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Evaluating the reproducibility and paleo-hydroclimate potential of coral skeletal Ba/Ca in the Gulf of Chiriquí, Panama

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ABSTRACT

Coral skeletal Ba/Ca (Ba/Ca_{cor}) has been found to be highly correlated with river discharge in some coastal settings. However, any hydrologic interpretation of Ba/Ca_{cor} time-series requires thorough evaluation of regional climate, even at sites in close proximity to one another. Here we explore how two corals can be used to provide insight into hydroclimate in the Gulf of Chiriquí, Panama (GoC) using Ba/Ca_{cor}, a region whose climate is dictated by seasonal and lower frequency shifts in the Intertropical Convergence Zone. The main purpose of this study is to provide a preliminary assessment of Ba/Ca_{cor} replication in pursuit of a regional geochemical network. The two corals analyzed in this study (Secas Island, S1 and Coiba, IC4A-2) were collected ~74 km apart and grew in different reef settings at vastly different distances from the main river discharge points. Analytical uncertainty prevents complete confidence determining whether a small geochemical offset Ba/Ca_{cor} exists between our two records. However, temporal variability in S1 and IC4A-2 are well correlated at all examined temporal scales ($r_{\text{monthly}} = 0.70$, $r_{\text{annual}} = 0.65$, $r_{\text{wet season}} = 0.67$, $r_{\text{dry season}} = 0.55$, $r_{\text{annual amplitude}} = 0.77$). Considering a potential geochemical offset may exist between the two corals, we took a conservative approach and examined S1 and IC4A-2 separately to establish a relationship with river discharge. Both corals, barring IC4A-2 dry season averages, are statistically significantly correlated to river discharge, permitting the creation of Reduced Major Axis regressions to quantify the relationship. Ultimately, in regions where river discharge dominates, a network of Ba/Ca_{cor} records may assist in reconstructing regional variability or notable deviations in hydroclimate. With additional and temporally longer Ba/Ca_{cor} records, we will be able to apply our framework to more clearly reconstruct river discharge variability throughout the GoC.

1. Introduction

The use of coral skeletal Ba/Ca (henceforth referred to as Ba/Ca_{cor}) measurements has been growing in the paleoclimate community as a proxy for multiple aspects of hydroclimate, including river discharge (e.g., Sinclair and McCulloch, 2004; LaVigne et al., 2016; Saha et al., 2018a). In order to reconstruct river discharge, the study site in question often exhibits seasonal variability in hydroclimate or recurrence of extreme flooding or droughts (e.g. Saha et al., 2018a; Brenner et al., 2017; LaVigne et al., 2016; Sinclair and McCulloch 2004) that can be directly correlated with Ba/Ca_{cor}. Although not guaranteed, reefs in proximity to land exposed to these large fluctuations in hydroclimate, show great promise for generating Ba/Ca_{cor}-based reconstructions. To that end, Panamanian reefs along the Pacific Ocean are excellent candidates for evaluating the relationship between Ba/Ca_{cor} and river discharge (LaVigne et al., 2016).

The Gulf of Chiriquí (GoC), located along the Pacific coast of Panama (Fig. 1), is an ideal study site to test the Ba/Ca_{cor}-river discharge proxy as 1) the region experiences extreme seasonal hydrologic variability dictated by meridional migrations of the Intertropical Convergence Zone (ITCZ) and 2) large massive *Porites* corals exist on the modern reefs. The Ba/Ca_{cor}-river discharge proxy can be used as a tool in understanding the hydroclimate of the GoC. The proxy provides the opportunity to extend and fill in the gaps of the limited instrumental river discharge

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record, in addition to evaluating atypical wet or dry seasons or identify El Niño events (Brenner et al., 2017). Furthermore, hydrologic-rainfall models with meteorological data suggest that river discharge in Pacific watersheds, specifically the Chiriquí and La Villa, are likely to be impacted in the face of warming in the 21st century with increasing precipitation signaling the need to more thoroughly evaluate their existing variability (Espinosa et al., 1997; Fábrega et al., 2013). Understanding river discharge is also economically significant, potentially impacting management of the Panama Canal, which relies on seasonal recharge of artificial reservoirs to supply water to operate the canal locks. Revenue from the Panama Canal generates ~8% of Panama's gross domestic product, supports agriculture and hydroelectricity, which supplies about 50% of the country's installed energy capacity (Secretaría de Energía, 2012; Fábrega et al., 2013). Considering this, long-term records of hydroclimate become incredibly valuable.

Sediment load, or the optical characteristic of turbidity, in rivers are often positively correlated with Ba/Ca_{cor} (e.g. McCulloch et al., 2003; Carriquiry and Horta-Puga, 2010; Prouty et al., 2010; Yamazaki et al., 2021) but the proxy is sensitive to other environmental parameters. These include, but are not limited to, river discharge, which is often correlated with sediment load (e.g. LaVigne et al., 2016; Saha et al., 2018a), precipitation (e.g. Horta-Puga and Carriquiry, 2012), upwelling (e.g. Lea et al., 1989; Shen et al., 1992; Reuer et al., 2003; Montaggioni et al., 2006; Ourbak et al., 2006), wind-driven dust (e.g. Bryan et al., 2019), productivity (e.g. Weerabaddana et al., 2021), biogeochemical cycling (e.g. Saha et al., 2018b), water temperature (e.g. Gaetani and Cohen, 2006), and pollutant contamination (e.g. Carriquiry and Horta-Puga, 2010) (see Weerabaddana et al., 2021 Table 1 for an overview). Occasionally, the proxy can be disturbed, for example by subtle variability in geography and ocean currents leading to misalignment between Ba/Ca_{cor} and flood plumes (e.g. Lewis et al., 2012; Walther et al., 2013). It is apparent that interpretation of the Ba/Ca_{cor} proxy is highly dependent on the study site's hydrography and ocean currents, climate, and/or coastal land use practices, and reef proximity. This warrants site-specific investigations to accurately assess environmental controls on Ba/Ca_{cor}. In this study, we utilize Ba/Ca_{cor} as a proxy for river discharge, based on local correlations to available instrumental data.

Generally, conclusions made by Ba/Ca_{cor} and other coral-based proxy studies, as well as those based on instrumental data, are strengthened and clarified through a network approach (e.g., Reuer et al., 2003; LaVigne et al., 2016; Tanzil et al., 2019), meaning that geochemical records from multiple coral cores in the same reef or region are generated to minimize influence of colony-specific biology (i.e. vital effects, e.g., Sinclair, 2005b) and provide a broader geographic perspective. There are still some unknowns, however, with the application of this method to the GoC. The GoC is large (~65 km × 30 km; D'Croz and O'Dea, 2009) and it is possible that proximity to the mainland (e.g., a river mouth), currents, or the geographic position of a small island may impact the coral geochemistry, namely annual amplitude. These factors, in conjunction with vital effects, could potentially lead to a geochemical offset (i.e. shift in mean value) between Ba/Ca_{cor} records in the GoC. The objective of this study is to begin to clarify these uncertainties by comparing Ba/Ca_{cor} from two corals collected 74 km apart at two geographically distinct islands along the Pacific coast of Panama in the GoC: Coiba Island (Coral ID: IC4A-2) (Brenner et al., 2017) and Secas Island (Coral ID: S1). Prior to this study Linsley et al. (1994) developed a multi-century coral $\delta^{18}O$ record with S1 and, with reanalysis by Brenner et al. (2016), elucidated an approximately decadal pattern, likely attributed to the Pacific Decadal Oscillation. In addition, Brenner et al. (2017) generated a Ba/Ca_{cor} record with IC4A-2, establishing the link with river discharge in the GoC. Here, we compare the 70-year record form IC4A-2 Ba/Ca_{cor} (1996.54–1917.96 CE) with the upper 67 years of a new Ba/Ca_{cor} record from S1 (1984.29–1917.96 CE). Each Ba/Ca_{cor} record correlates with local river discharge to differing degrees. Through evaluation of inter-colonial variability we outline a framework for evaluating preliminary replication of Ba/Ca_{cor} records with a conservative approach to interpretation while considering both analytical and environmental uncertainties.

