similar degrees of correlation for the pre-1950 interval (*G. bulloides* values around New England and western Europe for example). However, we feel that the pre-1950 data sparsity may not significantly contribute to the pre-1950 low isotope-SST correlations. Coastal land surface temperature measurements are much more comprehensive between 1871 and 1990, and those records maintain their correlations with the reconstructed SSTs over the interval in question, suggesting that the quality of reconstructed SST does not degrade with time.

[14] There are few other proxy records from the Cariaco Basin spanning the interval in question with sufficient temporal resolution that may clarify the long term correlation difficulties. A trace element study using corals taken near Isla Tortuga (northern rim of the Cariaco Basin) shows a dramatic change in Cd/Ca ratios around 1950 that is interpreted as a reduction in local upwelling [*Reuer et al.*, 2003]. However, the relation between upwelling and SST in the basin is not as straightforward as one might imagine. Instrumentally measured wind stress and SSTs are not highly correlated ($r = 0.3$) between A.D. 1950 and 1990 (comprehensive ocean atmosphere data set; *Woodruff et al.* [1987]). High-resolution faunal abundance data (generated from the same samples used in this study) representative of upwelling intensity [*Black et al.*, 1999] display an identical correlation coefficient ($r = 0.3$) when compared to the δ^{18}O data presented in this study, again indicating a nonlinear relationship between basin SST and upwelling. Additionally, neither the faunal abundance nor instrumentally measured zonal wind stress data supports the coral Cd/Ca-inferred reduction in upwelling intensity. While it is clear that some type of change occurred in local hydrographic conditions around 1950, the nature of that change and its potential impact on foraminiferal calcite δ^{18}O values is unclear.

[15] Despite the potential questions that arise from the A.D. 1871–1990 correlations, the geographic extent of the A.D. 1950–1990 correlations, the interval when confidence in the instrumental record is greatest, are critical because they demonstrate that subdecadal-scale oxygen isotope data from Cariaco Basin samples are indicative of more than just a local signal, and instead are representative of sea surface conditions over a much wider area of the Caribbean and tropical North Atlantic. An equally important point is that forty years of instrumental data may not be sufficient to calibrate this particular paleoclimate proxy. Had the instrumental record ended in 1950 (as opposed to just being very

