Climatic Constraints on Growth Rate and Geochemistry (Sr/Ca and U/Ca) of the Coral Siderastrea stellata in the Southwest Equatorial Atlantic (Rocas Atoll, Brazil)

Heitor Evangelista, Abdel Sifeddine, Thierry Corrège, Jacques Servain, Émilie Dassié, R. Logato, Renato Campello Cordeiro, Chuan-Chou Shen, Florence Le Cornec, J. Nogueira, et al.

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Key Points:
- Pseudo wind stress and SST are key players in the modulation of coral Sr/Ca and growth at the Equatorial Atlantic
- Coral Sr/Ca (U/Ca) x SST linear regression was achieved for Rocas Atoll
- Presently, the Intertropical Convergence Zone has minor effect on coral growth at Rocas Atoll

Supporting Information:
- Supporting Information S1

Correspondence to:
H. Evangelista
evangelista.uerj@gmail.com

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H. Evangelista[1,2], A. Sifeddine[2,3], T. Corrège[4], J. Servain[3,5], E. P. Dassié[3], R. Logato[1,2], R. C. Cordeiro[2], C.-C. Shen[6], F. Le Cornec[3], J. Nogueira[1,2], B. Segal[7], A. Castagna[1], and B. Turcq[2,3]

[1]LARAMG/DBB/IBRAG/Uerj, Pavilhão Harold L. Cunha, Subsolo, Maracanã, Rio de Janeiro, Brazil, [2]Universidade Federal Fluminense/Instituto de Química/Departamento de Geoquímica/Programa de Pós-graduação em Geoquímica, Outeiro de São João Batista s/n, Centro, Brazil, [3]IRD-Sorbonne Universités, UMR LOCEAN (IRD, UPMC, CNRS, MNHN), Paris, France, [4]Université Bordeaux, UMR CNRS 5805 EPOC, Allée Geoffroy Saint-Hilaire, Pessac, France, [5]Visiting Scientist at Fundação Cearense de Meteorologia e Recursos Hídricos, Aldeota, Fortaleza, Ceará, Brazil, [6]High-precision Mass Spectrometry and Environment Change Laboratory/Depart. Geosciences, National Taiwan University, Taipei, Taiwan, Republic of China, [7]Departamento de Ecologia e Zoologia, CCB, Universidade Federal de Santa Catarina, Florianópolis, Brazil

Abstract Although relatively rare compared to similar latitudes in the Pacific or Indian Oceans, massive coral colonies are present in the Tropical/Equatorial Southwestern Atlantic Ocean. However, detailed geochemical compositions of these corals are still largely unknown. In this work, we present growth rates, Sr/Ca, and U/Ca ratios of the coral colony (*Siderastrea stellata*) sampled at Rocas Atoll, off the Brazilian coast. These variables are primarily affected by sea surface temperature (SST) at seasonal scale, and by wind stress at interannual scale, these results represent a broad new finding. A lower significance at the interannual time scale between Sr/Ca and U/Ca with respect to SST is attributed to the low SST amplitude closed to Equator. An investigation on the dependence of coral growth rates with respect to the "cloud shading effect" promoted by the Intertropical Convergence Zone (ITCZ) does not show significant influence. Additionally, rain seems to act on local geochemistry of Sr/Ca ratios and growth rate at the decadal scale.

1. Introduction

Seasonal to interannual climate variability in the tropical Atlantic is a complex issue impacted by multiple competing influences (Mélice and Servain, 2003). Most of these influences are regional, as for instance the meridional gradient in sea surface temperature (SST) linked to changes in trade winds (Covey & Hastenrath, 1978; Handoh et al., 2006; Servain, 1991; Zhang & Delworth, 2005) and the InterTropical Convergence Zone (ITCZ), a broad region of low atmospheric pressure, transporting water vapor produced by convection. Other influences may originate from remote regions as the Atlantic Multidecadal Oscillation (AMO), the El Niño Southern Oscillation (ENSO) (Covey & Hastenrath, 1978; Evangelista et al., 2007), or the North Atlantic Oscillation (NAO) (Marshall et al., 2001). One great motivation to detail the tropical Atlantic climate variability raises from its socio-economically importance on the surrounding continents, mainly the agriculture practices which are directly impacted by droughts in NE-Brazil and in the sub-Saharan Africa (the Sahel region) (Hetzinger et al., 2010).

Massive, long-lived corals are recognized as notable geochemical archives that allow detailed marine environmental and climatic reconstructions at different time scales (Corrège, 2006; Dassié et al., 2014; Giry et al., 2010; Linsley et al., 1994). Corals calcify a skeleton of aragonite, a form of calcium carbonate, ($CaCO_3$), in which trace elements (e.g., Sr, U, and Mg) are incorporated as a function of seawater physical-chemical parameters and of metabolic conditions. Therefore, elemental ratios such as Sr/Ca, U/Ca and others may provide high resolved past oceanographic and climatic conditions (Le Cornec & Corrège, 1997).

In the western equatorial Atlantic Ocean, corals are rare and previous work on coral geochemistry mainly concentrated on samples retrieved from Rocas atoll (Pereira et al., 2016, 2017). Rocas Atoll (Figure 1) is located 400 km South of the Equator and 266 km offshore the Brazilian coast (03°52′S; 033°48′W). It is the only atoll formation in the Southwestern Atlantic Ocean. Due to its remote location from the continent, the atoll remains

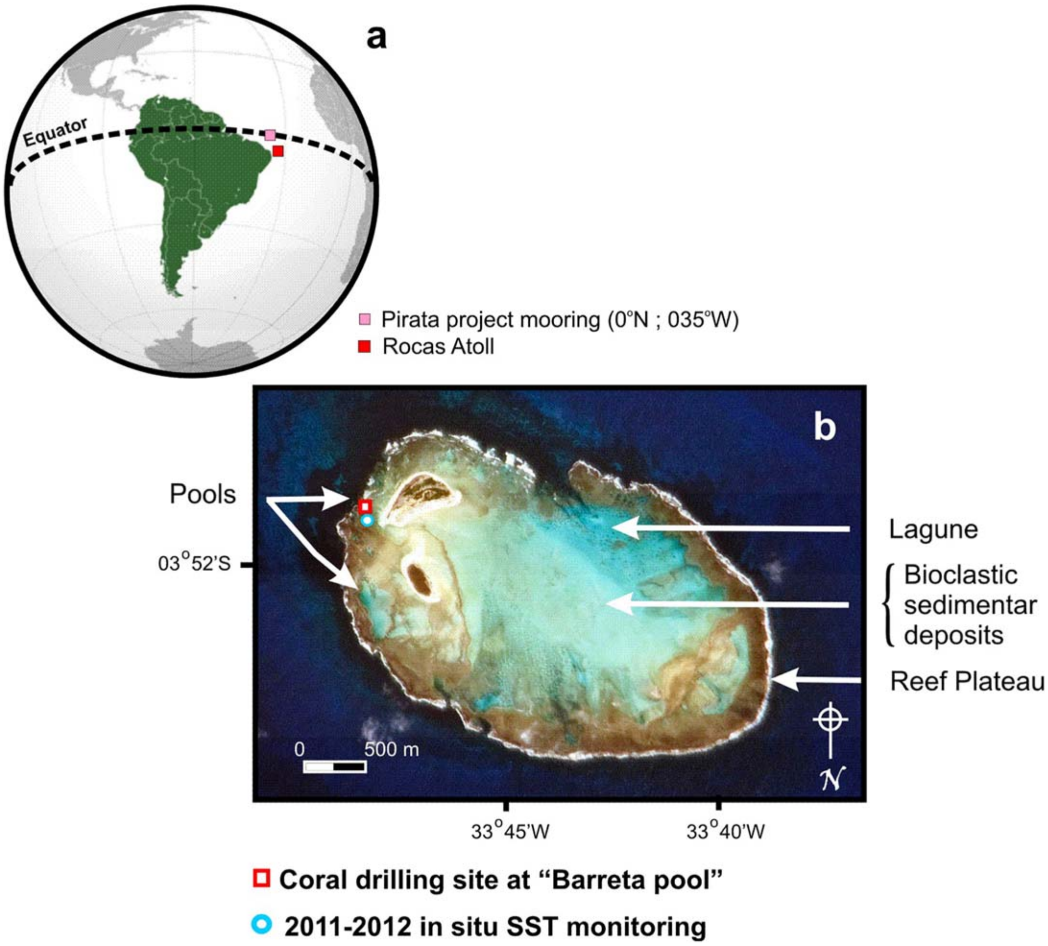

Figure 1. (a) Location of Rocas Atoll and the mooring (PIRATA project) where SST were measured in the West-Equatorial Atlantic; (b) the atoll main features, the coral drilling site and the location of *in situ* SST monitoring during 2011–2012.

largely undisturbed from human activities. The present study presents seasonal to interannual coral growth and trace element ratios (Sr/Ca and U/Ca) of a coral core (*Siderastrea stellata*) over the 1970–2009 time period, and investigates the influence of local, regional and remote meteo-oceanic conditions on these parameters.

