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INTERACTIONS BETWEEN HYDROLOGY AND BENTHIC COVERAGE AT ROCAS ATOLL

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ABSTRACT

Abiotic parameters and benthic coverage were determined in shallow habitats at Rocas Atoll. It was found daily and seasonal variations on seawater characteristics related to tides, pluviometry, daily solar cycle, and organisms' metabolism. Habitats with high coverage of carbonatic organisms were associated with the alkalinity of seawater, whereas habitats with elevated abundance of turf and macro algae were correlated to dissolved inorganic nutrients. Therefore, it is suggested that the availability of nutrients and carbonates in seawater are important for the organism's distribution in the atoll. Only seven corals settled on the plates during the experiment (Porites spp. and Siderastrea spp.). In order to better constrain the causes of the low coral recruitment in the atoll and predicted the effects of climate changes and ocean acidification over this important reef ecosystem, it is necessary to assess, in high resolution (i.e. week to monthly), the environmental variables that overlaps a short-term period.

Key Words: macroalgae; coral reefs; dissolved inorganic nutrients; environment variables.

RESUMO

Parâmetros abióticos e a cobertura bentônica foram determinados em habitats rasos no Atol das Rocas. Verificou-se variações diárias e sazonais nas características da água do mar relacionadas com marés, pluviometria, ciclo solar diário, e metabolismo dos organismos. Habitats com alta cobertura de organismos carbonáticos foram associados com a alcalinidade da água do mar, enquanto habitats com elevada abundância de tufos de algas e macroalgas foram correlacionados com a concentração de nutrientes inorgânicos dissolvidos. Portanto, sugere-se que a disponibilidade de nutrientes e de carbonatos em água do mar são importantes para a distribuição do organismo no atol. Apenas sete corais assentaram nas placas durante o experimento (Porites spp. e Siderastrea spp). A fim de melhor identificar as

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causas do baixo recrutamento de coral do atol e prever os efeitos das mudanças climáticas e acidificação dos oceanos sobre este importante ecossistema recifal, é necessário avaliar, em alta resolução (ou seja, semanal a mensal), as variáveis ambientais que se sobrepõe a um curto período de tempo.

Palavras chave: macroalgas, recifes de coral, nutrientes dissolvidos inorgânicos, variáveis ambientais.

INTRODUCTION

Rocas Atoll is the unique oceanic reef formation at the South Atlantic and offers an ideal system to study natural variations of benthic community assemblages. Its reef framework is well described by KIKUCHI and LEÃO (1997) and GHERARDI and BOSENCE (1999, 2001). One of Roca's characteristics that distinguishes it from other atolls concerns its composition. Encrusting coralline red algae, shells of vermetid gastropods, encrusting foraminifera and polychaetes worm tubes are the main carbonatic organisms responsible for the structure of Rocas Atoll. This is in contrast to the structure of atolls from the Indo-pacific and Caribbean waters, which are mainly constructed by hermatypic corals (KIKUCHI and LEÃO, 1997; GHERARDI and BOSENCE, 2001).

FONSECA et al. (2012) studyied reef flat community structure at Rocas, and found a great scarcity of hermatypic corals species and cover, stating that the reef flat is near solely dominated by turf forming and crustose macroalgae species. According to these authors, local, small-scale variability of physical and biotic factors in a well-defined reef geomorphic zone may harbor microcosms, each supporting unique benthic communities. In fact, LONGO et al. (2015) observed variations in benthic and reef fish communities, and feeding pressure on the benthos between open and closed pools at the atoll. They suggest that the dynamic in open pools is mostly driven by physical factors and the tolerance of organisms to harsh conditions, while in closed pools direct and indirect effects of species interaction play an important role.

The increasing demand for progress, since the industrial revolution, the concentration of carbon dioxide (CO_2) in the atmosphere has raised from 280 ppm to over 400 ppm in the present days (ALBRIGHT et al., 2016). This elevation is mainly caused by the fossil fuel burn and deforestation and has been causing a series of problems to the Earth equilibrium, such as climate changes, sea level rise and most recently a process known as ocean acidification (OA) (ANTHONY et al., 2011; ZEEBE, 2012). OA can be summarized as the process by which the rising atmospheric CO2 is absorbed by the ocean surface waters, increases the partial pressure of CO_2 (pCO_2), leading to a number of chemical changes including increased hydrogen ion concentrations (lower pH, more acidic) and reduced carbonate ion concentrations. (IGLESIAS-RODRIGUEZ et al., 2016).

Impacts of OA on marine calcifiers (organisms that depend on carbonate ions available on the seawater to build their skeletons, shells, etc.) are constantly been reported around the world, affecting physiological processes such as calcification, photosynthesis, and neurophysiological pathways. (DUPONT et al., 2010; ALBRIGHT and LANGDON, 2011; FABRICIUS et al., 2011; MELZNER et al., 2011). According to HOEGH-GULDBERG et al. (2007), reef ecosystems are among one of the most threatened environments. Nevertheless, OA can cause positive effects in other marine organisms, especially algae and seagrass, which use the CO2 in excess on the water to increase their photosynthetic activities elevating their primary production and growth (KROEKER et al., 2013). Those changes in the physiology of individuals can alter the dynamics of their populations and ultimately affect entire ecosystems (IGLESIAS-RODRIGUEZ et al., 2016).

As an isolated, near-pristine system, where natural mechanisms can still be studied under limited human impact, the comprehension of processes influencing biological communities and how they promote ecosystem functions is particularly important to

Rocas Atoll (LONGO et al., 2015). In this context, the goal of this study was to improve the understanding of physical-biological interactions at benthic communities in Rocas Atoll. Therefore providing data to support future investigations of the climate change and OA impacts at one of the most effective marine protected area in Brazil.