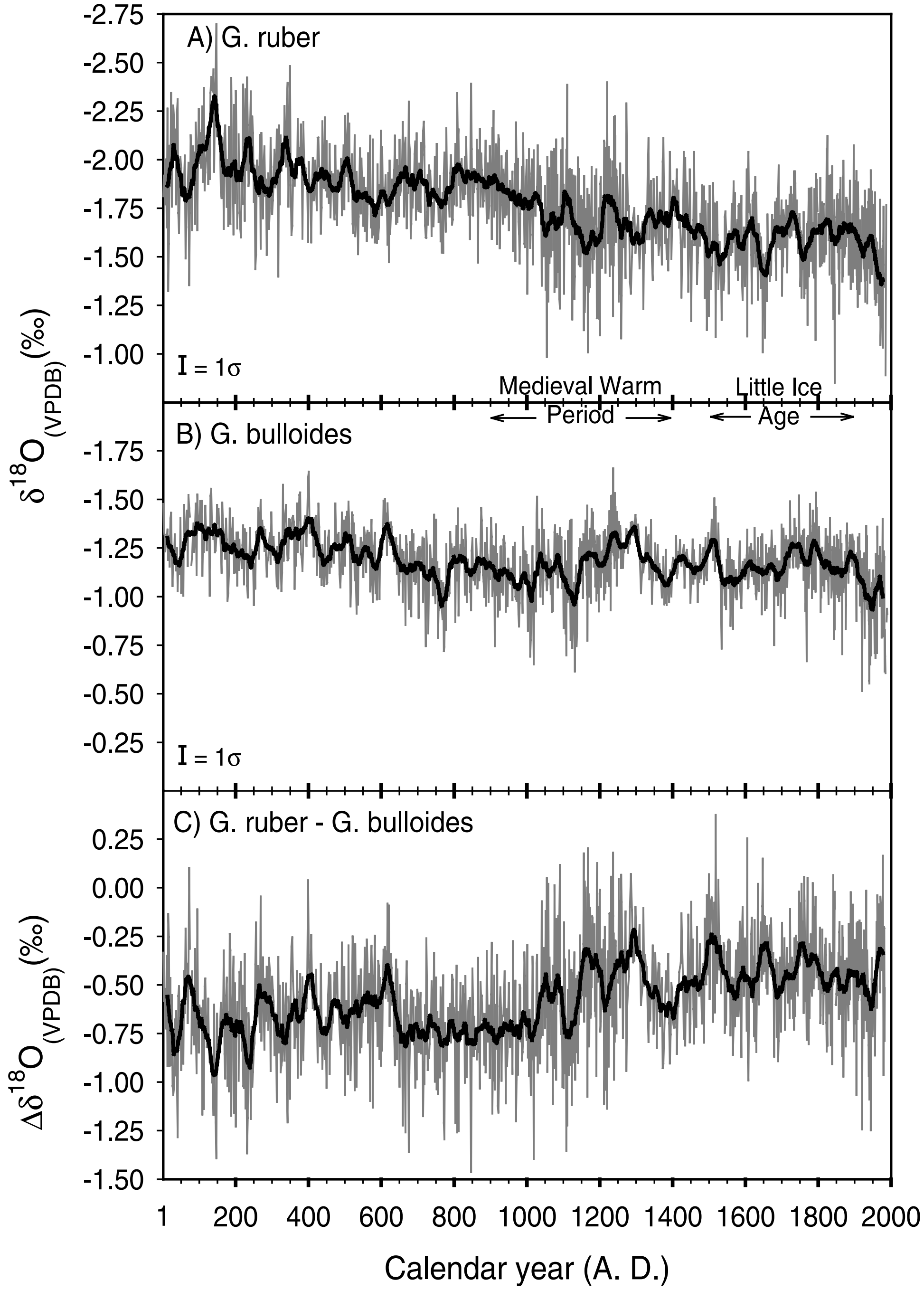

Figure 2. The $\delta^{18}O$ records for (a) *G. ruber*, (b) *G. bulloides*, and (c) $\Delta\delta^{18}O$. The shaded line in each plot corresponds to the raw data, and the heavy black line represents a 25-year running mean through the data. The one-σ error bar is shown in the lower left corner of each plot, and both plots' isotope data are equivalently scaled.

sporadic), one would have thought it very reasonable to interpret the entire record primarily in terms of SST change.

4.2. Caribbean and Tropical North Atlantic Temperature and Hydrographic Variability, 1–1990 A.D.

[16] The $\delta^{18}O$ records of both species for the period A.D. 1 to 1990 are characterized by considerable interannual to subcentury-scale variability (Figures 2a and 2b). As expected, overall $\delta^{18}O$ values for *G. ruber* are more negative than those for *G. bulloides* reflecting *G. ruber's* environmental preference for warmer surface conditions [*Kipp*, 1976; *Schmuker and Schiebel*, 2002] and *G. bulloides*' preference for colder, upwelling conditions [*Peterson et al.*, 1991; *Sautter and Thunell*, 1991]. *Globigerinoides ruber* $\delta^{18}O$ values also exhibit greater variability, ranging from

−0.85 to −2.70‰, while *G. bulloides*' values vary between −0.50 and −1.60‰ over the full length of the record (Figure 2). The δ^{18}O range observed in the core samples is similar to those measured from Cariaco Basin sediment trap samples; *G. ruber* trap samples vary between −0.7 and −2.3‰, and *G. bulloides* trap samples vary between −1.0 and −2.0‰ (K. Tedesco and R. Thunell, manuscript in preparation, 2004). Additionally, the *G. ruber* record displays a steady increase in δ^{18}O values over the 2000-year time series, with a distinct positive 0.25‰ shift in mean isotopic values occurring between A.D. 1000 and 1200.

