INVESTIGATING THE STRENGTH OF THE INDIAN MONSOONS DURING CLIMATE EXTREMES WITH STABLE ISOTOPE RECORDS IN CORALS

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ABSTRACT

The Indian monsoon affects the lives of over a billion inhabitants living in southern Asia via the hydrological cycle. Agriculture on land and freshwater discharge into the ocean. This discharge and nutrient cycling are tied with the monsoon cycles that directly impact society and the economy. Previous studies have demonstrated a strong connection between the strength of the Indian monsoon and the cooling of the North Atlantic during climate extremes, such as during the last glacial period 20,000 years ago, and the Little Ice Age (~1300-1870 A.D.). In our study, we compare the relative strength of the monsoon during two different climate states: the Little Ice Age (LIA) and the modern (2015) with proxy measurements obtained in surface corals from Saint Martin's Island, Southeast Bangladesh. We used the oxygen-isotope $^{18}O/^{16}O$ ratio ($\delta^{18}O_c$) of coralline aragonite ($CaCO_3$) to reconstruct changes in the $\delta^{18}O$ of seawater ($\delta^{18}O_w$) attributed to freshening from monsoon rains. During both climate states, corals recorded large variations in $\delta^{18}O_c$ (up to 2 parts per thousand or ‰). We attribute these changes, in part, to local salinity changes which are reflected by variability in $\delta^{18}O_w$ from local riverine discharge. While our records only represent 5-year snapshots and may not be representative of the average climate state, this data does not support that the monsoon was substantially weaker during the LIA compared to the modern. In this study, the coral records indicate subtle patterns of isotopic composition as a function of precipitation and temperature variability, serving as a preliminary for further study through longer records lasting a century. Beyond this, it would better our understanding of interactions between extremes in temperature and climate systems.

1 INTRODUCTION

Saint Martin's Island, Bangladesh lies in the heart of the Indian monsoon (FIGURE 1) where seasonal shifts in wind direction bring torrential rainfall. The summer monsoons, seasonal wind, and rains brought about by differential heating of the land and water, last from June to September every year. During the winter, the winds reverse towards the southwest direction, and precipitation is reduced. The seasonal cycle of the monsoon influences local seawater hydrography in two important ways. During the summer, sea surface temperature (SST) increases, bringing about an increase in rainfall and local riverine input which serves to lower salinity. The freshening of seawater leads to a decrease in $\delta^{18}O$ in seawater ($\delta^{18}O_w$) since precipitation has a much lower $\delta^{18}O$ as a result of the Raleigh Distillation process[3]. Oxygen isotopes undergo fractionation processes, where water containing the lighter ^{16}O isotope is more likely to get evaporated to form a gaseous or vapor state and then precipitated as liquid in rain. Hence, the freshening of seawater via precipitation results in a positive correlation between $\delta^{18}O_w$ and salinity, as both are lowered.

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Reliable instrumental records of SST and salinity are scarce beyond the early 20th century. Corals, however, provide a means for reconstructing surface water conditions beyond instrumental records because the $\delta^{18}O_c$ recorded by the corals depends upon both the $\delta^{18}O$ of the surrounding seawater and its temperature[7]. Fractionation of ^{16}O and ^{18}O increases with decreasing temperature so that higher $\delta^{18}O_c$ is associated with lower SSTs and lower $\delta^{18}O_c$ is associated with higher SSTs. Many corals display annual banding patterns that reflect changes in the density of the skeletal material. When x-rayed, the corals exhibit couplets of light and dark bands. Each dark-light couplet represents a one-year growth. With high resolution micro-milling, one can often obtain samples at monthly resolution for reconstructing past changes in salinity and SST.