2. Gulf of Chiriquí: Climate and study site suitability

The GoC abuts western Panama, which sits atop the Chorotega Block, a component of the Panama microplate (Marshall, 2007). The Chorotega fore arc, which lies along the GoC, is tectonically active and is responsible for Panama's rugged coastline (Marshall, 2007). Panamanian soils are typically rich in clay and extensive mangrove forests are found along the coast. The region's climate is characterized by seasonal precipitation driven by regular shifts in the ITCZ. As the northern hemisphere warms, the ITCZ migrates northward to ~8–12°N initiating Panama's wet season from May–November. During the boreal winter the ITCZ's southern shift results in the dry season (December–April) (Fig. 2). Seasonality in precipitation is stark, with monthly rainfall during the wet season averaging ~300 mm and ~100 mm during the dry season as indicated from a long-operating rain gauge at Barro Colorado (Fig. 2). Regional precipitation is also well correlated to a compilation of available river discharge data from Panama (i.e. the sum of time-matched river discharge records) (Hidrometeorología de la Empresa de Transmisión,

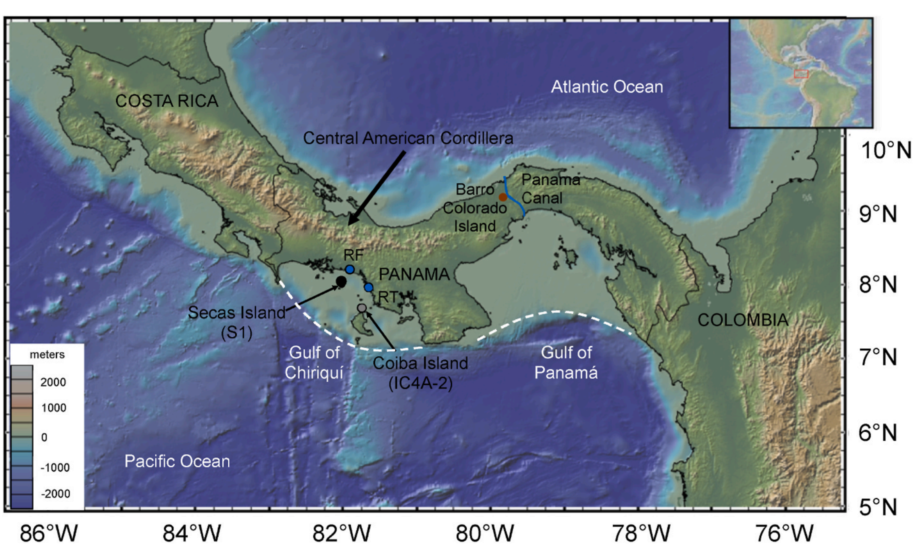


Fig. 1. Site map of Gulf of Chiriquí, Panama. The approximate boundaries of the Gulfs of Chiriquí and Panama are outlined by the dashed lines. Corals S1 (black) and IC4A-2 (grey) sites are ~74 km apart. The Central American Cordillera blocks the trade winds from blowing strongly over either study site, promoting stable SSTs. The approximate locations of where Rio Fonseca (RF, blue) and Rio Tabasara (RT, blue) terminate in the GoC, the Barro Colorado Island rain gauge (orange), and Panama Canal (blue line) are noted.

Table 1
Summary statistics for S1, IC4A-2 and Composite Ba/Cacor records. Values are presented as averages ± standard deviation with the 95% confidence interval in parentheses.

	IC4A-2 Total	IC4A-2 Overlap	S1 Total/Overlap	Q Overlap w/IC4A-2	Q Overlap w/S1
Record Period	*1996.54-1917.*96 CE	*1984.29-1917.*96 CE	*1984.29-1917.*96 CE	*1996.54–1971.04*	*1984.29-1971.*04 CE
Average Coral Growth Rate	*14.*1 mm	*13.7* mm	*11.*5 mm	*15.*6 mm	*10.2. mm*
Monthly Average	5.16 ± 0.54 (0.04), n = 944	5.13 ± 0.53 (0.04), n = 797	4.89 ± 0.62 (0.04), n = 797	156.50 ± 123.11 (14.05), n = 307	158.60 ± 128.53 (20.32), n = 160
Annual Average	5.15 ± 0.27 (0.06), n = 78	5.14 ± 0.28 (0.07), n = 66	4.89 ± 0.33 (0.08), n = 66	159.33 ± 40.16 (15.75), n = 26	163.24 ± 44.47 (12.28), n = 14
Annual Amplitude	1.43 ± 0.56 (0.13), n = 78	1.39 ± 0.58 (0.14), n = 66	1.45 ± 0.70 (0.17), n = 66	344.73 ± 104.77 (41.10), n = 26	351.33 ± 109.78 (58.68), n = 14
Wet Season Average	5.39 ± 0.36 (0.08), n = 78	5.37 ± 0.37 (0.09), n = 66	5.20 ± 0.45 (0.11), n = 66	213.18 ± 60.84 (23.86), n = 26	218.52 ± 65.60 (35.07), n = 14
Dry Season Average	4.83 ± 0.27 (0.06), n = 79	4.82 ± 0.26 (0.06), n = 66	4.55 ± 0.26 (0.06), n = 66	97.44 ± 26.19 (10.27), n = 26	97.72 ± 31.70 (16.94), n = 14

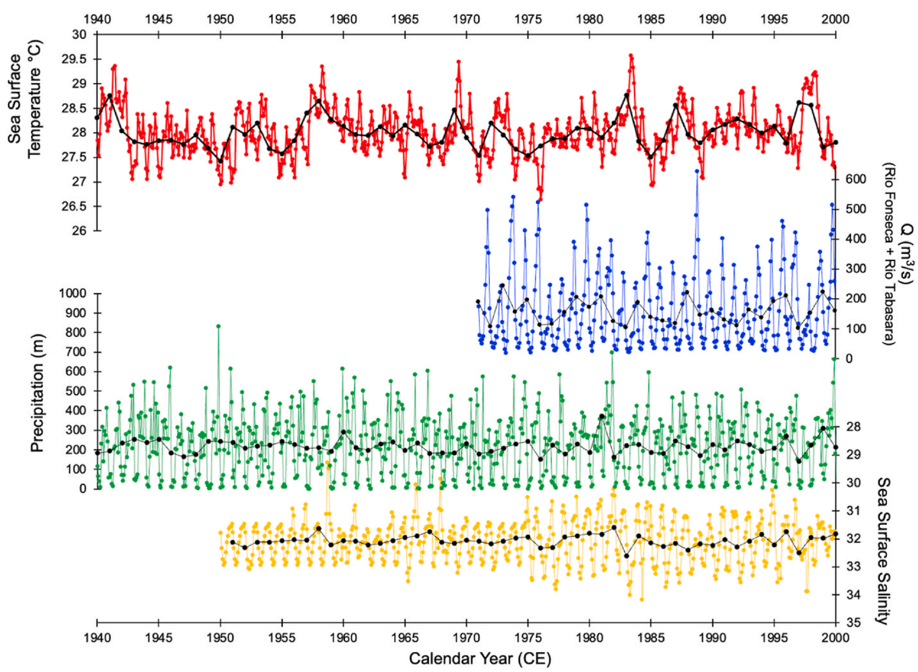


Fig. 2. Instrumental data at monthly and annual scales (black) describing sea surface temperature (SST, ERSST v5, Huang et al., 2017), composite river discharge (Q = Sum of Rios Fonseca and Tabasara Q, Hidrometeorología de la Empresa de Transmisión, Eléctrica, S.A), precipitation (Barro Colorado, Panama, Physical Monitoring Program of the Smithsonian Tropical Research Institute), and sea surface salinity (SSS) (Delcroix et al., 2011). SST exhibits little variability throughout the year, while Q, precipitation, and SSS have a clear annual cycle dictated by wet and dry seasonality.

Eléctrica, S.A) with no clear lag between seasonal maximum or minimum values (r = 0.57) (Fig. 2). Although 300 of Panama's 500 rivers terminate in the Pacific Ocean (ANAM, 2011; Fábrega et al., 2013), instrumental river discharge time series are extremely limited. Nonetheless, this correlation suggests that not only is river discharge related to ITCZ-driven rainfall but also has a regional signal in hydroclimate since the rain gauge site is ~300 km from the GoC.

