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Key Points:
- Last interglacial (LIG) coral Sr/Ca indicates 2.1 ± 0.7 °C cooler than modern tropical Atlantic sea surface temperatures at ~126 ka
- Paired coral Sr/Ca and δ^{18}O records indicate that fresher tropical Atlantic surface waters also occurred at ~126 ka
- Coral Sr/Ca and δ^{18}O records complement lower resolution less precisely dated marine sedimentary records of tropical Atlantic LIG climate

Supporting Information:
- Supporting Information S1

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Tropical Atlantic Cooling and Freshening in the Middle of the Last Interglacial From Coral Proxy Records

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Abstract The last interglacial (LIG; Marine Isotope Substage 5e, ~127–117 ka) experienced globally warmer than modern temperatures; however, profound differences in regional climate occurred that are relevant to the assessment of future climate change scenarios. Tropical Atlantic sea surface temperature (SST) and hydrology are intrinsic to the spatiotemporal evolution of past and future climate. We present eight monthly resolved coral Sr/Ca and δ^{18}O records (130–118 ka) to reconstruct mean western tropical Atlantic SST and seawater δ^{18}O changes during the LIG. Cooler and fresher than modern surface waters are indicated for the middle of the LIG at ~126 ka. This was followed by a rapid transition to modern-like SSTs and salinities that characterized the remaining part of the LIG. Our results, which account for differences found among corals, proxies, and SST calibration uncertainties, agree with western tropical Atlantic sediment records. Together, they suggest that an oceanic regime existed that differed from today.

Plain Language Summary The last interglacial is a period of time that occurred approximately ~127 to 117 thousand years ago and experienced globally warmer than modern temperatures, similar to those predicted by computer simulations of future climate change. However, little is known about the temperature and hydrology of the tropical oceans at this time. We analyzed fossil Caribbean corals that lived between 130 and 118 thousand years ago and record within their structures the properties of the seawater they inhabited. From these we reconstructed snapshots of past mean sea surface temperatures and the changing influences of regional ocean currents. Surprisingly, we found cooler and fresher than modern surface waters occurred within the tropical Atlantic at ~126 thousand years ago, a time usually associated with peak global warming. These anomalous conditions were followed by a rapid transition to modern-like sea surface temperatures and salinities that went on to define the remaining part of the LIG until ~118 ka. Our results agree with other reconstructions of last interglacial climate derived from tropical Atlantic sediment records. Together, they suggest changes in ocean currents that transport waters into the Caribbean and we highlight the complementary use of widely different marine archives to assess past climate change.

1. Introduction

The warmer climate of the last interglacial (LIG; Marine Isotope Substage (MIS) 5e, 127–117 ka) is partially analogous to that expected during future climate change scenarios. Moreover, a greater understanding of past climatic spatiotemporal evolution is required to better contextualize anthropogenic influences upon present and future climate. Recent compilations of sea surface temperatures (SST) have reconstructed a range from ~2 °C warmer than preindustrial (P.I.) to no significant change in global temperatures (CLIMAP project members, 1984; McKay et al., 2011; Otto-Bliesner et al., 2013; Turney & Jones, 2010) during the LIG. These values are comparable to future climate change projections and identify the LIG as a useful analogy of warmer than modern SST requiring further environmental characterization. Importantly, the LIG differed from present due to an orbital configuration that promoted increased seasonality of insolation in the Northern Hemisphere (Berger, 1978) and regional differences, such as pronounced warming in the extratropics (>23.5°N and 23.5°S) (Capron et al., 2014). Although the LIG is not a perfect analog for future climate change, insights can be gained into the feedback mechanisms and drivers that underpin future climate change scenarios at a regional scale (Fischer et al., 2018). For instance, the Atlantic Meridional Overturning Circulation (AMOC) plays an important role in regulating the heat capacity of the oceans and paleoclimate records suggest that it was repeatedly weakened during the LIG

(Tzedakis et al., 2012, 2018). AMOC dynamics are partly governed by the heat and freshwater budget of the Caribbean Sea and tropical Atlantic (Leduc et al., 2007) and so this region is important to the understanding of climate change.

Records of foraminifera $\delta^{18}O$, Mg/Ca, and assemblages, as well as alkenones ($U^{k'}_{37}$) recovered from marine sediment cores, are typically used to explore tropical Atlantic mean SSTs. Foraminifera Mg/Ca-SST and $\delta^{18}O$ records may be used to calculate the $\delta^{18}O$ content of seawater ($\delta^{18}O_{seawater}$), an indicator of past hydroclimate change. Similarly, within the skeletal remains of corals, Sr/Ca can be measured to reconstruct SSTs and, when paired with coral $\delta^{18}O$ measurements, $\delta^{18}O_{seawater}$ values can be isolated (Brocas et al., 2018a; Felis et al., 2004, 2015; McCulloch et al., 1994). LIG sedimentary records reliable explore the broad variability of mean LIG tropical Atlantic climate from single measurements representing centennial to millennial time intervals. However, the age models that underpin these single measurements are reliant on orbital tuning methods. Fossil corals, absolutely dated using ^{230}Th/U techniques with well-constrained uncertainties (Obert et al., 2016), offer independent, short (<100 years) and internally consistent records that portray the response to climatic variability on subseasonal to annual time scales. This allows mean values to be calculated from hundreds to thousands of individual monthly measurements which are easier than marine sediment records to assess for any diagenetic contamination and unidentified seasonal bias. The interpretation of sedimentary records may be limited by assumption of globally synchronous LIG warmth, lower sampling resolution, possible seasonal bias in proxies, temporal averaging in core sampling, choice of proxy calibration, and age uncertainties (Hoffman et al., 2017; Leduc et al., 2010). Whereas, fossil coral reconstructions must consider uncertainties associated with unknown water depth (paleoreef environment), life histories, biological kinetic effects, and uncertainties regarding individual coral proxy sensitive to SST (DeLong et al., 2010; Felis et al., 2004, 2015; Flannery et al., 2017). Such proxy-specific attributes and uncertainties can be complementary, and so we seek commonalities between coral and sedimentary paleoclimate records with the aim of better constraining LIG spatiotemporal temperature and hydrological change. Previously, fossil corals have reconstructed modern-like tropical Atlantic SSTs and $\delta^{18}O_{seawater}$ seasonality during the late (Felis et al., 2015) and early stages of the LIG, while higher than modern seasonalities were found between ~123 and 126 ka (Brocas et al., 2016a, 2018a). These changes coincided concurrently with higher than modern seasonality of insolation and were indicative of Intertropical Convergence Zone (ITCZ) dynamics at that time. We further aim to decipher whether the tropical Atlantic mean conditions were altered in response.

2. Materials and Methods

2.1. Coral Material and Proxies

Eight fossil *Diploria strigosa* colonies were recovered from the southern Caribbean island of Bonaire (Caribbean Netherlands; 12°10′N, 68°18′W) and dated using ^{230}Th/U techniques to between 117.7 and 129.7 ka (Table S1 in the supporting information; (Felis et al., 2015; Obert et al., 2016)). These coral colonies were potentially transported by wave activity until they finally became a cemented part of the reef; however, *D. strigosa* corals are common in the upper 10 m of the reef environment at Bonaire today (Obert et al., 2016). Full site and coral details are described by Felis et al. (2015) and Brocas et al. (2016a). Consistent with well-established methodologies and techniques (Felis et al., 2009; Giry et al., 2010 , 2013), coral colonies were sectioned parallel to growth, analyzed for diagenesis (X-ray images, petrographic thin sections, powder XRD) (Brocas et al., 2016a) and microsampled for paired Sr/Ca geochemistry and $\delta^{18}O$ isotopic analysis. The dense thecal skeletal element of *D. strigosa* was targeted for microsampling because it has previously been demonstrated to reliably yield monthly resolved records of sea surface properties for the middle to late Holocene (Giry et al., 2012 , 2013; Hetzinger et al., 2006) and LIG (Brocas et al., 2016a , 2018a; Felis et al., 2015). The monthly interpolated coral Sr/Ca records are available from Brocas et al. (Brocas et al., 2016b), while the $\delta^{18}O$ and $\delta^{18}O_{seawater}$ records were obtained from Brocas et al. (2018b). Mean Sr/Ca, $\delta^{18}O$, and $\delta^{18}O_{seawater}$ values for our LIG corals were calculated by averaging the monthly values for each year (January to December), and then averaging these annual mean values for the entire record of a given coral. The coral reference material JCp-1 (Hathorne et al., 2013) was analyzed with the modern, Holocene, and last interglacial Bonaire corals at MARUM (University of Bremen) (Brocas et al., 2016a; Felis et al., 2015; Giry et al., 2012), and the average Sr/Ca values reported in these studies agree within their uncertainty and so no further adjustments were performed.