Here, we compare the strength of the monsoon during two different climate states: the Little Ice Age (LIA, ~1300-1870 A.D.) and the modern (died in 2015) by comparison of their stable isotope and trace metal chemistry. It is hypothesized that the monsoon should have been weaker during the LIA. Satellite data suggests St. Martin's Island does not experience large seasonal variations in SST (range of less than 3°C). Therefore, large changes in $\delta^{18}O_c$ should be driven by changes in $\delta^{18}O_w$ with lower $\delta^{18}O_w$ recorded during the summer monsoon. Seasonal variation in SST can also modify $\delta^{18}O_c$. In order to constrain this seasonal variability in SST, we present measurements of coral Sr/Ca, which has been shown to be a reliable recorder of temperature[3]. Finally, we use the carbon-isotope ratio of ^{13}C to ^{12}C ($\delta^{13}C_c$) as an indicator of coral feeding strategy (photosynthesis vs heterotrophy) and $\delta^{13}C$ of the dissolved inorganic carbon pool (DIC) in seawater.

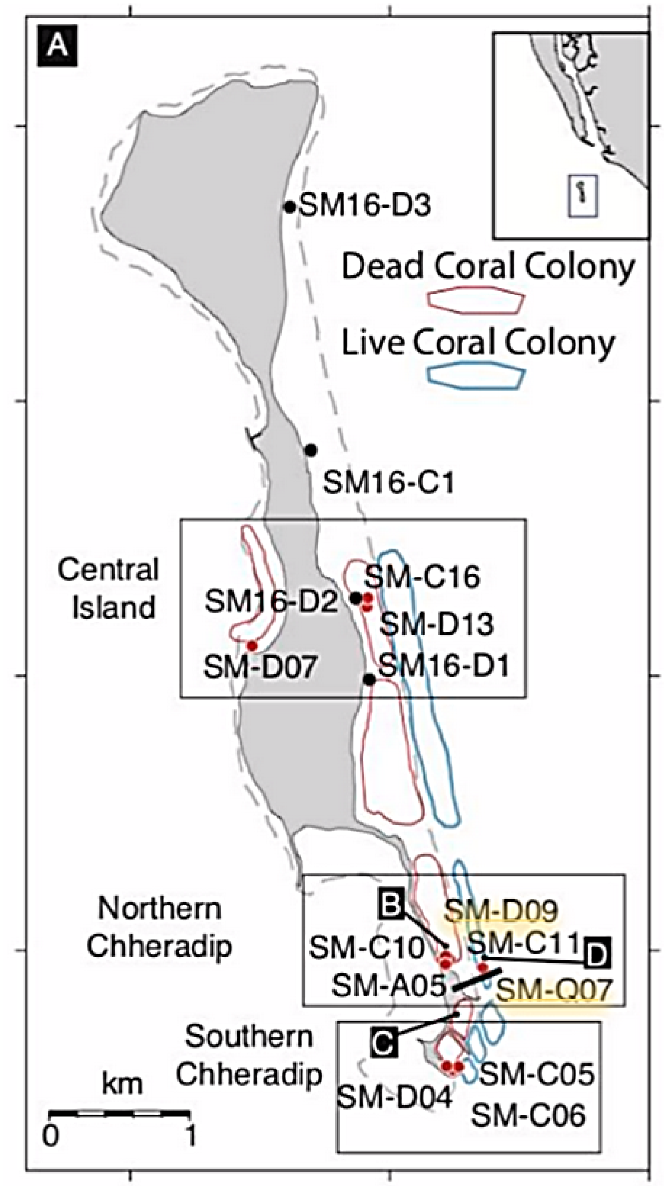
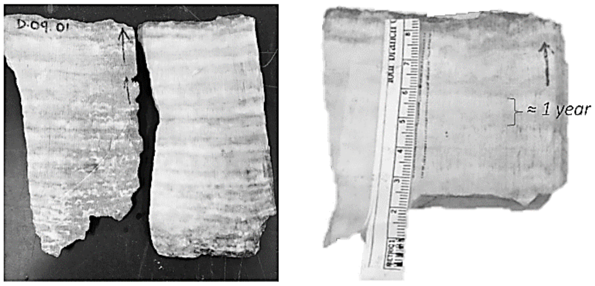