STUDY AREA

Rocas Atoll is situated at latitude 3°51'S and longitude 33° 49'W, 266 km from the city of Natal, Rio Grande do Norte, and 145 km from Fernando de Noronha Archipelago, Pernambuco, Northeastern Brazil (Fig. 17). Rocas is the only atoll formation in the South Atlantic and is placed on the Fernando de Noronha Seamount Chain (KIKUCHI; LEÃO, 1997). With an axis of 3.35 km by 2.49 km, a reef area of 6.56 km^2 and a perimeter of 11 km, Rocas is one of the smallest atolls in the world (PEREIRA et al., 2010).

According to VILLAS-BOAS et al. (2005), the variation in shape and growth of framework building coralline algae and their role in reef structure is directly related to hydrodynamic energy. The reef rim perimeter can be as wide as 600m, and presents a number of intertidal pools, from narrow fissures to large pools with sandy bottoms (KIKUCHI and LEÃO, 1997; GHERARDI and BOSENCE, 2001).

There are two sand islands, Farol and Cemitério. The research base was constructed at the Farol Island, and it is surrounded by low-standing vegetation that is used as nesting sites for thousands of marine birds. In the middle of this cay there is the Lama Bay, whose fauna depends on the tide dynamics, and it is usually a refugee area for juvenile lemon sharks. Rocas' sedimentary environment is composed entirely of carbonate skeleton derived from its own reef structure, which goes through continuous degradation by physical processes such as wave action (PEREIRA et al., 2013).

The climate is equatorial, and the prevailing wind directions is from southeasterly with maximum wind speed of 11 m s^{-1} (HOFLICH, 1984). There is a rainy season from approximately March through July and a dry season from approximately August through February (APAC, 2016). The tides range from 0–3.8 m in a semi-diurnal and mesotidal regime, resulting in a half-daily cycle of almost complete submersion during high tide (only the sandy islands remain emerged) and almost complete emersion during low tide.

This tidal dynamics results in strong currents when the atoll is either filling or draining and during high tides (GHERARDI and BOSENCE, 2001). The available reef area in its internal portion during the low tide, when tidal currents have ceased, can be distinguished in three main habitats: the shallow permanent lagoon, and the open and closed pools. Open pools communicate with the exterior of the atoll even during low tides, and are more exposed to wave action than closed pools, which remain completely isolated from the exterior area of the atoll during low tide (LONGO et al. 2015).

MATERIAL AND METHODS

The data was sampled during December 2012 through December 2014. In total, were six research expeditions to Rocas Atoll, lasting between 3 to 4 weeks, four during the dry and two during the rainy season. Two open pools (Salão and Podes Crer), four closed ones (Cemitério, Tartarugas, Âncoras and Porites) and two fixed stations, one in each extremity of Farol's island were chosen as sampling sites. Station I is a shallow pond, that during the slack water period (about 3 hours between the end of the ebb tide trough the low tide and the begging of the flood tide) reaches around 0.7 m deep. This station receives influence from the Lama Bay discharge during the ebb tide and during the flood and spring tides from the Barretinha Channel (Northwest). The station II is the shallowest, with average 0.4 m water depth during the slack water period and receives influence from the Barretão Channel (North).

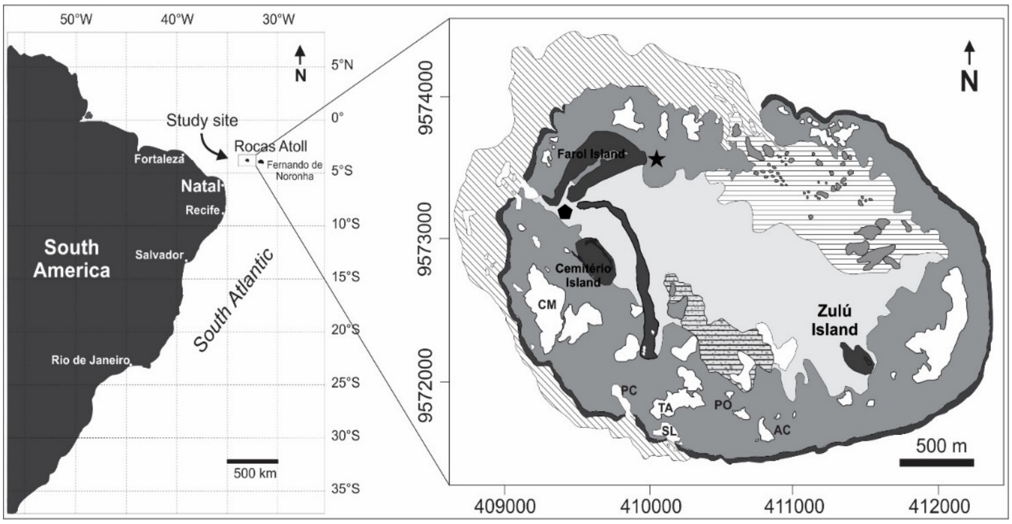

Figure 1 – Studied areas at Rocas Atoll, indicating the sampling sites. Stations near the channels: pentagon (Station I) and star (Station II); Closed pools: CM (Cemitério); TA (Tartarugas); AC (Âncoras); PO (Porites) and Open pools: PC (Podes Crer) and SL (Salão). Adapted from PEREIRA et al., 2013

Hydrology

Seawater samples were collected using Niskin bottle during the low tide at the sub-surface and near the bottom of the pools and at the fixed stations, the water samples were collected only at sub surface in intervals of 2 hours for 12 hours. Abiotic parameters such as water temperature (C) and pH (total) were determined in situ, using a HANNA electrode with 0.01 precision. Dissolved oxygen (DO) analysis were carried out at the Rocas Atoll research station within 24 hours (with an accuracy of ± 0.03 mL. L^{-1}) according to the modified methodology of Winkler, described at STRICKLAND and PARSONS (1972). Other parameters such as salinity (S), total alkalinity (TA) and dissolved inorganic nutrients were analyzed in the laboratory of chemical oceanography at Universidade Federal de Pernambuco (UFPE). Seawater samples were poisoned with saturated mercuric chloride (DICKSON et al., 2007) and TA was measured by open cell titration as described in ROUNDS (2012). The quality of the measurements was confirmed by analyzing certified reference materials (Batch 132) provided by Andrew Dickson, from Scripps Institution of Oceanography before and after a round of samples. Measurements were corrected based on the mean difference between the measured and the certified values of the CRMs (accuracy 4.94%). Replicates of seawater samples (50 mL) were kept protected from temperature and light variations, and used to measure the salinity according to the Mohr-Knudsen method described by STRICKLAND and PARSONS (1972). Other seawater replicates (500 mL) were immediately frozen in Rocas and transported to the laboratory were levels of phosphate, nitrate, nitrite (STRICKLAND and PARSONS, 1972) and silica (GRASSHOFF et al., 1983) were determined.