Coral Sr/Ca is an established proxy for SST, in particular at Bonaire and on seasonal time scales (Brocas et al., 2016a; Felis et al., 2015; Giry et al., 2012). However, in the absence of a conclusive mean Sr/Ca-SST calibration for tropical Atlantic *D. strigosa* corals from which to infer LIG mean temperature changes, we used the annual mean Sr/Ca-SST relationships of −0.066 (Hetzinger et al., 2006) and −0.140 (Felis et al., 2009, 2018) mmol/mol per °C. These reflect the upper and lower values within the range of previously established calibration slopes. The annual mean Sr/Ca-SST relationship of −0.066 mmol/mol per °C derives from the same study (Hetzinger et al., 2006) as the well-established −0.042 mmol/mol per °C commonly used for seasonal SST reconstructions from *D. strigosa* (Brocas et al., 2016a; Giry et al., 2012; von Reumont et al., 2016; Xu et al., 2015). The annual mean Sr/Ca-SST relationship of −0.140 mmol/mol per °C (Felis et al., 2009 , 2018) derives from a calibration of the more commonly studied *Porites* spp., and has been previously used to infer mean SST changes on interannual (Felis et al., 2009 , 2018) and glacial-interglacial time scales from *Isopora* spp. (Felis et al., 2014). Coral $\delta^{18}O$ values reflect SST and the $\delta^{18}O$ of seawater, allowing coral $\delta^{18}O_{seawater}$ to be calculated by subtracting the coral Sr/Ca-SST component from the coral $\delta^{18}O$ signal (Cahyarini et al., 2008). Consequently, we also applied the corresponding annual coral $\delta^{18}O$-SST relationships of −0.196‰ per °C (Hetzinger et al., 2006) and −0.213‰ per °C (Felis et al., 2009 , 2018).

2.2. Coral Proxy Error Estimation and Uncertainties

We calculated a "full error" (f.e.) in order to address potential sources of uncertainty surrounding individual mean fossil coral Sr/Ca-SST, $\delta^{18}O$, and $\delta^{18}O_{seawater}$ values at Bonaire (described within Text S1 in the supporting information). The f.e. for each coral mean proxy value (Sr/Ca, $\delta^{18}O$, and $\delta^{18}O_{seawater}$) was calculated using the standard deviation, the standard error of the mean, and the propagation methods outlined by Mudelsee (2014). The mean values of three modern corals (Giry et al., 2012) were used to calculate a weighted mean with its internal and external errors representing between-colony variability. The internal error was derived from the standard errors of the means of the relevant records, while the external error, which may hint at systematic interrecord variations, was given by the standard deviation over the relevant records (Mudelsee et al., 2014). To avoid making overstatements from too small uncertainties, we took a conservative approach that used the maximum of either the internal or external error to calculate the f.e. (Bevington & Robinson, 1992). Thus, the f.e. (°C) is given via Gaussian error propagation as

$$\text{f.e.} = x \times \text{SQRT}\left((\sigma a \div; a)^2 + (\sigma b \div; b)^2\right)$$

Whereby, x = proxy value calibrated to SST (e.g., $x = a \times b$).

a = The the reported proxy to SST calibration slope (given as ΔSST/Δproxy).

σa = The reported proxy to SST calibration error.

b = The proxy value minus the three modern coral weighted mean.

σb = The maximum internal or external error of b for the three modern coral weighted mean.

The significance of coral mean proxy values was determined by assessing its f.e. relative to the ±1 maximum error (internal or external) of the weighted mean. Coral mean Sr/Ca-SST, δ18O, and $\delta^{18}O_{seawater}$ anomalies were calculated from modern by subtracting the weighted mean of three modern Bonaire *D. strigosa* colonies.

2.3. Comparing LIG Coral Sr/Ca and $\delta^{18}O_{seawater}$ to Sedimentary Records

We compiled tropical Atlantic (0–35°N, 100–30°W) LIG SST reconstructions that derive from sedimentary foraminiferal assemblage transfer functions and Mg/Ca-SST as well as sedimentary $U^{k'}{}_{37}$ records. LIG SST anomalies (sedimentary ΔSST) have been previously compiled by Turney and Jones (2010), McKay et al. (2011), and Hoffman et al. (2017) and defined using different methodologies that best addressed specific research questions and uncertainties (Figure S1 in the supporting information). Our study defined sedimentary ΔSST by subtracting the most recent from the nearest reconstructed SST to 125.8 ka within sedimentary records. Similarly, foraminiferal assemblage-derived ΔSST resulted from subtracting the core top values from the peak SST of a 3-point running average over the MIS 5e interval, as per CLIMAP Project Members (1984). The annual foraminiferal assemblage SST records of the CLIMAP Project Members

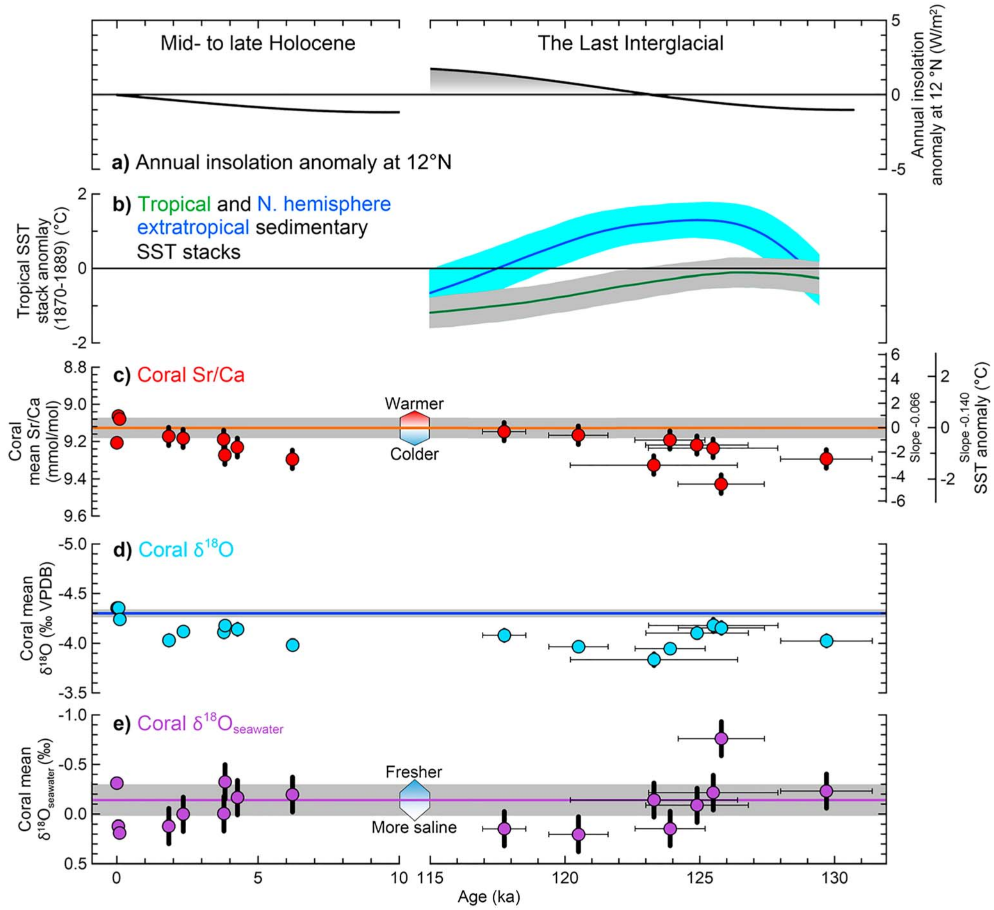

Figure 1. Reconstructions of tropical Atlantic mean climate during the middle to late Holocene and last interglacial (LIG). (a) Mean annual insolation anomaly from present at Bonaire (12°N) (Berger, 1978). (b) LIG tropical (23.5°N–23.5°S) and extratropical northern hemisphere (>23.5°N) (green and blue, respectively) sedimentary sea surface temperature (SST) stack, anomaly from the 1870–1889 average (Hoffman et al., 2017) with ±2 standard deviation (grey and blue shading, respectively). Mean coral (c) Sr/Ca, (d) δ^{18}O, and (e) $\delta^{18}O_{seawater}$ for modern, middle to late Holocene (Giry et al., 2012), late LIG (Felis et al., 2015), and LIG (this study). (c) Mean coral Sr/Ca-SST anomaly calculated using the annual mean Sr/Ca-SST relationships of −0.066 (Hetzinger et al., 2006) and −0.140 (Felis et al., 2009 , 2018) mmol/mol per °C. (e) Mean coral $\delta^{18}O_{seawater}$ calculated using the Hetzinger et al.'s (2006) Sr/Ca-SST and corresponding coral δ^{18}O-SST relationship of −0.196‰ per °C (Hetzinger et al., 2006). The horizontal colored lines illustrate each coral proxies respective three modern coral weighted mean with the maximum of its ±1 internal or external error shaded. Vertical and horizontal error bars illustrate, respectively, the ±1 full error (f.e.) and ^{230}Th/U-age uncertainty (±2σ level; (Obert et al., 2016)). Modern and middle to late Holocene ages and coral δ^{18}O f.e. are smaller than symbol size.

