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Coral-based climate records from tropical South Atlantic: 2009/2010 ENSO event in C and O isotopes from Porites corals (Rocas Atoll, Brazil)

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ABSTRACT
Coral skeletons contain records of past environmental conditions due to their long life span and well calibrated geochemical signatures. C and O isotope records of corals are especially interesting, because they can highlight multidecadal variability of local climate conditions beyond the instrumental record, with high fidelity and sub-annual resolution. Although, in order to get an optimal geochemical signal in coral skeleton, sampling strategies must be followed. Here we report one of the first coral-based isotopic record from the Equatorial South Atlantic from two colonies of Porites astreoides from the Rocas Atoll (offshore Brazil), a new location for climate reconstruction. We present time series of isotopic variation from profiles along the corallite valley of one colony and the apex of the corallite fan of the other colony. Significant differences in the isotopic values between the two colonies are observed, yet both record the 2009/2010 El Niño event - a period of widespread coral bleaching - as anomalously negative δ18O values (up to −1 permil). δ13C is found to be measurably affected by the El Niño event in one colony, by more positive values (+0.39 ‰), and together with a bloom of endolithic algae, may indicate physiological alteration of this colony. Our findings indicate that corals from the Rocas Atoll can be used for monitoring climate oscillations in the tropical South Atlantic Ocean.

Key words: coral, climate change, Rocas Atoll, carbon and oxygen isotopes, South Atlantic Ocean.

INTRODUCTION
Geochemical information from massive, boulder-like corals has long been used to reconstruct climate oscillations through time (Corrège 2006, DeLong et al. 2013, Felis and Rimbu 2010, Felis et al. 2000, Hereid et al. 2012, Kilbourne et al. 2008, Linsley et al. 1994, Moses and Swart 2006, Swart et al. 2010). These corals can live for hundreds of years and are natural archives with annual density bands, visible in X-ray images of cross-sections of their aragonite skeleton (Buddemeier et al. 1974, Knutson et al. 1972). These bands allow dating and assessing
the duration of environmental perturbations in the shallow-marine tropical environment, ranging from a few years to centuries and before the instrumental record.

Such coral-based climate records have been reported for different tropical localities in the Pacific Ocean (Alibert and Kinsley 2008, Asami et al. 2004, Beck et al. 1992, Cobb et al. 2003, Dunbar et al. 1994, Guilderson and Schrag 1998, 1999, Hereid et al. 2012), Indian Ocean (Kuhnert et al. 1999), Caribbean (Kilbourne et al. 2008, Medina-Elizalde et al. 2002, Moses and Swart 2006, Winter et al. 1991), Red Sea (Al-Rousan et al. 2003, Felis and Rimbu 2010, Felis et al. 2000, Klein and Loya 1991), but there is a lack of records for the Tropical South Atlantic Ocean.

The analysis of the geochemical composition along the coral growth axis, allows the reconstruction of environmental parameters at the sea-surface. Such geochemical investigations provide a better understanding of climate oscillations, which can be used as a background for paleoceanographic models (Gagan et al. 2000, Kilbourne et al. 2008, Schrag and Linsley 2002).

Oxygen and carbon isotope ratios are extensively used as proxies to identify environmental and physiological factors in hermatypic corals (Weber and Woodhead 1970, 1972). For decades, oxygen isotopes of coral skeletons have been used for climatic reconstructions (Dunbar et al. 1994, Gagan et al. 1994, Kuhnert et al. 1999, Wei et al. 2006, Corrêa et al. 2006, Moses and Swart 2006, Moses et al. 2006, Hereid et al. 2012, Chen et al. 2013 among others). Depending on local conditions, δ18O in corals reflects sea-surface temperature (SST) (Dunbar et al. 1994, Fairbanks and Dodge 1979, McConnaughey 1989, Pätzold 1984, Weber and Woodhead 1970, 1972, Wefer and Berger 1991) and sea-surface salinity (SSS) (Cole and Fairbanks 1990, Linsley et al. 1994). Carbon isotopes, in turn, are more complicated to interpret due to a multitude of physiological controls (Swart 1983).

The signal of the δ18O in corals can be used as a proxy for climatic disturbances like the El Niño Southern Oscillation (ENSO). Pacific coral-based ENSO reconstructions have been used by researchers to understand the range of natural variability of the ENSO in modern and Pre-historical time (Cobb et al. 2003, 2013, Dunbar et al. 1994, Hereid et al. 2012, 2013).

The year 2010 was marked by anomalously high sea-surface temperatures that led to a bleaching event throughout coral reefs of the tropical oceans (Krishnan et al. 2011). At Rocas Atoll, Ferreira et al. (2013) reported anomalous temperatures during the years of 2009 and 2010 which caused coral bleaching. Those authors pointed out the susceptibility of the Rocas Atoll to El Niño events and their potential detrimental effects on this reef. In this study, we report on a coral-based record of oxygen and carbon isotopes from two Porites colonies. We relate anomalous isotope signals observed in contemporaneous parts of the corals, to thermal stress triggered by the 2009/2010 ENSO event.

**STUDY SITE**

The Rocas Atoll is the only atoll located in the western part of the South Atlantic (3°51′S, 33°49′W), 266 km from the coastal city of Natal, northeastern Brazil (Fig. 1). The equatorial location of Rocas Atoll leads to minimal SST seasonal variability (26 to 29 °C) with larger inter-annual variability, analogous to the study sites in the equatorial Pacific, where the same genus Porites was investigated (McConnaughey 1989, Omata et al. 2006).

The Rocas Atoll offers a great opportunity to investigate the influence of ENSO at a location practically devoid of human influence. The atoll receives no direct terrestrial runoff and ocean and atmosphere are the key players determining the environmental conditions at the locality. Therefore,
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(1941) rising up from depths of 4,000 m (Kikuchi and Leão 1997, Pereira et al. 2013). The evolution of this complex reef included colonization by coralline algae, coral reefs, molluscs, and crustaceans on the guyot. The accumulation of marine carbonate provided the basis for the ring ellipsoid reef (Gherardi and Bosence 2001).

Based on core drilling combined with a shallow seismic refraction survey, Kikuchi and Leão (1997) identified three units comprising the Rocas Atoll. The topmost unit is a 12 m-thick Holocene sequence with seismic velocity of 0.33 km/s. This Holocene sequence is mainly composed of encrusting coralline algae, vermetid gastropods, encrusting foraminifera (*Homotrema rubrum*) and corals. The second and third unit have seismic-velocities of 2.50 km/s (Pleistocene?) and 4.70 km/s, respectively, the latter corresponding to velocities typical for basaltic rocks.

The oldest 14C radiometric age for coral skeletons of drill holes was 4.86 ± 0.21 ky BP at the depth of 11.2 m (Kikuchi and Leão 1997). Nevertheless, this age may not correspond to the beginning of the reef development. Thus, it is assumed that the initiation of reef growth began before 4.86 ka, with a build-up rate ranging from 1.5 to 3.2 m/kyr (Kikuchi and Leão 1997).

**MATERIALS AND METHODS**

**CORAL COLLECTION**

Two small colonies (~15 cm of diameter) of the massive coral *Porites astreoides* were collected from a depth of about 3 m at the Cemitério (PC2 colony) and Tartaruga (PT2 colony) tide pools from the reef complex in July 2012 (Fig. 2).