Benthic coverage

Ceramic tiles (225 cm^2), conditioned for three months, were arranged into settlement units and deployed at Âncoras, Cemitério, Porites and Podes Crer pools. From December 2012 through December 2013, 10 unites were distributed per pool. Each unit consisted of four pairs of tiles separated by a PVC ring of three cm. The units were fixed at the reef on the horizontal and vertical positions (Fig. 2 a, b). From December 2013 to December 2014, we changed the deployment of the tiles. Throughout this period, the settlement units consisted in 18 pairs of tiles, divided in three different orientations (vertical, horizontal and inclined 45°), randomly arranged into a stainless steel mesh and anchored at the sand bottoms of the pools. In each pool, we installed three settlement unit (Fig. 2c, d).

At the end of each year, the settlement plates were collected from the pools and transported to the scientific station where they were analyzed under stereomicroscope and photographed. The density of organisms from different categories was then determined: bryozoans (Bry), vermetids (Verm), serpulids (Serp) and corals (Coral). When present, coral recruits were identified and measured. To estimate the benthic coverage of macroalgae (MAL) and crustose coralline algae (CCA), the area (cm^2) occupied by those organisms was measured with the software ImageJ using the photography of the plates.

During the expedition of November 2014, the benthic coverage on the pools was also evaluated with point intercept transect surveys. Salão pool was the only one where transect observations were not carried out due to unsafe dive conditions. In total, four transects of 20 m, with 40 points at 0.5 m intervals, and 5 m apart from one another were evaluated in each pool by scuba diver. The identification of the organisms were grouped in categories as follow: macroalgae (MAL), turf algae (TUR) –layer of tightly, crustose coralline algae (CCA), sponge (ESP), sand (SAND), *Zoanthus sociatus* (ZSO), and the corals *Mussismilia hispida* (MHI), *Porites astreoides* (PAS) and *Siderastrea stellata* (SST).

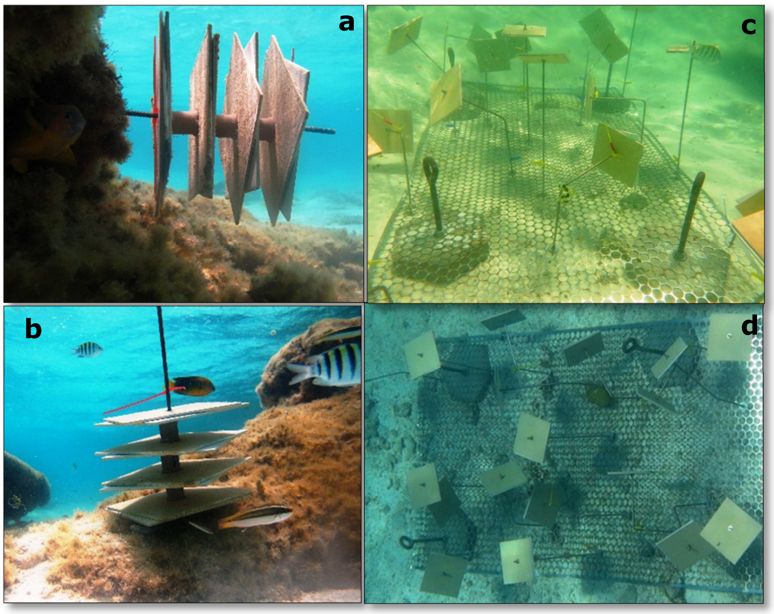

Figure 2. Settlement units displayed in 2013 (a, b) and 2014 (c, d) at tidal pools in Rocas Atoll.

Data analysis

The environmental variables were tested for significance by comparing the different sampling points (Âncoras, Cemitério, Porites, Tartarugas, Podes Crer, Salão, and Fixed station I and II), grouped sites (open pools, closed pools and channels), climate periods (dry and rainy season) and sampling years (2012-2014), with Wilcoxon/Kruskall-Wallis tests. The benthic coverage categories of the settlement plates were compared by sampling points and sampling years also with Wilcoxon/Kruskall-Wallis tests. To explore potential relationships between the abiotic parameters and the structure of the benthic community we conducted a Principal Component Analysis (PCA). Statistical analyses were performed using the software JMP®10.0.2 (SAS Institute Inc., 2012) and the level of significance adopted was 0.05.

RESULTS

The annual average precipitation (Fig. 3) for the years 2012, 2013 and 2014 were 89.9±92.9 mm, 87±101 mm and 106±120 mm, respectively. During the present study the main pluviometry was 172±92.2 mm for the rainy season (February until July) and 16.9±20.7 mm for the dry season (August until January).

At the fixed stations it was observed diurnal variations for some of the environment parameters analyzed, such as temperature, pH, and DO that presented lower values from 5 pm until 8 am and high values around 10 am and 4 pm. Total alkalinity did not show a significant variation along the day, but indicate a tendency of high values during nighttime and lower values along the day (Fig. 4a). Unlike the variables described before, the nutrient salts and silica did not show diurnal variations (Fig. 4b).