[17] Interestingly, neither record shows the distinctive multicentury-scale variability that is so characteristic of a prior record of trade wind and northern North Atlantic SST fluctuations generated from one of the cores used in this study (PL07-71 BC; *Black et al.* [1999]). There is also surprisingly little correlation between *G. ruber* and *G. bulloides* δ^{18}O and their respective population data [*Black et al.*, 1999, 2001]. As previously noted, the correlation coefficient between instrumental SST and wind stress between 1950 and 1990, and between *G. bulloides* δ^{18}O and *G. bulloides* abundance (an indicator of trade wind intensity and upwelling variability; *Black et al.* [1999]) are both 0.3. While just significant at the 95% level, the correlations suggest that the faunal abundance data perhaps vary more as a function of nutrient dynamics and that the relationship between basin SST and upwelling is not necessarily linear.

[18] As amply demonstrated by the A.D. 1950–1990 correlations, the stable oxygen isotope composition of *G. ruber* and *G. bulloides* reflects the hydrography of the Caribbean and tropical North Atlantic, the problem is isolating the temperature and salinity components from the overall δ^{18}O signal. Until this issue is resolved, one approach to interpreting the respective species' δ^{18}O records is to examine the end-member possibilities (i.e., the isotopic signal is driven entirely by temperature or entirely by salinity) and assume that the reality is somewhere in between.

4.2.1. δ^{18}O Records as a Function of Temperature Variability

[19] Given the difficulties of precisely matching instrumental SSTs with those calculated from published isotope-paleotemperature equations during the 1950–1990 calibration interval, the discussion will instead focus on relative temperature changes over the length of the record, assuming a δ^{18}O change of 1.0‰ is equivalent to a 4.2°C change in SST [*Epstein et al.*, 1953; *Craig*, 1965].

[20] The overall trend toward more positive values is perhaps the most dominant feature in the *G. ruber* δ^{18}O record. The change in *G. ruber* suggests late summer/early fall SSTs cooled by approximately 2.1°C over the last 2000 years, while the *G. bulloides* data indicate that late fall/early winter SSTs either remained the same or cooled by only about 0.5°C over the same interval. If the long-term δ^{18}O trend is controlled entirely by temperature, the relative species' δ^{18}O changes suggest that cooling was a seasonal phenomena with much greater cooling occurring during late summer/early fall than during late fall/early winter. A previous study using Cariaco Basin material, but with lower resolution than our record, noted an identical 0.5‰ increase in pink *G. ruber* δ^{18}O values [*Tedesco and Thunell*, 2003b]. A similar decreasing temperature signal was noted for Northern Hemisphere surface temperatures over the last 1000 years [*Mann et al.*, 1999], although the magnitude of the hemispheric temperature change is much less than what the *G. ruber* data suggests. A lower-resolution *G. ruber* δ^{18}O record spanning the last ~3000 years taken from the Bermuda Rise (33°41.6′N, 57°36.7′ W) does not show the same trend toward more positive values over the interval of overlap [*Keigwin*, 1996]. However, SSTs in the area of the Bermuda Rise do not correlate well with our A.D. 1950–1990 calibration (Figure 1a), and thus it is not surprising that the longer records do not show similar trends.

[21] The trend toward more positive *G. ruber* isotopic values could also have been caused by a gradual increase in upwelling intensity over the last 2000 years and resultant cooling of average annual SSTs. The convergence between the isotopic values ($\Delta\delta^{18}$O) of surface-dwelling *G. ruber* and those of somewhat deeper-dwelling *G. bulloides* (Figure 2c) implies increased vertical mixing and hence upwelling over the length of the record [e.g., *Lin et al.*, 1997; *Patrick and Thunell*, 1997; *Weinheimer et al.*, 1999; *Pak and Kennett*, 2002]. *Tedesco and Thunell* [2003b] indicate a specific increase in upwelling intensity at approximately A.D. 900, that within the age model errors of both studies is coincident with a decrease in the $\Delta\delta^{18}$O presented in this study. However, this particular upwelling event is not necessarily supported by foraminiferal census data. Coincident with the $\Delta\delta^{18}$O decrease is a large decrease in *G. bulloides* abundance [*Black et al.*, 2001], previously used in Cariaco Basin studies as an indicator of upwelling intensity [*Black et al.*, 1999]. The respective $\Delta\delta^{18}$O decreases could also be interpreted as a decrease in the strength of the local rainy season as the $\Delta\delta^{18}$O shift in both records is driven primarily by a change in *G. ruber* data, the local rainy season representative.