We first present in section 2 the main geological and climatological characteristics of Rocas Atoll, then we provide detailed information about how the coral core was sampled and analyzed. Besides the coral database we used some available meteo-oceanographic parameters from the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) project (Bourlès et al., 2008), the National Centers for Environmental Prediction (NCEP) Reanalysis, the SERV (Servain et al., 1985) and FUNCENE (Meteorology and Water Resources Foundation of Ceará State/Brazil) databases.

Two key questions are addressed herein: (1) what is the influence of local to large-scale meteo- oceanographic modes of variability on the coral record? ; and (2) how changes in the ITCZ displacement may impact coral growth rates? The ITCZ presence is related to lowering solar radiation reaching the surface and changing in winds, precipitation, and SST patterns. Interpretations raised from this work provide the basis for future paleoclimate reconstruction to be conducted at Rocas Atoll. Main results are detailed and discussed in section 3.

2. Materials and Methods

2.1. General Characteristics of Rocas Atoll

2.1.1. Basic Geomorphology/Geology of Rocas Atoll

Rocas atoll is located in the Fernando de Noronha submarine ridge off the northeastern Brazilian coast (Figure 1). It is an ellipsoidal atoll, 3.7 km long (E-W) and 2.5 km large (N-S). The ridge is an island chain composed of seamounts, one guyot, one atoll, and several islands, all aligned in an approximate east-west direction extending from 032° to 036°W and from 3° to 4°S. Rocas Atoll is rising 4 km from the ocean floor (Cordeiro et al., 2013; Kikuchi & Leão, 1997). The Holocene geological sequence of Rocas Atoll show a predominant coralline algae structure, formed by corals, encrusting foraminifera *Homotrema rubrum* and vermetid gastropods. It is estimated that the current reef growth began about the mid-Holocene (~4.8 ky BP) with vertical accretion rate (VAR) varying from 1.5 to 3.2 m ky^{-1} (Kikuchi & Leão, 1997). VAR varied in both time and space, with the older part of the reef (3,500-2,600 year BP), and the younger one (1,000–500 year BP) growing faster than the intermediate section (2,500-490 year B.P.) (Gherardi & Bosence, 2005).

2.1.2. Living Resources of Rocas Atoll

Today, the reef structure is composed of various encrusting organisms: coralline algae, vermetid gastropods, encrusting foraminifera (*Homotrema rubrum; acervulinids*), polychaetes worm tubes, corals, mollusks, sponges, and cemented sediments. Coralline algae constitute the primary builders of the reef, with *Porolithon cf. pachydermum* being the most significant coralline algae genus (Gherardi & Bosence, 1999, 2001). Fifteen species of corals have been described among which six are endemic to the Brazilian coast. Corals mostly occur along the 200 m wide entrance channel of the northern side of the atoll and along the narrower channel on the western side (Figure 1).

2.1.3. Regional Climatology of Rocas Atoll

Rocas Atoll is located in the western part of the Atlantic warm pool (Cintra et al., 2014; Kikuchi & Leão, 1997). The close proximity to the Equator makes the surface ocean relatively warm throughout the year, with a 2°C SST-seasonal range from ~26°C in August-September (end of austral winter) to ~28°C in March-April (end of austral summer). The interannual SST variability also presents a low amplitude (<1.5°C) (Servain et al., 1985). In this region, the surface wind flows predominantly from the south-east (~50% and ~70% during austral summer and austral winter respectively) and from the east (~35% and 25% during austral summer and winter, respectively), with an annual average of the wind velocity around 11 m s^{-1} (Höflich, 1984). The pseudo wind stress (PWS) which is the shear stress exerted by the wind on the ocean surface, is the product of the wind vector and the wind speed. Seasonal and interannual PWS variability range from ~10 to 28 m^2 s^{-2}, respectively (Servain et al., 1985). Associated to this ocean-atmosphere surface dynamics, turbulent processes in the upper ocean close to the atoll are significantly stronger during the austral winter than during summer time. ITCZ seasonal displacement also affects Rocas Atoll climatology. At the end of summer (March-April), when the SST is warmer and the pseudo wind stress more unstable (~15 m^2 s^{-2}), the ITCZ southern edge reaches Rocas Atoll. This displacement of the ITCZ brings a cloud cover condition over the atoll accompanied by increased precipitation and humidity, and reduced incoming solar radiation and salinity (Servain et al., 2014). During winter time (August-September), the ITCZ is displaced northward around 12°N–15°N, leading to opposite climatic conditions (Servain et al., 1985) (Figure 2). Cloudiness has an impact on the daytime photosynthetically active radiation as demonstrated over the Great Barrier Reef by Leahy et al. (2013). Coral symbiont algae (zooxanthellae) use the sunlight for photosynthesis; therefore changes in solar radiation flux influence coral development, and thus growth rate.

2.2. Coral Species Presentation

The coral genus used in this study is *Siderastrea*. This genus has been widely used in paleo-oceanographic studies from Central America, the Caribbean (e.g., Gischler & Oschmann, 2005; Guzmán & Tudhope, 1998; Reuer et al., 2003), and along the African coast (Moses et al., 2006a, 2006b). Two species of *Siderastrea* occur in Brazil, namely *Siderastrea radians*, which occurs also in the Caribbean, and *Siderastrea stellata*, which is endemic to the Brazilian coast (Laborel, 1969). Following the differentiation method proposed by Menezes et al. (2014) we were able to identify our coral as *Siderastrea stellata*. This species is widely distributed along the Brazilian coast, ranging from the State of Maranhão, on the right margin of the Amazon River delta, down to the Cabo Frio region, in Rio de Janeiro State (Hetzel & Castro, 1994). *Siderastrea stellata* also occurs offshore of the Fernando de Noronha Island and inside Rocas Atoll, where it represents by far the most dominant species (Echeverría et al., 1997). *Siderastrea stellata* are massive coral colonies having star-like polyps of large diameter (~3.2 mm in average). They are commonly found in shallow waters ranging from 3 to 10 m depth, mostly on horizontal substrates (Segal & Castro, 2000). Colonies rarely reach 30 to 40 cm in diameter, but there are reports of larger colonies along the coast of Armação dos Buzios, Rio de Janeiro State (Oigaman-Pszczol & Creed, 2003). *Siderastrea stellata* is well resistant to intense sedimentation fluxes and hydro-dynamism (Chevalier, 1987), and colonies living in sandy or gravel substrates have been observed in reefs along the cost of Bahia State and Rio Grande do Norte State.

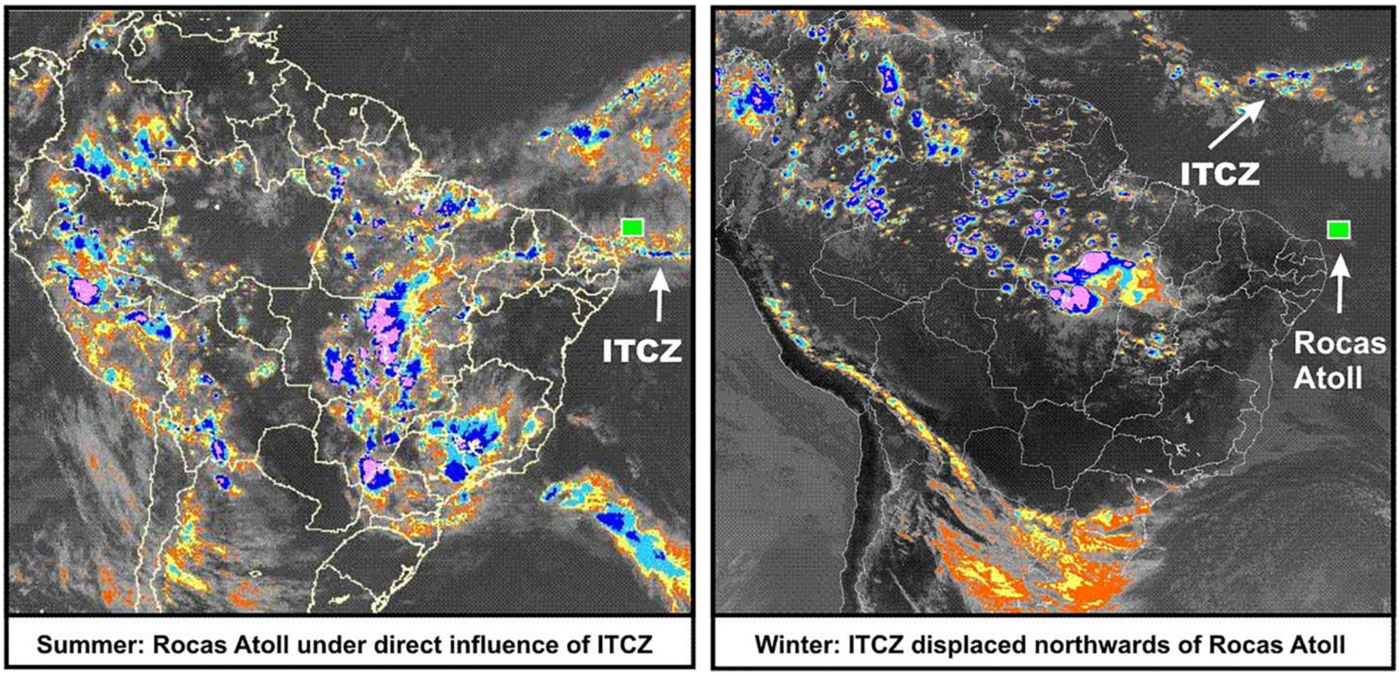

Figure 2. Typical Intertropical Convergence Zone (ITCZ) position with respect to Rocas Atoll during (a) austral summer and (b) austral winter (b). Color palette denotes precipitable water. (Images are from the Meteosat image gallery at http://www.cptec.inpe.br/).