(1984) often derive from the averaged LIG summer and winter records (unless specified the boreal season is always referred to) and requires a correction for possible seasonal bias (Hoffman et al., 2017), which we performed (Text S1 in the supporting information).

3. Results and Discussion

3.1. LIG Coral Sr/Ca-SST Anomalies

During the early LIG, one coral dated to 129.7 ka indicates significantly (±f.e.) higher mean Sr/Ca than the three modern coral weighted mean and thus cooler SSTs (Figure 1c). This may reflect a prolonged influence upon the tropics of the prior termination II deglacial event. Two of five corals, dated to between 123 and 126 ka, and termed mid-LIG, also reconstruct significantly higher than modern Sr/Ca. The highest of these, at ~126 ka, reveals significantly cooler than modern coral Sr/Ca-SST of between 4.6 ± 1.7 and 2.1 ± 0.7 °C when using the published annual mean Sr/Ca-SST calibration slopes of Hetzinger et al. (Hetzinger et al., 2006) and Felis et al. (Felis et al., 2009; Felis et al., 2018), respectively. However, a mid-LIG cooling of 4.6 ± 1.7 °C, as determined by using the Sr/Ca-SST calibration of Hetzinger et al. (Hetzinger et al., 2006), is improbable due to its similarity with tropical Atlantic cooling estimates for the Last Glacial Maximum. This ranged from 2.5 (Schmidt & Spero, 2011) to 4.8 °C (Ziegler et al., 2008). Consequently, we favor the calibration of Felis et al. (2009, 2018), which has previously been applied to reconstruct SST changes on glacial-interglacial time scales, indicating a mid-LIG cooling of 2.1 ± 0.7 °C.

Importantly, our finding of 2.1 ± 0.7 °C mid-LIG cooling remains significant regardless of the specific coral Sr/Ca-SST calibration used or when the combined error estimation of Abram et al. (2009) is considered (Figure S2a in the supporting information). This is also plausible within the thermal tolerance of *D. strigosa* corals if the modern mean annual SST at Bonaire (ERSSTv3b, 1910–2000 (Smith et al., 2008)) and the Sr/Ca-SST seasonality for the mid-LIG (Brocas et al., 2016a) are considered. Therefore, this coral likely inhabited waters between 23 and 28 °C, a range similar to that for optimal survival today, which is 25–29 °C (Fricke & Meischner, 1985), and higher than the lowest adaptable thermal tolerance of 18 °C (Stoddart, 1969). These corals grew at ~0.7 cm/year, a typical rate for LIG *D. strigosa* (Brocas et al., 2016a), and no systematic influence of mean annual growth rates upon Sr/Ca or $\delta^{18}O$ was found (Figure S2e in the supporting information). In addition, 2.1 ± 0.7 °C cooler than modern mid-LIG SSTs are consistent with another independent characterization of LIG tropical SSTs that derived from coral occurrence-based distribution modeling (Lauchstedt et al., 2017). Taken together, these studies suggest cooling of tropical, and warming of subtropical, oceans during the mid-LIG.

The mid-LIG was a time interval when atmospheric greenhouse gas concentrations were similar to P.I. (Langebroek & Nisancioglu, 2014) and tropical annual insolation was marginally lower than today (Figure 1a) (Berger, 1978). While mid-LIG seasonality of insolation was higher than modern and has been linked to increased seasonality of coral Sr/Ca-SST at Bonaire (2016a), it is unlikely that annual insolation was directly responsible for our observed cooling. This implies a regional oceanic influence on mean SSTs at that time. In regards to the spatiotemporal evolution of LIG tropical Atlantic SSTs, the mid-LIG cooling was followed by an abrupt warming to modern-like SSTs within ~2 ka. While not as abrupt or significant, a similar trend to warmer SSTs is also seen from the middle to late Holocene (Giry et al., 2012). When all eight LIG corals were taken as a single weighted mean, we found that the LIG was 1.8 ± 1.0 °C (Hetzinger et al., 2006) or 0.8 ± 0.4 °C (Felis et al., 2009, 2018) significantly cooler than the three modern coral weighted mean. No indications of warmer than modern SSTs typically associated with the LIG were found.

3.2. LIG Tropical Atlantic Sedimentary and Model-Derived SST Anomalies

Our reconstructed 2.1 ± 0.7 °C tropical Atlantic SST cooling at ~126 ka derives from over 170 measurements (10 years at monthly interpolated resolution; Table S1 in the supporting information) of coral Sr/Ca, and broadly agrees with foraminiferal assemblage transfer function-derived tropical Atlantic ΔSST (Figures 2, S1, and S3). Such transfer function records are potentially influenced by surface water calibration cold biases resulting from the assumption of comparable thermal structure between P.I. and the Last Glacial Maximum (Telford et al., 2013). This assumption remains valid while no indication of altered subsurface-surface thermal relationships during the LIG is known. Marine sedimentary records typically lack an absolutely dated chronology for the LIG, inhibiting further spatiotemporal interpretations of SSTs. Furthermore, ΔSST reconstructed by sedimentary $U^{k'}_{37}$ and foraminiferal Mg/Ca can be 0.5 to 1.5 °C warmer than foraminiferal assemblage reconstructions. The Colombian Basin Mg/Ca record (Schmidt et al., 2004) reconstructs SSTs at low temporal resolution and may well reflect a summer SST bias (Figure S4, record no. 6) (Schmidt & Spero, 2011). Similarly, the Cariaco Basin $U^{k'}_{37}$ record reflects a tendency toward warmer spring-summer SSTs as a result of higher unsaturation ratios within this upwelling influenced site (Herbert & Schuffert, 2000) (Figure S4 in the supporting information; record no. 6). Although both records are excluded from the global sedimentary ΔSST compilations of Turney and Jones (2010) and Hoffman et al. (Hoffman et al., 2017), we include them here for regional completeness. Gulf of Mexico foraminiferal assemblage (CLIMAP project members, 1984) and Mg/Ca-derived (Ziegler et al., 2008) ΔSST reconstructions indicate a 1.4 °C cooling and 1.9 °C warming, respectively. This discrepancy has been attributed to foraminiferal Mg/Ca-SST sensitivity toward an expanded Atlantic Warm Pool and a strengthened Loop Current during summer, which drew in relatively warm Caribbean waters at that time (Nürnberg et al., 2008; Ziegler et al., 2008). The mean annual nature of *G. ruber*-derived Mg/Ca-SST has recently been supported (Richey et al., 2019) and, age uncertainties considered, this record indicates cooler SST during the early LIG consistent with our findings.

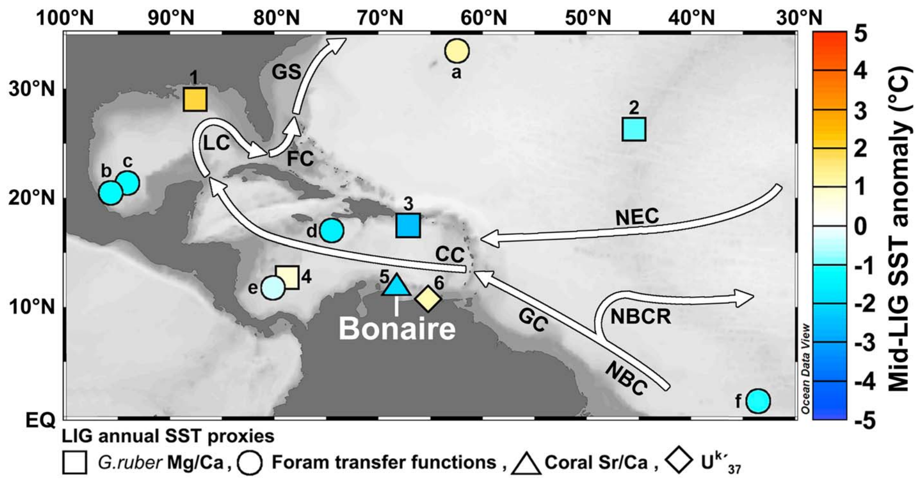

Figure 2. Tropical Atlantic mid-LIG SST anomalies from sedimentary records and Bonaire coral Sr/Ca mean SST anomaly at ~126 ka (triangle, 5) using the Felis et al.'s (2009 ,2018) SST calibration. Sedimentary proxy records derive from foraminiferal assemblage transfer functions (lettered circles a–f: CLIMAP Project Members (CLIMAP project members, 1984)), foraminiferal Mg/Ca-SST (numbered squares: 1 (Ziegler et al., 2008), 2 (Imbrie et al., 1989), 3 (Hüls & Zahn, 2000), and 4 (Schmidt et al., 2004)), and sedimentary U$^{k'}_{37}$ (diamond 6: Herbert and Schuffert (2000)). Dominant ocean currents, the Gulf Stream (GS), Florida Current (FC), Loop Current (LC), Caribbean Current (CC), Guiana Current (GC), North Equatorial Current (NEC), North Brazil Current (NBC), and its July to December retroflection (NBCR), are illustrated. Map generated with Ocean Data View (Schlitzer, 2015).