[22] Annual upwelling variability in the Cariaco Basin is controlled by the annual migration of the ITCZ and trade winds, with maximum upwelling intensity occurring when the ITCZ and trade wind belt are at their southernmost position of the year. A recent study of Holocene ITCZ variability derived from Cariaco Basin sediments indicates that the average annual position of the ITCZ has drifted southward over the last 10 kyr [*Haug et al.*, 2001, 2003]. The southward migration of the ITCZ and trade winds over the last 2000 years would result in a gradual increase in upwelling intensity and thus lead to smaller $\Delta\delta^{18}$O values. Alternatively, there may have been an increase in trade wind intensity while the ITCZ maintained a more stable paleoposition.

[23] Spectral analysis on the *G. ruber* δ^{18}O using the methods of *Mann and Lees* [1996] indicates concentrations of variance at 8.7 to 8.9 years, 7.3 to 7.7 years, 6.0 to 6.4 years, and 5.3 years. Several of these peaks hint at an El Niño-Southern Oscillation (ENSO) connection. However, while ENSO does have an effect on Atlantic SSTs and Caribbean rainfall [*Enfield and Mayer*, 1997; *Giannini et al.*, 2000], individual ENSO events are not clearly observable in the *G. ruber* record.

[24] Comparisons to well-known climate perturbations such as the Medieval Warm Period (MWP; A.D. 900–1400) and the Little Ice Age (LIA; A.D. 1500–1900) are complicated by the long-term $\delta^{18}O$ increase. Both species' records suggest an interval of warmer SSTs prior to ~A.D. 1600–1900. *Globigerinoidesruber* data suggest that late summer/early fall SSTs were approximately 0.6°C warmer during the MWP relative to the LIA. The *G. bulloides* data hint at a two-stage LIA, a sequence observed in many other locations. Still, while the respective species' $\delta^{18}O$ data correctly sequence the relative temperature change between the so-called MWP and LIA, the long-term trend suggests that tropical SSTs were even warmer prior to the onset of the MWP.

4.2.2. $\delta^{18}O$ Records as a Function of Salinity Variability

[25] Regional salinity variations also likely contribute to the total $\delta^{18}O$ signal preserved by foraminifera in the Cariaco Basin. A $\delta^{18}O$-salinity relationship has not been established for the Cariaco Basin itself, but several equations have been established for the Caribbean and equatorial Atlantic [*Fairbanks et al.*, 1992; *Watanabe et al.*, 2001]. Both of these $\delta^{18}O$-salinity equations indicate a 0.2‰ change in $\delta^{18}O$ is equivalent to a regional sea surface salinity (SSS) change of approximately 1.0 practical salinity unit (psu).

[26] The long-term trend toward more positive *G. ruber* $\delta^{18}O$ values is equivalent to as much as a 2.5 psu increase in Caribbean and tropical North Atlantic SSSs assuming that all of the $\delta^{18}O$ shift is salinity-related. Given the modern range of global SSS, a 2.5 psu change in Caribbean surface waters over the last 2000 years suggests there can be significant variations in regional and potentially hemispheric hydrologic regimes under essentially modern boundary conditions. Additionally, this range of SSS variability suggests that the poor correlations observed for our A.D. 1871–1990 SST-$\delta^{18}O$ calibration are likely a function of a strong salinity overprint.

[27] Indeed, ITCZ variability may influence local and regional SSS fluctuations and thus have an affect on the multicentury trends in the A.D. 1–1990 $\delta^{18}O$ record. The gradual southward shift in the mean annual position of the ITCZ and its associated rainfall over the last 10 kyr that *Haug et al.* [2001] suggest could potentially alter the hydrologic balance of the Caribbean and tropical Atlantic and produce the observed increase in the *G. ruber* $\delta^{18}O$ record. Both the *Haug et al.* [2003] paleoprecipitation and *G. ruber* $\delta^{18}O$ data show the same long-term linear trend (Figure 3) indicating decreasing precipitation over the circum-Caribbean associated with a southward migration of the ITCZ or a decrease in precipitation intensity. The resulting increased aridity may have increased SSS as recorded by more positive $\delta^{18}O$ values. Despite showing the same overall trend, the respective records do not significantly correlate on decadal to centennial timescales, but the lack of high-frequency correlation may be a function of what each record represents. Specific events within the Ti record may be more indicative of local continental input, whereas the isotope data may be more representative of broader sea surface hydrologic changes. *Nyberg et al.* [2001] inferred a shift toward more humid tropical Atlantic conditions around A.D. 850–1000, in contrast to what our isotope data indicate. Still, *Nyberg et al.* [2002] suggest that northern Caribbean surface salinities have increased by approximately 1.7 psu over the last 2000 years based on a much lower resolution foraminiferal $\delta^{18}O$ record (Figure 3). Coupled $\delta^{18}O$-Sr/Ca variations in a shorter sclerosponge record from the central Caribbean suggest that Caribbean salinities may have fluctuated by 2 psu over the last 650 years [*Hasse-Schramm et al.*, 2003].