2.3. Coral Drilling

In November 2009, one coral core was retrieved from a massive coral colony of *Siderastrea stellata*, as part of two Brazil-France projects RECORD (Reconstructing the Climate from cORal Drilling) and CLIMPast as well as the Laboratoire Mixte International (LMI)/PALEOTRACES. The coral sampling at Rocas Atoll was authorized by ICMBio (Register Ibama: 3887527). The drilling was performed along the maximum growth axis of the colony (vertical axis), using a pneumatic gun attached to a hollow steel drill ($\sim$ 6 cm internal diameter) with carbide cutters at one end. The total length of the coral core is 34.3 cm and consists of three continuous fragments. The coral was collected at a location known as "Barreta" (Figure 1), from a colony growing at about 2 m depth during low tide. Coral colony diameter ranged from 30 to 35 cm. Coral core was cut in half with a saw to produce a 1.5 cm thick slab (Figure 3a). This slab was washed with Milli-Q water, in a sonicated bath for 30 minutes before drying in oven with constant temperature of 40°C for 24 hours. The sample is curated at the *Laboratório de Radioecologia e Mudanças Globais* (LARAMG) of Rio de Janeiro State University - Brazil with the identification SID2. Coral slab was screened for possible diagenesis using a MEV + EDS technique at the *Institut de Recherche pour le Développement* (IRD). No sign of secondary recrystallization or partial dissolution processes were visible in our sample; a description of this diagenesis study is presented in Logato (2011).

2.4. Coral Chronology

The coral core slabs were X-rayed at HUPE/Rio de Janeiro State University (Brazil). Images were digitalized and their original contrasts were slightly modified to enhance light and dark growth bands. Coral growth bands were counted by naked eye, to produce a chronology. A succession of one light and one dark band corresponds to one year of coral growth (Knutson et al., 1972). We marked by a yellow line (Figure 3b) each annual dark band and used those bands to count down the number of years (Figure 3b). The coral colony was collected with a live top, thus the topmost age is known, it is November 2009. The coral sample spanned 40 years covering the period from 1970 to 2009.

To validate the coral growth chronology, the coral core was dated by U-Th technique at the High-precision mass Spectrometry and Environmental Change laboratory (HISPEC), Department of Geosciences, National Taiwan University (NTU). Four sub-samples (0.09–0.15 g each) were taken from layers of the coral core, then cleaned again with ultrasonic methods and processed for dating (Shen et al., 2003, 2008, 2012). U-Th isotopic compositions and contents of the subsamples were analyzed on a multi-collector inductively-coupled

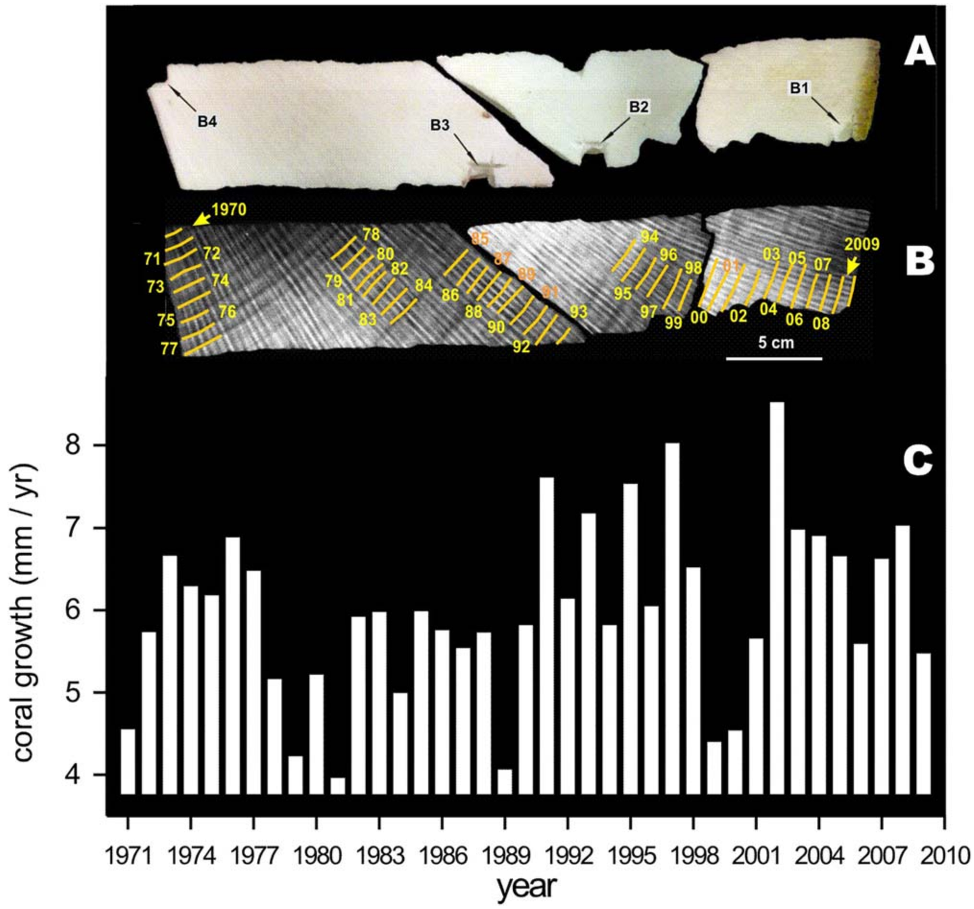

Figure 3. (a) Coral pieces. B1, B2, B3 and B4 are locations where sub-samplings for U-Th dating analyses were taken; (b) X-Ray image of *Siderastrea stellata* core with annual growth bands defined. Chronology was taken from the year of sampling (2009); (c) coral growth rate variability.

plasma mass spectrometer (MC-ICP-MS) with single secondary electron multiplier protocols (Shen et al., 2012). Uncertainties in the U-Th isotopic data and ^{230}Th dates are given within two standard deviations of the mean, unless otherwise noted (Table 1). Age corrections were calculated using an estimated initial atomic ^{230}Th/^{232}Th ratio of $4 \pm 2 \times 10^{-6}$ (Shen et al., 2012). Chronology based on band counting does not differ significantly from U-Th dating results (Table 1). The only exception is #B1 and its ^{230}Th date of 2000.2 ± 1.9 AD is significantly older than banding date of 2008.0 ± 1.0 AD. This apparent old age is most likely biased by old carbonate detritus with high ^{230}Th/^{232}Th ratio (Shen et al., 2008).

Table 1
U-Th Isotopic Compositions and Contents and Ages for Rocas Atoll Coral Subsamples by MC-ICPMS, Thermo Electron Neptune, at HISPEC, NTU

SID2 subsample	Weight g	^{238}U ppb	^{232}Th ppt	δ^{234}U measured[a]	[^{230}Th/^{238}U] ($\times 10^{-4}$) activity[b]	[^{230}Th/^{232}Th] ppm[c]	Age Uncorrected	Age corrected[b,d]	δ^{234}U$_{initial}$ corrected[e]	Chemistry date AD	^{230}Th date AD	Density band date AD
#B1	0.0935	2587.0 ± 4.2	194.0 ± 7.5	145.0 ± 2.4	1.250 ± 0.182	27.5 ± 4.1	11.9 ± 1.7	10.2 ± 1.9	145.0 ± 2.4	2010.39	2000.2 ± 1.9	2008.0 ± 1.0
#B2	0.1067	2414.4 ± 5.2	139.5 ± 6.6	148.7 ± 3.0	1.618 ± 0.171	46.2 ± 5.4	15.4 ± 1.6	14.0 ± 1.8	148.7 ± 3.0	2010.39	1996.3 ± 1.8	1996.0 ± 1.0
#B3	0.1038	2333.2 ± 4.3	168.0 ± 6.8	142.9 ± 2.3	2.163 ± 0.192	49.6 ± 4.8	20.7 ± 1.8	19.0 ± 2.0	142.9 ± 2.3	2010.39	1991.4 ± 2.0	1991.0 ± 1.0
#B4	0.0924	2632.8 ± 4.7	259.3 ± 7.6	147.4 ± 2.5	4.525 ± 0.193	75.9 ± 3.9	43.1 ± 1.8	40.8 ± 2.2	147.4 ± 2.5	2010.39	1969.6 ± 2.2	1970.0 ± 1.0

Note. Analytical errors are 2σ of the mean.
[a] $\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1) \times 1{,}000$. [b] $[^{230}Th/^{238}U]_{activity} = 1 - e^{-\lambda 230 T} + (\delta^{234}U_{measured}/1{,}000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](1 - e^{-(\lambda 230 - \lambda 234)\, T})$, where *T* is the age. Decay constants used are 9.1577×10^{-6} yr^{-1} for ^{230}Th, 2.8263×10^{-6} yr^{-1} for ^{234}U (Cheng et al., 2000), and 1.55125×10^{-10} yr^{-1} for ^{238}U. [c] The degree of detrital ^{230}Th contamination is indicated by the [^{230}Th/^{232}Th] atomic ratio instead of the activity ratio. [d] Age corrections were calculated using an estimated atomic ^{230}Th/^{232}Th ratio of 4 ± 2 ppm. [e] $\delta^{234}U_{initial}$ corrected was calculated based on ^{230}Th age (T), i.e., $\delta^{234}U_{initial} = \delta^{234}U_{measured} \times e^{\lambda 234 * T}$, and T is corrected age.