Sea surface salinity (SSS) in the GoC responds to these variations in precipitation and river discharge, and potentially advection of higher salinity open ocean water. Throughout the year SSS oscillates between 30.5 (wet season) and 33.5 (dry season) (Delcroix et al., 2011) (Fig. 2). It is important to note that Delcroix et al. (2011) SSS data are based on offshore measurements and may not perfectly reflect GoC conditions. Additionally, we truncate the SSS record at 1957, because prior to that time data were sparse and infilling likely did not reflect actual conditions.

Unlike SSS, the sea surface temperatures (SSTs) in the GoC are relatively consistent throughout the year, hovering at ~28 °C with a seasonal range of ~2 °C (~29°-27 °C) (Fig. 2). The seasonally narrow SSTs are due in large part to the topographic blocking of the trade winds by the Central American Cordillera, which minimize seasonal upwelling (Fig. 1). Given the strong seasonality in precipitation and river discharge, as well as a lack of seasonal variability in SST and upwelling, we consider the GoC to be a suitable study site to utilize the Ba/Ca$_{cor}$-river discharge proxy.

3. Methods

3.1. Coral collection and sample preparation

This study is based on two coral cores, both removed from large, living, *Porites lobata* colonies in the GoC using SCUBA and a hydraulic drill. The first coral core was collected in July 1996 nearby Coiba Island (coral ID: IC4A-2) (7°25′ N, 81°42′ W) at a depth of 3 m and totaled 2.3 m in length. The IC4A-2 Ba/Ca$_{cor}$ was previously published by Brenner et al. (2017). The second coral core, whose Ba/Ca$_{cor}$ is presented for the first time here, was collected near Secas Island (coral ID: S1), 25 km southwest of mainland Panama in the center of the Gulf (7°59′ N, 82°3′ W), in June 1984 (Fig. 1). S1 is 2.8 m in length and was collected at 3 m water depth. The upper portion (~760 cm) of the Ba/Ca record is presented here.

The coring sites are located in the central (S1) and southeastern (IC4A-2) portions of the GoC and are ~74 km apart. The extracted coral cores were 8 cm in diameter and cut lengthwise along a longitudinally consistent transect into 7 mm thick slabs with a water-cooled rock saw. Each slab was cleaned in a deionized water bath with a high-energy (500W, 20 kHz) probe sonicator for about 10 min per side then completely air dried at room temperature. Slabs were then X-rayed in an HP cabinet X-ray system (at 35 Kv). The X-rays elucidated density banding in the coral core, with one high- and low-density couplet attributed to an annual layer. We identified the maximum growth axis of the corallite fan for sample drilling with the X-ray positives (See Supplementary Material). We used a variable speed Dremel drill fit with a spherical, diamond-tipped dental drill bit to excavate a continuous ~2 mm wide by ~2 mm deep trough. Discrete samples for Ba/Ca analysis were collected at a 1-mm interval, with drilled coral skeletal powders stored in microcentrifuge tubes. Regions where banding was indecipherable or corallites grew perpendicular to the cut slab were avoided.

3.2. Coral Ba/Ca measurements

We digested coral powder aliquots of 280–320 μg samples in 2% HNO_3. We vortexed each vial to ensure complete digestion and solution homogeneity. Vials were not acid cleaned per laboratory protocol, and samples and coral standards were not digested until the day of ICP-OES analysis. Ba/Ca analysis was conducted on a 2013 Thermo iCap 6500 ICP-OES paired with a CETAC autosampler at the Lamont-Doherty Earth Observatory. We analyzed an in-run reference based on a matrix match (MaMa) solution that mimicked the coral's geochemistry, adopting the technique outlined by Schrag (1999), with a Ba/Ca molar ratio of 7.3 μmol/mol. The ICP-OES was calibrated each day with five MaMa dilution standards. Each coral sample was bookended with the MaMa solution in order to make the appropriate corrections for machine drift. During the analysis of both IC4A-2 and S1, we analyzed the JCp-1 coral standard (Okai et al., 2002), which yielded an average value of 6.13 μmol/mol (n = 193, long-term average) with a standard deviation (σ) of 0.59 μmol/mol.

The interlaboratory comparison of Ba/Ca in JCp-1 by Hathorne et al. (2013) is based on a combination of ICP-OES and ICP-MS measurements, yielding a robust average of 7.465 μmol/mol with a robust standard deviation of 0.655 μmol/mol (n = 9). However, other studies that have focused on an assessment of JCp-1 Ba/Ca have noted differences between ICP-OES and ICP-MS derived values (e.g., Cantarero et al., 2017) and have then yielded better precision than the original Hathorne et al. (2013) findings (e.g., Weerabaddana et al., 2021). For the analysis of S1 on samples dating from 1960 through 1917, we also utilized a new in-house standard made of a Caribbean *Siderastrea siderea* coral supplied to us by Dr. Henry Wu (Leibniz Centre for Tropical Marine Research: ZMT in Bremen, Germany) (here termed Wu ZMT LDEO). The lifetime average Ba/Ca value of repeat measurements of Wu ZMT LDEO was 6.62 μmol/mol (n = 311) with a standard deviation (σ) of 0.12 μmol/mol. Replicate analysis of IC4A-2 and S1 yielded average differences of 0.10 μmol/mol and 0.11 μmol/mol, respectively.

3.3. Chronology development

We exploit our understanding of Panama's wet-dry seasonality, coral calcification patterns, near-monthly 1 mm sample intervals and oscillations in the coral geochemistry to develop our chronologies. During the dry season the corals produce lower-density skeleton when photosynthetic rates and skeletal extension rates both increase due to decreased cloud cover, less frequent storms and increased solar radiation reaching the Earth's surface (Wellington and Glynn 1983). During the wet season in Panama, ITCZ driven storms, cloud cover, and increased water turbidity dampen photosynthetic rate in *Porites*, which leads to reduced extension rate and an increase in skeletal density. The decrease in the extension rate might also be in-part a stress response to the input of fresh water and subsequent decrease in salinity. Each low- and high-density band couplet represents one year of growth. These couplets are determined via X-ray positives, in which low-density bands appear lighter (white) and high-density bands appear darker (black).

Visual assessment of the skeletal structure provides a first order chronology but is refined by pairing the X-rays with geochemical seasonal or annual age-control points. When sampled at 1-mm increments, analysis of *Porites* corals in this region generate geochemical series with on average ~10 mm/year in S1 to ~14 mm/year in IC4A-2. Based on our established understanding of Ba/Ca_{cor} and hydroclimate in the GoC (Brenner et al., 2017), the wettest and driest months of the year correspond to the maxima and minima in the Ba/Ca_{cor}, respectively, with an insignificant correlation to seasonal changes in SST (see Supplementary Material). There are limited multi-year observational river discharge records from rivers that terminate in the Gulf of Chiriquí and overlap with the IC4A-2 and S1 time series. Available data are from Rios Fonseca and Tabasara, beginning in 1971 CE. Note that river discharge is a composite value, which is the sum of time-matched river discharge data from the Rio Fonseca and Rio Tabasara discharge data. Taken together, instrumental river discharge and precipitation records indicate that October is on average the wettest month and March the driest month of the year. Therefore, for the purposes of constructing an age model, we use age control points that tie coral Ba/Ca_{cor} annual minima to mid-March and Ba/Ca_{cor} annual maxima to mid-October.

We first made age assignments to the 1 mm-increment Ba/Ca_{cor} record with the two tie-points year. Then, we interpolated to a final 12 points per year time-series (referred to as the monthly record). For parity and to account for the newly drilled S1 sample path for Ba/Ca, the chronologies for both S1 and IC4A-2 were both newly developed for this study using the combination of X-rays and coral Ba/Ca. The IC4A-2 Ba/Ca_{cor} timeseries, which was originally constructed based strictly on $\delta^{18}O$ and published in Brenner et al. (2017), is updated here by considering Ba/Ca_{cor} and X-rays. Since Brenner et al. (2017) examined Winter-Spring-Summer-Fall averages, the main conclusions with respect to Coiba Island's IC4A-2 are not substantively different even though the chronology was updated.