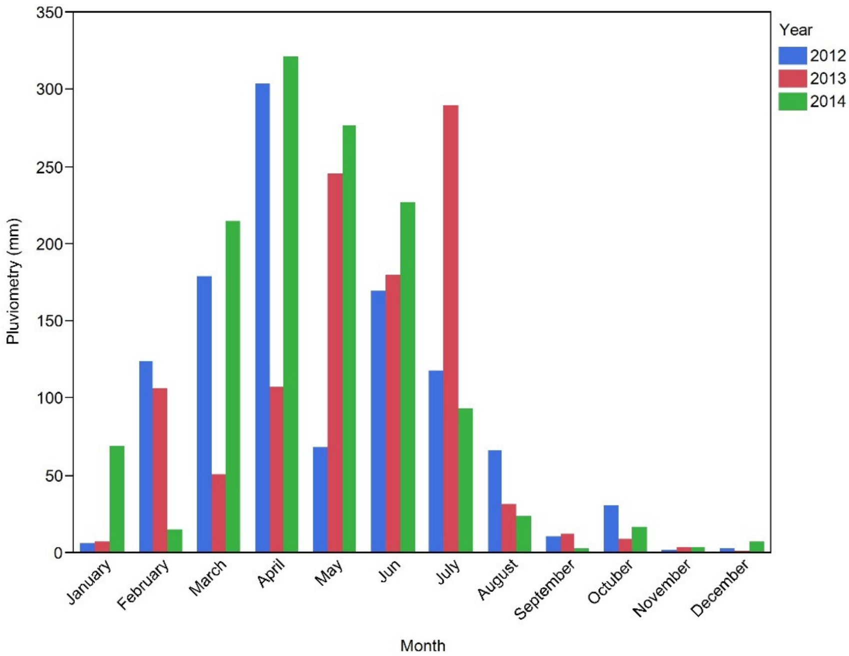

Figure 3. Monthly precipitation (mm) of the region throughout the years of study. Source: APAC, 2016 for Fernando de Noronha station.

Table 1 summarizes all the results obtained for the environment variable analyzed. The fixed stations near the channels showed the largest values (2520±107 μmol.Kg_{sw}^{-1}) of TA and of PO_4 (0.47± 0.51 μM) when compared to open and closed pools. At the open pools, it was observed high average values for DO (5.77±1.04 mL.L^{-1}) and pH (8.38±0.18). Analyzes of variations among the sampling points, indicates the influence of the pH values measured at Podes Crer pool in this difference mentioned above. This open pool, in particular, also stood out for lower mean TA (2339±122 μmol.Kg_{sw}^{-1}).

There was significant differences on the nutrient values when comparing Fixed station I and Fixed Station II separately, Station I had the highest values for PO_4 (0.57± 0.61 μM), NO_2(0.13±0.22 μM), NO_3 (3.38± 4.7 μM). DO, phosphate and salinity showed seasonal variation with higher values generally observed in the dry season and temperature more often displayed larger values during the rainy season (Table 1).

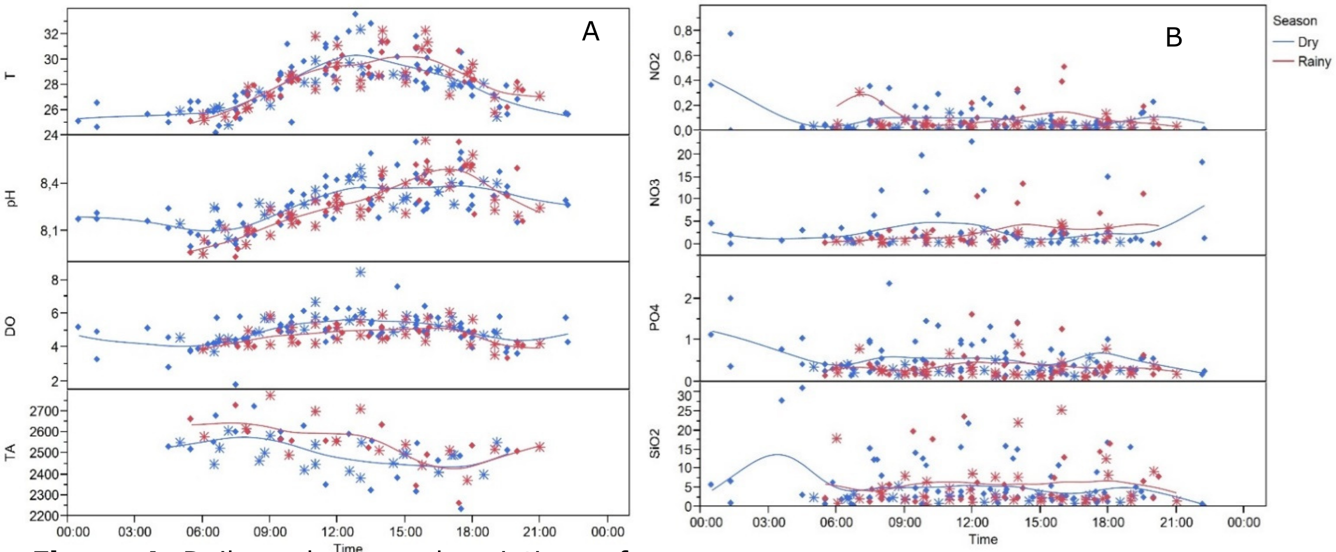

Figure 4. Daily and seasonal variations of the environmental parameters collected at the fixed stations at Rocas Atoll. Diamont: station I, Asterisk: station II. In red data collected during the rainy season and blue the dry one. T- Temperature (°C), pH (total scale), DO- Dissolved oxygen (mL. L^{-1}), TA- Total alkalinity (µmol. Kg_{sw}^{-1}) , NO_2 – Nitrite (µM), NO_3- nitrate (µM), PO_4- phosphate (µM), SiO_2 – Silica (µM)

Table 1 - Spatial and seasonal variation of hydrological parameters (mean±SD) measured at Rocas Atoll. (*) Significant different mean values (p<0.05, Wilcoxon test). T- Temperature (°C), pH (total scale), DO- Dissolved oxygen (mL. L^{-1}), TA- Total alkalinity (µmol. Kg_{sw}^{-1}), NO_2 – Nitrite (µM), NO_3- nitrate (µM), PO_4- phosphate (µM), SiO_2 – Silica (µM).