**ANNUAL EXTENSION RATE**

The two colonies were cut into halves, and one half was cut into 5-mm thick slices parallel to the vertical growth axis of the whole colony. After cutting, these slices were air-dried and X-ray images were

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**Figure 1** - Location and aerial southward view of the Rocas Atoll.
taken. X-ray positives were used to select a track for extension rate measurement as well as sampling path for C and O isotopic analyses. The coral slabs were sampled along ontogenic profiles, considering the skeletal architecture. The PC2 coral slab was sampled in the valley between corallites (Fig. 3a), whereas the PT2 coral slab was sampled following the central axis of a corallite fan (Fig. 3c). This method improves the knowledge of sampling methods in *Porites* coral skeletal architecture for geochemical analysis, thus expanding upon some previous studies (Alibert and McCulloch 1997, Cohen and Hart 1997, DeLong et al. 2013, Gagan et al. 2012, Marshall and McCulloch 2002). The tracks were located where the banding density presented the least disturbed pattern, avoiding imperfections in the skeleton architecture such as bore holes or encrusting organisms. In order to derive information about the depth extent of the coral tissue at the time of coral collection, no bleaching was applied to the slices.

Annual extension rates were determined from sclerochronology data using CoralXDS Software 3.0. To this end, several transects in the digital image of the coral X-radiography were analyzed. Transects that showed clear banding patterns were chosen for C- and O-isotope investigation.

**Carbon and Oxygen Isotope Analyses**

Analyses of C and O isotopes of carbonates were performed at the Stable Isotope Laboratory...
Porites CORAL-BASED RECORD IN THE SOUTH ATLANTIC

Carbonate samples (aragonite; 4–20 mg) were collected using a modified hand held dental drill at intervals of 1 mm (or 2 mm, in a few cases) for both colonies. CO$_2$ gas from micro-drilled powder was extracted in a high-vacuum line after reaction with 100% orthophosphoric acid at 25 °C for one day. Released CO$_2$ was analyzed after cryogenic cleaning in a VG Isotech, double inlet, triple-collector SIRA II or Thermofinnigan Delta V Advantage mass spectrometer and results are reported in δ notation in permil (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard. Borborema Skarn

Figure 3 - PC2 and PT2 corals collected from the Cemitério and Tartarugas tide pool in the Rocas Atoll. (a) X-ray of a 5-mm-thick slice from the PC2 colony with a transect generated using the software CoralXDS; (b) Coral slice indicating location of points analyzed for O and C isotopes, tissue layer and the endolithic sign; (c) X-ray of a 5-mm-thick slice from the PT2 colony with transect generated using the software CoralXDS; (d) Coral slice indicating the location of points analyzed for O and C isotopes and tissue layer.
Calcite (BSC), calibrated against international standards, was used as the reference gas and reproducibility of the measurements was better than ±0.1 ‰ (1 sd) for both, carbon and oxygen isotope ratios. The values obtained for the standard NBS-20 in separate runs against BSC, yielded $\delta^{13}C_{\text{VPDB}} = -1.05$ ‰, and $\delta^{18}O_{\text{VPDB}} = -4.22$ ‰. These results are in close agreement with the values reported by the US National Bureau of Standards (-1.06 ‰ and -4.14 ‰, respectively).

RESULTS

ANNUAL EXTENSION RATE AND SCLEROCRONOLOGY

The X-radiograph of the PC2 colony shows relatively clear banding (Fig. 3a). Extension rate analysis and sampling for C- and O-isotope determination were preformed along a corallite valley through almost the entire PC2 slab (Fig. 3b). The number of banding pairs indicates an age of 11 years for specimen PC2 (Fig. 7). The extension rate for this section ranged from 4.0 to 8.9 mm/a with an average of 5.8 ± 1.5 mm/a (1 sd, n= 11). This colony exhibits a significant reduction in the extension rate between the years of 2008 - 2010 (Table I), coinciding with the pronounced El Niño Southern Oscillation (ENSO) pointed out by Ferreira et al. (2013) who reported strong sea-surface temperature anomalies from Rocas locality in 2009-2010 (ENSO).

The X-ray radiography of the PT2 colony shows a clear banding pattern (Fig. 3c). The extension rate analysis and sampling for C and O isotope measurements on this colony were preformed along the central axis of a corallite fan (Fig. 3d). The PT2 colony is interpreted to have reached an age of 7 years according to the number of banding pairs (Fig. 7). The extension rate for the investigated section ranges from 6.3 to 9.5 mm/a, with an average of $8.1 \pm 1.3$ mm/a (1 sd, n= 7).

STABLE ISOTOPES

The total data of $\delta^{13}C$ and $\delta^{18}O$ analysis are presented in Table II. The $\delta^{13}C$ values for the PC2 colony range from -0.90 to +0.47 ‰, with median value of -0.13 ‰ (±0.30, 1 sd, n = 61) and a total range of 1.37 ‰. The $\delta^{13}C$ values for the PT2 colony skeletal, range from -1.88 to -0.13 ‰ with median value of -0.75 ‰ (±0.45, 1 sd, n = 56) and a total range of 1.75 ‰ (Fig. 4).

Skeletal $\delta^{18}O$ values range from -5.16 to -3.63 ‰ VPDB, with median value of -4.05 ‰ (±0.25 VPDB,1 sd, n = 61) and a total range of 1.53 ‰ at the PC2 colony and from -5.52 to -3.88 ‰, with median value of -4.24 ‰ (±0.26 VPDB, 1 sd, n = 56) and a total range of 1.64 ‰ at the PT2 colony (Fig. 4).

The average values from the two colonies investigated here differ from each other in $\delta^{18}O$ and a more pronounced difference exists in $\delta^{13}C$ ($t$ test, confidence level< 0.05) (Fig. 4). The colonies can be distinguished from each other in a cross plot of $\delta^{18}O$ and $\delta^{13}C$ values (Fig. 5). This offset might result from sampling in different skeletal architecture (i.e. corallite valley in PC2 and apex of bump in PT2) or may be an indication that environmental and/or physiological controls operate in different ways in the Cemitério and Tartarugas tide pools.

DISCUSSION

ANNUAL EXTENSION RATE AND ENSO

Several studies have attempted to explain the influence of ENSO events on coral-growth rates, but have reached contrasting conclusions. Glynn et al. (1996) reported decreasing extension rates of Porites lobata at the Clipperton Atoll during the 1987 ENSO event. Gischler et al. (2009) and Dunbar et al. (1994) also reported lower skeletal growth-rates during ENSO events in Pleistocene corals from Southern Florida and in recent Pavona ssp. from the Galapagos Islands. Evangelista et
al. (2007), in contrast, noted a positive feedback of coral-growth rates with ENSO events in *Favia leptophylla* at the Abrolhos Coral Reef Bank (ACRB) on the Brazilian coast. These authors suggested that during ENSO events, ACRB experienced favorable conditions (i.e. increases in light abundance and lower sediment influx) to coral growth. At Rocos Atoll, the growth rate of the PC2 coral colony seems to be reduced during ENSO events, as indicated by the slower growth of specimen PC2 during such an interval.