[28] Several studies of tropical paleoclimate have suggested that regional hydrologic balances may be influenced by solar variability. *Hodell et al.* [2001] argue that variations in solar activity influenced the precipitation to evaporation ratio of the Yucatan Peninsula based on stable oxygen isotope and geochemical analyses of lake sediments. *Linsley et al.* [1994] observed significant changes in a coral $\delta^{18}O$ record from the east coast of Panama that demonstrated a strong variance near eleven years, particularly during the 1800s. However, the coral $\delta^{18}O$ displayed a poor direct correlation with sunspot number, and thus a direct link between solar variability and tropical climate could not be inferred. On a slightly longer timescale, *deMenocal et al.* [2000] suggest that abrupt changes in the moisture balance of tropical Africa were related to small, gradual changes in insolation.

[29] Prior studies from the Cariaco Basin have indicated at least indirect linkages between solar variability and climate proxies. *Peterson et al.* [1991] related a 200-year periodicity found in a record of Cariaco Basin upwelling variability to solar cycles. *Black et al.* [1999] noted a similarity between trade wind intensity in the southern Caribbean and changes in ^{14}C production, a function of solar variability. Spectral analysis on *G. bulloides* $\delta^{18}O$ reveals peaks centered at 112 years, 13.5 years, 11 years, 9 years, and several peaks between 7.6 and 6.0. Within the bandwidth estimate, the peaks at 112 and 11 years hint at apparent sunspot periodicities. A comparison of sunspot number to a five-point smooth of the *G. bulloides* $\delta^{18}O$ record over the last three centuries (Figure 4) shows remarkably similar trends, particularly over multidecadal to century timescales. Cross-spectral analysis of the raw *G. bulloides* $\delta^{18}O$ data and sunspot number reveals coherent peaks above the 95% significance level centered at 158 years, 24 years, 10.9 years, and 8.2 years. Within the bandwidth estimate, these peaks correspond to the 121-, 22-, and 11-year sunspot cycles.

[30] The mechanism linking solar variability to regional hydrologic balance (or temperature) changes is unclear. Solar variability is an oft-invoked driver of decadal- to century-scale climate change, but it has always been difficult to explain how small changes in insolation result in a large climatic response. Some type of amplification mechanism must be required [e.g., *Stuiver and Braziunas*, 1993; *Beer et al.*, 2000; *Reid*, 2000]. Variations in ultraviolet irradiance is known to cause changes in stratospheric conditions, but how those changes influence the troposphere, and hence surface climate, remains debatable [*Shindell et al.*, 1999; *Beer et al.*, 2000; *Reid*, 2000].