Despite the different methodologies used, our compilation of tropical Atlantic sedimentary ΔSST agrees with those of other authors (Figures 2 and S1). The global tropics SST stack of Hoffman et al. (2017) (Figure 1b) would report even cooler mid-LIG ΔSST if referenced to modern times and not to P.I. Modern and late-Holocene winter (March-April-May) tropical Atlantic SSTs are closely related to the strength of the easterly Caribbean low-level jet that drives oceanic waters into the Caribbean (Wang, 2007; Wurtzel et al., 2013). Consequently, cooler than modern mid-LIG SSTs might reflect increased ocean advection of cooler equatorial Atlantic surface waters (Figure 2, record f) into the Caribbean Sea due to a reorganization of oceanic currents. This may be related to the warmer temperatures that induced stronger, more variable, Greenland ice sheet melt previously documented within the Northern Hemisphere and its effect on AMOC strength (Capron et al., 2014; Sánchez Goñi et al., 2012). Indeed, despite age uncertainties, our finding is contemporaneous with the north Atlantic cold, "red layer," event C27 (Nicholl et al., 2012; Tzedakis et al., 2018) associated with meltwater outbursts and suggests a broader influence of LIG climate instabilities.

3.3. LIG Tropical Atlantic Hydrological Change

The differences between our paired mean coral Sr/Ca-SST (Figure 1c) and coral $\delta^{18}O$ (Figure 1d) estimates highlight the influence of $\delta^{18}O_{seawater}$ as a proxy for LIG hydrological changes at the sea surface. Regardless of the specific coral proxy to SST relationships used (Figure S2 in the supporting information), reconstructed coral $\delta^{18}O_{seawater}$ indicates significantly fresher than modern surface waters at 125.8 ka, and a tendency toward more saline waters toward the late LIG (Figure 1e). This tendency is similar to that observed during the middle to late Holocene (Giry et al., 2013). However, fresher than modern surface waters at 125.8 ka were not accompanied by seasonal indicators of hydroclimate such as the increased coral $\delta^{18}O_{seawater}$ seasonality (Figure 3c) and a two-month lead of coral $\delta^{18}O$ versus Sr/Ca (Figure 3d) found at 123.9 ka by Brocas et al. (2018a). Such a phase difference between paired proxy measurements that share a SST component and internal age model led to the conclusion that the annual cycle of surface waters peaked two months earlier than modern, occurring in July/August and December/January, respectively. Furthermore, this coincided with higher than modern simulated tropical Atlantic precipitation (Brocas et al., 2018a; Nikolova et al., 2013; Pedersen et al., 2016) implying that at 123.9-ka precipitation dictated the hydrological regime in contrast to the modern oceanic dominated regime.

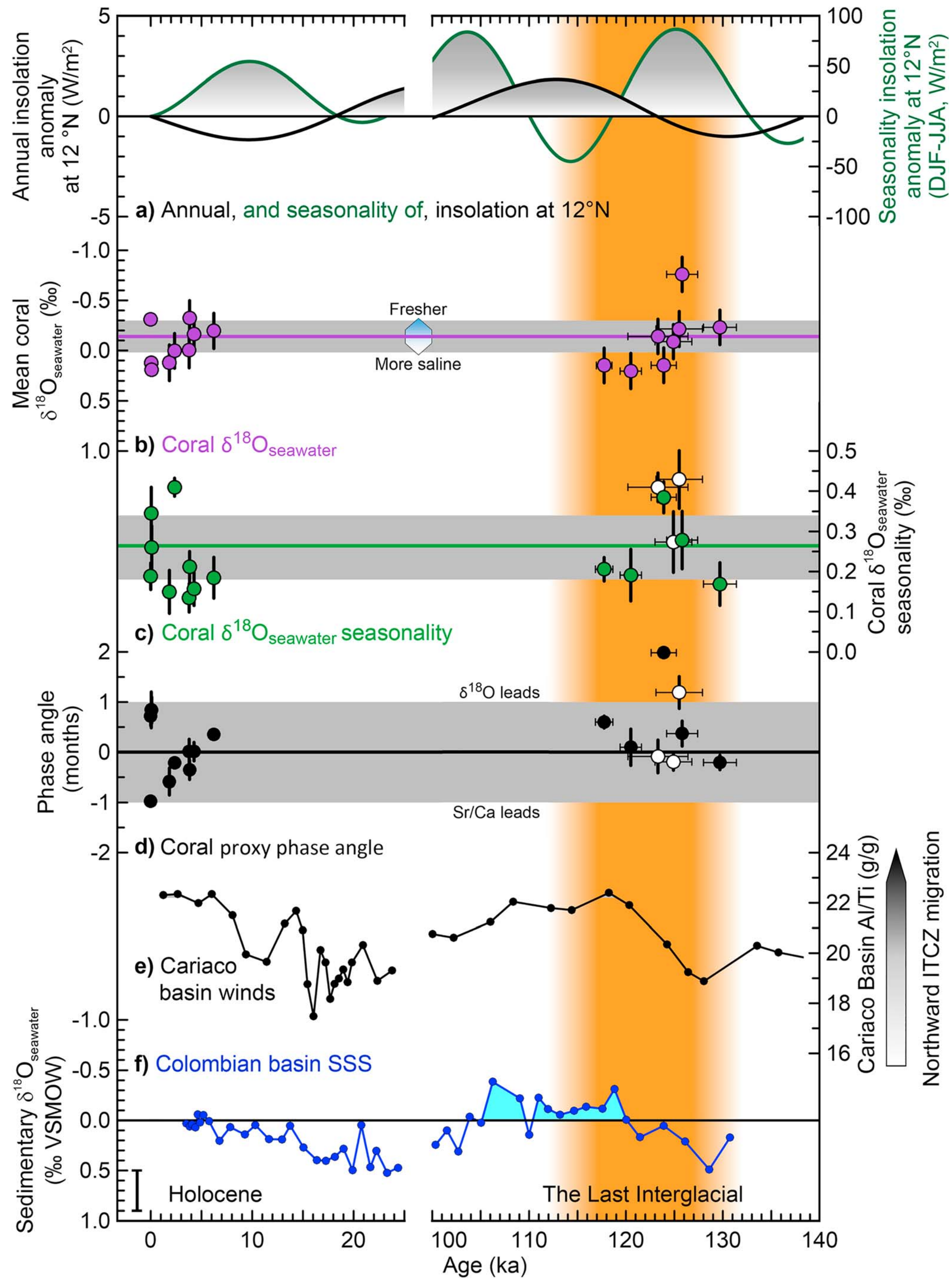

Figure 3. Last interglacial (LIG; this study), late LIG (Felis et al., 2012), and middle to late Holocene (Giry et al., 2013) coral $\delta^{18}O_{seawater}$ and sedimentary evidence for tropical Atlantic hydroclimate perturbations. (a) Annual (black) and seasonality of (green, JJA minus DJF) insolation at 12°N, positive anomalies from present are shaded (Berger, 1978). (b) Bonaire coral mean $\delta^{18}O_{seawater}$ calculated using the Sr/Ca- and δ^{18}O-SST annual relationship of −0.066 mmol/mol per °C and −0.196‰ per °C, respectively (Hetzinger et al., 2006). Purple horizontal line is the weighted three modern coral mean with its ±1 external error shaded. Vertical error bar denote ±1 full error. (c) Bonaire coral $\delta^{18}O_{seawater}$ climatology seasonality (Brocas et al., 2018a) calculated using the Sr/Ca- and δ^{18}O-SST seasonal relationship of −0.042 mmol/mol per °C and −0.196‰ per °C, respectively (Hetzinger et al., 2006). Black horizontal line is the three modern coral average with its ±1 standard deviation shaded. Vertical error bar denote ±1 standard error. (d) Bonaire coral phase angle relationship between paired Sr/Ca and δ^{18}O records (Brocas et al., 2018a). Black vertical lines are 95% confidence intervals. Shading indicates ±1-month potential interpolation uncertainties. (b–d) Unrepresentative records of less than 10 years are indicated by white circles. Horizontal error bars indicate ^{230}Th/U-age uncertainty at 2σ level (Obert et al., 2016). Modern and middle to late Holocene ages are smaller than symbol size. (e) Increased Cariaco Basin sedimentary Al/Ti ratios indicate increased eolian transported dust due to a more northerly displaced ITCZ. (f) Sedimentary record of $\delta^{18}O_{seawater}$ from ODP site 999A (12°N, 78°W; Colombian basin; (Schmidt et al., 2004)). Fresher than mid-Holocene values are shaded light blue. Black bracket (bottom left) signifies the ±1σ propagated error for this record.