In the PC2 colony, endolithic microorganisms generated a green band over the distance of 2 cm from the top (Fig. 3b). Endolithic algae can inhabit the skeleton of several coral species (Shashar and Stambler 1992), frequently forming green dense bands (Highsmith 1981). Hartmann et al. (2010) relate characteristic green bands in coral skeletons, to stress events that could lead to the complete loss...
TABLE II
O and C isotope results for the transects through the PC2 and PT2 colonies (see Figs. 3b and 3c).

| Sample  | Distance (mm) | $\delta^{18}$O PDB | $\delta^{13}$C PDB | Sample  | Distance (mm) | $\delta^{18}$O PDB | $\delta^{13}$C PDB |
|---------|---------------|---------------------|---------------------|---------|---------------|---------------------|---------------------|
| PC2.2   | 2             | -3.87               | 0.401               | PT2.3   | 2             | -4.523              | -0.834              |
| PC2.4   | 4             | -3.631              | 0.392               | PT2.4   | 4             | -4.238              | -0.737              |
| PC2.6   | 6             | -4.087              | 0.281               | PT2.5   | 5             | -4.181              | -0.481              |
| PC2.7   | 7             | -3.93               | 0.296               | PT2.6   | 6             | -4.063              | -0.566              |
| PC2.8   | 8             | -3.76               | 0.306               | PT2.7   | 7             | -4.032              | -0.19               |
| PC2.9   | 9             | -3.996              | -0.116              | PT2.8   | 8             | -4.032              | -0.126              |
| PC2.10  | 10            | -4.14               | -0.07               | PT2.9   | 9             | -4.085              | -0.143              |
| PC2.11  | 11            | -5.02               | -0.605              | PT2.10  | 10            | -4.165              | -0.667              |
| PC2.12  | 12            | -4.255              | -0.148              | PT2.11  | 11            | -4.267              | -0.756              |
| PC2.13  | 13            | -3.968              | -0.018              | PT2.12  | 12            | -4.338              | -1.225              |
| PC2.14  | 14            | -4.067              | -0.122              | PT2.13  | 13            | -4.411              | -1.107              |
| PC2.15  | 15            | -3.917              | 0.348               | PT2.14  | 14            | -4.311              | -1.631              |
| PC2.16  | 16            | -                   | -                   | PT2.15  | 15            | -4.323              | -0.811              |
| PC2.17  | 17            | -3.939              | -0.104              | PT2.16  | 16            | -4.232              | -0.756              |
| PC2.18  | 18            | -4.218              | -0.184              | PT2.17  | 17            | -4.183              | -0.786              |
| PC2.19  | 19            | -3.974              | -0.233              | PT2.18  | 18            | -4.223              | -0.766              |
| PC2.20  | 20            | -5.165              | 0.077               | PT2.19  | 19            | -4.196              | -0.554              |
| PC2.21  | 21            | -3.963              | 0.387               | PT2.20  | 20            | -4.197              | -0.577              |
| PC2.22  | 22            | -3.951              | 0.477               | PT2.21  | 21            | -4.115              | -1.164              |
| PC2.23  | 23            | -3.927              | 0.427               | PT2.22  | 22            | -4.329              | -0.944              |
| PC2.24  | 24            | -4.655              | -0.53               | PT2.23  | 23            | -4.208              | -0.243              |
| PC2.25  | 25            | -3.992              | -0.231              | PT2.24  | 24            | -4.211              | -0.436              |
| PC2.26  | 26            | -4.052              | -0.141              | PT2.25  | 25            | -4.227              | -0.416              |
| PC2.27  | 27            | -4.002              | -0.371              | PT2.26  | 26            | -4.267              | -0.463              |
| PC2.28  | 28            | -4.64               | -0.499              | PT2.27  | 27            | -4.238              | -0.321              |
| PC2.29  | 29            | -4.046              | -0.154              | PT2.28  | 28            | -4.31               | -1.239              |
| PC2.30  | 30            | -                   | -                   | PT2.29  | 29            | -5.518              | -1.881              |
| PC2.31  | 31            | -4.517              | -0.124              | PT2.30  | 30            | -4.447              | -1.196              |
| PC2.32  | 32            | -4.028              | -0.158              | PT2.31  | 31            | -4.856              | -0.851              |
| PC2.33  | 33            | -4.078              | -0.385              | PT2.32  | 32            | -4.104              | -0.504              |
| PC2.34  | 34            | -4.001              | -0.447              | PT2.33  | 33            | -3.88               | -0.42               |
| PC2.35  | 35            | -4.114              | -0.904              | PT2.34  | 34            | -4.046              | -0.34               |
| Sample | Distance (mm) | $\delta^{18}$O PDB | $\delta^{13}$C PDB | Sample | Distance (mm) | $\delta^{18}$O PDB | $\delta^{13}$C PDB |
|--------|--------------|-------------------|-------------------|--------|--------------|-------------------|-------------------|
| PC2.36 | 36           | -4.168            | -0.859            | PT2.35 | 35           | -4.123            | -0.125            |
| PC2.37 | 37           | -4.13             | -0.58             | PT2.36 | 36           | -4.13             | -0.332            |
| PC2.38 | 38           | -4.172            | -0.234            | PT2.37 | 37           | -5.078            | -1.045            |
| PC2.39 | 39           | -4.257            | -0.286            | PT2.38 | 38           | -4.335            | -1.342            |
| PC2.40 | 40           | -4.272            | -0.456            | PT2.39 | 39           | -4.369            | -1.643            |
| PC2.41 | 41           | -3.964            | -0.154            | PT2.40 | 40           | -4.409            | -1.489            |
| PC2.42 | 42           | -4.368            | -0.32             | PT2.41 | 41           | -4.35             | -0.558            |
| PC2.43 | 43           | -4.085            | -0.071            | PT2.42 | 42           | -3.898            | -0.19             |
| PC2.44 | 44           | -3.944            | 0.106             | PT2.43 | 43           | -4.228            | -0.395            |
| PC2.45 | 45           | -3.921            | 0.083             | PT2.44 | 44           | -4.469            | -0.7              |
| PC2.46 | 46           | -4.004            | 0.042             | PT2.45 | 45           | -4.032            | -0.144            |
| PC2.47 | 47           | -4.202            | -0.155            | PT2.46 | 46           | -4.28             | -0.351            |
| PC2.48 | 48           | -4.117            | -0.113            | PT2.47 | 47           | -                | -                 |
| PC2.49 | 49           | -3.939            | -0.095            | PT2.48 | 48           | -4.56             | -1.39             |
| PC2.50 | 50           | -4.049            | 0.099             | PT2.49 | 49           | -4.324            | -0.766            |
| PC2.51 | 51           | -3.964            | 0.178             | PT2.50 | 50           | -4.379            | -0.442            |
| PC2.52 | 52           | -3.954            | 0.228             | PT2.51 | 51           | -4.229            | -0.58             |
| PC2.53 | 53           | -3.971            | -0.157            | PT2.52 | 52           | -4.3              | -0.982            |
| PC2.54 | 54           | -4.013            | 0.154             | PT2.53 | 53           | -                | -                 |
| PC2.55 | 55           | -4.143            | -0.121            | PT2.54 | 54           | -4.291            | -0.834            |
| PC2.56 | 56           | -4.116            | -0.152            | PT2.55 | 55           | -4.171            | -0.738            |
| PC2.57 | 57           | -4.033            | -0.201            | PT2.56 | 56           | -4.401            | -1.109            |
| PC2.58 | 58           | -3.982            | -0.132            | PT2.57 | 57           | -4.214            | -1.24             |
| PC2.59 | 59           | -4.205            | -0.189            | PT2.58 | 58           | -4.488            | -1.668            |
| PC2.60 | 6            | -4.115            | -0.135            | PT2.59 | 59           | -4.243            | -1.478            |
| PC2.61 | 61           | -3.941            | 0.154             | PT2.60 | 60           | -4.427            | -1.29             |
| PC2.62 | 62           | -4.13             | 0.045             |        |              |                   |                   |
| PC2.63 | 63           | -                | -                 |        |              |                   |                   |
| PC2.64 | 64           | -4.092            | -0.076            |        |              |                   |                   |
| PC2.65 | 65           | -4.01             | -0.313            |        |              |                   |                   |
| PC2.66 | 66           | -4.232            | -0.469            |        |              |                   |                   |
The colonization of the coral skeleton by endolithic microorganisms might therefore indicate a stress event suffered by the colony. The sea-surface temperature anomalies at Rocas Atoll (Fig. 6) during the 2009-2010 ENSO event (Ferreira et al. 2013) is a probable trigger of the bloom of endolithic algae in the PC2 colony.