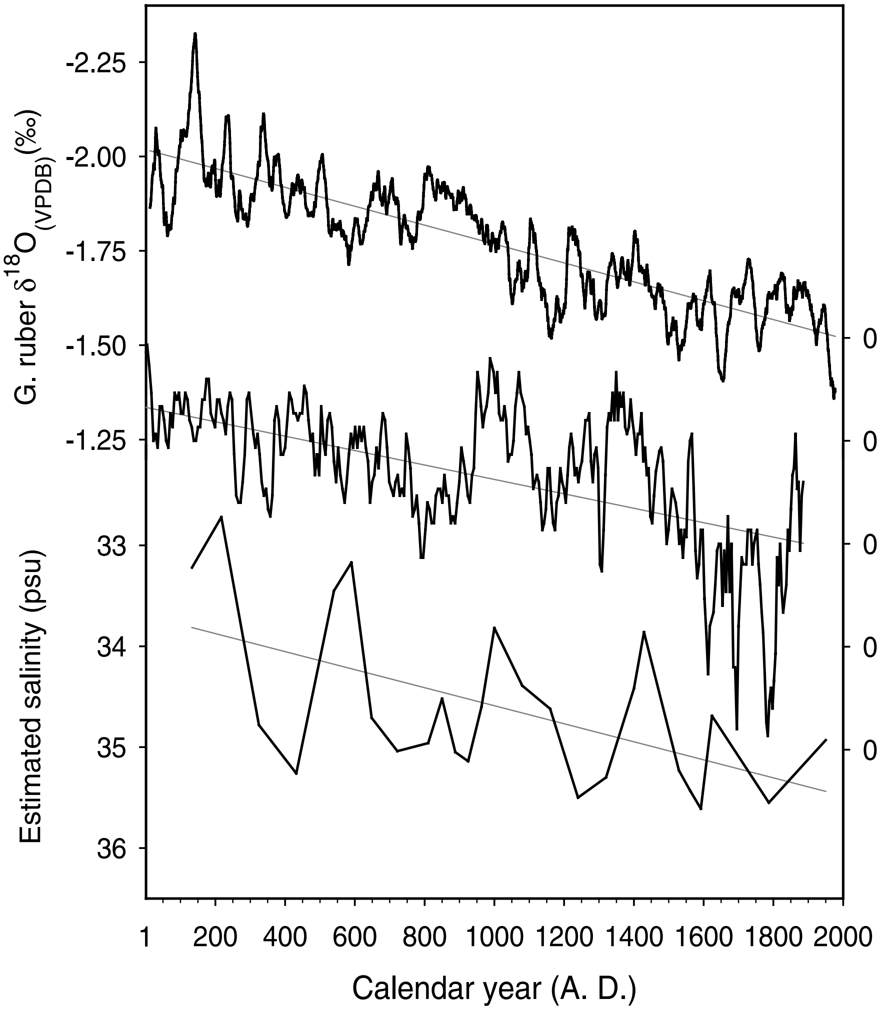

Figure 3. Comparison of *G. ruber* $\delta^{18}O$ (25-year running smooth) to sediment titanium composition [*Haug et al.*, 2001] representing continental runoff through time and $\delta^{18}O$-estimated salinities for the northern Caribbean [*Nyberg et al.*, 2002]. A first-order regression line is shown for each data set indicating the respective trends toward less precipitation and/or more saline conditions over the last 2000 years in the circum-Caribbean, presumably associated with a southward migration of the ITCZ's average annual position and its associated rainfall.

Solar-related changes in cosmic ray flux may influence the formation of ice condensation nuclei and cloud formation [*Reid*, 2000]. However, this effect appears to be most pronounced at middle- and high-latitudes [*Kniveton and Todd*, 2001] rather than low latitudes, and additionally is one of the most controversial aspects of Sun-climate relationships. Climate model experiment results have indicated that solar variations can influence Hadley circulation, thus leading to changes in regional precipitation and possibly salinity balance patterns [*Rind and Overpeck*, 1993]. Despite the uncertain nature of the potential Sun-climate link, the match between the $\delta^{18}O$ data and sunspot numbers is intriguing.

4.2.3. $\delta^{18}O$ Records as a Function of Carbonate Ion Variability

[31] As one additional explanation, at least some of the variability observed in the $\delta^{18}O$ records may be a function of variations in seawater carbonate ion concentration. Both laboratory and field studies have noted that increases in carbonate ion concentrations can result in foraminifera tests with lower $\delta^{18}O$ [*Spero et al.*, 1997, 1999; *Bijma et al.*, 1998]. A long-term increase in carbonate ion concentration could produce the 0.5‰ decrease observed in the *G. ruber* record. However, one would expect to see an even greater trend in the *G. bulloides* record as the laboratory-calibrated $\delta^{18}O/[CO_3^{2-}]$ slope for *G. bulloides* (-0.0045) is twice that of *G. ruber* (-0.0022) [*Spero et al.*, 1999]. Alternatively, the decrease in *G. ruber* $\delta^{18}O$ could be a result of an increase in seasonal seawater carbonate ion concentration. If carbonate ion concentration were a controlling factor then one might expect $\delta^{18}O$ to covary with $\delta^{13}C$ [*Spero et al.*, 1997], which our data do not. Unfortunately, there are no measurements of seasonal or annual carbonate ion concentration of Cariaco Basin waters, and we are thus unable to