FIGURE 1: *Saint Martin's Island: the location of LIA coral D09-01corresponds to SM-D09. The modern coral location corresponds to that of SM-Q07*[4]

2 METHODOLOGY

Both LIA and modern corals in this study belong to the *Porites species*, which are stony corals with small polyps. Porites are important in paleoclimatology studies, frequently used as recorders of past marine conditions. The corals tend to be grey-brown to white in color and form hemispherical mounds or 'microatolls' in intertidal zones in the Indo-Pacific waters[4]. They can have greenish tints to the outer walls, due to their symbiotic relationship with single-celled zooxanthellae within the tissues, or more specifically, corallites. Corallites, skeletal cups formed from each polyp, are composed of calcium carbonate and precipitated as the mineral aragonite. The corals were collected during sampling expeditions to St Martin's Island in 2015/2016. At present, they are stored in airtight containers and drilled using a micro-mill to collect samples along a transect.



ABOVE:
FIGURE 2: *Sampled D09-01 Porites lobata coral*

BELOW:
FIGURE 3: *Sampled Living Porites lutea coral*

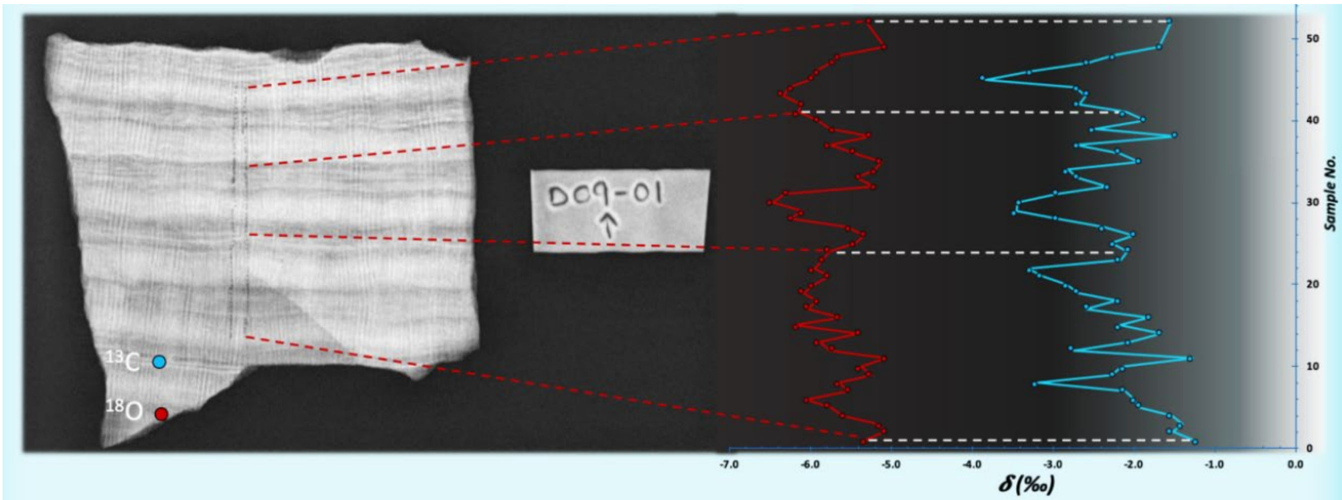
To identify the banding patterns and to guide micro-milling, x-rays of the slabs were taken at the Radiology Lab at Robert Wood Johnson University Hospital, New Brunswick. We micro-sampled the slabs at 0.5 to 1 mm spacings parallel to the growth axis using a manual drill. Annual growth bands are ~1 cm wide and suggest our sampling resolution is monthly. Approximately 80 µg of each powdered sample was analyzed by stable isotopic mass spectrometry in the stable isotope facility in the Department of Earth & Planetary Sciences at Rutgers University. Isotope data was reported relative to PDB (Pee Dee Belemnite, the standard established for $\delta^{18}O$ and $\delta^{13}C$) in the standard per mil (‰) notation (EQUATION 1). Measurement precision (1 SD) is 0.08‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$, respectively. For the strontium-calcium (Sr/ Ca) analysis, an adjoining transect of D09-01 was micro-milled and sampled at a similar spacing. ~70 µg of coral powder was acidified to 400 microliters of 3% nitric acid and analyzed by an inductively coupled plasma atomic emission spectrophotometer or ICP-OES for Sr/Ca isotopic ratios (at the Dept. of Marine and Coastal Sciences), similar to methods in Schrag, 1999[6]. Sr/Ca ratios were converted to SST via EQUATION 2, demonstrating a temperature sensitivity of about 2 °C for a change of 0.1 in Sr/Ca.