3.4. Coral Ba/Ca network assessment

In order to appropriately apply a network approach to the interpretation of Ba/Ca_{cor} records in this region we must assess geochemical offsets between the two corals. The offset was calculated as the absolute value difference between S1 and IC4A-2 time-matched Ba/Ca_{cor}. We used ± 2σ analytical precision (Wu ZMT LDEO and JCp-1) as our statistical threshold to determine if a geochemical offset between the two corals could be identified. The ± 2σ analytical precision Wu ZMT LDEO- and JCp-1-based thresholds are heretofore referred to as the Wu and JCp-1 thresholds, respectively. We calculated the percentage of time-matched points in a given record that exceeded our thresholds to examine each record as a whole. We applied this practice to monthly, annual, annual amplitude, wet season, and dry season Ba/Ca_{cor} treatments of the overlapping portions of S1 and IC4A-2 (~1918–1984).

All reported correlations are evaluated with the Pearson's Product Moment Correlation (*r*). The *r* values were assessed for significance using the following two-part method outlined in Dima et al. (2005). Firstly, the effective degrees of freedom (N_{eff}) were calculated, with estimation methods outlined in Leith (1973) and Jones (1975), to account for autocorrelation in the timeseries:

$$N_{eff} = N\left[\frac{1-r_1}{1+r_1}\right]$$

Here, N refers to the size of sample (i.e. length of time series) and r_1 is the first lag in the autocorrelation. Autocorrelation lag coefficients were calculated in R using the *acf* function applied to the product of the timeseries for which correlation is being tested (Dima et al., 2005). The N_{eff} was then used to calculate the Student's *t* statistic (von Storch and Zwiers, 1999):

$$t = r\left[\left[\frac{N_{eff} - 2}{1 - r^2}\right]\right]^{1/2}$$

where r refers to the correlation coefficient. The t-statistic was compared to the two-tailed critical value of t at the $p < 0.05$ significance level. All reported correlations are significant at the $p < 0.05$ significance level or greater unless otherwise indicated.

3.5. Coral Ba/Ca-river discharge calibration

Ba/Ca_{cor}-river discharge calibrations were calculated with a reduced major axis (RMA) regression and 95% confidence intervals reported on the slope and intercept. RMA regressions were calculated in R using the *lmodel2* package (listed as a Standardized Major Axis regression, SMA, in *lmodel2*). RMA regressions minimize the distance from both the x and y direction to the trendline for each data point, permitting a symmetrical application of the regression equation allowing one to calculate either Ba/Ca_{cor} or river discharge as the dependent variable. One limitation is that calculation of an RMA regression does not permit the significance testing of the slope (Leduc, 1979; Legendre and Legendre, 1998), however the significance of the correlation coefficient is tested (e.g. Correndo et al., 2017). We performed the RMA regressions on monthly, annual average, wet season average, and dry season average Ba/Ca_{cor} values and assessed regression skill via root mean square error (RMSE). The calibrations presented here can be considered an update to the Brenner et al. (2017) calibration, which was calculated based strictly on IC4A-2 from an age model based only on coral $\delta^{18}O$ and with Winter-Spring-Summer-Fall seasonality. Regressions with statistically significant r values were applied to Ba/Ca_{cor} to generate reconstructions. Note that since the regression window is limited to 25 years (~1971–1996 CE) for IC4A-and 12 years (~1971–1983 CE) for S1, if Ba/Ca_{cor} values from the total coral record fell below the range of the regression, negative river discharge values were generated. These values, were manually converted to 0 m^3/s (Brenner et al., 2017). Additionally, a first order long-term trend was calculated via an ordinary least squares regression for all Ba/Ca_{cor} data treatments that yielded a significant correlation with river discharge. The significance of the trend was evaluated via their r with consideration of N_{eff} and the slopes with their 95% confidence interval were calculated.

4. Results

Coral IC4A-2 provides a Ba/Ca_{cor} record from 1917.9 to 1996.5 and S1 Ba/Ca_{cor} from 1917.9 to 1984.3, with a ~66-year overlap (Fig. 3). Summary statistics calculated based on both the total coral records and overlapping period between the two records are listed in Table 1. The average Ba/Ca_{cor} during the entirety of the S1 and IC4A-2 records were 4.89 ± 0.62 (95% Confidence Interval: 0.04) μmol/mol and 5.16 ± 0.54 (95% Confidence Interval: 0.04) μmol/mol and, respectively (Table 1). When only considering the portion of IC4A-2 that overlaps with S1 from 1984.29 to 1917.96, the average IC4A-2 Ba/Ca_{cor} value was 5.13 ± 0.53 (95% Confidence Interval: 0.04) μmol/mol.

The average monthly offset (±1 standard deviation) between the two records is 0.41 ± 0.30 μmol/mol with 65.5% (n = 522) and 1.5% (n = 12) exceeding the Wu (0.24 μmol/mol) and JCp-1 (1.18 μmol/mol) thresholds, respectively (Fig. 4). Threshold exceedance for the annual average (annual amplitude) records yielded an average of 0.30 ± 0.18 (0.36 ± 0.27) with 63.6% (n = 42) (69.7% (n = 46)) of the overlapping record surpassing the Wu threshold. No annual average or annual amplitude offsets exceeded the JCp-1 threshold. The wet season offset is 0.34 ± 0.21 μmol/mol and dry season offset is 0.30 ± 0.21 μmol/mol, within error of one another. While 65.1% (n = 43) of the wet and 55.2% (n = 37) of the dry season values exceed the Wu threshold, no wet or dry season offsets exceeded the JCp-1 threshold (Fig. 4). During the overlapping period, the two corals were correlated at the monthly (12 points per year) (r = 0.70), annual (r = 0.65), annual amplitude (r = 0.77) wet season (r = 0.67), dry season (r = 0.55) scales (Fig. 3, Table 2).

The IC4A-2 and S1 Ba/Ca_{cor} records overlap with our composite instrumental river discharge from 1971.04 to 1996.54 and 1971.04–1984.29, respectively. During these two periods, the composite

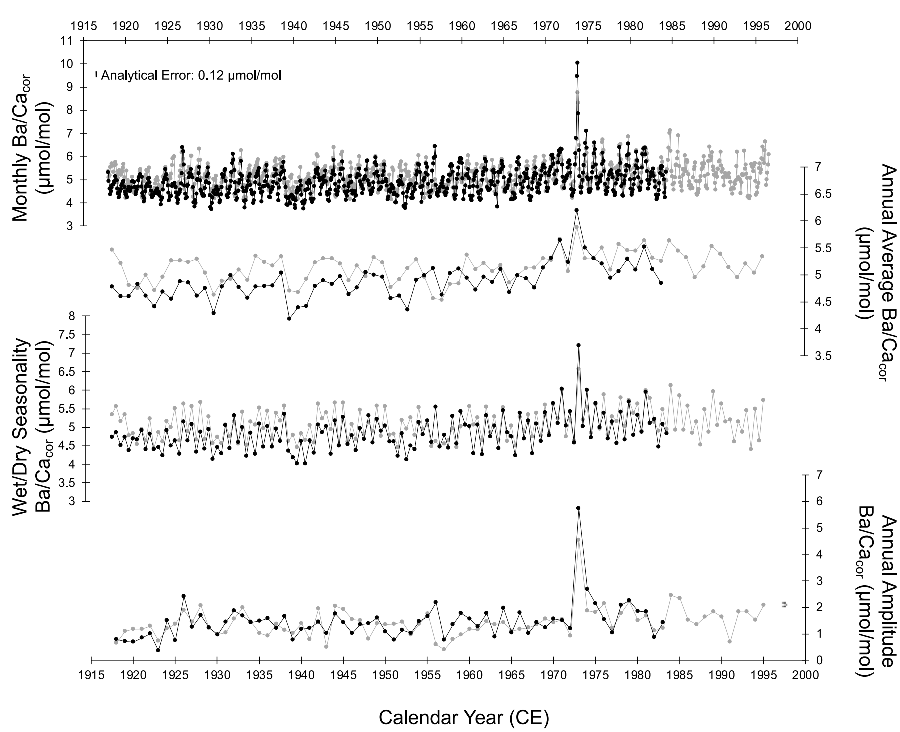


Fig. 3. Ba/Ca_{cor} records generated from S1 (black) and IC4A-2 (grey) monthly, wet-dry seasonality, annual averages, and annual amplitude values. Vertical error bar (upper left corner) represents one standard deviation of our in-lab standard (Wu ZMT LDEO). See Table 1 for summary statistics and Table 2 for correlations between S1 and IC4A-2 correlations.