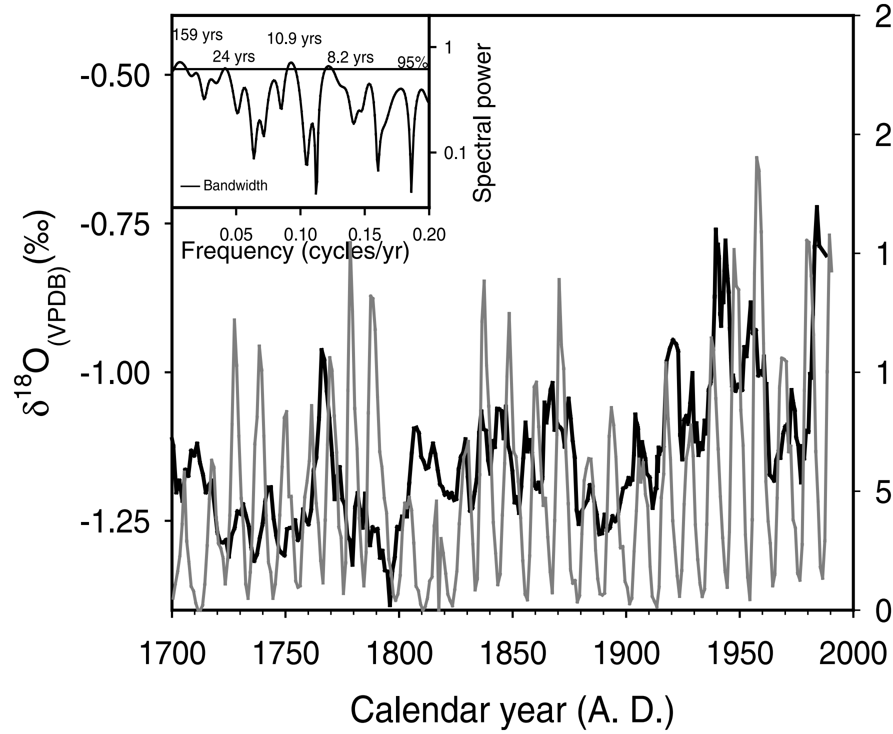

Figure 4. Comparison between *G. bulloides* δ^{18}O (5-point running smooth; black line) and sunspot number (gray line) over the last three centuries. Both records exhibit very similar trends, particularly over multidecadal timescales. The δ^{18}O values are more negative (wetter or warmer conditions) when sunspot numbers are high. Inset shows the cross-spectral analysis between raw *G. bulloides* δ^{18}O and sunspot numbers. Peaks with coherency above the 95% confidence limit occur centered at 159, 24, 10.9, and 8.2 years. Within the bandwidth estimate (.017241) these peaks correspond to the 121-, 22-, and 11-year sunspot cycles.

estimate the potential effects of changing carbonate ion concentration on the long-term isotopic record.

5. Conclusions

[32] High-resolution δ^{18}O records generated from seasonally representative planktic foraminifera represent hydrographic conditions in the Caribbean and tropical North Atlantic over the last 2000 years. δ^{18}O data strongly correlate to tropical SSTs over the period of continuous instrumental overlap, but correlations to an earlier interval when the instrumental record is discontinuous implies that salinity fluctuations may account for a significant portion of the total variability observed over the full record. A long-term trend toward more positive δ^{18}O values in *G. ruber* suggests that the Caribbean and tropical North Atlantic have either cooled and/or become more saline over the last 2000 years. Comparisons to other proxy records of ITCZ and regional evaporation/precipitation variability suggest that upwelling-induced temperature changes and precipitation pattern-related salinity fluctuations control the observed millennial- and submillennial-scale δ^{18}O variability. δ^{18}O fluctuations on decadal to century scales may also be controlled by salinity fluctuations that in turn are at least indirectly influenced by solar variability.

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