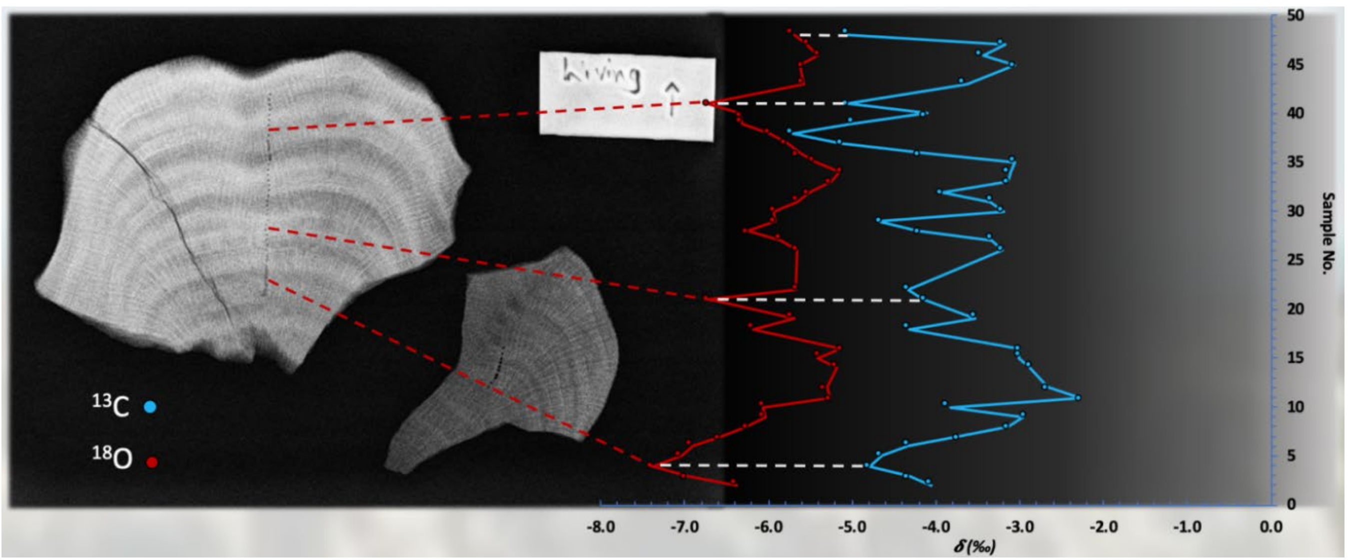
$$\delta O^{18} = \left(\frac{\left(\frac{18O}{16O}\right)_{sample}}{\left(\frac{18O}{16O}\right)_{standard}} - 1 \right) \times 1000\ ‰ \qquad (1)$$

$$SST = - \frac{Sr/Ca - 10.79}{0.068} \qquad (2)$$

EQUATION 1: *$\delta^{18}O$ is the ratio of stable isotopes oxygen-18 (^{18}O) to oxygen-16 (^{16}O), in a sample relative to the ratio in a standard. It is defined in "per mil" (‰, parts per thousand)*

EQUATION 2: Porites Sr/Ca = 10.790 (±0.043)– 0.068 (±0.002) x SST (°C), *where the Sr/Ca ratio is expressed in mM/M units.*[5]