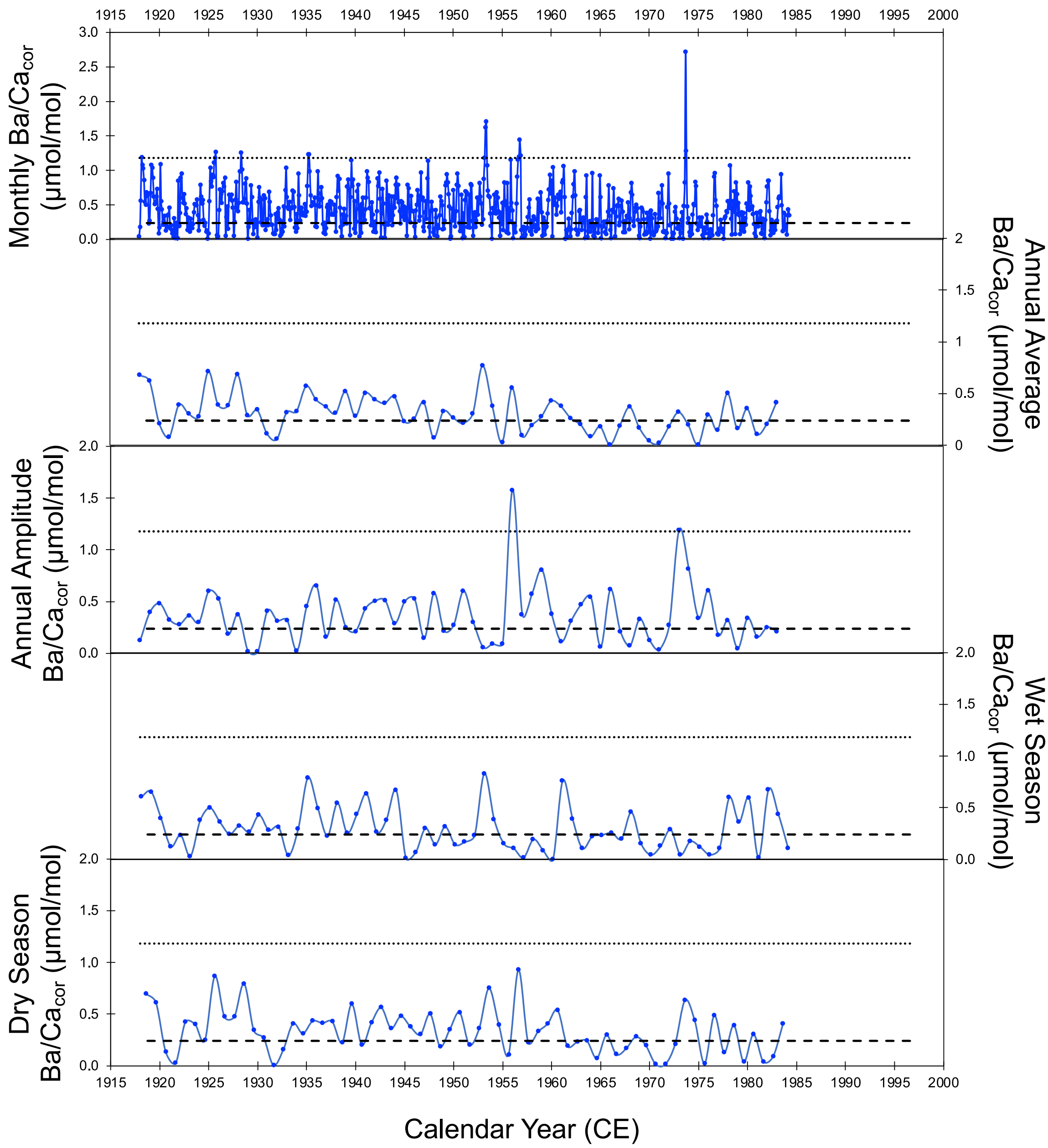


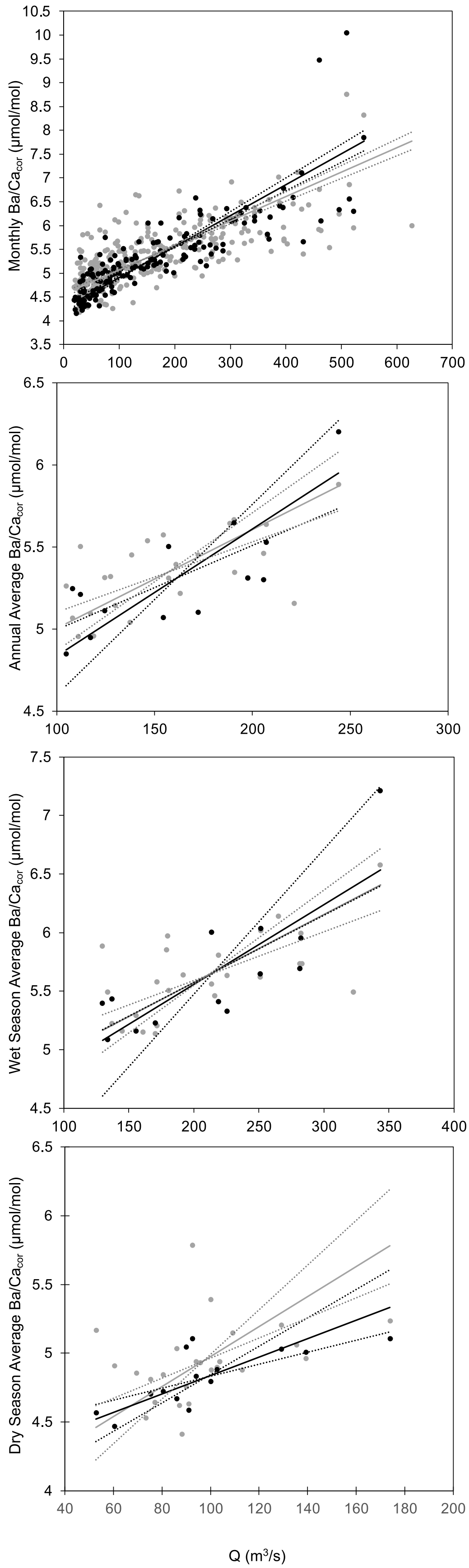
Fig. 4. Ba/Ca$_{cor}$ offset records (i.e. absolute difference between S1 and IC4A-2) calculated based on monthly, annual average, annual amplitude, wet season average, and dry season average time-matched S1 and IC4A-2 values. The dashed and dotted lines represents 2σ analytical error based on lab standard precision, representing the Wu and JCp-1 thresholds, respectively.

Table 2
Pearson Product-Moment Correlation Coefficients (*r*) for S1 and IC4A-2 Ba/Ca$_{cor}$ and each coral compared with the composite river discharge (Q) record. N$_{eff}$ are provided in parentheses. All values are significant at $p < 0.05$ unless the correlation is italicized.