		T (C)	pH	S	DO	SiO_2	PO_4	NO_2	NO_3	TA
Site	Channel	28.2±1.96	8.28±0.16	35.4±1.14	4.92±0.83	5.37±5.92	0.47±0.51*	0.1±0.18	2.84±4.18	2520±107*
	Close	28.3±1.04	8.26±0.09	35.5±1	5.34±0.86	7.08±8.08	0.38±0.66	0.06±0.04	1.48±1.46	2445±56.6
	Open	28.9±1.61	8.38±0.18*	35.6±1.05	5.77±1.04*	8.51±10.3	0.35±0.25	0.06±0.05	1.66±1.23	2388±101
Sampling points	Âncoras	27.9±0.96	8.25±0.09	35.1±1.05	5.27±0.9	6.63±6.7	0.38±0.4	0.08±0.05	1.83±1.35	2458±47.5
	Cemitério	28.4±0.95	8.26±0.09	35.6±0.93	5.34±0.81	7.46±9.34	0.3±0.4	0.05±0.03	1.5±2	2442±25.8
	Fixed Station I	28.2±2	8.27±0.16	35.6±1.16	4.85±0.81	5.94±6.33	0.57±0.61	0.13±0.22*	3.38±4.7	2522±122
	Fixed Station II	28.3±1.9	8.28±0.15	35.2±1.08	5.05±0.87	4.31±4.95	0.3±0.17	0.05±0.05	1.34±1.22	2518±91.9
	Podes Crer	29.4±1.6	8.49±0.17*	35.5±0.95	6.35±0.93	10.9±12.2*	0.34±0.2	0.05±0.07	1.41±1.21	2339±122*
	Porites	28.3±1.08	8.27±0.09	35.5±0.97	5.6±0.94	6.25±6.92	0.27±0.11	0.05±0.03	1.53±1.14	2438±101
	Salão	28.2±1.36	8.23±0.07	35.8±1.2	4.94±0.5	5.03±5.27	0.37±0.31	0.06±0.03	2.22±1.15	2437±34.9
	Tartarugas	28.4±1.17	8.26±0.08	35.7±1.02	5.16±0.81	7.85±9.25	0.54±1.14	0.06±0.03	1.17±1.11	2444±26.9
Season	Dry	28±1.72	8.28±0.14	36±0.65*	5.14±0.91	5.52±5.88	0.5±0.66*	0.07±0.1	2.55±4.01	2469±91.9
	Rainy	28.7±1.61*	8.29±0.16	34.8±1.22	5.18±0.94	7.27±8.83	0.34±0.28	0.09±0.18	2.13±2.61	2488±123

The benthic coverage at Rocas pools was evaluated with two different methodologies. The results obtained for algal cover was similar in both methodologies, the open pool showed high coverage of CCA, while the close pools where dominated by macro and turf algae. However, it was observed only seven coral recruits on the settlement experiment, and the coral cover was better estimated with transects.

Overall, the macroalgae (MAL) was the most abundant benthic coverage in the settlement plates, ranging from 74.7± 23.9% at Cemitério to 35.8± 20.4 % at Podes Crer. It was observed significant difference between the pools, Cemitério and Âncoras presented the highest MAL percentage and Tartarugas and Podes Crer the lowest. Podes Crer was the pool with higher crustose carbonate algae coverage (CCA%). For this open pool it was possible to recover the ceramic tiles on both years studied, therefore, annual differences in the recruitment could be tested. In 2013, the surface area coverage by CCA was 61.3± 41.2 cm^2 while in 2014 was 115± 69.8 cm^2. The percentage of area with no recruitment was significantly different for Tartarugas settlement plates, were about half of the surface area was not colonized (nude) (Table 2).

The density of bryozoans (BRY) was similar at Âncoras and Tartarugas with 41.7± 62.7 individuals per 225 cm^2 and 21.1± 36.1 individuals per 225 cm^2 respectively. There was no difference between the densities of serpulids polichaetes (mainly *Spirobis* sp.) among the pools in 2013, but the density observed at Podes Crer in 2014 was significantly lower than the one for the previous year. The density of vermetids represented by two different species identified on the plates (*Petaloconchus* sp. e *Dendropoma* sp.) was significantly lower than the ones observed for bryozoans and serpulids. However, the distribution among the pools was equal to the bryozoans. Âncoras and Tartarugas formed the group of pools with higher density while Cemitério and Podes crer showed the lowest (Table II).

It was not observed variations on coral recruitment. In 2013, four recruits were recognized, one *Siderastrea* sp. and two *Porites* sp. at Podes Crer and one *Porites* sp. at Âncoras (Fig. 5). In 2014, two recruits of *Siderastrea* sp. and one *Porites* sp. were observed at Podes Crer.

Table II. Benthic coverage and density of organisms (N/225 cm^2) recruited at the settlement plates displayed at tide pools at Rocas Atoll during 2013 and 2014. Legend: Crustose carbonatic algae (CCA), Macroalgae (MAL), bryozoans (Bry), vermetidis (Verm), serpulids (Serp) and corals (Coral).

Year	2013				2014	
Pool (n)	Âncoras (29)	Tartarugas (16)	Cemitério (23)	Podes crer (37)	Cemitério (38)	Podes crer (28)
CCA (cm^2)	31.7± 30.9	32.1± 33.1	23± 33.8	61.3± 41.2	9.1± 13.5	115± 69.8
CCA (%)	13.3± 13	13.5± 14	9.69± 14.2	25.9± 17.4	3.91± 5.76	49.1± 29.2
MAL (cm^2)	148± 66	88.1± 62.8	177± 56.7	84.9± 48.5	179± 57.8	102± 68.8
MAL (%)	62.3± 27.8	37.1± 26.5	74.7± 23.9	35.8± 20.4	77.8± 23.3	45.1± 30.5
NUDE (%)	24.4± 23.4	49.3± 31.2	15.6± 14.4	38.4± 23.8	18.3± 24	5.78± 12.5
BRY	41.7± 62.7	21.1± 36.1	12.8± 14.1	21.7± 32.3	19.3± 18.3	9.93± 9.57
SERP	55.1± 69.9	19.2± 17.8	25.2± 33.5	61.9± 56.9	23.7± 24.2	5.07± 5.62
VERM	1.55± 3	1.13± 1.81	0.22± 0.52	0.51± 1.12	0.49± 0.99	0.67± 1.14
CORAL	0.03± 0.19	0	0	0.08± 0.36	0	0.11± 0.42