Such hydroclimate perturbations were interpreted as an intensification and expansion of the summer ITCZ into the southern Caribbean Sea in response to an increased seasonality of insolation at that time (Figure 3a) (Brocas et al., 2018a). Interestingly, this did not result in freshening of mean surface water conditions at 123.9 ka. Without such hydroclimate indicators, the freshening of mean conditions at 125.8 ka was not due to summer ITCZ expansion but oceanic advection. We note that surface water freshening in the Colombian basin is demonstrated by a sedimentary record for the late LIG (Figure 3e) (Schmidt & Spero, 2011) and interpreted as a response to increased ITCZ-induced summer precipitation. Recent reevaluations of Colombian Basin foraminiferal Mg/Ca-SST have explored further the different calibrations and uncertainties associated with the influence of salinity on the carbonate system (Richey et al., 2019; Thirumalai et al., 2016 , 2018). Thirumalai et al. (2016) utilized a higher resolution sea level curve and considered salinity effects to highlight the apparent early and mid-LIG warmth and late LIG freshening, relative to modern. Our interpretation is consistent with these authors who further revealed that large regional difference existed within the Caribbean Sea due to differing sensitivities to AMOC changes.

Fresher and cooler mean surface waters in the southern Caribbean Sea at 125.8 ka could be an indication of enhanced tropical Atlantic oceanic advection during the mid-LIG. We speculate that a reorganization of AMOC drove relatively fresh and cool equatorial Atlantic surface waters into the Caribbean Sea at that time. ITCZ and AMOC dynamics are closely coupled, such that a strengthened AMOC evidences increased interhemispheric extratropical temperature gradients that are conducive to the northward expansion/migration of the ITCZ (Schneider et al., 2014). The transition from 125.8 ka toward warmer and more saline mean conditions at 123.9 ka is consistent with a progressive expansion of the ITCZ into the southern Caribbean during that period. At northward expanding ITCZ likely suppressed the easterly trade winds that promote surface heat loss, vertical mixing, and the advection of cooler and fresher oceanic waters into the Caribbean Sea. This scenario agrees with the reconstruction of increased sedimentary Al/Ti within the Cariaco Basin, indicative of reduced eolian material and changed wind fields during a northerly migration of the ITCZ at that time (Figure 3d) (Yarincik et al., 2000). Additionally, this transition to warmer and fresher surface waters may have been influenced by the gradual intensification of the summer NBCR between 125 and 115 ka that diverted cooler and fresher oceanic and Amazon waters away from the Caribbean Sea (Govin et al., 2015). While our coral findings are observable year on year within their respective records, it is also plausible that the described climatic shifts may be in part attributed to changes in the behavior of regional multidecadal phenomena. Unfortunately, the length of our records prohibits exploring this further. Our coral $\delta^{18}O_{seawater}$ reconstructions reduce the paucity of records that reconstruct the spatiotemporal evolution of tropical Atlantic hydrology and hydroclimate at the sea surface during the LIG.

4. Conclusions

Our southern Caribbean coral Sr/Ca and $\delta^{18}O$ records indicate 2.1 ± 0.7 °C cooler and fresher than modern mean tropical Atlantic sea surface conditions at ~126 ka. This result is consistent with SST reconstructions from foraminiferal transfer functions, indicating regional commonalities despite proxy specific uncertainties. Together, these reconstructions indicate cooler than modern tropical Atlantic SSTs during the middle of the LIG, a period that was characterized by warmer North Atlantic SSTs. We suggest that this resulted from increased oceanic advection of equatorial Atlantic surface waters, possibly related to a reorganization of AMOC at that time. The cooler and fresher than modern surface water conditions in the southern Caribbean Sea at ~126 ka were followed by a rapid transition to modern-like SSTs and more saline conditions at ~125 ka that more or less characterized the remaining part of the LIG until 118 ka. Our coral results also suggest that a progressive expansion of the summer ITCZ into the southern Caribbean Sea occurred later in the LIG, at ~124 ka, probably dampening trade winds and oceanic advection. We conclude that mean SST and $\delta^{18}O_{seawater}$ reconstructions derived from monthly resolved coral Sr/Ca and $\delta^{18}O$ records are a beneficial independent source of evidence for the spatiotemporal evolution of tropical Atlantic climate during past warmer periods, such as the LIG.

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Erratum

In the originally published version of this article, there were errors in Figure 1b and its legend. These errors have since been corrected, and the present version may be considered the authoritative version of record.

(Geophysical Research Letters)

Supporting Information for

Tropical Atlantic cooling and freshening in the middle of the last interglacial from coral proxy records

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Contents of this file

Introduction

This supporting information contains text describing potential uncertainties associated with coral proxy reconstructions at Bonaire. A table is provided detailing ^{230}Th/U ages and the number of monthly resolved years that comprise each Bonaire mean coral Sr/Ca and δ^{18}O value. Additional figures pertinent to the study of last interglacial (LIG) sea surface temperatures (SST) using fossil coral material from the island of southern Caribbean island of Bonaire are provided. Mean coral Sr/Ca, δ^{18}O, δ^{18}Oseawater and growth rates are presented to illustrate that no temperature dependent growth relationship exists within our proxy records. All other data was obtained from their specific reference and treated accordingly. We compare our assessment of mid- last interglacial coral Sr/Ca-SST anomalies from modern to compilations of tropical Atlantic sedimentary records. In doing so we illustrate all LIG tropical Atlantic SST records to highlight the context in which our coral Sr/Ca and δ^{18}O records are significant to the interpretation of LIG SSTs.

Text S1

Due to Bonaire's geographical setting, corals from this island are considered a good source of open ocean environmental reconstructions (Giry et al., 2012; Brocas et al., 2016a, 2018a), however uncertainties exist associated with LIG fossil material. Absolute ^{230}Th/U dating of these corals includes inherent age uncertainties between 0.8 and 3.1 ka (±2σ) (Obert et al., 2016; Brocas et al., 2016a) and their coral proxy mean values derive of records of between three and 37 years. Therefore, our major findings describe records containing ≥10 years and are termed according to shared ^{230}Th/U ages and overlapping errors (supporting information table S1). Coral colonies retrieved from Bonaire's lower reef terrace were potentially transported by wave activity until they finally became a cemented part of the reef, preventing a precise determination of the absolute water depth these LIG corals inhabited (Obert et al., 2016). Moreover, our corals were recovered between 20 and 90 m inland, from terraces that were uplifted 1.5 to 5.5 m, at a rate 0.02 to 0.08 meters per 1000 years (Engel et al., 2012) and during a time when maximum global mean relative sea level (RSL) are widely cited to have been 6.6 to 9.0 m above present sea level (Kopp et al., 2009). Taken together, we approximate that our corals inhabited a reef crest between 5 and 15 m of the sea surface, a similar habitat range to modern *D.strigosa* at Bonaire. Previous studies (Kilbourne et al., 2004; Asami et al., 2013; Felis et al., 2012, 2014) corrected for the influence of RSL changes on the Sr and δ^{18}O content of seawater over glacial/interglacial time scales (Stoll et al., 1999, Waelbroeck et al., 2002). However, assumed changes in seawater Sr/Ca during glacial sea level lowstands have large uncertainties, but are of minor relevance for the interpretation of fossil corals from interglacial highstands (Stoll et al., 1999; Asami et al., 2009; Felis et al., 2012, 2014). A potential influence on local seawater properties are the centers of seasonal (December to May) upwelling found in the vicinity of the Gulf of Venezuela and the Cariaco Basin, ~300 km to the south- west and east of the island, respectively. Due to an eastward flowing undercurrent immediately to the south of Bonaire (Andrade et al., 2003), upwelling of cold and more saline water filaments is inhibited and does not influence Bonaire on timescales greater than a week (Bak et al., 2005). Furthermore, both the carbonate platform and the freshwater input, via relief rainfall, at Bonaire is insufficiently large to significantly alter local Sr composition of seawater (Swart et al., 2002).