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2.5. Coral Growth Rate Determination

Annual coral growth rate was obtained by measuring the total distance, along the maximum growth, of a set of consecutive light and dark bands, Figure 3b. Annual coral growth ranged from 3.76 mm/yr (1981) to 8.53 mm/yr (2002) with mean annual growth of 6.01 $\pm$ 1.08 mm/yr. Higher periods of growth rates were observed in 1972–1976, 1990–1997, and 2000–2008, while lower periods of growth rates were observed in 1970–1971, 1977–1981, 1985–1989, and 1998–2000. Our results are comparable to growth rates studies using *Siderastrea* genus: 4.06 $\pm$ 1.44 mm/yr (DeLong et al., 2014) and 4.9 $\pm$ 0.9 mm/yr (Flannery et al., 2017). A slight increasing trend toward present is observable in the coral growth rate time series (Figure 3c). Data set of annual coral growth was tested for normality using Komolgorov-Smirnoff statistical test performed with the PAST software.

2.6. Coral Geochemical Analyses

Coral slabs were fixed to a 3-axis computer-controlled micro-drilling machine, equipped with a 1.0 mm diameter dental drill bit. A $\sim$ 1 mm deep by $\sim$ 1 mm wide groove was excavated at 1 mm increments, yielding, in average, six subsamples per year. Samples were analyzed for Sr/Ca and U/Ca at the IRD center in Bondy, France. Powdered coral samples ($\sim$100 µg each) were diluted in 2% nitric acid (Suprapur 65% nitric acid, Merck) and analyzed with a ICP-MS (model 7500cx, Agilent). Details of the analytical technique are provided in Le Cornec and Corrège (1997). Analytical precision for the Sr/Ca and U/Ca was assessed by using one standard deviation (1σ) calculated on repeated analyses (n = 17) of a home-made coral standard. These aliquots were prepared with the same reagents as the samples and inserted within sample runs. The precision was 0.0023 mmol/mol for Sr/Ca and 0.0043 μmol/mol for U/Ca. Accuracy was inferred from two certified standards: a reference material, CCH-1 (Liège University, Belgium); and a coral standard NC20 (IRD/Bondy). Both were measured by ICP-MS and ICP-AES. Accuracy is $\sim$0.6% for Ca and $\sim$0.06% for Sr. Data set of Sr/Ca and U/Ca were tested for normality using Komolgorov-Smirnoff statistical test performed with PAST software.

The conversion of coral depth domain to time domain followed the sequence:

1. From the x-ray image we made the counting of coral density bands and measured their width. The chronology was established backward from the year of collection (2009) in a way that each density band pair correspond to 1 year;
2. Later on, this chronology was confirmed using U/Th date method;
3. Sub-samples for Sr/Ca and U/Ca were taken successively through the density bands (from the top to the bottom part of the slab). An average number of 6.4 sub-samples for each density band pair were obtained; therefore we considered each geochemical data as representative of approximately 2-month interval.

2.7. SST and Wind Measurements

To better constrain daily seawater temperature at Barreta pool, where the coral core was collected, we deployed a portable, autonomous, Hobo-type sensor. It was installed 2 m below the sea surface during low tide and recorded the SST variability (Hobo SST hereafter) from 23 May 2011 to 22 May 2012. We compared the Hobo SST with ocean observations measured by the PIRATA mooring located at 0°N – 035°W (this is the PIRATA mooring closest to Rocas Atoll). PIRATA database is available at http://www.pmel.noaa.gov/tao/disdel/frames/main.html. Parameters investigated were daily surface wind speed (Figure 4a) and SST (Figure 4b). These two time series exhibit a clear inverse relationship with increased winds during the austral winter and the opposite occurring during the summer. No tidal record was available from Rocas Atoll, therefore we compared Hobo SST with daily tide measurements at Fernando de Noronha Archipelago (Figure 4c). The amplitude of the tide time series varies from 0.5 m to 2 m, with a mean average of about 1.5 m.

A decreasing trend going from 28.5°C to 24.5°C, from austral autumn to spring is observed in the *in situ* Hobo SST record. During this period, a remarkable higher frequency mode of variability of 15-day, with an amplitude of about 2°C is present. During the following two months (from October to November 2011) the mean Hobo SST increased up to about 27°C, keeping the 15-day periodicity. At the end of the record (from November 2011 to May 2012) Hobo SST remained relatively stable with values closed to 27°C. The 15-day periodicity is also present during this steady period, but with very smaller amplitude (a few 1/10's of °C).

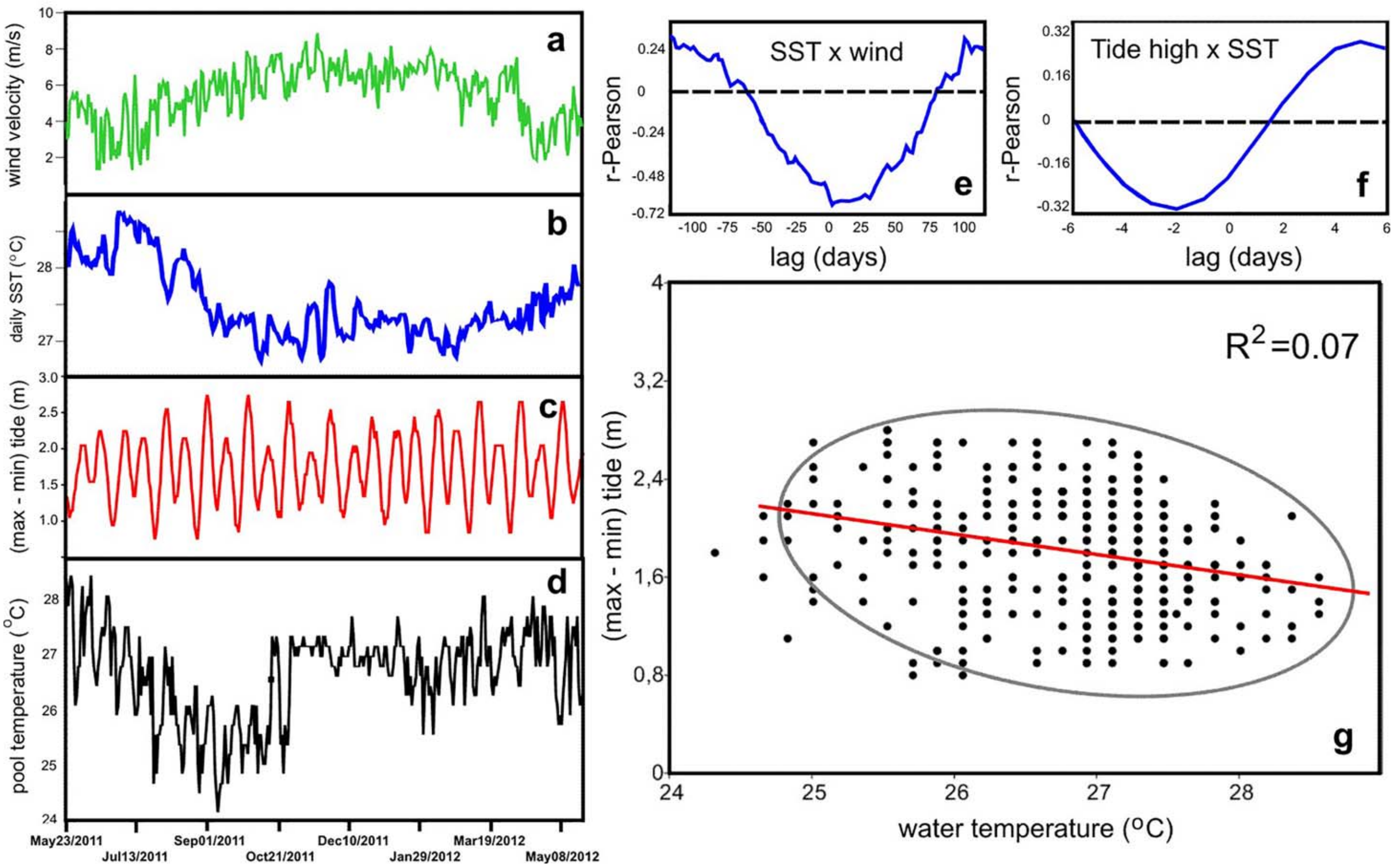

Figure 4. Daily record from May 23, 2011 to May 22, 2012 of: (a) wind velocity (m s^{-1}) and (b) SST (°C) at 0°N-035°W both from the PIRATA Project; (c) tide amplitude (m) from Tide Station at Fernando de Noronha Is. (3°51′S, 032°25′W); (d) water temperature at the pool where the coral core was sampled in Rocas Atoll; (e) lag correlation (days) between SST and wind; (f) lag correlation (days) between tide amplitude and water temperature (*in situ*); (g) correlation between *in situ* water pool temperature and tide amplitude. 95% confidence ellipse and regression curve are shown.