The results for the benthic coverage evaluated by point intercept transects are shown at Figure 6. The most abundant category at the only open pool surveyed (Podes Crer) was CCA, which represents 42.7% of the coverage, followed by the percentage of

Siderastrea stellata coverage (29.9%). While for all closed pools, the non-calcified algal turfs (TUR) was the dominant category, with 62.2% at Porites, 40.7% at Cemitério, 34.4% at Âncoras and 25% at Tartarugas.

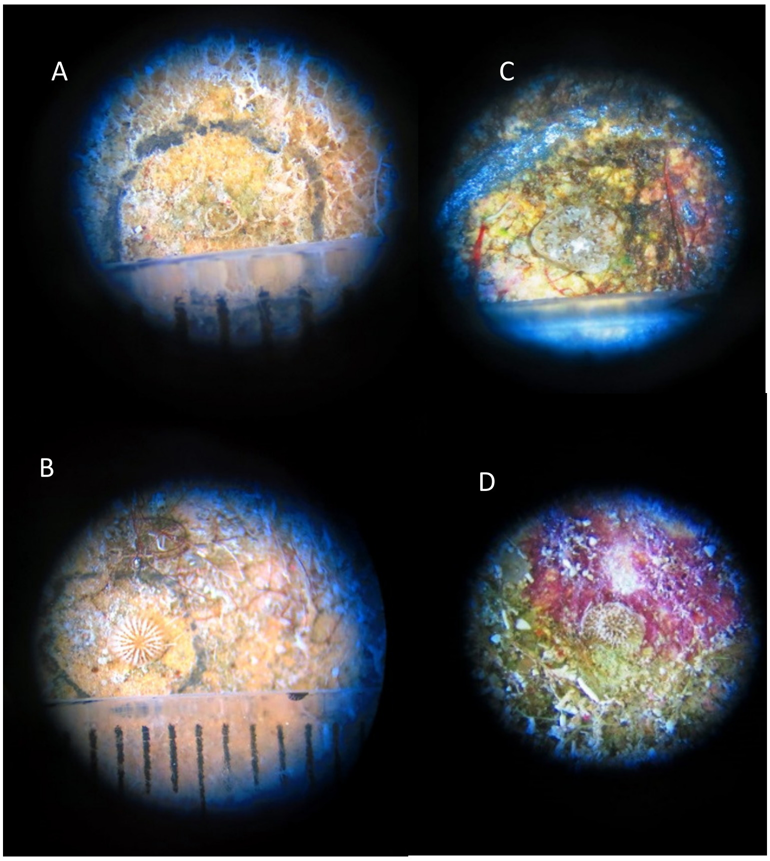

Figure 5. Coral recruits observed at the settlement plates displayed at Podes Crer (A, B, C) and Âncoras (D) pool during 2013. The recruit B is *Siderastrea* sp. The others (A, C, D) are *Porites* sp. Size of Recruits: A- 0.405 mm^2; B- 3.667 mm^2; C- 3.592 mm^2; D- 3.248 mm^2

The interaction between the abiotic parameters and benthic community at Rocas pools was investigated with PCA. The PCA revels that two sets of components explained 75.9% (Fig 7. A) and 72.5% (Fig 7. B) of the variances included in those environmental parameters. While samples from the open pool (Podes Crer) were grouped by direct association between temperature, pH, DO, salinity, CCA and corals, samples from closed pools (Cemitério) were separated by the positive correlation from MAL, TUR, SAND and opposite to the availability of nutrient.

Therefore, results from this analyses suggests the tendency of habitats with high coverage of carbonatic organisms consume the alkalinity of seawater, and habitats with elevated abundance of algae (MAL and TUR) are direct related to the assimilation of dissolved inorganic nutrients.

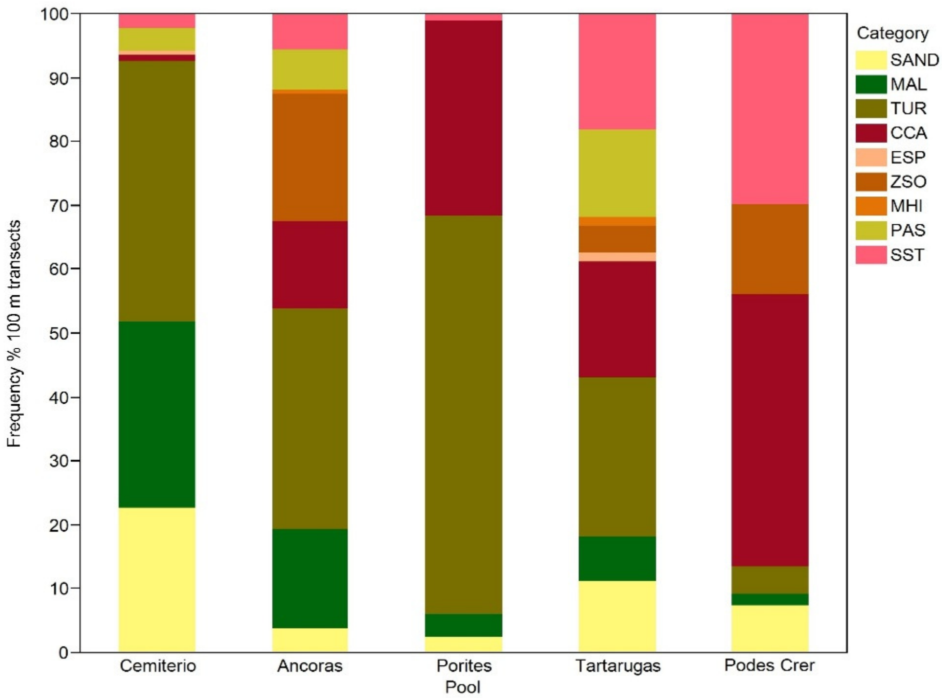

Figure 6. Percent coverage of the main benthic categories observed at Rocas Atoll tidal pools. macroalgae (MAL), turf algae (TUR), crustose coralline algae (CCA), sponge (ESP), sand (SAND), *Zoanthus sociatus* (ZSO), *Mussismilia hispida* (MHI), *Porites astreoides* (PAS) and *Siderastrea stellata* (SST).