The PT2 colony grew faster than PC2 and did not show any marked endolithic algae bloom (Fig. 3d). There is no clear relationship between the growth recorded in the PT2 colony and an ENSO event. The absence of a microalgal bloom...
suggests that this coral may not have suffered from bleaching, even though δ¹⁸O data (Fig. 7) point to thermal stress during the year of 2009. Corals seem to respond differently to stress events. Even among individuals of a single species at the same place in the reef, some colonies can be damaged by stress, whereas others are not (Brown et al. 1986, Lough and Barnes 1990, Winter et al. 1991).

The depth extent of coral tissue at the time of extraction differs between the two studied colonies, PT2 (~8 mm) and PC2 (~5 mm). The skeleton space occupied by the tissue layer (i.e. the polyp body) varies according to the environmental conditions, presenting a wider layer where conditions to coral development are better (Barnes and Lough 1992). In unfavorable conditions (i.e. wave action, higher sedimentation rate etc.) abrasion of coral tissue may happen (Cruz-Piñón et al. 2003), leading to negative effects on the formation of the coral skeleton (Cortés and Risk 1985, Scoffin et al. 1992). The difference in the tissue layer observed in these two colonies could be used as a parameter for unravelling environmental conditions that influenced the coral development. Here, a wider tissue layer coincides with faster coral growth rate underlining that colonies from the same species can have different extension rates in the same reef complex. Moreover, the disparity in δ¹⁸O and δ¹³C behavior (discussed later) complements the array of information on the environmental and physiological patterns for each colony.

Although no strong correlation between ENSO phases and coral growth rates at Rocas Atoll was found, different extension rates and tissue layer thicknesses between the two specimens indicate different susceptibility of colonies to environmental stress (recorded as endolithic algae blooms). The complexity of the atoll environment, including hydrodynamics, tide regime and size of tide pool, for example, exerts strong control on the geochemical signals recorded in coral skeleton and its morphology.

STABLE ISOTOPES

δ¹³C fluctuations in the coral skeleton have been discussed for over 40 years (McConnaughey 1989, Swart 1983, Swart et al. 1996, Weber and Woodhead 1970). Currently, the common interpretation is that this variation has been governed by the fractionation of carbon isotopes in the internal inorganic carbon pool (Erez 1978, Goreau 1963, 1977). Bicarbonate derived from the surrounding sea water is modified by the fractionation during CO₂ respiration (Furla et al. 2000) and, more strongly, during photosynthetic reactions (McConnaughey 2003, Swart 1983).

In the photosynthetic processes, ¹²C is preferentially processed by the symbionts, resulting in metabolic fractionation (McConnaughey 1989, Swart 1983). Alternatively, Erez (1978) proposed that photosynthesis leads to lowering of δ¹³C in the coral carbonate by adding ¹³C-depleted CO₂ into coral skeletons. Later findings of Swart et al. (1996) in the Florida Reefs, support Erez’s hypothesis that photosynthesis causes decrease in δ¹³C. The true mechanism, by mean of which δ¹³C values are influenced in the coral skeleton, however, is still a matter of debate.

From the abovementioned, δ¹³C changes in the coral skeleton would be expected during a stress event leading to coral bleaching (i.e. loss of zooxanthellae). Changes in carbon isotope values would be expected because the metabolic fractionation by photosynthesis would drop drastically during a bleaching event, unless another symbiont assumes the main role of the photosynthetic process. In this case, the endolithic algae bloom could lead to a more intense metabolic fractionation.

Higher values of δ¹³C at the onset of the bloom of endolithic algae (Fig. 7a) are recorded in the PC2 colony. The δ¹³C enrichment across the endolithic bands might be a response of metabolic fractionation governed by increasing photosynthetic activity during the algae bloom (Hartmann et al. 2010).
There are two δ\(^{13}\)C trends separated by the endolithic mark in the PC2 coral skeleton: the first, after the ENSO event embracing 4 years (2009-2012), shows more positive values of δ\(^{13}\)C (mean= +0.09 ‰) and the second, prior to the event (2002-2008), presents a seasonal cycle with lighter δ\(^{13}\)C values (mean= -0.20 ‰).

Other authors credited enriched δ\(^{13}\)C in *Porites* corals, to slow skeletogenesis during bleaching events, due to kinetic effects in the period of carbonate precipitation (Allison et al. 1996, Suzuki et al. 2003). This could generate δ\(^{13}\)C enrichment during slow calcification, according to the McConnaughey model (McConnaughey 1989). In contrast, Leder et al. (1991) found different behaviors of isotopes in response to bleaching event in 1987 on *Montastrea annularis* corals in the Caribbean, casting doubts to the reliability on isotopic composition, which might not always be a useful tool.

At the PT2 colony, δ\(^{13}\)C values follow a very consistent seasonal cycle (Fig. 7b). Contrary to this, in the PC2 colony neither a disturbance in the δ\(^{13}\)C curve after the ENSO event nor any apparent endolithic algae signal in its skeletal structure are present. It seems that this colony, even though having experienced a stress episode during the 2009/2010 ENSO event, did not undergo bleaching. The steady cycle of δ\(^{13}\)C through the section (Fig. 7b) could be interpreted as a normal or healthy condition between the coral and its symbionts, since no evident disruption in this symbiosis is displayed by the δ\(^{13}\)C behavior.

Moreover, the PT2 colony shows a more pronounced variability in C isotopes and generally lighter values. This could be explained by two features: (i) a negative correlation of growth rate with isotope ratios would be expected, pointing to a relation where faster growth, indicated by tissue layer and growth rate analysis (Table III), leads to more disequilibrium δ\(^{13}\)C due to kinetic effects during skeletogenesis (Allison et al. 1996, Suzuki et al. 2003); or (ii) the fact that the PT2 colony was sampled in the coralite apex (Fig. 3c), considered by DeLong et al. (2013) as optimal sampling track, truly reflecting the isotopic composition (Fig. 7b).

The δ\(^{18}\)O curve for the PC2 colony (Fig. 7a) is marked by anomalously low values, which, according to the sclerochronology, were recorded in the years of 2009 and 2011, whereas the δ\(^{18}\)O curve for the PT2 colony (Fig. 7a) displays a pronounced anomalously negative value in the year of 2009 and a less pronounced one in 2008. Although different δ\(^{18}\)O excursions were respectively recorded just before and after 2009 in the PT2 and PC2 colonies, both are in agreement with anomalous values in the year of 2009 that exhibited maximum positive temperature anomalies of 1.61 °C at the Rocas site (Fig. 6). This temperature spike is larger than the ENSO 1997/1998 anomaly of 1.21 °C for Rocas Atoll, responsible for one of the most severe, worldwide bleaching events (Ferreira et al. 2013).