ABOVE:

FIGURE 4: *LIA coral D09-01. Note that δ18O and δ13C variations are aligned with the high-density and low-density banding displayed in the X-ray image. The red lines plot the δ18O variations and the blue lines, δ13C.*

BELOW:

FIGURE 5: *δ18O and δ13C variations shown alongside an X-ray image in the modern coral.*

3 RESULTS

FIGURE 4 and FIGURE 5 show stable isotope results in the two corals– fossil D09-01 (U-Th dated to 1762) and modern (collected in 2015), respectively. Oxygen isotopic ratios, $\delta^{18}O$ and carbon isotopic ratios $\delta^{13}C$ were primary indicators of past sea conditions. The $\delta^{18}O$ is a function of temperature and salinity, while $\delta^{13}C$ measures productivity and increased photosynthesis from vegetation and organisms that have a symbiotic relationship with corals. This relationship correlates with the amounts of sunlight received over time.

Repeating patterns of high and low $\delta^{18}O$ and $\delta^{13}C$ are associated with the banding patterns in both the LIA and modern corals (FIGURE 4 and FIGURE 5). These patterns suggest that the changes in isotopic values are driven by seasonal changes. The banding patterns suggest both coral records represent 5 years growth. Both the mean and range in $\delta^{18}O$ in the modern coral is similar to that of the LIA coral (~ 1.2‰). The mean LIA coral $\delta^{18}O$ is higher, by 0.2‰ compared to the modern sample, although differences in the mean values are not statistically significant (TABLE 1 and TABLE 2). The range in $\delta^{13}C$ of the living coral are similar to those in the LIA coral, about 3‰. The modern coral average, however, is about 1.5‰ lower compared to the LIA coral. Paleotemperature equations based on $\delta^{18}O_c$ in Porites indicate a temperature increase of 1°C for a $\delta^{18}O$ decrease of 0.22‰[7]. Therefore, an amplitude change of 1.2‰ would reflect a ~5.5 °C range in SST, or about twice what is observed in instrumental records. Sr/Ca ratios are converted to SST suggest temperatures ranging between 25 and 30°C although a number of Sr/Ca values yield unreasonably high SSTs (FIGURE 6 and FIGURE 7) and there is no obvious pattern to suggest a seasonally related signal. High Sr/Ca ratios (low SST) do not correlate with low $\delta^{18}O_c$ as would be predicted if changes in SST were the dominate control on both proxies.

D09-01		
	$\delta^{13}C$	$\delta^{18}O$
Mean	-2.347	-5.704
Standard Deviation	0.612	0.383

SM Living		
	$\delta^{13}C$	$\delta^{18}O$
Mean	-3.820	-5.902
Standard Deviation	0.791	0.554

ABOVE:

TABLE 1: *Mean and standard deviation of the Fossil coral isotope values*

BELOW:

TABLE 2: *Mean and standard deviation of the Living coral isotope values*

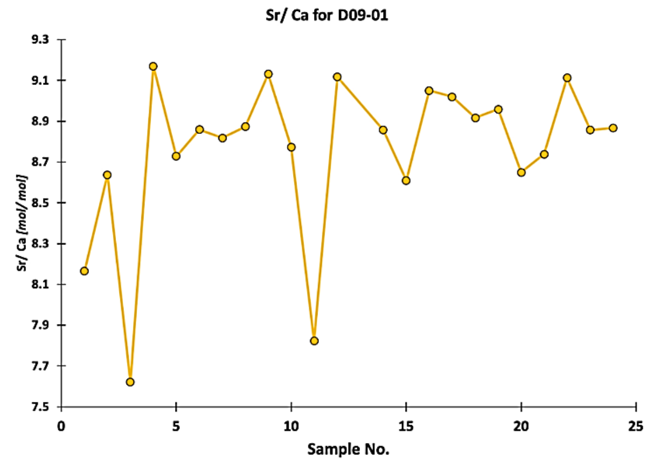
4 DISCUSSION

The observation that changes in $\delta^{18}O_c$ covary with changes in $\delta^{13}C_c$ suggests that they are driven by a common mechanism– the strength of the Indian monsoonal rainfall. Since $\delta^{13}C$ is not sensitive to changes in temperature, we conclude the most likely explanation is that isotopic changes in both the LIA and modern corals are due to changes in $\delta^{18}O$ and $\delta^{13}C$ in the local seawater during increased riverine discharge (freshening) resulting from the monsoon rains. Since $\delta^{18}O$ in seawater averages about 0‰ and river as well as rain values are in the range of -5 to -10‰, mixing these two endmembers provides a first order explanation to our coral results. $\delta^{18}O_W$ in the Bay of Bengal strongly correlates with salinity changes in the region, rather than purely SST[1]. From the equation derived from $^{18}O_w$ and salinity data in the Bay of Bengal (EQUATION 3) a change of 1.2 ‰ in $^{18}O_w$ would represent a change in salinity of about 6 p.s.u. (FIGURE 6), This range would likely be beyond the tolerance limits for a coral and its symbionts.

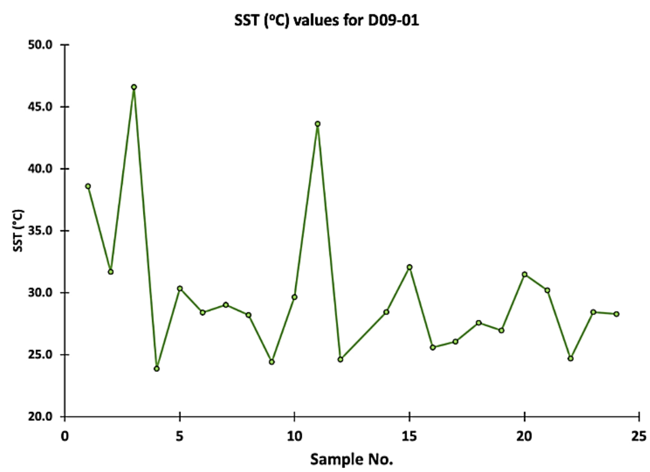
We cannot, however, discount that some of the seasonal variability in $\delta^{18}O_c$ is due to changes in SST, as suggested by the Sr/Ca data. We therefore conclude that about 50% of the 1.2‰ amplitude change in $\delta^{18}O_c$ is due to seasonal changes in SST (3°C) and 50% due to salinity changes of about 3 p.s.u.– the effects are additive. Higher SSTs during summer warming serve to lower $\delta^{18}O_c$ due to a decrease in isotopic fraction with increasing temperatures. Increased precipitation and riverine input during the summer monsoon both add water with lower $\delta^{18}O$ and thus serves to lower $\delta^{18}O_w$ and hence $\delta^{18}O_c$. Lower $\delta^{13}C$ is associated with lower $\delta^{18}O$ and may indicate increased riverine input of low $\delta^{13}C$ in total dissolved inorganic carbon (DIC). Seasonal variation of around 2‰ in $\delta^{13}C_c$ may also reflect changes in coral metabolism related to feeding strategy[2]. For example, during the winter months cloud cover is

$$\delta^{18}O_{seawater}\,(‰) = 0.18 \times SSS(p.s.u) - 5.9(‰/p.s.u) \qquad (3)$$