The range of the seasonal variability in Hobo SST (~4°C) is significantly larger than the SST variability in the open ocean (~1.5°C), which is not surprising given the strong buffering effect of the deep ocean. However, both series present similar temporal variability. The lowest PIRATA SSTs (around 27°C) occurs during highest wind speed values record (between 5 and 8 m s^{-1}). Low-frequency decrease of Hobo SST during the first part of the record seems in agreement with the slow decrease in SST and increase in wind velocity between July and September-October 2011, observed at the PIRATA mooring. Both Hobo SST and PIRATA data sets (SST and wind speed) present relative steady values between October 2011 and April 2012. Lag-correlation between PIRATA database for the atoll region (SST and wind speed) shows a significant correlation of ($r = -0.72$), near time lag ~0, (Figure 4e). The 15-day periodicity observed in Hobo SST is apparently related to the bi-monthly periodicity of the tide amplitude. Nevertheless, coefficient of determination R^2 indicates that only ~7% of the atoll pool temperature variance is explained by the tide action (Figures 4f and 4g).

To look at the possible influence of SST and wind speed variability on our coral records we need time series that span the same length (1970–2009). For the remaining of the manuscript we decided to use SST and sea surface wind stress from the SERV monthly database (Servain et al., 1985, 2014). SERV is a monthly 2° × 2° grid box data sets spanning from 30°N to 20°S, and covering the 1964 to present day period. SERV SST combines data from both PIRATA observing moorings and the Voluntary Observing Ships (VOS) reports. Herein SERV wind surface data are represented by two pseudo wind stress components (PWS_x and PWS_y in $m^2\ s^{-2}$) that is defined as the total wind velocity (m s^{-1}) multiplied by its zonal (Wx) or meridional (Wy) wind speed components respectively. For the remaining on this manuscript, we focused only on the zonal component of PWS (PWSx) since that component is continually oriented westward throughout the year,

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while the meridional component of PWS (PWSy) changes its direction seasonally from austral winter (northward) to austral summer (southward), making it more difficult to draw any conclusion.

2.8. Rain and ITCZ Latitudinal Displacements

Rain was recorded at one of the nearest continental meteorological station with respect the atoll. It is located at the Northeast Brazilian sector (Fortaleza, 03° 44′ S; 038° 34′ W). It is located ~500 km west of Rocas Atoll on the same latitude, therefore under similar ITCZ influence. Historical precipitation database enclose the 1974–2008 time period (http://www.funceme.br/).

To gain a better insight into the possible ITCZ influence on coral variability, we compared coral growth rate with ITCZ relative position with respect to the Atoll. According to de Carvalho and Oyama (2013), over Rocas Atoll, the ITCZ spreads around 3 degrees of latitude (3° in March to 6° in October). The method we used to infer ITCZ latitudinal positioning is the Interpolated Outgoing Long wave Radiation (OLR) method (Ferreira et al., 2005). The OLR represents the total radiation emitted by the atmosphere that is going to space; its maximum wavelength is located in the infrared band. However, tops of convective clouds are relatively colder, which affects the OLR values. The method used in his study, selects OLR values between 160 to 230 W (Ferreira et al., 2005) which discards stratocumulus and medium altitude clouds from the analyses. The ORL data set is available on the Climate Data Center of the National Oceanic and Atmospheric Administration (CDC/NOAA) website. The OLR database spans the period from 1975 to 2008 and has a spatial coverage of 2.5° × 2.5°. The method is based on identifying OLR minimum values for the Atlantic Ocean. Each identified OLR value, with its associated longitude and latitude, is plotted into a geo-referenced frame resulting in a line representing the averaged position of the ITCZ. Data were sampled at a monthly resolution to encompass the years of coral growth. In this technique we also consider de Carvalho and Oyama (2013) work, in which they estimate the width of the ITCZ along the year. By doing this at a monthly resolution, we were able to pin point years when the ITCZ reached Rocas Atoll for at least one month.

3. Results and Discussion

3.1. Coral Parameters and Their Use as Potential SST Proxies

At interannual time scale, coral parameters (Sr/Ca, U/Ca and growth rate) are significantly correlated to each other (Table 2). Significant positive correlation exists between Sr/Ca and U/Ca time series ($r = 0.82$, $p = 0.000$) and significant negative correlations were observed between Sr/Ca and U/Ca versus coral growth ($r = -0.42$, $p = 0.011$; $r = -0.49$, $p = 0.003$, respectively). This is consistent with a biomineralization mechanism in which coral Sr(U)/Ca is highly dependent on the mass fraction of aragonite precipitated by scleractinian corals following the concept that it is a biological controlled process modulated by environmental parameters.

Sr/Ca, U/Ca, and SERV SST time series are presented in Figures 5a and 5b (annual geochemical data is presented in the Supporting Information S1). SERV SST presents a marked seasonal variability with mean of 27.3 ± 0.64°C (1σ), ranging from 26.0 to 28.9°C. Coral geochemical data, however, does not exhibit a similar variability throughout the record timeline. Mean Sr/Ca is 8.98 ± 0.0511 mmol/mol (1σ) ranging from 8.87 to

Table 2
Sr/Ca-SST Correlation Values for Comparison in the Present Work

Coral site	Correlation (r-Pearson)	Reference
New Caledônia/Tropical Pacific	−0.87	Beck et al. (1992)
Great Barrier Reef, Australia/Tropical Pacific	−0.8 / −0.99	Gagan et al. (1998)
Alina Reeef, Florida/Tropical Atlantic	−0.82 / −0.94	Swart et al. (2002)
Florida/Tropical Atlantic	−0.96	Maupin et al. (2008)
Bermudas, Caribe/Tropical Atlantic	−0.73 / −0.86	Goodkin et al. (2005)
Virgin Islands, Caribe/Tropical Atlantic	−0.95	Saenger et al. (2008)
Gulf of Mexico/Tropical Atlantic	−0.95 / −0.98	DeLong et al. (2014)
Rocas Atoll, Brazil/Equatorial Atlantic	−0.63	This issue

Note. r-Pearson values refer to in situ SST measurements (except for "this issue" that uses regional SST data).