One of the δ\(^{18}\)O excursion of the PC2 colony matches the signal of endolithic microorganisms in the coral skeleton (Fig. 7a), indicative of bleaching event, as discussed before, and coincides with the temperature anomalies during the 2009-2010 El Niño-Southern Oscillation event (ENSO) mentioned by Ferreira et al. (2013).

δ\(^{18}\)O is controlled by the interplay of temperature and the seawater isotopic composition,

### Table III

|     | PC2         | PT2         |
|-----|-------------|-------------|
| Mean δ\(^{18}\)O (‰VPDB) | -4.10 ± 0.25 | -4.29 ± 0.26 |
| Mean δ\(^{13}\)C (‰VPDB) | -0.10 ± 0.3  | -0.78 ± 0.45 |
| Mean growth rate (cm/a) | 0.58 ± 0.15  | 0.81 ± 0.13  |
| Tissue layer (cm) | 0.5  | 0.8 |
where the latter is controlled by changes in precipitation, evaporation and local upwelling (Suzuki et al. 2003). The observed rapid shifts (> 1.0 ‰) towards negative values might express the response to higher SST and are supported by the anomalous temperature at Rocas Atoll during this time (Ferreira et al. 2013). The oxygen isotope curve up to 2009 does not exhibit any similarly low value as observed during and after the ENSO event (except for the year of 2008 in PT2 coral).

Clearly the O isotope spikes in the corals cannot really be true temperature spikes but rather represent disequilibrium aragonite formation related to thermal stress (otherwise we would be speaking about a 4 degree temperature anomaly, which we didn’t observe). It seems that while the timing of such events might be faithfully recorded by the corals, the magnitude might be misestimated due to the stressing effect on the corals during skeletogenesis.

In a tide-pool environment, tide regime is expected to generate noise in the isotopic signal leading to problems in the identification of an ENSO event. Changes in the seawater isotopic composition are unlikely to produce these signals, because the phenomenon behind these changes (i.e. evaporation, precipitation and upwelling) occur at higher frequency and are expected to be recorded in coral skeleton multiple times. We therefore conclude that the isotope signals are controlled by changes in SST, despite apparent disequilibrium effects during mineralization of the coral skeleton.

Linear regressions between δ¹⁸O and δ¹³C (Fig. 6) display a weak positive relationship (PC2, \( r^2 = 0.20; p < 0.0001 \); PT2, \( r^2 = 0.36; p < 0.0001 \)). If δ¹³C expresses kinetic fractionation by physiological activity (photosynthesis and respiration) and if δ¹⁸O responds to SST fluctuation (i.e. more negative values mean higher SST), increases in SST lead to depletion in δ¹³C, which means lower photosynthetic activity and higher respiration (Coles and Jokiel 1977).

Positive correlations of oxygen and carbon isotope values are common in ahermatypic coral, whose metabolic activity and respiration are the only processes directly influencing the isotopic fractionation. In hermatypic corals, photosynthesis affects the O – C isotope relationship that, occasionally, presents a completely random pattern (Swart 1983).

McConnaughey (1989) has ascribed positive correlations between δ¹³C and δ¹⁸O to carbonates showing kinetic isotopic fractionation patterns, which implies isotopic fractionation in carbonates being controlled mainly by kinetics rather than by physiological processes. Alternatively, Fairbanks and Dodge (1979) pointed out that the relationship between insolation and temperature, controls the degree of correlation between oxygen and carbon isotopes.

Although Swart et al. (1996) have found inverse correlation between photosynthesis/respiration rates (P/R), based on Coles and Jokiel (1977) we believe that at higher temperatures, when photosynthesis/respiration rates are reduced, the contribution of ¹²C from respiration to the internal carbon pool increases, thereby generating the observed positive correlation.

Moreover, the hottest and coldest months at Rocas Atoll are respectively April and September while the maximum and minimum peaks of insolation are in January and July, respectively. This out-of-phase relationship of temperature and insolation supports the Fairbanks and Dodge (1979) ¹³C-insolation model.

The observed positive correlation of C and O isotopes is ambiguous and might be related to kinetic fractionation (McConnaughey’s proposal) or be the product of changing photosynthesis/respiration rates (Fairbanks and Dodge’s proposal).

Here we prefer the suggestion of Fairbanks and Dodge, indicating a fractionation mainly governed by temperature and respiration processes. This conclusion is based on two observations: (1)
Temperature at the inner reef can reach higher levels in the tide pools during low tides potentially favoring a lower photosynthesis/respiration rate; and (2) the $\delta^{13}C$ shift during algae bloom in specimen PC2 indicates that the colony responded to a physiological turnover, thus the carbon-isotope signal seems to be governed mainly by coral physiology, are not by kinetic effects.

**CORALLITE APEX X CORALLITE VALLEY**

The importance of investigating the variability of $\delta^{18}O$ and $\delta^{13}C$ values for different colonies in similar environments is well known (Guilderson and Schrag 1999, Leder et al. 1991, 1996). The mean $\delta^{18}O$ for the PC2 colony is 0.19‰ higher than that for the PT2 one, which is in the range of inter-colony variability in $\delta^{18}O$ of 0.15–0.40‰ reported for *Porites* from some tropical Pacific Islands (Guilderson and Schrag 1999, Linsley et al. 1999, Stephens 2004). The average difference of 0.68‰ in $\delta^{13}C$ between the PC2 and PT2 colonies (Fig. 5) is probably due to physiological controls, as $\delta^{13}C$ is believed to be partly and variably influenced by photosynthesis/respiration processes (Swart 1983).

The influence of skeletal architecture on the isotopic signal cannot be neglected. DeLong et al. (2013) provided new insights on sampling methods to improve coral-based reconstructions mainly by appraisal of the skeletal architecture, where the optimal geochemical signal can be obtained at the central axis of a corallite fan, whereas suboptimal signals, as the ones derived from corallite valleys, can result in loss of geochemical information. Moreover, geochemical determinations in the valley between corallites have yielded higher $\delta^{18}O$ and Sr/Ca values than the apex bump, implying colder temperatures of about 1 to 2 °C (Alibert and McCulloch 1997, Cohen and Hart 1997).

Our data seems to support results reported by Alibert and McCulloch (1997) and Cohen and Hart (1997), who stated that suboptimal sampling, in case of corallite valleys, can yield colder temperatures. In our study, we found differences in $\delta^{18}O$ values between PC2 (corallite valley) and PT2 (corallite fan) colonies, with PT2 being depleted in relation to PC2 by an average of 0.19‰, and in the maximum and minimum values by 0.25 and 0.36‰, respectively. These offsets suggest a bias of approximately 1 °C (using the mean value), based on different *Porites* calibrations that yielded slopes varying from $-0.134$ (‰/°C) to $-0.262$ (Omata et al. 2006) and for Galapagos Islands (which has a latitude similar to Rocas Atoll but is situated in the Pacific Ocean), calibrations yielded $0.209$ ‰/°C (McConnaughey 1989).