Importantly, three modern corals successfully reconstructed local instrumental SST seasonality (Giry et al., 2012), providing confidence that they also represent typical between colony offsets associated with the above described uncertainties, time intervals, biological kinetic effects, and uncertainties regarding individual coral proxy sensitive to SST (Felis et al., 2004, 2015; DeLong et al., 2010; Flannery et al., 2017). These between-colony offsets among modern corals of the same reef have complicated the reconstruction of mean SST from fossil corals of the Holocene (Felis et al., 2003, Abram et al., 2009; Giry et al., 2012) and the last glacial-interglacial cycle (Felis et al., 2004; 2012, 2014). We therefore utilizes an approach to error estimation that incorporates between colony offsets at Bonaire and uncertainties associated with the calibration of mean coral Sr/Ca to SST. Our corals geochemical and isotopic measurements exhibited no growth dependent relationship which might manifest itself as a season bias in our data. Each annual cycle of data was screened to ensure that it was a) comprised of at least 11-12 measurements so that monthly interpolation was representative and b) exhibited complete sinusoidal curves with raw data points not clustered around a specific season. The annual foraminifera assemblage SST records of the CLIMAP Project Members (1984) often derive from the averaged LIG summer and winter records. This, results in a seasonal bias, which we corrected for by subtracting from the sedimentary ΔSST the difference between a) the average of June-July-August (JJA) and December-January-February (DFJ) SST and b) the annual average SST, using a 1 x 1° grid of Extended Reconstructed Sea Surface Temperature version 3b (ERSSTv3b) dataset for 1910-2000 (Smith et al., 2008). This correction was consistent with that applied by ΔSST by Hoffman et al. (2017), but wasn't necessary for tropical Atlantic foraminiferal Mg/Ca-SST records (Richey et al., 2019). Comparison to ERSSTv3b maintains consistency with the instrumental datasets previously used to evaluate Bonaire coral SST reconstructions (Giry et al., 2016; Brocas et al., 2016) and minor differences were found between other instrumental data products.

Table S1

Terms used	Coral I.D.	Record length (years)	Mean samples per year	^{230}Th/U age (ka)	^{230}Th/U age error (ka) (±2σ)	Coral Sr/Ca Mean (mmol/mol)	Coral Sr/Ca Full error (mmol/mol)	Coral δ^{18}O Mean (‰VPDB)	Coral δ^{18}O Full error (‰VPDB)
Modern	BON-0-A	15	14	0.00	0.00	9.208	N/A	-4.35	N/A
	BON-9-B	13	15	0.06	0.05	9.063	N/A	-4.35	N/A
	BON-9-A	30	12	0.10	0.08	9.079	N/A	-4.24	N/A
Mid- to late Holocene	BON-20-A	7	15	1.84	0.02	9.173	0.049	-4.03	0.047
	BON-6-A	68	11	2.35	0.05	9.183	0.049	-4.12	0.040
	BON-7-A	39	11	3.79	0.03	9.188	0.049	-4.11	0.040
	BON-7-B	33	13	3.83	0.03	9.273	0.049	-4.18	0.043
	BON-4-G	23	11	4.27	0.03	9.232	0.050	-4.14	0.051
	BON-3-E	67	11	6.22	0.05	9.295	0.049	-3.98	0.044
Late LIG	BON-5-D	20	11	117.7	0.8	9.147	0.049	-4.08	0.050
	BON-5-A	14	15	120.5	1.1	9.147	0.050	-3.97	0.044
N/A	BON-28-A	6	17	123.3	3.1	9.326	0.049	-3.84	0.059
Mid- LIG	BON-12-A	37	13	123.9	1.3	9.192	0.049	-3.95	0.043
	BON-26-A	3	13	124.9	1.9	9.219	0.049	-4.10	0.038
	BON-24-AII.2	5	14	125.5	2.4	9.236	0.049	-4.18	0.062
	BON-13-AI.1	10	16	125.8	1.6	9.428	0.050	-4.15	0.054
Early LIG	BON-33-BI	10	13	129.7	1.7	9.293	0.049	-4.02	0.050

Table S1

Details of the Bonaire corals measured for Sr/Ca and δ^{18}O and their full error (±1σ) at during the last interglacial (LIG) (this study), late LIG (Felis et al., 2015), the mid- to late Holocene and modern times (Giry et al., 2012). Terms used to group corals were assigned based on ^{230}Th/U age and weighted errors (Obert et al., 2016; Brocas et al., 2016a). BON-28-A was not grouped due to its large overlapping age error. All original monthly resolved coral Sr/Ca data (https://doi.org/10.1594/PANGAEA.862148) and coral δ^{18}O and δ^{18}Oseawater data (https://doi.org/10.1594/PANGAEA.877852) are available from PANGAEA.

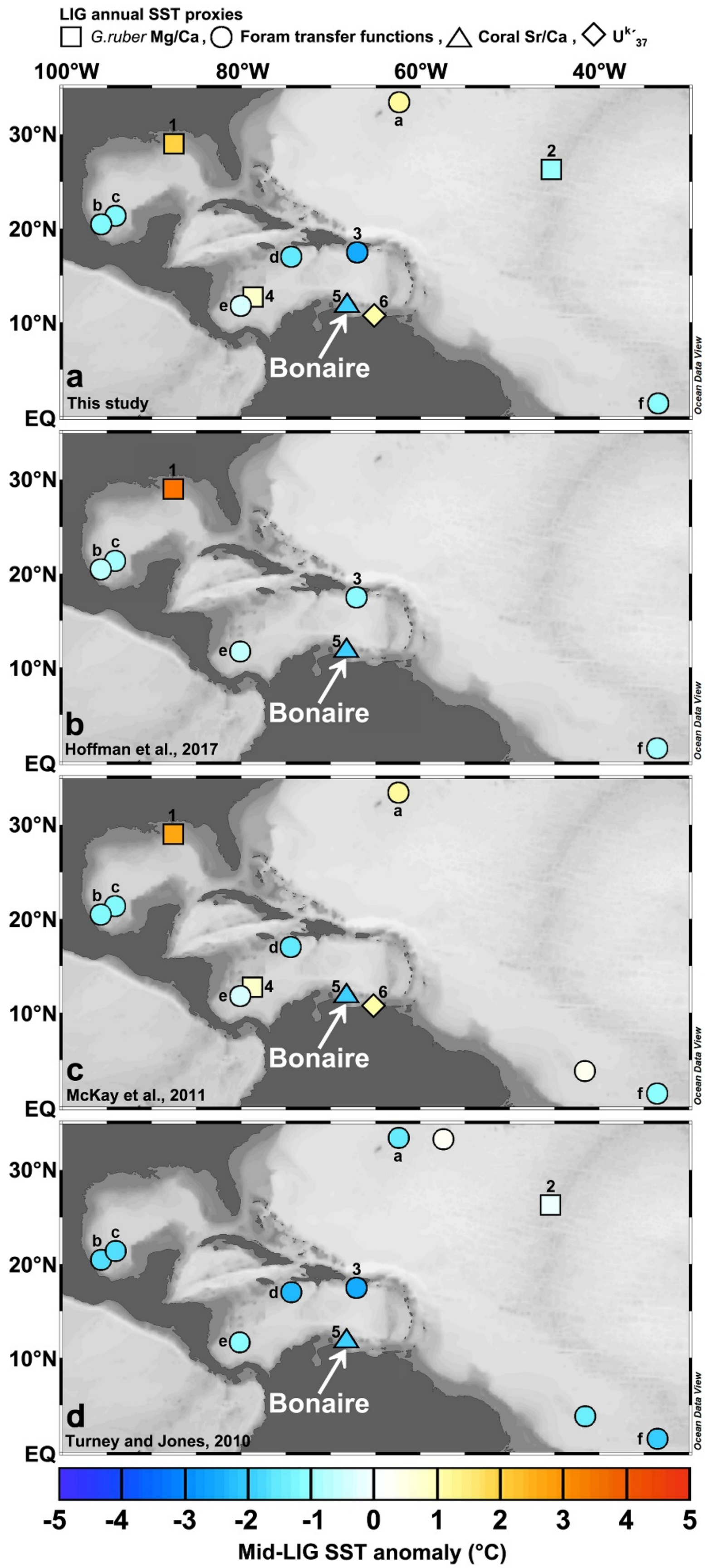

LIG annual SST proxies
G.ruber Mg/Ca , Foram transfer functions , Coral Sr/Ca , $U^{k'}_{37}$
100°W
80°W
60°W
40°W
30°N
20°N
10°N
EQ
Bonaire
a
This study
b
Hoffman et al., 2017
c
McKay et al., 2011
d
Turney and Jones, 2010
Ocean Data View
-5
-4
-3
-2
-1
0
1
2
3
4
5
Mid-LIG SST anomaly (°C)