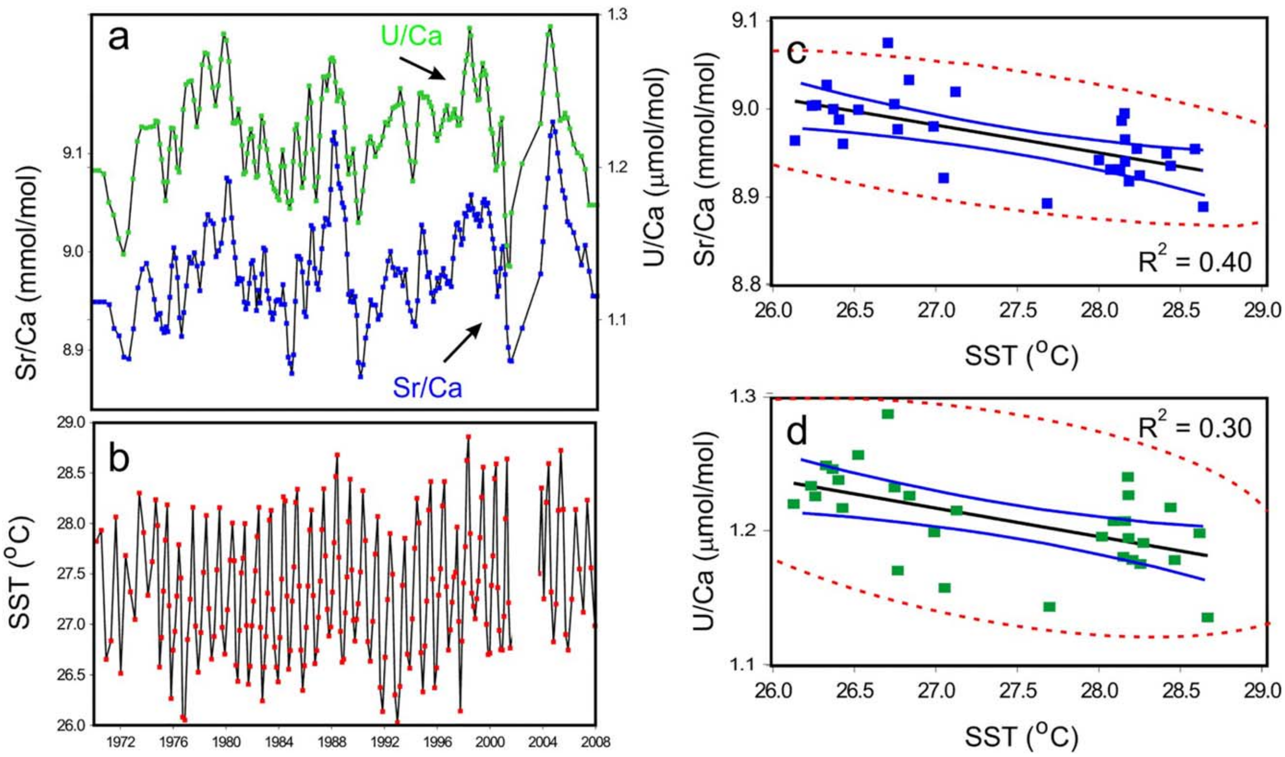

Figure 5. (a) Sr/Ca and U/Ca variability along the coral core of Rocas Atoll; (b) bi-monthly SST (SERV monthly database); (c) Regression, corresponding confidence interval, and 95% confidence ellipse for Sr/Ca; (d) the same for U/Ca (n = 15).

9.13 mmol/mol while the U/Ca mean is 1.12 ± 0.031 μmol/mol (1σ), ranging from 1.13 to 1.21 μmol/mol. These behaviors constrain a direct relationship between Sr/Ca and U/Ca versus SERV SST. For years of fast growth rates our sampling spatial resolution allows to recover a higher number of sub-samples which leads to a better constrain of the annual cycle. However, for years of slower growth rate this seasonal cycle is truncated. The influence of sub-sampling resolution on the seasonal geochemical cycles have been presented in various studies (Bagnato et al., 2004; Dassié & Linsley, 2015; DeLong et al., 2007; Maupin et al., 2008).

In order to recover the relation between SST and the geochemical data, we selected years of fast growth rate, when the seasonal cycles of Sr/Ca and U/Ca were distinctively achieved, i.e., 1972, 1975, 1977, 1979, 1981, 1982, 1983, 1989, 1991, 1994, 1995, 2000, 2001, 2006, and 2007. From this approach, linear regressions between SERV SST and both Sr/Ca and U/Ca were made using seasonal data of the selected years (Figures 5c and 5d). As expected, at seasonal time scale, significant negative correlation is observed between SERV SST time series and Sr/Ca (r= −0.63; n = 30; p = 0.00017) and for U/Ca (r= −0.55, n = 30; p = 0.00175). At this time scale, SST seems to be the leading factor of both Sr/Ca and U/Ca seasonal variability. This result indicates that *Siderastrea stellata* does present a potential as predictor SST variability.

$$Sr/Ca(mmol/mol) = -0.0314SST(^oC) + 9.8304\ (r = -0.63;\ n = 30;\ p = 0.00017) \quad (1)$$

$$U/Ca(\mu mol/mol) = -0.0216SST(^oC) + 1.8009\ (r = -0.55;\ n = 30;\ p = 0.00175) \quad (2)$$

Sr/Ca versus SST calibration equation slopes and intercepts are in the range of a previously published study by Maupin et al. (2008) who used *Siderastrea siderea* at bimonthly resolution and reported values ranging from −0.034 mmol/mol °C^{-1} to −0.044 mmol/mol °C^{-1} and from 9.878 to 10.138, for their slope and intercept respectively. Using the same *Siderastrea sidereal* species but with a higher temporal resolution, Delong et al. (2014) reported slightly higher slope and intercept values ranging from −0.043 mmol/mol °C^{-1} to −0.047 mmol/mol °C^{-1} and from 10.11 to 10.25, respectively. This difference in slope and intercept is partly due to the sampling resolution (i.e. our bimonthly sampling tends to smooth the record and to lower the slopes and intercepts) but the small SST amplitude at Rocas atoll compared to the Gulf of Mexico where Delong et al (2014) *Siderastrea sidereal* samples come from could also play a role. Similarly, the slope and intercept of the U/Ca versus SST relationship in *S. stellata* are smaller than the published ones from the genus *Porites* sampled at monthly resolution (slope: 0.037 to 0.046; intercept: 2.11 to 2.26; Corrège et al., 2000; Fallon et al., 1999; Sinclair et al., 1998), although an inter-genera difference cannot be ruled out. A comparison of our correlation level of Sr/Ca-SST with other studies is presented at Table 2.

When we look at the annual averaged data, the correlation between Sr/Ca and SERV SST assumed an unexpected positive value ($r=+0.40$, $p=0.016$). At seasonal time scale, SST amplitude at Rocas Atoll may reach ~3°C, but at inter-annual time scale, SST amplitude is ~1°C (for the period covering the coral growth). This small SST amplitude might not be sufficient to influence Sr/Ca variability. Finally, the bi-monthly temporal resolution might not be enough at this specific location to resolve the full seasonal cycle which could bring some artifacts influencing the calibration as already presented by Dassié and Linsley (2015).

3.2. Influence of Surface Wind on Coral Geochemistry and Growth Rate

Growth rate is significantly correlated to Sr/Ca ($r=-0.42$; $p=0.011$) and have presented a positive trend from ~5 mm/yr to 6 mm/yr along the overall time scale (Figure 6a). SST variability is known to be well related to surface wind stress through changes in ocean boundary layer thickness and stratification (e.g., Zheng et al., 2009). In our study region, the zonal component of wind stress (PWSx), is negatively correlated to SST at interannual time scale ($r=-0.39$; $p=0.020$). A SST warming (cooling) is associated with a relaxation (strengthening) of the zonal wind stress. PWSx and Sr/Ca present similar trends and interannual variability (Figure 6b), and are statistically negatively correlated ($r=-0.48$, $p=0.003$). By contrast, neither U/Ca nor growth rate, present a significant correlation with PWSx ($r=-0.17$, $p=0.323$; $r=-0.20$, $p=0.248$; respectively). From these results we may conclude that while SST is the leading factor of Sr/Ca variability at seasonal time scale, at the interannual time scale, coral skeleton Sr/Ca variability is not SST-dependent but is mainly influenced by wind stress variability. Note that since values of PWSx tends to be more negative toward the present date (easterly trades), indicating an increase in wind speed, a slightly simultaneous