Even though the skeletal architecture issues are still a matter of concern when considering highly accurate and precise coral-based climate reconstructions (DeLong et al. 2013), geochemical signals of the ENSO of 2009/2010 can be detected with high fidelity.

**ENSO AND STABLE-ISOTOPE SIGNAL**

The effect of the El Niño-Southern Oscillation in South America was investigated by Ropelewski and Halpert (1987, 1996). According to these authors, the South American continent has two areas of precipitation patterns associated to ENSO events, one in the Northeastern of South America (NSA) and another in the Southeastern of South America (SSA).

At the NSA, where Rocas Atoll is located, Ropelewski and Halpert (1987) highlighted a consistent relationship between ENSO and precipitation, with dry seasons in the area during ENSO events. Such ENSO-related droughts had been previously described by Hastenrath and Heller (1977), who pointed out the strong pattern between extremely dry season in the Northeast Brazil and El Niño phases. Kousky et al. (1984) suggested that this low precipitation may be related to increasing atmospheric subsidence over Northern South
America which perturbs the Walker and Hadley circulations over South America, in turn causing a westward displacement of the Atlantic Walker circulation during ENSO events.

Such perturbation would cause physical, chemical and biological changes in the marine system via atmospheric-ocean interaction. This feedback might be imprinted in the isotopic composition of the coral skeleton, as a response of SST changes affecting coral $\delta^{18}O$ and, more indirectly, by coral physiological factors, affecting $\delta^{13}C$.

The negative $\delta^{18}O$ excursion observed in the present study might be a response to the severe thermal stress caused by the ENSO of 2009/2010. Thermal stress on coral reefs has been reported also for the year 2005 in the 1000 km long Mesoamerican reef system. The reef systems in the Southern Tropical America region experienced severe coral bleaching during this year, causing a severe crisis from the oceanic reefs of Colombia in the Southwestern Caribbean to Brazilian reefs in the Western Atlantic. However, the severity of bleaching varied greatly and bleaching mortality was generally low (Wilkinson and Souter 2008).

Although the isotopic record of coral colony PC2 reaches back to 2002, and a geochemical signal from the ENSO of 2005 might have be expected, no corresponding excursion was observed. The fact that PC2 was sampled in a valley between corallites might account for the loss of geochemical signal. Nevertheless, in Brazil, the HotSpots of 2005 affected reefs from South Bahia (Itacolomis and Abrolhos reefs) with a rise in temperature of 0.75 °C above maximum summer averages. The National Oceanic and Atmospheric Administration (NOAA) has not detected a major Hotspot in the satellite images, suggesting this to be a doldrum-like event (Wilkinson and Souter 2008). Approximately 25 % of the coral cover was affected by bleaching during the 2005 ENSO for the two areas (Leão et al. 2010). The Hotspot at Rocos Atoll during 2005 barely exceeded 0.5 °C (Ferreira et al. 2013) and no bleaching event was reported for this site, and this might also explains the lack of oxygen isotopic excursion recorded in the PC2 colony.

**CONCLUSIONS**

We presented one of the first coral-based isotopic records in *Porites* of a remote atoll in the South Atlantic, the Rocos Atoll. Such coral-based record seems to be a good proxy in the search for anomalous climatic fluctuations. Here we recognized anomalous $\delta^{18}O$ and $\delta^{13}C$ linked to the 2009/2010 ENSO event.

$\delta^{18}O$ negative excursions were recorded in both colonies investigated here. The magnitude of the geochemical record apparently misestimates (up to 4 °C) the true temperature observed at the place (1.6 °C) and a calibration would be necessary to assure accurate temperature values inferred via $\delta^{18}O$.

We investigated differences in the geochemical signal by sampling in the corallite valley and corallite fan. $\delta^{18}O$ recorded on the corallite valley was depleted compared to the corallite fan by 0.19 ‰. Nevertheless, both corallite valley and the corallite fan seemed to faithfully record the 2009/2010 ENSO event.

Changes in $\delta^{13}C$ after the ENSO event at the PC2 colony were interpreted as a consequence of coral bleaching (inferred via endolithic algae bloom) leading also to changes in the $\delta^{13}C$ values. Depleted $\delta^{13}C$ values in the PT2 colony might have been a consequence of disequilibrium conditions due to faster growth rates or an effect of sampling in the corallite fan.

The coral-based records in this study assure that the Rocos Atoll is a vital site in the record of climate oscillations in the Tropical South Atlantic Ocean. Moreover, it warns us that the current global climate changes threaten coral reefs in the
South Atlantic Ocean, even in pristine places as Rocas Atoll.

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REFERENCES

ALIBERT C and KINSLEY L. 2008. A 170-year Sr/Ca and Ba/Ca coral record from the western Pacific warm pool: 1. What can we learn from an unusual coral record? J Geophys Res 113: C04008.

ALIBERT C AND MCCULLOCH MT. 1997. Strontium/calcium ratios in modern porites corals from the Great Barrier Reef as a proxy for sea surface temperature: Calibration of the thermometer and monitoring of ENSO. Paleoceanography 12: 345-363.

ALLISON N, TUDHOPE A AND FALLICK A. 1996. Factors influencing the stable carbon and oxygen isotopic composition of Porites lutea coral skeletons from Phuket, South Thailand. Coral Reefs 15: 43-57.

AL-ROUSAN S, AL-MOGHRABI S, PÄTZOLD J and WEFER G. 2003. Stable oxygen isotopes in Porites corals monitor weekly temperature variations in the northern Gulf of Aqaba, Red Sea. Coral Reefs 22: 346-356.

ASAMI R, YAMADA T, IRYU Y, MEYER CP, QUINN TM AND PAULAY G. 2004. Carbon and oxygen isotopic composition of a Guam coral and their relationships to environmental variables in the western Pacific. Palaeoecogr Palaeoclimatol Palaeoecol 212: 1-22.

BARNES DJ and LOUGH JM. 1992. Systematic variations in the depth of skeleton occupied by coral tissue in massive colonies of Porites from the Great Barrier reef. J Exp Mar Bio Ecol 159: 113-128.

BECK JW, EDWARDS RL, ITO E, TAYLOR FW, RECY J, ROUGERIE F, JOANNOT P AND HENIN C. 1992. Sea-surface temperature from coral skeletal strontium/calcium ratios. Science 257: 644-647.

BROWN B, TISSIER M, HOWARD LS, CHARUCHINDA M AND JACKSON JA. 1986. Asynchronous deposition of dense skeletal bands in Porites lutea. Mar Biol 93: 83-89.

BUDDEMEIER RW, MARAGOS JE AND KNUTSON DW. 1974. Radiographic studies of reef coral exoskeletons: Rates and patterns of coral growth. J Exp Mar Bio Ecol 14: 179-199.

CHEN T, YU K AND CHEN T. 2013. Sr/Ca–sea surface temperature calibration in the coral Porites lutea from subtropical northern South China Sea. Palaeoecogr Palaeoclimatol Palaeoecol 392: 98-104.
COBB KM, CHARLES CD, CHENG H AND EDWARDS RL. 2003. El Niño/Southern Oscillation and tropical Pacific climate during the last millennium. Nature 424: 271-276.

COBB KM, WESTPHAL N, SAYANI HR, WATSON JT, DI LORENZO E, CHENG H, EDWARDS RL AND CHARLES CD. 2013. Highly variable El Niño-Southern Oscillation throughout the Holocene. Science 339: 67-70.