Figure S1. Tropical Atlantic last interglacial (LIG) SST anomalies (ΔSST) complied for a) this study, b) Hoffman et al. (2017), c) McKay et al. (2011) and d) Turney and Jones, (2010). The location of Bonaire and our coral finding of ~2°C cooler than modern SST at ~126 ka using the Sr/Ca-SST calibration of Felis et al., (2009) is illustrated (triangle, 5). LIG SST reconstructions derived from foraminifera assemblage transfer functions (lettered circles a-f: CLIMAP Project Members et al. (1984)), Mg/Ca (numbered squares: 1 (Ziegler et al., 2008), 2 (Imbrie et al., 1989), 3 (Hüls and Zahn, 2000) and 4 (Schmidt et al., 2004)), and Uk'37 (diamond 6: Herbert and Schuffert, (2000)). Turney and Jones, (2010) derived sedimentary ΔSST by averaging reconstructed SST over the MIS 5e isotopic plateau and subtracting the average SST within the nearest 2° x 2° gridded instrumental data series (1961-1990). Whereas, McKay et al. (2011) defined sedimentary ΔSST as the average SST of 5 ka centered on peak LIG SST, minus the average SST between 0 and 5 ka. Furthermore, McKay et al. (2011) and Hoffman et al. (2017) only considered sedimentary records with a resolution less than 3 and 4 ka, respectively, on their published age models. Hoffman et al. (2017) calculated ΔSST for each proxy record with reference to the HadISST1.1 1870-1889, based on this periods SST being closest within this database to the pre-industrial. Maps generated with Ocean Data View (Schlitzer, 2015)

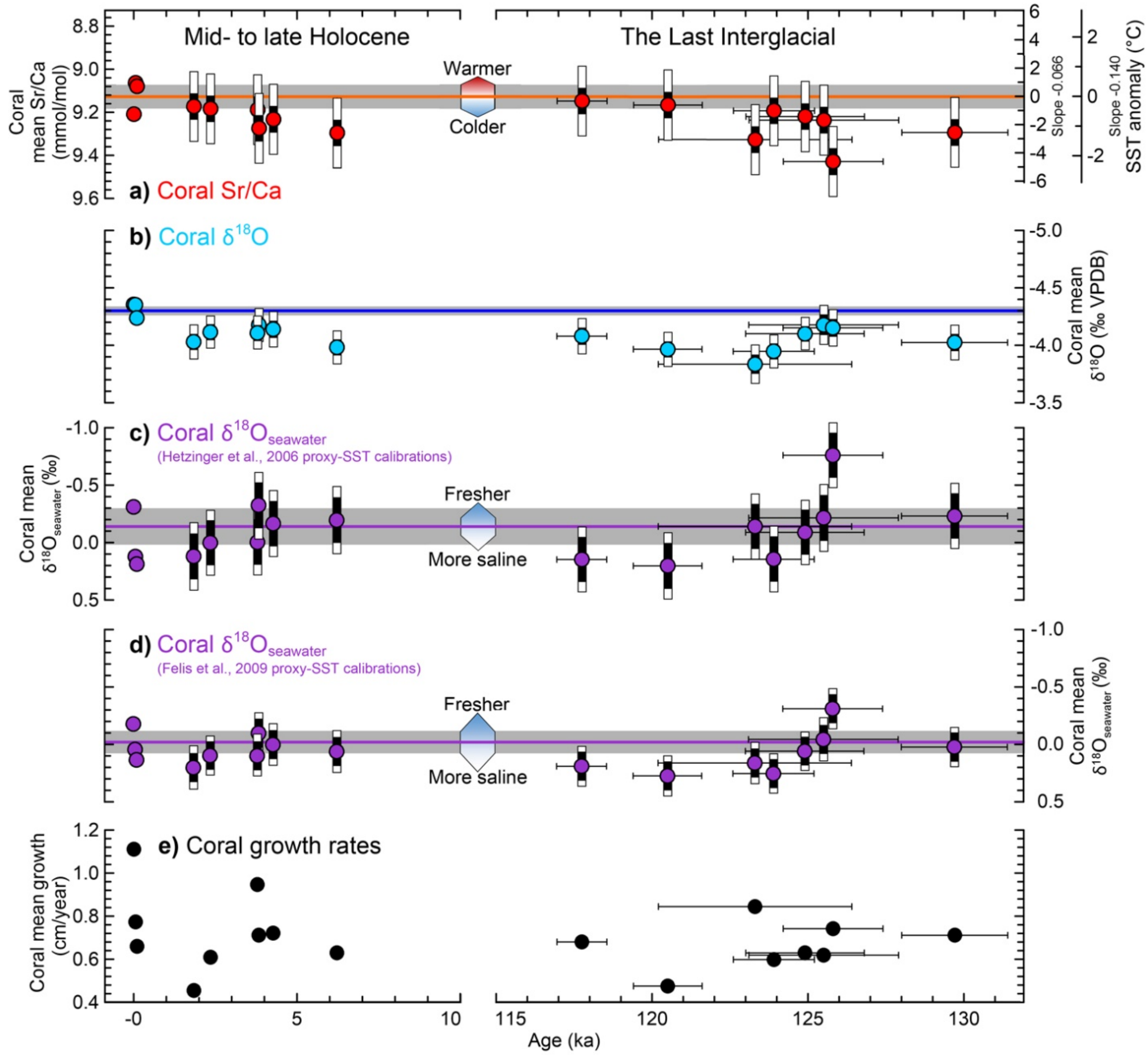


Figure S2. Tropical Atlantic mean annual coral proxies compared to their respective annual average growth rates. Records reconstruct climatic conditions during modern, mid- to late Holocene (Giry et al., 2012), late LIG (Felis et al., 2015) and the Last Interglacial (this study) periods. a) Coral Sr/Ca derived SST anomaly from the three modern coral weighted average is calculated using the annual Sr/Ca-SST relationship of -0.066 and -0.140 mmol/mol per °C from Hetzinger et al. (2006) and Felis et al. (2009), respectively. These values are used to subtract the SST component from b) paired mean annual coral δ^{18}O measurements in order to calculate δ^{18}Oseawater. Coral mean annual δ^{18}Oseawater calculated using the δ^{18}O-SST relationship of c) -0.196 ‰ per °C (Hetzinger et al., 2006) and d) -0.213 ‰ per °C (Felis et al., 2009) and their respective Sr/Ca-SST relationships. Individual error bars represent the ± full error (filled, reported at 1σ) and ±1 combined error (hollow, calculated at 2σ, Abram et al., 2006). Three coral modern weighted mean is indicated by the horizontal lines with, ±1 the largest of the internal or external error (grey shading). Horizontal error lines indicate ^{230}Th/U-age uncertainty at 2σ level (Obert et al., 2016). Modern and mid- to late Holocene ages are smaller than symbol size. e) Mean annual coral growth rates reveal no biological influence on proxy records.