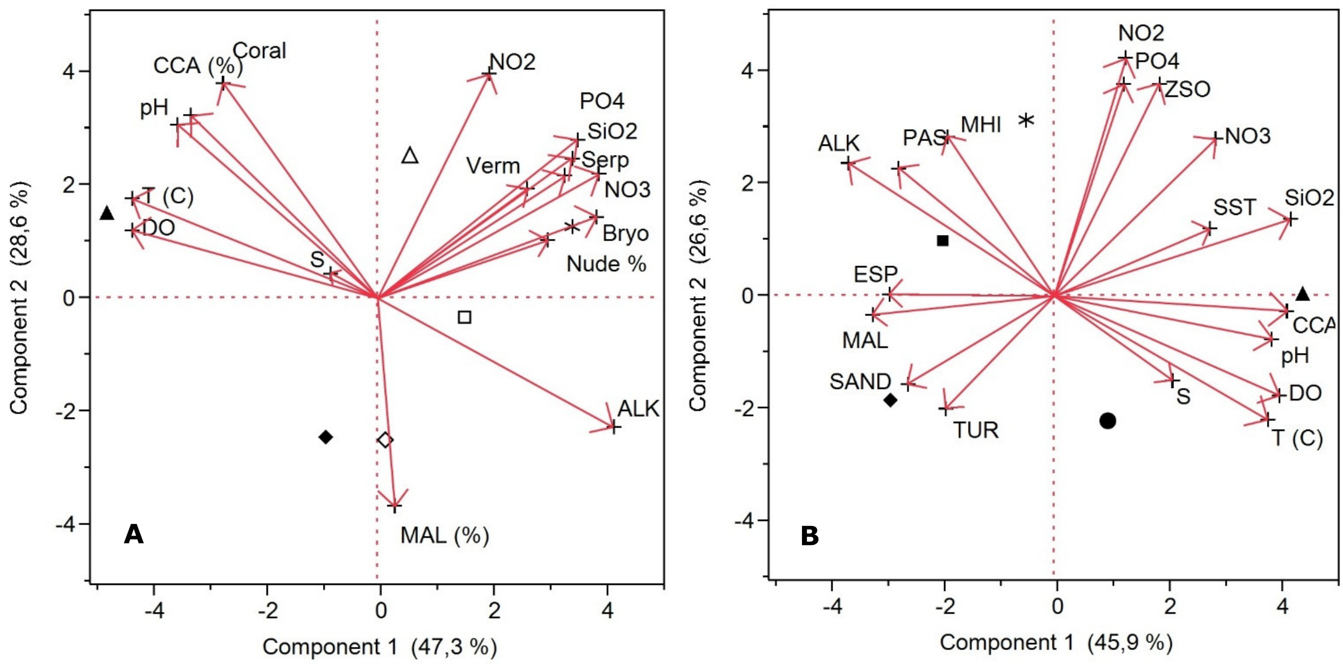

Figure 7- Principal Component Analyzes of hydrological data and benthic coverage obtained at the settlement plates (A) and point intercept transects (B). Pools: diamond – Cemitério; asterisk – Âncoras; square- Tartarugas; circle- Porites; triangle- Podes Crer. 2013 -open symbols; 2014- closed ones. Benthic coverage: macroalgae (MAL), turf algae (TUR), crustose coralline algae (CCA), sponge (ESP), sand (SAND), *Zoanthus sociatus* (ZSO), *Mussismilia hispida* (MHI), *Porites astreoides* (PAS) and *Siderastrea stellata* (SST). Recruitment categories: bryozoans (Bryo), serpulids (Serp); vermetidis (Verm), corals (Coral) Hydrology: T (C)- temperature (°C); S– salinity; DO– Dissolved oxygen; SiO_2- Silicate, NO_3– nitrate, NO_2– nitrite, PO_4– phosphate, ALK-total alkalinity.

DISCUSSION

The results presented here reveal diurnal variations for some abiotic parameters such as temperature, DO, pH and TA, while others were relatively constant (dissolved inorganic nutrients) at the fixed stations. These diurnal changes suggest a link with tides, daily solar cycle, and the volume exchange with semi-enclosed pools. Nonetheless, they also demonstrate the ability of Rocas Atoll organisms' metabolism to alter open superficial seawater characteristics. One evidence that the biology may influence these abiotic parameters is the similar daily variation between pH and DO. These parameters showed values increasing along the day, when photosynthesis is taking place and an inverted pattern at night, due to the dominance of respiratory processes (ANTHONY et al. 2011; SHAW et al. 2012). Accordingly, processes of calcification and dissolution may be responsible for the variation on TA values (ALBRIGHT et al., 2016).

The present study also observed seasonal variations in temperature, salinity and phosphate. JALES (2015), studying phytoplankton seasonal and spatial variations at Rocas, also observed higher temperatures during the rainy season, however, the salinity reported was also high (36.2). In the present study the salinity recorded was 34.8±1.22 for the rainy and 36±0.65 for the dry season. It is more likely that the difference in the methodologies to obtain these values are responsible for the variation among the studies, since JALES (2015) used a manual Atago refractometer, model S/Mill-E with a scale range of 0 to 100 and an interval of 1, and we adopted the Mohr-Knudsen method. The results of this study are in accordance with FEITOSA and PASSAVANTE (2004) that obtained a salinity of 35.29 (Mohr- Knudsen method) for the dry season (January 1999).