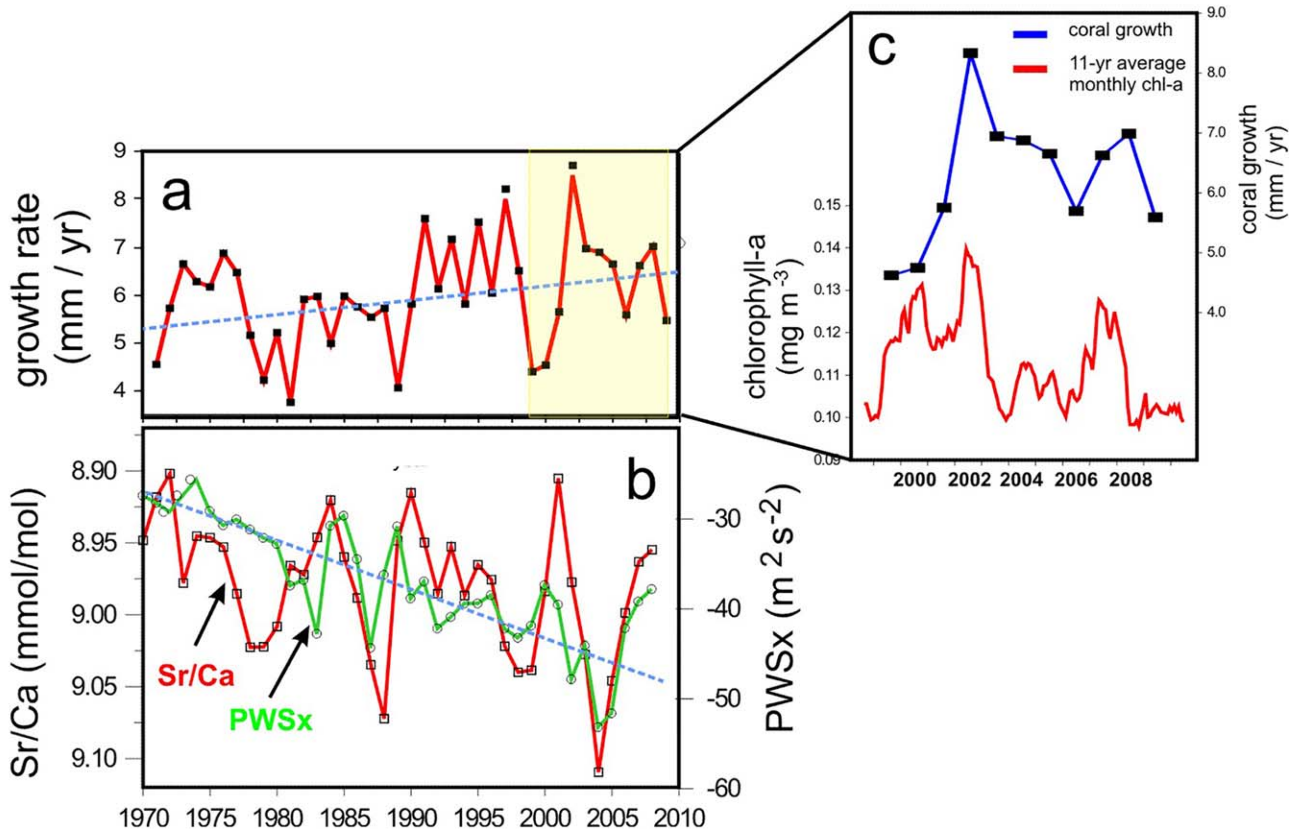

Figure 6. (a) Coral growth time series; (b) Sr/Ca and pseudo wind stress; (c) coral growth and Chlorophyll-a inferred from SeaWiff. Dotted lines are linear trends for growth rate in Figure 6a and PWSx in Figure 6b.

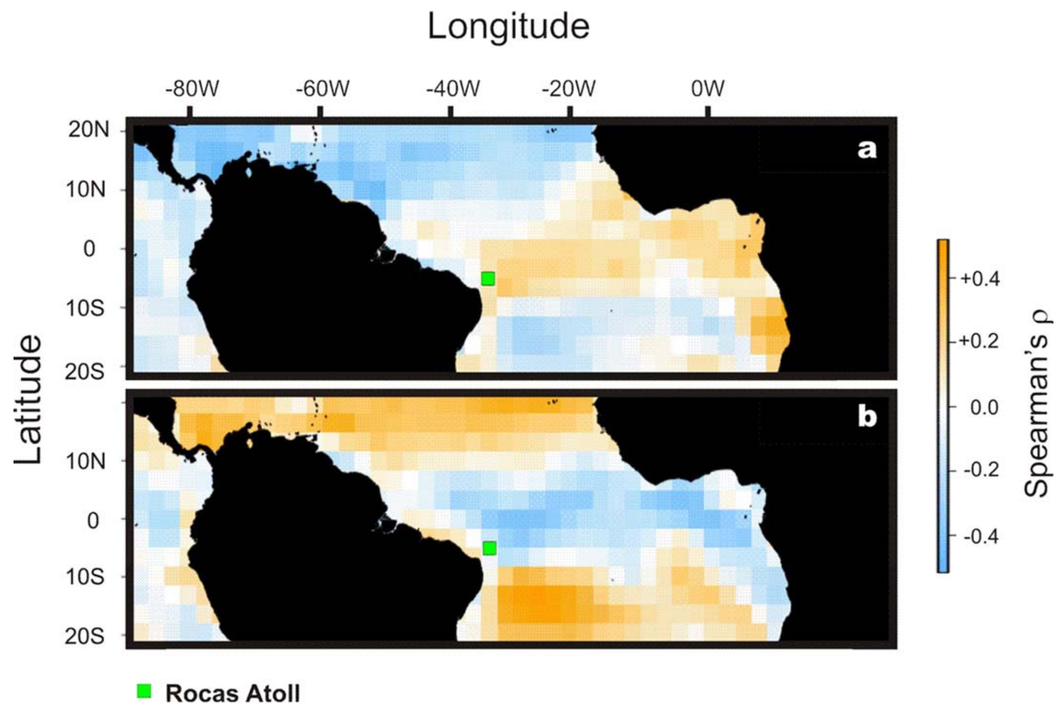

Figure 7. Spearman's ρ correlation maps for (a) coral growth rate and PWSx; (b) for coral Sr/Ca and PWSx. (PWSx data from NCEP/NCAR reanalysis. Time series were detrended).

increase trend in coral growth is observed. A comparison of coral growth with chlorophyll-a concentrations (inferred for the atoll region by remote sensing – SeaWiffs/https://oceancolor.gsfc.nasa.gov/) also indicates these two last parameters covaried between 1999 and 2009 (Figure 6c). This association maybe be related to the ressuspention of biogenic material/nutrients inside and outside the atoll due to increasing wind action during the last decades. Chlorophyll-a data are related to the total algal biomass in the ocean. Therefore an indicator of the growth and development of the phytoplankton community. Chlorophyll-a concentrations in the phytoplanktonian cells change according to nutrients and environmental conditions. Therefore, the observed co-variability between coral growth and Chlorophyll-a support the relative importance to growth pattern at Equator of light conditions, SST and nutrient apportionment.

To better understand to which geographical extent surface winds are associated with coral growth rate and Sr/Ca, we created correlation maps between coral parameters and the geographically distributed wind speed extracted from NCEP/NCAR reanalysis (available at http://www.esrl.noaa.gov/psd/) in the tropical South Atlantic (Figure 7). Correlation maps are shown in Figures 7a and 7b, we used the Spearman's values since PWSx database behaved as non-normal. We observed significant correlations between Sr/Ca, growth rate, and PWSx at significant levels along the vicinity of the Equator, along with the South Equatorial current. This suggest that the response of Sr/Ca and growth rate to wind dynamics at Rocas Atoll is not a local respond but it is impacted by larger scale dynamic processes.

Table 3 summarizes the correlation coefficients values and their respective p values among coral parameters (Sr/Ca, U/Ca and growth rate), climatic parameters (SST, PWSx, and rain/precipitation), and climate indexes (ENSO, NAO, and AMO). Concerning the influence of climatic indexes on regional parameters: SST is significantly correlated with both AMO ($r = 0.59$; $p = 0.000$) and NAO ($r = -0.35$; $p = 0.037$). This indicates an influence of the North Atlantic Ocean SST and a major impact of the air-sea interactions, precipitation and storms, represented by the NAO (Marshall et al., 2001). PWSx is also correlated with AMO ($r = -0.73$; $p = 0.000$) and ENSO ($r = 0.42$; $p = 0.012$).

3.3. ITCZ Influence on Coral Variability

Figure 8 depicts monthly displacements of the ITCZ mean position using outputs from the OLR method (shaded areas are the 95% confidence levels of the technique). We defined the "cloud shading years" as

Table 3
Correlation Matrix Among Coral Parameters and Related Atmospheric-Climate Indexes

	Coral parameters			Atmospheric-ocean interaction			Climate index		
	Growth rate	Sr/Ca	U/Ca	SST	PWSx	Rain	NAO	SOI	AMO
Growth rate	1								
Sr/Ca	**−0.424** (p=0.011)	1							
U/Ca	**−0.494** (p=0.003)	**0.824** (p=0.000)	1						
SST	−0.099 (p=0.569)	**0.403** (p=0.016)	0.089 (p=0.609)	1					
PWSx	−0.201 (p=0.248)	**−0.482** (p=0.003)	−0.172 (p=0.323)	**−0.393** (p=0.020)	1				
Rain	0.131 (p=0.455)	−0.060 (p=0.733)	−0.007 (p=0.973)	0.139 (p=0.426)	**0.379** (p=0.025)	1			
NAO	0.208 (p=0.230)	−0.210 (p=0.225)	−0.104 (p=0.553)	**−0.352** (p=0.037)	0.074 (p=0.672)	0.088 (p=0.615)	1		
SOI	−0.069 (p=0.692)	−0.135 (p=0.439)	−0.201 (p=0.247)	0.266 (p=0.122)	**0.419** (p=0.012)	0.291 (p=0.090)	−0.168 (p=0.333)	1	
AMO	0.291 (p=0.090)	0.242 (p=0.162)	−0.164 (p=0.348)	**0.599** (p=0.000)	**−0.729** (p=0.000)	−0.119 (p=0.495)	−0.201 (p=0.247)	0.026 (p=0.882)	1

Note. p-values are indicated and values in bold are statistically significant at 0.05 confidence level.