COHEN AL AND HART SR. 1997. The effect of colony topography on climate signals in coral skeleton. Geochim Cosmochim Acta 61: 3905-3912.

COLE JE AND FAIRBANKS RG. 1990. The Southern Oscillation recorded in the δ18O of corals from Tarawa Atoll. Paleoceanography 5: 669-683.

COLES S AND JOKIEL P. 1977. Effects of temperature on photosynthesis and respiration in hermatypic corals. Mar Biol 43: 209-216.

CORRÊGE T. 2006. Sea surface temperature and salinity reconstruction from coral geochemical tracers. Palaeogeogr Palaeoclimatol Palaeoecol 232: 408-428.

CORTÈS JN AND RISK MJ. 1985. A reef under silitation stress: Catalina, Costa Rica. Bull Mar Sci 36: 18.

CRUZ-PiñON G, CARRICART-GANIVET JP AND ESPINOZA-AVALOS J. 2003. Monthly skeletal extension rates of the hermatypic corals Montastrea annularis and Montastrea faveolata: biological and environmental controls. Mar Biol 143: 491-500.

DELONG KL, QUINN TM, TAYLOR FW, SHEN CC AND LIN K. 2013. Improving coral-base paleoclimate reconstructions by replicating 350 years of coral Sr/Ca variations. Palaeogeogr Palaeoclimatol Palaeoecol 373: 6-24.

DUNBAR RB, WELLINGTON GM, COLGAN MW AND GLYNN PW. 1994. Eastern Pacific sea surface temperature since 1600 A.D.: The δ 18 O record of climate variability in Galápagos Corals. Paleoceanography 9: 291-315.

EREZ J. 1978. Vital effect on stable-isotope composition seen in foraminifera and coral skeletons. Nature 273: 199-202.

EVANGELISTA H, GODIVA D, SIFEDDINE A, LEÃO ZMAN, RIGOZO NR, SEGAL B, AMBRIZZI T, KAMPEL M, KIKUCHI RK AND LE CORNEC F. 2007. Evidences linking ENSO and coral growth in the Southwestern-South Atlantic. Clim Dyn 29: 869-880.

FAIRBANKS RG AND DODGE RE. 1979. Annual periodicity of the the 18O/16O and 13C/12C and ratios in the coral Montastrea annularis. Geochim Cosmochim Acta 43: 1009-1020.

FELIS T, PÁTZOLD J, LOYA Y, FINE M, NAWAR AH AND WEFER G. 2000. A coral oxygen isotope record from the northern Red Sea documenting NAO, ENSO, and North Pacific teleconnections on Middle East climate variability since the year 1750. Paleoceanography 15: 679-694.

FELIS T AND RIMBU N. 2010. Mediterranean climate variability documented in oxygen isotope records from northern Red Sea corals—A review. Glob Planet Change 71: 232-241.

FERREIRA BP, COSTA MBSF, COXEY MS, GASPAR ALB, VELEDA D AND ARAUJO M. 2013. The effects of sea surface temperature anomalies on oceanic coral reef systems in the southwestern tropical Atlantic. Coral Reefs 32: 441-454.

FURLA P, GALGANI I, DURAND I AND ALLEMAND D. 2000. Sources and mechanisms of inorganic carbon transport for coral calcification and photosynthesis. J Exp Biol 203: 3445-3457.

GAGAN MK, AYLI LK, BECK JW, COLE JE, DRU ERM, DUNBAR RB AND SCHrag DP. 2000. New views of tropical paleoclimates from corals. Quat Sci Rev 19: 45-64.

GAGAN MK, CHIVAS AR AND ISDALE PJ. 1994. High-resolution isotopic records from corals using ocean temperature and mass-spawning chronometers. Earth Planet Sci Lett 121: 549-558.

GAGAN MK, DUNBAR GB AND SUZUKI A. 2012. The effect of skeletal mass accumulation in Porites on coral Sr/Ca and δ18O paleothermometry. Paleoceanography 27: 1-16.

GERARDI DFM AND BOSENE D. 2001. Composition and community structure of the coralline algal reefs from Atol das Rucas, South Atlantic, Brazil. Coral Reefs 19: 205-219.

GERARDI DFM AND BOSENE DWJ. 1999. Modeling of the Ecological Succession of Encrusting Organisms in Recent Coralline-Algal Frameworks from Atol Das Rucas, Brazil. Palaios 14: 145.

GISCHLER E, HUDSON JH AND STORZ D. 2009. Growth of Pleistocene massive corals in south Florida: low skeletal extension-rates and possible ENSO, decadal, and multi-decadal cyclicities. Coral Reefs 28: 823-830.

GLYNN PW, VERON JEN AND WELLINGTON GM. 1996. Clipperton Atoll (eastern Pacific): oceanography, geomorphology, reef-building coral ecology and biogeography. Coral Reefs 15: 71-99.

GOES CA. 2005. Correntes superficiais no Atlântico Tropical, obtidas por dados orbitais, e sua influência na dispersão de larvas de lagosta. Dissertação de Mestrado em Sensoriamento Remoto. São José dos Campos, São Paulo (INPE-1111-TDI/ 111). Instituto Nacional de Pesquisas Espaciais - INPE, 35 p. (Unpublished).

GOREAU T. 1963. Calcium carbonate deposition by coralline algae and corals in relation to their roles as reef-builders. Ann N Y Acad Sci 109: 127-167.

GOREAU TJ. 1977. Coral Skeletal Chemistry: Physiological and Environmental Regulation of Stable Isotopes and Trace Metals in Montastrea annularis. Proc R Soc B Biol Sci 196: 291-315.

GUILDERSON T AND SCHrag D. 1999. Reliability of coral isotope records from the Western Pacific Warm Pool: A comparison using age-optimized records. Paleoceanography 14: 457-464.
An Acad Bras Cienc (2015) 87 (4)

Guilderson TP and Schrag DP. 1998. Abrupt Shift in Subsurface Temperatures in the Tropical Pacific Associated with Changes in El Niño. Science 281: 240-243.

Hartmann AC, Carilli JE, Norris RD, Charles CD and Deheyn DD. 2010. Stable isotopic records of bleaching and endolithic algae blooms in the skeleton of the boulder forming coral Montastrea faveolata. Coral Reefs 29: 1079-1089.

Hastenrath S and Heller L. 1977. Dynamics of climatic hazards in northeast Brazil. Q J R Meteorol Soc 103: 77-92.

Hereid KA, Quinn TM and Okumura YM. 2013. Assessing spatial variability in El Niño-Southern Oscillation event detection skill using coral geochemistry. Paleoceanography 28: 14-23.

Hereid KA, Quinn TM, Taylor FW, Shen CC, Lawrence Edwards R and Cheng H. 2012. Coral record of reduced El Niño activity in the early 15th to middle 17th centuries. Geology 41: 51-54.

Highsmith RC. 1981. Lime-boring algae in hermatypic coral skeletons. J Exp Mar Biol Ecol 55: 267-281.

Kikuchi RKP and Leão ZMAN. 1997. Rocos (Southwestern Equatorial Atlantic, Brazil): An Atoll Built Primarily By Coralline Algae, in: Proceedings 8th International Coral Reef Symposium, p. 731-736.