Resolution	S1 – IC4A2	IC4A-2 - Q	S1 - Q
Monthly Average	0.70 (75)	0.73 (36)	0.84 (17)
Annual Average	0.65 (21)	0.60 (40)	0.77 (20)
Annual Amplitude	0.77 (55)	0.47 (33)	0.68 (14)
Wet Season Average	0.67 (30)	0.61 (41)	0.81 (13)
Dry Season Average	0.55 (39)	*0.32 (30)*	0.75 (17)

river discharge record yielded an average wet season value of 213.2–218.5 m^3/s and dry season value of 97.44–97.72 m^3/s, for IC4A-2 and S1, respectively. (Table 1). We evaluated variability in proxy sensitivity through our Pearson Product moment correlation coefficients while considering the reduced sample size (N$_{eff}$) due to autocorrelation. The Ba/Ca series from the two corals were well correlated to river discharge when comparing the monthly, annual average, and annual amplitude data treatments (Table 2). At seasonal (i.e. wet-dry) resolution, the two corals also correlate to river discharge with $r_{S1} = 0.91$ and $r_{IC4A\text{-}2} = 0.79$. However, decomposing the record to examine wet and dry seasons separately indicates a more complex relationship. While the wet season Ba/Ca$_{cor}$ records from both corals were significantly correlated to river discharge, only S1 dry season Ba/Ca$_{cor}$ was correlated to dry season river discharge.

RMA regressions were calculated for all data treatments (Fig. 5) with calibration equations and associated RMSE are reported in Table 3. The RMA regression based on dry season values in IC4A-2 did not yield a significant correlation to river discharge, and therefore this data



(caption on next column)

Fig. 5. S1 (black) and IC4A-2 (grey) Ba/Ca$_{cor}$ vs. Q at monthly, annual average, wet season average and dry season average resolution with Reduced Major Axis (RMA) regressions. Note that the IC4A-2 dry season-based regression is not statistically significant, based on the *r* value while all others are significant at the $p < 0.05$ level or better. The 95% confidence intervals are depicted for S1 (black dotted lines) and IC4A-2 (grey dotted lines). Associated Calibration equations are provided in Table 3.

treatment was omitted from the reconstruction (Fig. 5). RMSE was lower (regression skill higher) for all S1-based regressions compared to IC4A-2, except when considering monthly resolution. Additionally, there were subtle but statistically significant positive trends calculated through reconstructed river discharge for all data treatments (Fig. 6, Table 4). For each data treatment, the rate of increase (i.e. slopes) are not significantly different between the two corals (Table 4).

5. Discussion

5.1. Regional replication evaluation

We evaluated whether inter-colony Ba/Ca$_{cor}$ variability could impact the development of a coherent description of regional climate. For all data treatments, at least 55% of each record exceeded the Wu threshold (Fig. 4), indicating that the calculated offset cannot solely be explained by measurement uncertainty. Specifically considering monthly resolution, a temporal lag, which could be due to systematic errors in chronology development or water circulation leading to GoC heterogeneity, could explain some of the offsets between the coral records. However, when we used a lag of ±1 to ±3 months this did not notably reduce offsets, with a maximum decrease of 4% in Wu threshold exceedance.

Therefore, a geochemical offset between the corals might exist, at least during approximately half the overlapped period. However, the differences are not consecutive and appear to diminish towards the present. This becomes apparent when we divide the records into pre and post 1950 portions. The difference is most stark when considering annually resolved Ba/Ca$_{cor}$, with only 44% of the post-1950 record exceeding the Wu threshold compared to 81% exceedance in the pre-1950 portion. This could mean that the conditions influencing Ba/Ca$_{cor}$ are on average becoming more homogeneous in the GoC towards the present. Generally, Wu threshold exceedance was due to larger Ba/Ca$_{cor}$ values recorded in IC4A-2 compared to S1 (Fig. 3). However, during the 1955-56 and the 1973-74 La Niña events the Ba/Ca$_{cor}$ offset dramatically increased, with larger Ba/Ca$_{cor}$ reported by S1. During these events, the differences recorded by the two corals might indicate temporary heterogeneity in GoC [Ba/Ca$_{seawater}$], or greater river discharge or sediment load effects in the Secas Island area of the GoC.

Due to 5x greater (0.65 vs. 0.12 μmol/mol) analytical error associated with JCp-1 analyses, we rely on the Wu threshold to identify potential geochemical offsets. Only monthly and annual amplitude Ba/Ca$_{cor}$ ever exceeded our JCp-1 threshold, and at a meager 1.5% and 3.0% of the record, respectively. Our JCp-1 Ba/Ca results and the published Ba/Ca results of replicate analyses of JCp-1 (e.g. Hathorne et al., 2013) indicate an uncertainty that would also make it difficult to evaluate even the large seasonal changes in Ba/Ca$_{cor}$. Importantly, the difference in analytical uncertainty based on Wu ZMT LDEO versus JCp-1, supports the need to re-evaluate the use of JCp-1 as a community standard for Ba/Ca$_{cor}$ measurements. At present, JCp-1 may not be the ideal standard for detailed Ba/Ca$_{cor}$ investigation and other standards should be considered.

Furthermore, it is not uncommon for replicate *Porites* corals to have Sr/Ca or $\delta^{18}O$ offsets (i.e. difference of the mean), even when they are from the same species of coral and/or are located in close proximity to one another (e.g. Linsley et al., 1999; Suzuki et al., 2005; McGregor et al., 2011). These offsets have been attributed to vital effects (i.e. sensitivity of biological processes associated with calcification) or even subtle variations in ocean currents and/or heterogeneity in ambient

Table 3
RMA-based calibration equations for S1 and IC4A-2 using all data treatments with associated root mean square error (RMSE). Note that the equation based on IC4A-2 dry season averages is not statistically significant based on its *r* value (denoted with asterisk in bottom row). The CI range represents the 95% confidence interval.

Temporal Resolution	Coral	Calibration Equation	RMSE
Monthly	S1	0.006 (CI:0.006–0.007) × Q+4.3 (CI:4.17–4.35)	72.3
Monthly	IC4A-2	0.005 (CI:0.005–0.006) × Q+4.6 (CI:4.49–4.61)	47.5
Annual Avg.	S1	0.008 (CI:0.005–0.012) × Q+4.1 (CI:3.44–4.48)	16.6
Annual Avg.	IC4A-2	0.006 (CI:0.004–0.008) × Q+4.4 (CI:4.02–4.67)	97.3
Wet Season Avg.	S1	0.008 (CI:0.005–0.012) × Q+3.8 (CI:3.0–4.4)	39.9
Wet Season Avg.	IC4A-2	0.006 (CI:0.004–0.008) × Q+4.4 (CI:3.9–4.8)	52.1
Dry Season Avg.	S1	0.007 (CI:0.004–0.010) × Q+4.2 (CI:3.8–4.4)	20.6
Dry Season Avg.	IC4A-2	0.011 (CI:0.007–0.016) × Q+3.9 (CI:3.4–4.2)*	30.3

conditions that was previously unknown or underappreciated. The presence of a geochemical offset may not exist for all coral species and Ba/Ca$_{cor}$ offsets have not been as thoroughly explored. However, LaVigne et al. (2016) noted that co-located coral colonies did yield taxon-specific Ba/Ca$_{cor}$ findings in the Gulf of Panama. Therefore, a thorough evaluation of inter-colony variability is necessary whenever a network or coral replication study is developed.

At this stage, we can begin to ascertain whether differences between the two records exist but attributing a source can only be speculative. Due to analytical error and to avoid over interpretation, it is difficult to confidently assert whether and why a Ba/Ca offset exists between S1 and IC4A-2. The implication being that we cannot unequivocally determine whether the Ba/Ca series generated from these corals can be used to reconstruct a GoC-wide river discharge signal as opposed to more local changes. If a geochemical offset does exist, the difference between the two records could be due to either colony-specific vital effects and/or [Ba/Ca$_{seawater}$] heterogeneity within the GoC. The [Ba/Ca$_{seawater}$] variability could be related to the Ba source or GoC circulation. However, without additional instrumental data, *in situ* data, or replicate cores from the same reef, it is difficult to narrow down these possibilities. While S1 and IC4A-2 qualitatively appear to replicate one another, we cannot rule out that a true geochemical offset does exist between these two Ba/Ca$_{cor}$ records.