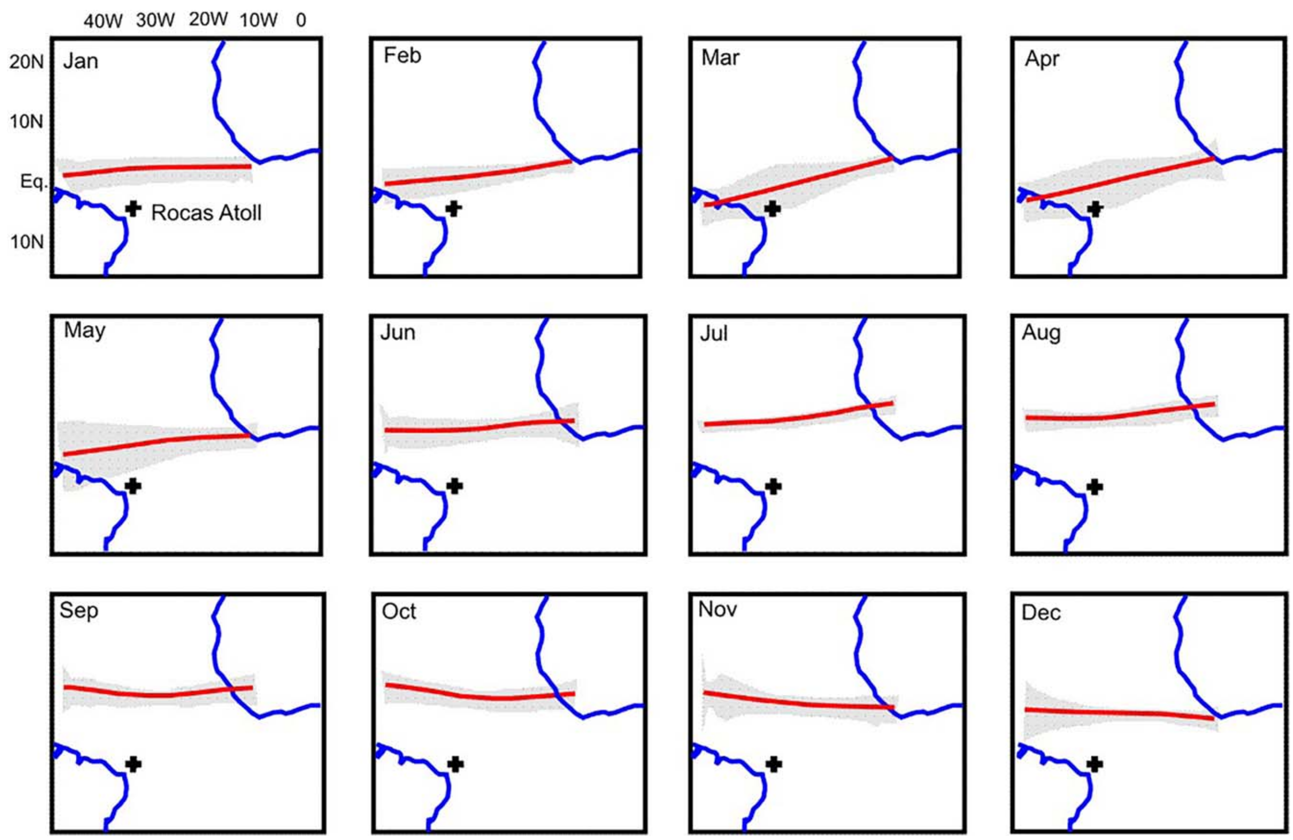

Figure 8. Monthly ITCZ displacements relative to Rocas Atoll (indicated by a cross) based on OLR method (see text). Shaded areas are 95% confidence interval. The analyzed period spanned the period 1975–2013.

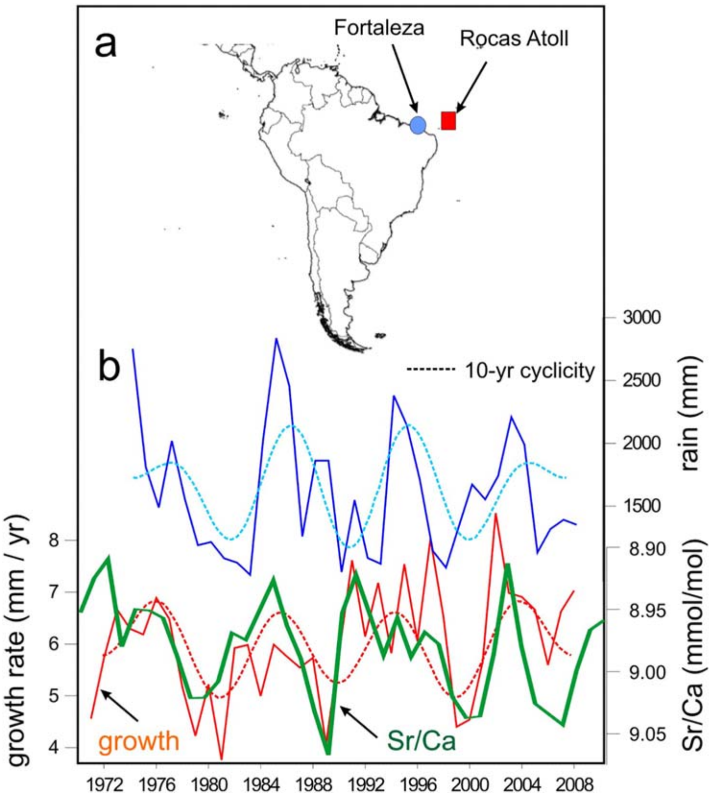

Figure 9. (a) Rocas Atoll site and Fortaleza Meteorological Station at the Brazilian coast; (b) rain data from Fortaleza/FUNCEME station – see text), coral growth and Sr/Ca annual data. Dotted curves are 10-yr phase extracted from rain and growth data.

years when the ITCZ reaches/shades the atoll for at least 1 month: 1975, 1977, 1978, 1981, 1984, 1985, 1986, 1987, 1989, 1991, 1992, 1994, 1995, 1996, 1999, 2002, 2003, and 2008. Considering years with and without shading effect, we selected growth values for these two groups. For years under the ITCZ influence, the mean growth was 6.11 ± 0.99 (1σ), n = 18, and for years without the ITCZ influence we found 5.94 ± 1.28 (1σ), n = 16. There is a slight increase in growth rate for the years with the ITCZ influence, nevertheless applying a Student-t test for equality of means we obtained no statistical difference between groups at 95% confidence interval. We attribute this lack of association to the fact that over the course of the year, the ITCZ does not stay long enough over the atoll to produce any measurable change in coral growth rate. The southernmost edge of the ITCZ reaches the atoll more commonly in March-April period.

Rain events (Figure 9a) are usually associated to runoff processes happening at the surface. In the case of Rocas Atoll runoff might be considered as a potential agent to deliver enriched guano material (nutrients), from the great quantity of migrating birds existing the whole year at that site, into the pool's shallow waters where corals live. Another possibility would be the input of remineralized benthic nutrients and carbonates since Rocas Atoll shows a predominant coralline algae structure. Although we did not find statistically significant the correlation between rain and neither growth nor Sr/Ca (see Table 3), it is clear that these parameters have a strong decadal signal. In Figure 9b we superimpose the 10-yr phase of rain and growth and one may observe that they covariate over time. This leads to conclude that rain may effect growth (positively) and Sr/Ca at longer time scale.

Climatic modes of variability such as ENSO, NAO, and AMO might be responsible for both the ITCZ position and therefore the rain amount variability at Rocas atoll. Table 3 summarizes the correlation coefficients values and their respective p values among coral parameters (Sr/Ca, U/Ca and growth rate) and climate indexes (ENSO, NAO, and AMO). Concerning the influence of climatic indexes on regional parameters: SST is significantly correlated with both AMO ($r = 0.59$; $p = 0.000$) and NAO ($r = -0.35$; $p = 0.037$). This indicates an influence of the North Atlantic Ocean SST and a major impact of air-sea interactions, precipitation, and storms, represented by the NAO (Marshall et al., 2001). PWSx is also correlated with AMO ($r = -0.73$; $p = 0.000$) and ENSO ($r = 0.42$; $p = 0.012$). The interannual to decadal variability observed in both the Sr/Ca growth rate might be influenced by a combination of climatic modes.

4. Conclusions

In this paper, we analyzed possible influences of local and regional meteo-oceanographic conditions on physical and chemical variabilities of a massive coral core (*Siderastrea stellata*) at Rocas Atoll, located in the southwest equatorial region of the Atlantic Ocean. Chronology was established by density band counting on digitalized X-ray images and validated by the U-Th radiometric technique. The coral record presents 40 years of oceanic conditions from 1970 to 2009.

At seasonal time scale, linear regression between Sr/Ca, U/Ca, and SST presented slopes values comparable to previously published studies using same species. At the interannual scale, Sr/Ca, U/Ca and growth rate were all significantly correlated to each other, but not correlated with SST. This lack of relationship might be due to the small SST inter-annual variability, whose amplitude does not exceed 1.5°C. Conversely Sr/Ca is significantly correlated with the surface wind, more specifically the zonal pseudo wind stress (PWSx), a variable that presents greater regional mode of variability. Over the last decades, a positive trend in growth rate was accompanied by an increase in the wind stress.

An investigation on the influence of the ITCZ over Rocas Atoll indicated no significant influence on coral growth rates. We attribute such lack of association to the short duration of the "cloud shading" effect, normally restricted to 1 or 2 months per year on average. Additionally, precipitation data taken from the nearest meteorological station at Fortaleza/Brazil vary with same phase of Sr/Ca and coral growth at the decadal time scale, suggesting that rain may favor the nutrient redistribution inside the atoll due to washout processes as well as potentially provide remineralized benthic materials and carbonates algae structures to the water column.

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