Amongst the fixed stations, it was clear the impact of the Lama Bay over the nutrients concentration in station I. The results indicate an influence of the excrement of seabirds that can be washed away during the tide dynamics. The phosphate concentration was higher at station I, and those values contributed to the seasonal variation reported here. Swell events occurred during the dry season increased the hydrodynamics at the atoll, causing relatively longer periods of water residence time at Lama Bay (PINHEIRO, Pers. Comm), suggesting more dilution of the seabirds' guano. The influence of the seabirds' excrement on the concentration of nutrients was also discussed by FEITOSA and PASSAVANTE (2004).

Among the sampling sites, it was chosen two open pools, and in between them, the Salão presented more constant values for the abiotic parameters studied, similar to the observed for oceanic waters surrounding the atoll (JALES, et al., in press). Unfortunately, due to persistent strong waves and currents, it was not possible to realize the transects and the settlement units we deployed were completely destroyed. In contrast, Podes Crer showed significant variations compared to all the other pools: lowest TA (2339±122 μmol.Kg_{sw}^{-1}) and highest pH (8.49±0.17), and SiO_2 (10.9± 12.2 μM), and those results seem to influence its benthic cover.

The number of coral recruits observed during the study was extremely low compared to recruitment rates observed at others reef ecosystems in northeastern Brazil (MAIDA; FERREIRA, 1995; CASTRO et al., 2006). Variations in recruitment rates are generally attributed to factors such as fluctuations in larvae production (SAMMARCO; ANDREWS, 1988), planktonic phase survival (BAK; ENGLE, 1979), and post-settlement mortality processes, which occurs by predation, competition with other organisms on the substrate and premature death of individuals settled on inappropriate substrate (FABRICIUS; METZNER, 2004). Abiotic factors such as light, temperature, salinity and sedimentation have also been observed to influence the recruitment process and may induce or inhibit settlement (SAMMARCO 1983; RUIZ-ZÁRATE; ARIAS-GONZALEZ, 2004).

PINHEIRO et al. (in press), studying some aspects of the dominant coral specie (*Siderastrea stellata*) life history at Rocas, point out that 41.2± 18.5% of its population is considered mature (diameters higher than 10 cm) and has a high potential of maintenance and recovery. However, they observed a low frequency of young colonies with diameters ranging from 0 to 2 (1.8±1.12%) and 2.1- 4 cm (8.9±3.87%) that may be a consequence of a reduced recruitment event caused by two sequential positive sea surface temperature anomalies (2009 and 2010) (FERREIRA et al. 2012). It is possible that the results observed here indicate this impact of warming waters on coral reproduction, but further studies about larval dispersal, tidal dynamics, and polyp fecundity rates are necessary in order to draw solid conclusions about the recruitment failure event.

Although only *S. stellata, P. asteroides* and *M. hispida* were shown in the present study, *Montastrea cavernosa, Favia gravida, Porites branneri* and *Madracis decactis*, were also observed during the fieldwork, but not recorded as results due to the methodology and low abundance (PINHEIRO, per comm.) The total coral coverage we found was 33.15% at Tartarugas, 29.9 at Podes Crer, 12.51% at Âncoras, 5.93% at Cemitério and 1.22% at Porites. Those results are in accordance with a previous study by FERREIRA et al (2012) that observed 50.6 ±6.0 % at Salão; 34.0 ±14.2% at Podes Crer; followed by 22.5 ±7.8% in Tartarugas and the lowest coverage, 5.6 ±6.1% at Cemitério.

Turf algae and macroalgae were the most representative categories of benthic cover respectively at transects and settlement plates methodologies. In a study conducted by LONGO et al. (2015), the algal turfs were also the dominant group in tidal pools inside the atoll. However, they classified the turf in two categories; articulated calcareous algae largely dominated algal turfs of open pools, whereas turfs from closed pools presented a greater contribution of non-calcified algae. In their research, it was considered comparative analysis of the reef fish assemblage, benthic cover, the composition, nutritional traits and associated cryptofauna of algal turfs, and fish feeding pressure on benthos. They found differences in patterns of community structure and feeding pressure on benthos between the open and closed pools, and attributed those differences also to the distinct hydrodynamic conditions and related amount of sediment in open and closed pools.

In the present study, the PCA showed a clear correlation between the benthic coverage and abiotic parameters that corroborated the findings of LONGO et al (2015). Habitats with high coverage of carbonatic organisms were direct correlated with temperature, pH, and DO, and indirect correlated with the alkalinity of seawater, whereas habitats with elevated abundance of macro and turf algae were indirect associated with the concentration of dissolved inorganic nutrients.

CONCLUSION

Here we presented an integrated approach describing environment variables and its associations at shallow reef habitats at Rocas Atoll. Our main results suggest that:

1. Abiotic parameters variations might be related with tides, daily solar cycle, and volume exchange from semi-enclosed pools as well as organisms' metabolisms (photosynthesis, respiration, calcification and dissolution) and seabirds' excrements;

2. The availability of dissolved inorganic nutrients on the seawater may contribute for the distribution of the organisms in the atoll, since sites with dominance of macro and turf algae were indirectly associated with the concentration of nutrients;

3. Habitats with high frequency of carbonatic organisms might be associated with decreased concentration of alkalinity;

4. The number of corals settled on the ceramic tiles was low when compared to recruitment rates of others studies in Brazil and may indicate an impact of

warming waters on coral reproduction, however, further studies about larval dispersal, and polyp fecundity rates are necessary to draw solid conclusions about the recruitment failure event.

Nevertheless, especially due to the predicted effects of increasing CO_2 in the atmosphere (ocean warming and acidification), that can bring negatives impacts on carbonatic organisms and positive ones on macroalgae, it is recommended to closely monitor such interaction. Rocas, as the only atoll in the South Atlantic and the first and more effective marine reserve in Brazil, needs to be alert to the consequences of potential phase shifts processes there are happening in other reefs around the world.

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