Kilbourne KH, Quinn TM, Webb R, Guilderton T, Nyberg J and Winter A. 2008. Paleoclimate proxy perspective on Caribbean climate since the year 1751: Evidence of cooler temperatures and multidecadal variability. Paleoceanography 23: 1-14.

Klein R and Loya Y. 1991. Skeletal growth and density patterns of two Porites corals from the Gulf of Elat, Red Sea. Mar Ecol Prog Ser 77: 253-259.

Knutson DW, Buddemeier RW and Smith SV. 1972. Coral chronometers: seasonal growth bands in reef corals. Science 177: 270-272.

Kousky VE, Kangro MT and Cavalcanti IFA. 1984. A review of the Southern Oscillation : oceanic-atmospheric circulation changes and related rainfall anomalies. Tellus 36: 490-504.

Krishnan P, Dam Roy S, George G, Srivastava RC, Anand A, Murugesan S, Kaliyamoorthy M, Vikas N and Soundararajan R. 2011. Elevated sea surface temperature during May 2010 induces mass bleaching of corals in the Andaman. Curr Sci 100: 111-117.

Kuhnt H, Pätzold J, Hatcher B, Wyrwoll KH, Eisenhauer A, Collins LB, Zhu ZR and Wefer G. 1999. A 200-year coral stable oxygen isotope record from a high-latitude reef off Western Australia. Coral Reefs 18: 1-12.

Leão ZMAN, Kikuchi RKP, Oliveira MDM and Vasconcellos V. 2010. Status of Eastern Brazilian coral reefs in time of climate changes. Panam J Aquat Sci 5: 224-235.

Leder JJ, Swart PK, Szmant AM and Dodge RE. 1996. The origin of variations in the isotopic record of scleractinian corals: I. Oxygen. Geochim Cosmochim Acta 60: 2857-2870.

Leder JJ, Szmant AM and Swart PK. 1991. The effect of prolonged “bleaching” on skeletal banding and stable isotopic composition in Montastrea annularis Preliminary observations. Coral Reefs 10: 19-27.

Linsley BK, Dunbar RB, Wellington GM and Mucciarone DA. 1994. A coral-based reconstruction of Intertropical Convergence Zone variability over Central America since 1707. J Geophys Res 99: 9977-9994.

Linsley BK, Messier RG and Dunbar RB. 1999. Assessing between-colony oxygen isotope variability in the coral Porites lobata at Clipperton Atoll. Coral Reefs 18: 13-27.

Lough JM and Barnes DJ. 1990. Intra-annual timing of density band formation of Porites coral from the central Great Barrier Reef. J Exp Mar Bio Ecol 135: 35-57.

Marshall JF and Mcculloch MT. 2002. An assessment of the Sr/Ca ratio in shallow water hermatypic corals as a proxy for sea surface temperature. Geochim Cosmochim Acta 66: 3263-3280.

McConnaughey T. 1989. 31C and 18O isotopic disequilibrium in biological carbonates: I. Patterns. Geochim Cosmochim Acta 53: 151-162.

McConnaughey TA. 2003. Sub-equilibrium oxygen-18 and carbon-13 levels in biological carbonates: carbonate and kinetic models. Coral Reefs 22: 316-327.

Medina-Elizalde M, Gold-Bouchot G and Cea-Moreno V. 2002. Lead contamination in the Mexican Caribbean recorded by the coral Montastrea annularis (Ellis and Solander). Mar Pollut Bull 44: 421-431.

Moses CS and Swart PK. 2006. Stable isotope and growth records in corals from the island of Tobago: Not simply a record of the Orinoco. Proceedings of 10th International Coral Reef Symposium, Okinawa, Japan, p. 580-587.

Moses CS, Swart PK and Dodge RE. 2006. Calibration of stable oxygen isotopes in Siderastrea radians (Cnidaria:Scleractinia): Implications for slow-growing corals. Geochem Geophys Geosystems 7: 1-14.

Omata T, Suzuki A, Kawahata H, Nojima S, Minoshima K and Hata A. 2006. Oxygen and carbon stable isotope systematics in Porites coral near its latitudinal limit: The coral response to low-thermal temperature stress. Glob Planet Change 53: 137-146.

Pätzold J. 1984. Growth rhythms recorded in stable isotopes and density bands in the reef coral Porites lobata (Cebu, Philippines). Coral Reefs 3: 87-90.

Pereira NS, Manso VAV, Macedo RJ, Dias JMA and Silva AMC. 2013. Detrital carbonate sedimentation of the Rocos Atoll, South Atlantic. An Acad Bras Cienc 85: 57-72.
Richardson PL and Walsh D. 1986. Mapping climatological seasonal variations of surface currents in the tropical Atlantic using ship drifts. J Geophys Res 91: 10537.

Ropelewski CF and Halpert MS. 1987. Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation. Mon Weather Rev 115: 1606-1626.

Ropelewski CF and Halpert MS. 1996. Quantifying Southern Oscillation-Precipitation Relationships. J Clim 9: 1043-1059.

Schrag DP and Linsley BK. 2002. Corals, Chemistry, and Climate. Science 296: 277-278.

Scoffin TP, Tudhope AW, Brown BE, Chansang H and Cheeney RF. 1992. Patterns and possible environmental controls of skeletogenesis of Porites lutea, South Thailand. Coral Reefs 11: 1-11.

Shashar N and Stambler N. 1992. Endolithic algae within corals - life in an extreme environment. J Exp Mar Bio Ecol 163: 277-286.

Stephans CL. 2004. Assessing the reproducibility of coral-based climate records. Geophys Res Lett 31: L18210.

SuZuki A, Gagan MK, Fabricius K, Isdale PJ, Yukino I and Kawahata H. 2003. Skeletal isotope microprofiles of growth perturbations in Porites corals during the 1997-1998 mass bleaching event. Coral Reefs 22: 357-369.

Swart P. 1983. Carbon and oxygen isotope fractionation in scleractinian corals: a review. Earth-Science Rev 19: 51-80.

Swart P, Leder J, Szmant A and Dodge R. 1996. The origin of variations in the isotopic record of scleractinian corals: II. Carbon. Geochim Cosmochim Acta 60: 2871-2885.

Swart PK, Greer L, Rosenheim BE, Moses CS, Waite AJ, Winter A, Dodge RE and Helmle K. 2010. The $^{13}$C Suess effect in scleractinian corals mirror changes in the anthropogenic CO$_2$ inventory of the surface oceans. Geophys Res Lett 37: L05604.

Weber J and Woodhead P. 1970. Carbon and oxygen isotope fractionation in the skeletal carbonate of reef-building corals. Chem Geol 6: 93-117.

Weber JN and Woodhead PMJ. 1972. Temperature dependence of oxygen-18 concentration in reef coral carbonates. J Geophys Res 77: 463-473.

Wefer G and Berger WH. 1991. Isotope paleontology: growth and composition of extant calcareous species. Mar Geol 100: 207-248.

Wei G, Sun M, Li X and Nie B. 2000. Mg/Ca, Sr/Ca and U/Ca ratios of a porites coral from Sanya Bay, Hainan Island, South China Sea and their relationships to sea surface temperature. Palaeogeogr Palaeoclimatol Palaeoecol 162: 59-74.

Wilkinson C and Souter D. 2008. Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre, Townsville, 152 p.

Winter A, Goenaga C and Maul GA. 1991. Carbon and oxygen isotope time series from an 18-year Caribbean reef coral. J Geophys Res 96: 16673-16678.