Therefore, if we were to combine these two coral records into one composite record, i.e. averaging time-matched Ba/Ca$_{cor}$, it would be prudent to normalize these records first, as is typical in the paleoceanography field (e.g. Ren et al., 2003; Corrège, 2006; Wu et al., 2014). Here, this process would include removing the mean Ba/Ca$_{cor}$ from the two corals during the overlapping period, either by subtraction or division of the mean from each. A normalized, composite record would provide insight into relative changes in Ba/Ca$_{cor}$ and the GoC rather than absolute ones (See supplementary material for normalization methods and composite). That being said, the decision to normalize prior to combining one's own geochemical records can be made on a

Table 4
Slope and Pearson Product-Moment Correlation Coefficients (*r*) for long-term trend (ordinary least squares) of S1 and IC4A-2 river discharge (Q) reconstructions. All trends are statistically significant with the T stat exceeding T crit in consideration of N$_{eff}$ (see methods in main text).

Temporal Resolution	Coral	Slope (±95% Confidence Interval, Q × Calendar Year-1)	*r*
Monthly	S1	1.57(±0.31)	0.33
Monthly	IC4A-2	0.90(±0.28)	0.2
Annual Avg.	S1	1.39 (±0.44)	0.62
Annual Avg.	IC4A-2	0.75 (±0.42)	0.37
Wet Season Avg.	S1	1.62 (±0.56)	0.58
Wet Season Avg.	IC4A-2	1.00 (±0.58)	0.37
Dry Season Avg.	S1	0.97 (±0.42)	0.5

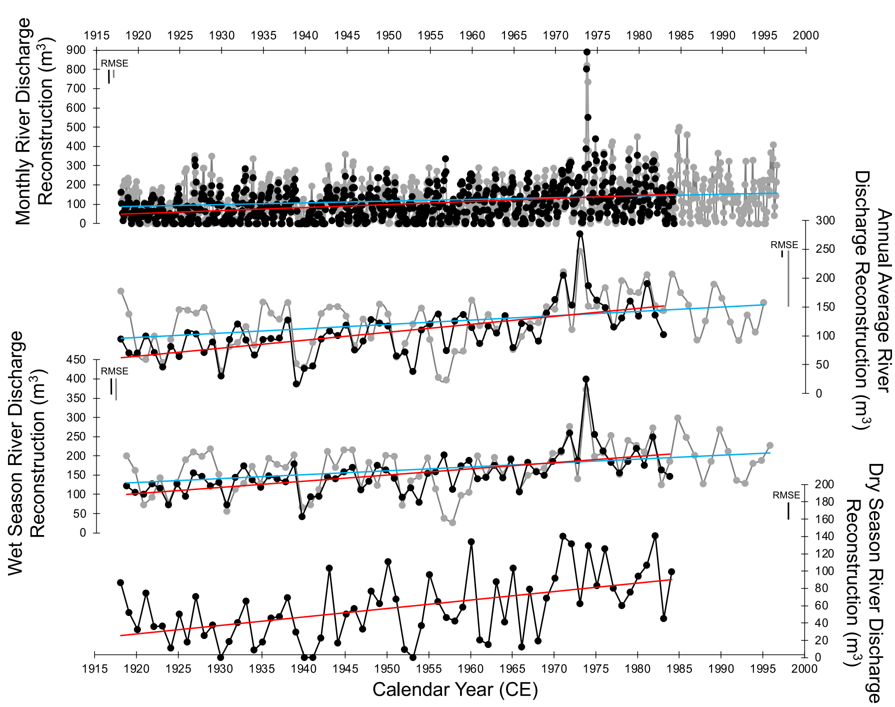


Fig. 6. Reconstructed river discharge records and long-term trends generated from S1 (black) and IC4A-2 (grey) at monthly, annual average, wet season average, and dry season average resolution. The vertical error bars reflect regression skill as RMSE (see Table 3). The reconstructions are calculated with the RMA regressions presented in this study (Table 3; Fig. 5) and trends (S1: red, IC4A2: blue) are calculated for the overlapping period between S1 and IC4A-2 via simple ordinary least squares. See Table 4 for information on trend slope and correlation. There is no IC4A-2 dry season reconstruction since the calculated RMA regression was not statistically significant for this data treatment. RMSE error indicated as vertical bars for S1 (black) and IC4A-2 (grey) reconstructions at each temporal resolution.

study-by-study basis, depending on one's confidence in ability or need to discern a true geochemical offset from analytical uncertainty. Ultimately, this lack of clarity signals the need to further refine community-wide Ba/Ca_{cor} ICP-OES-based standards if we endeavor to robustly evaluate replication.

5.2. Ba/Ca_{cor}-river discharge calibration Evaluation and recommendations

The purpose of the RMA-based calibration is to quantify the relationship between Ba/Ca_{cor} and river discharge. The calibration then provides the opportunity to convert and interpret Ba/Ca_{cor} in terms of river discharge when instrumental records are unavailable. The results of our correlation testing indicated that RMA regressions would be appropriate to establish a proxy calibration equation for all data treatments except the IC4A-2 dry season. Importantly, the RMA regression permits a symmetrical application of the calibration equation (Smith, 2009). In deference to the offset uncertainty discussed in section 5.1, our RMA regressions and reconstructions are based on the individual Ba/Ca_{cor} records, rather than a composite. A calibration based on a composite record based on more than two corals, a weighted least squares regression can be considered, with Ba/Ca_{cor} data points with lower error (e.g. standard deviation, range) more heavily weighted.

From the intra-coral perspective, there does not appear to be a statistically significant difference between regressions based on different temporal resolutions (Fig. 5, Table 3). This suggests that temporal resolution of Ba/Ca_{cor} doesn't substantively alter the proxy relationship, at least when averaged from monthly values. This finding is not entirely unexpected. For example, Mohtar et al. (2021) analyzed cores two *Porites* spp. cores from the Federated States of Micronesia (Kosrae Island and Woleai Atoll). An intra-coral comparison of monthly, wet season, dry season, and annual average resolution-based Sr/Ca-SST calibrations did not yield significantly different slopes. The pattern held for the $\delta^{18}O_{seawater}$-SSS calibrations, except the wet and dry season-based regressions at Woleai Atoll appear to be beyond 1σ error of one another (Mohtar et al., 2021).

While we are unable to conclusively identify the presence or absence of a Ba/Ca geochemical offset for our various coral data treatments, associated inter-coral regressions for annual average and wet season records are within error of one another. This suggests that there might be some possibility to generate gulf-wide conclusions regarding river discharge with our two coral Ba/Ca_{cor} records. It should be noted that in the GoC river discharge data are limited and, to our knowledge, there are no investigations of $[Ba/Ca_{seawater}]$ in the GoC, with only a few measurements in the Gulf of Panama (LaVigne et al., 2016). Therefore, we can only assert that our Ba/Ca_{cor}-river discharge relationship is correlational. In addition, the influence of non-climate-related variability on Ba/Ca_{cor}, such as land use changes, is unconstrained. Future work will aim to flesh out the coral network in the GoC with additional Ba/Ca_{cor} records, ideally to more clearly reconstruct river discharge throughout the gulf. This will include samples closer to mainland Panama so sensitivity of the Ba/Ca_{cor}-river discharge can be compared with distance from the coast in the GoC. Additional valuable samples could include replicate cores from the same reef, or at least in close proximity to one another to address the spatial variability vs. vital effect conundrum discussed earlier.

One outcome of this study is to establish a framework for how to evaluate corals that can be assembled to develop a regional network in the GoC. Thus far we have 1) established Ba/Ca_{cor} records are correlated at a variety of temporal resolutions, 2) evaluated a potential offset in Ba/Ca_{cor} to the best of our ability, and 3) calculated RMA-based calibration equations for data treatments that were statistically significantly correlated to river discharge. Replication of trace metal records is critical, and recommended by others investigating river discharge, as reproducibility cannot be assumed (Lewis et al., 2018).

The fourth component of our evaluation process is to reconstruct river discharge through application of our calibration equations (Fig. 6). Since the data presented here represent the initial stage of our GoC network, with further analysis of S1 and other coral cores to be included in the future, interpretation of the reconstruction is not the primary objective here. Instead, our focus is how to calculate and apply Ba/Ca_{cor} calibration equations.