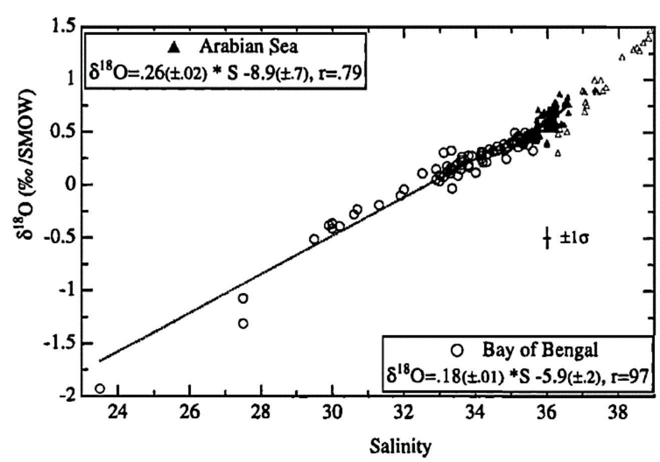
EQUATION 3: $\delta^{18}O_{seawater}$ (‰) = 0.18 × SSS(*p.s.u*) - 5.9($^{‰}/_{p.s.u}$)
P.S.U – *practical salinity unit*



TOP:
FIGURE 6: *Sr/Ca isotope ratios from LIA sample (Transect 3). Several values yield extreme values in Sr/Ca (e.g. 7 to 8)*



MIDDLE:
FIGURE 7: *Temperatures derived from the Sr/Ca ratios using equation 2 in the LIA coral (Transect 3).*
NOTE: *Very low Sr/Ca (FIGURE 4) translate to high and extreme and unreasonable estimates of SSTs (e.g. > 32°C).*



BOTTOM:
FIGURE 8: *Note the linear and positive correlation between $\delta^{18}O$ of seawater with salinity, obtained from the Bay of Bengal. The slope suggests a change of about 0.2‰ per one unit change in salinity*[1].

reduced and photosynthesis enhanced by the symbiotic zooxanthellae. During photosynthesis, ^{12}C is favored over ^{13}C so the pool of DIC becomes enriched in ^{13}C thereby increasing $\delta^{13}C_c$ during warmer, sunny months. During the summer monsoon cloud cover is increased and photosynthesis reduced. Corals may rely more on heterotrophic feeding of zooplankton and $\delta^{13}C_c$ reflects incorporation of a pool of low ^{13}C (e.g. -25‰). The offset between $^{13}C_c$ in the modern versus the LIA coral is significant (1.3‰) and may reflect changes brought about by increased and/or changing agriculture. Specifically, increased rice production in this region during the 20th century would have added a pool of lower ^{13}C (~-15‰) to the riverine total DIC pool.

Certain values of Sr/Ca corresponding to unrealistic temperatures may be due to local effects, such as changes in the Sr/Ca delivered to the study area by rivers or perhaps due to changes in the rates of calcification in the coral.

5 CONCLUSIONS

Stable isotope records obtained in both LIA and modern corals at St. Martin's Island, Bangladesh display changes at monthly resolution, driven by the seasonal monsoon. We estimate variability in $^{18}O_c$ is split equally between changes in SST and changes in $^{18}O_w$. The average $\delta^{18}O_c$ in the D09-01 fossil coral is only 0.2‰ higher compared to the living and leads us to conclude the monsoons were only slightly weaker during the Little Ice Age. That is, a combination of lower SSTs and/or increased salinity (decreased freshening) could explain the differences between the Living and LIA coral $\delta^{18}O$ records. Longer records in both $^{18}O_c$ and Sr/Ca will be needed to make a statistically significant comparison between the two climate states. Our pilot study shows the potential for generating century-long historical records of the monsoon, via records of stable isotopes and trace metals. This would provide much needed spatial and temporal resolution for climate models and climate forecasting. Indeed, monsoons arise in any location where a strong land-sea contrast is present, from South Asia and northern Australia to West Africa and southwestern North America—bringing to light how paleoclimate research on the monsoons would better quantify as well as benefit our understanding of the world's climate and its impact. Further work should include obtaining seawater samples for measurements of $\delta^{18}O$, salinity, Sr/Ca, and Sr-isotope data at St. Martin's Island along with measurements of trace metal concentrations in Porites corals that might serve as a "fingerprint" for identifying riverine discharge■

6 ACKNOWLEDGEMENTS

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