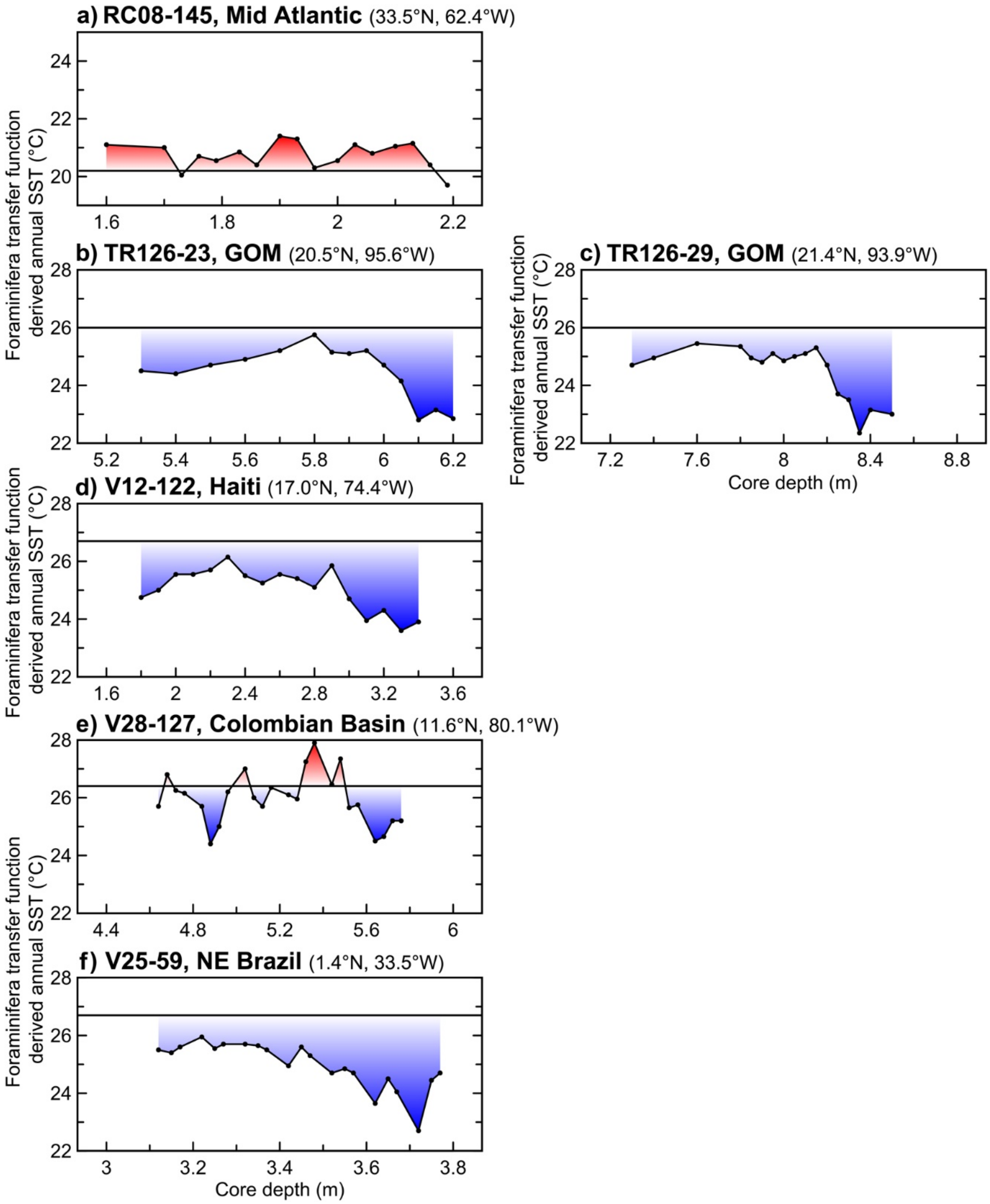
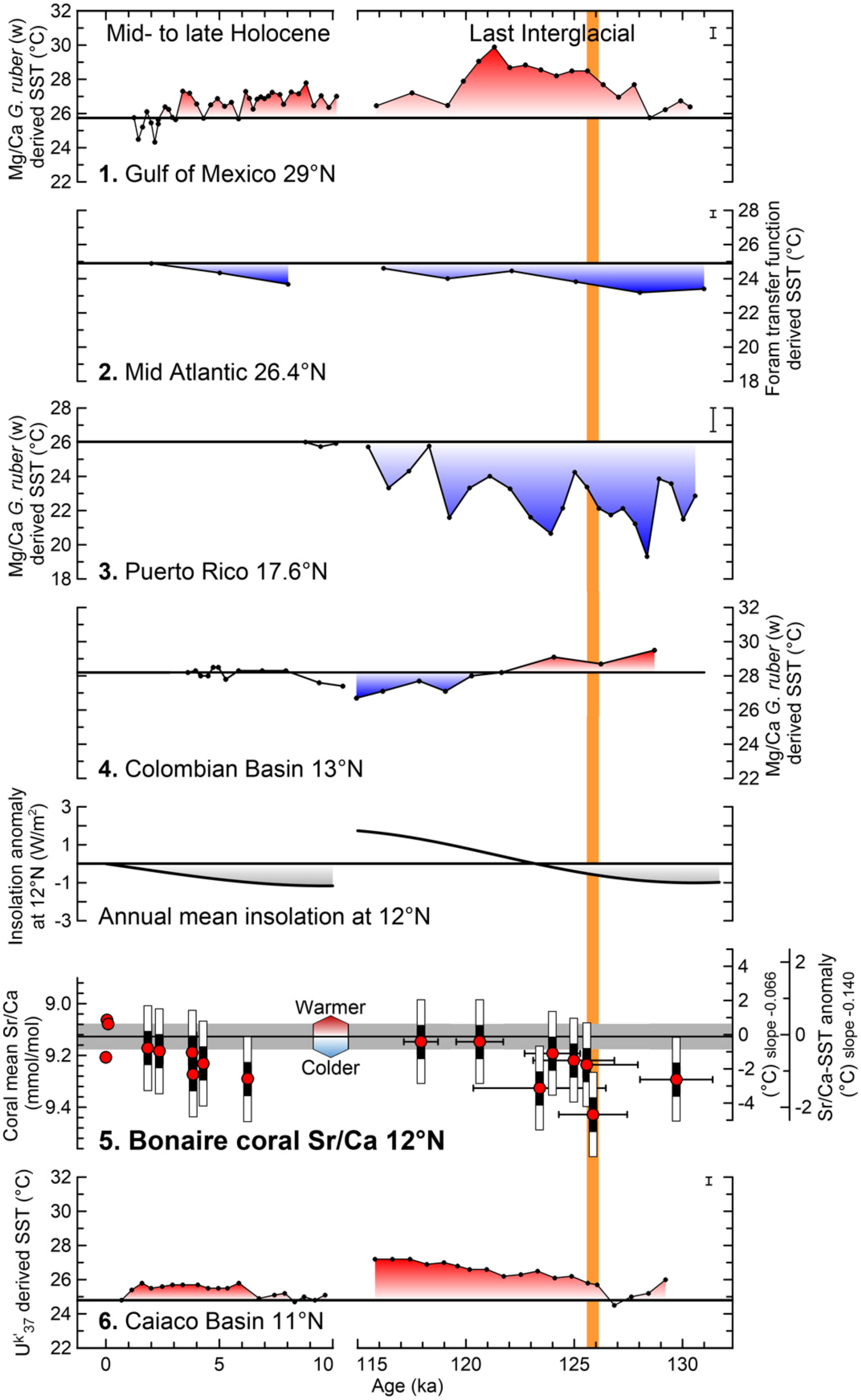


Figure S3. Last interglacial foraminifera assemblage transfer functions derived SST for various sites within the tropical Atlantic. Horizontal dark lines illustrates the core top value with red and blue shading indicating departures from this, respectively. All records originate from CLIMAP Project Members, (1984).



Mid- to late Holocene
Last Interglacial
Mg/Ca G. ruber (w) derived SST (°C)
1. Gulf of Mexico 29°N
Foram transfer function derived SST (°C)
2. Mid Atlantic 26.4°N
3. Puerto Rico 17.6°N
4. Colombian Basin 13°N
Insolation anomaly at 12°N (W/m²)
Annual mean insolation at 12°N
Coral mean Sr/Ca (mmol/mol)
Warmer
Colder
(°C) slope -0.066
Sr/Ca-SST anomaly (°C) slope -0.140
5. Bonaire coral Sr/Ca 12°N
U$^{k'}_{37}$ derived SST (°C)
6. Caiaco Basin 11°N
Age (ka)

Figure S4. Coral and sedimentary records that reconstruct annual sea surface temperatures (SST) during the mid- to late Holocene and last interglacial (LIG). Record 5 illustrates Bonaire (12°N) coral mean annual Sr/Ca for the last interglacial (LIG) (this study), late LIG (Felis et al., 2015), the mid- to late Holocene and modern times (Giry et al., 2012). Coral Sr/Ca derived SST anomaly from the 3 modern coral weighted average (horizontal black line with ± external error depicted by grey shading) is calculated using the annual Sr/Ca-SST relationship of -0.066 (Hetzinger et al., 2006) and -0,140 mmol/mol per °C (Felis et al., 2009). The error bars depict the ±1 combined error (hollow, Abram et al., 2009) and ±1 full error (filled, this study). Horizontal error lines indicate 230Th/U-age uncertainty at ±2σ level (Obert et al., 2016). Modern and mid- to late Holocene ages are smaller than symbol size. Annual mean insolation anomaly from modern (W/m2) received at 12°N (Berger, 1978) is illustrated above. Sedimentary archives derived from G. ruber Mg/Ca (numbered squares 1: (Ziegler et al., 2008), 2: (Imbrie et al., 1989), 3: (Hüls and Zahn, 2000) and 4: (Schmidt et al., 2004)), and Uk'37 (diamond 6: Herbert and Schuffert, 2000) proxy compilations are illustrated for the western tropical Atlantic (0° - 35°N x 100° - 30°W). These records are numbered according to latitude and correspond to figure 1. LIG warmer or colder than the most recent reconstructed SST are shaded red and blue, respectively. The reported ±1 standard deviation is depicted in the top right of each record. Vertical orange shading indicates the date ascribed to our coldest dwelling coral at 125.8 ka.