We can, however, make some preliminary assessments. It is valuable to reconstruct river discharge at different temporal resolutions. There are subtle but significant positive trends over the record's overlapping period in the monthly, annual, wet, and dry season river discharge reconstructions. The positive slopes indicate an increase in river discharge over time (See Fig. 6, Table 4). Qualitatively, this is particularly apparent since ~1965 CE (Fig. 6). Additionally, there was a decrease in the number of negative reconstructed river discharge values that needed to be manually converted to 0 m^3/s in the recent period, further suggesting an increase in terrestrial material reaching the GoC reefs. This interpretation assumes that all Ba/Ca_{cor} variability can be attributed to river discharge rather than vital effects or other environmental drivers. Longer reconstructions will also permit more in-depth quantification of changes to river discharge and the hydrologic cycle and can include more robust techniques such as singular spectrum analysis. Additionally, all reconstructions appear to yield a peak in river discharge at the time of the 1973-74 La Niña, which are typically periods of enhanced wetness in Panama (Fig. 6). This peak in Ba/Ca_{cor}-derived river discharge exceeds what is captured by the instrumental data and could mean that Ba/Ca_{cor} is capturing changes in sediment load, not strictly river discharge. We speculate that during this period, an additional Ba source may be influencing Ba/Ca_{cor}, such as remobilization of Ba stored in marsh/mangrove sediments via flood waters (Coffey et al., 1997; Moore and Shaw, 2008). The remobilization of stored Ba in sediments may also be responsible for higher-than-expected Ba/Ca_{cor} values, according to our linear regressions (Fig. 5), during large flood events. It is possible, however, that the existing gauge system is not accurately capturing gulf-wide conditions.

Regression skill is higher for all S1-derived calibration equations, except at the monthly scale. The higher RMSE for IC4A-2 indicates that Ba/Ca_{cor} as a predictor of river discharge is generally less accurate than S1. This may be due to a few reasons. The available instrumental river discharge data might not reflect conditions at Coiba Island. There is a river on Coiba Island that discharges into the GoC near our coral record, however, we were not able to locate discharge data for this river. Again, potential vital effects could also be overprinting the IC4A-2 record more so than in S1.

In developing river discharge calibrations for a Ba/Ca_{cor} network, we recommend taking care when determining sample interval, and therefore temporal resolution, of coral slabs when hand drilling. In the case of S1, there is no statistically significant intra-coral difference between the regressions calculated based on annual average versus monthly or seasonal Ba/Ca_{cor}. However, that pattern does not hold for IC4A-2 as there is no statistically significant relationship between Ba/Ca_{cor} and river discharge during the dry season. During the dry season river discharge approaches 0 m^3/s and other sources of spatial variability could be dominating the IC4A-2 Ba/Ca_{cor} record. Therefore, if we limited sample drilling or data interpretation to the seasonal scale, results could have led to a misunderstanding of the Ba/Ca_{cor}-river discharge proxy. To that end, if absolute rather than relative change in river discharge is desired, colony-specific calibrations are likely most accurate. We acknowledge that this approach is not always possible, for example when coral records do not temporally overlap with instrumental data. In this case, we recommend normalizing data to calculate relative changes in river discharge.

Reconstructed river discharge records from coral Ba/Ca can be used to extend instrumental data. With longer records, we can uncover low frequency variability (i.e. decadal) and long-term trends in river discharge. The utility of reconstructed records can also extend beyond the summarization of seasonality in river discharge. Future work generating longer geochemical records can include a multi-proxy assessment of hydroclimate as well as defining anomalies or atypical behavior (e.g. atypical wet or dry seasons) and quantified identification and recurrence of El Niño events and other lower frequency variability.

5.3. Additional considerations to interpretation of Ba/Ca_{cor} in the GoC

Our interpretation of the Ba/Ca_{cor}-river discharge proxy assumes that [Ba] in estuaries along the Pacific coast of Panama largely exhibits conservative behavior and the major source of Ba to the GoC is via rivers. Generally, riverine Ba desorbs from sediment at low salinities, $\leq\sim5$ (Edmond et al., 1978; Li and Chan, 1979; D'Olivo and McCulloch, 2022). In some estuaries, [Ba] does appear to be a conservative tracer of salinity when waters exceed 10–15 (salinity units) (e.g. Coffey et al., 1997) and the salinity of the Gulf of Chiriquí (GoC) estuary, where our analyzed corals are from, is $>$ 30 salinity units.

Further, our interpretation of Ba/Ca_{cor} assumes there is no significant contribution of desorbed Ba from resuspension or introduction of Ba from other sources (e.g. upwelling, Shaw et al., 1998; Sinclair, 2005a). It is still possible, however, that Ba stored in intertidal marsh sediments or mangroves, which line the GoC, can contribute to the overall Ba supply when resuspended by storm water or periods of high flow (Coffey et al., 1997; Moore and Shaw, 2008). In tropical regions, mangrove forests, which are extensive along the GoC coast, where Ba and Mn can be released via surface water runoff and tidal exchange from anoxic pore-waters and sediments and marsh sediments (Mori et al., 2019; Moyer et al., 2012). Esslemont et al. (2004) attributed some variation in their Ba/Ca_{cor} signal to mechanical dredging and winds, however in the GoC's the Cordillera minimizes the wind risk. Conservative behavior has still been recorded in estuaries. For example in the Burdekin River estuarine mixing zone in Northeastern Australia, Ba exhibits conservative behavior in the flood-plume as it desorbs from sediments carried by the river (D'Olivo and McCulloch, 2022). The use of Ba/Ca_{cor} as a proxy for sediment load in the central Great Barrier Reef was supported by the desorption and conservative mixing (D'Olivo and McCulloch, 2022).

Generally, balancing the Ba budget in an estuary is extremely difficult, due to unquantified uncertainties, such as the aforementioned storage in marsh sediments and mangrove forests. We do not have the instrumental or *in situ* data to conclusively rule in or out many of these sources of Ba variability in the GoC. Therefore, it is extremely difficult to understand all estuarine and coastal Ba fluxes at our site. Since there is minimal impact of trade winds and a lack of human development immediately along much of the GoC coast, we speculate that, if they exist at our site, the most likely candidates confounding the Ba/Ca_{cor} signals are resuspension of stored sediments during high flow or storms or from sediments in mangroves and marsh sediments (e.g. Moore and Shaw, 2008; Santos et al., 2011). The uncertainty discussed here warrants site-specific investigation, with local calibrations when possible, for paleohydrologic evaluation.

6. Conclusion

Here we provide a framework for evaluating multiple Ba/Ca_{cor} records, evaluating geochemical offsets, and reconstructing river discharge. In the GoC, Ba/Ca_{cor} functions as an effective proxy for river discharge at various temporal resolutions. It is difficult to be perfectly confident in determining whether a geochemical offset is present between the various S1 and IC4A-2 data treatments as we are limited by analytical error. To address this uncertainty, we recommend evaluating the relationship between coral Ba/Ca_{cor} and river discharge with a colony-specific perspective. Alternatively, in this or other similar situations, if coral Ba/Ca_{cor} time-series are combined into a composite record and the presence of a geochemical offset cannot be ruled out, they should be normalized. This will instead result in the evaluation of relative rather than absolute river discharge variability. We acknowledge that the Ba/Ca_{cor} offsets identified here may not exist in all coral genera or locations. Omitting IC4A-2 dry season averages, all other coral Ba/Ca_{cor} data treatments exhibited a statistically significant relationship with river discharge. The preliminary river discharge reconstructions presented here indicate that extreme events (e.g. 1973-74 La Niña) can be captured in all temporal resolutions, with a positive linear trend calculated for all data treatments. This finding suggests a gradual increase in river discharge or sediment load over time.

The creation of additional and temporally longer Ba/Ca_{cor} records will permit a rigorous assessment of river discharge on the GoC, including protracted or contracted wet or dry seasons, lower frequency variability (e.g. Pacific Decadal oscillation), as well as climate phenomena such as ENSO. A multi-coral network in the GoC can be used to create a robust understanding of river discharge and also be used to identify any subtle nuance that may exist. With a significant economic impact via agriculture, drinking water supply, Panama Canal management, and hydroelectricity, it is imperative to thoroughly evaluate baseline hydroclimate to improve predictions and planning.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

A link to the data respository is provided in the Acknowledgements. This link will be populated once the paper is accepted.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csr.2023.105104.

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