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ARTIGO

Patterns of diversity and abundance of Radiozoa (Polycystina) of Rocas Atoll, Southwestern Tropical Atlantic

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ABSTRACT: Polycystine are typically pelagic, highly diversified and abundant. Due to their ecological importance in the planktonic marine trophic web, where they act as a link in the microbial loop, they are considered to be some of the main primary producers/consumers. This paper's main goal was to evaluate the composition and temporal dynamics of the Radiozoa Polycystine of the Rocas Atoll, Brazil. The samples were collected in 2010, 2012 and 2014, and they were obtained through oblique hauls extended to a depth of 80% of the local depth, or, at most, up to 200 m, with a plankton net with 64 µm mesh size. 76 Polycystine taxa were identified divided into the orders Nassellaria (12 families) and Spumellaria (9 families). Among the taxa identified, 65.8% occurred exclusively in 2014. Spumellaria exhibited the smallest richness and highest density (1217.02 org.m^{-3}), with the predominance of *Dictyocoryne truncatum*. 2014 was the year with the greatest richness and total density (1871.3 org.m^{-3}). The ANOSSIM showed a significant difference between the years 2010 and 2014, confirmed by MDS and PCA. The temperature was the most explanatory parameter, with higher values in 2010, as well as oxygen and chlorophyll-*a*, as opposed to the nutrients, with higher values in 2014, mainly Silicon dioxide. *Lophophaena hispida, Acanthodesmia viniculata, Dictyophimus* sp., *Amphispyris toxarium*, and *Tholospyris* sp. were good indicators for 2014 (higher amount of nutrients), while Spongodiscus *resurgens* for 2010 (higher temperatures) and *Zygocircus productus* simultaneously for 2010/2014. It can be inferred that the Polycystine class was more successful in 2014 when higher nutrient values contributed positively to the greater abundance of this class.
Keywords: Tropical microzooplankton, Protist plankton, Bioindicator, Temporal variation

Padrões de diversidade e abundância de Radiozoa (Polycystina) do Atol Rocas, Atlântico Tropical Sudoeste

RESUMO: Os Polycystina, são tipicamente pelágicos, altamente diversificados e abundantes. Devido sua importância ecológica na teia trófica marinha planctônica, onde atuam como elo na alça microbiana, são considerados alguns dos principais produtores/consumidores primários. Este trabalho objetivou-se avaliar a composição e dinâmica temporal dos Radiozoa Polycystina do Atol das Rocas, Brasil. As amostras coletadas em 2010, 2012 e 2014, foram realizadas através de arrastos oblíquos desde 200m de profundidade até a superfície ou 80% da profundidade local, com rede bongo de 64 µm de abertura de malha. Foram identificados 76 taxa da classe Polycystina distribuídas nas Ordens Nassellaria, com 12 famílias e Spumellaria com 9. Dos taxa identificados 65,8% foram exclusivos de 2014. Spumellaria apresentou a menor riqueza e maior densidade (1217,02 org.m^{-3}), com predominância de *Dictyocoryne truncatum*. O ano com a maior riqueza e densidade total foi 2014 (1871,3 org.m^{-3}). O ANOSSIM mostrou diferença significativa entre os anos 2010 e 2014, confirmado pelo MDS e PCA. A temperatura foi o parâmetro mais explicativo, com maiores valores em 2010, assim como oxigênio e clorofila-a, ao contrário dos nutrientes, com valores mais altos em 2014, principalmente dióxido de silício. *Lophophaena hispida, Acanthodesmia viniculata, Dictyophimus* sp., *Amphispyris toxarium* e *Tholospyris* sp. foram bons indicadores para 2014 (maior quantidade de nutrientes), enquanto *Spongodiscus resurgens* para 2010 (maiores temperaturas) e *Zygocircus productus* simultaneamente para 2010/2014. Pode-se deduzir que a classe Polycystina foi mais bem-sucedida em 2014, quando elevados valores de nutrientes contribuíram positivamente para a maior abundância desta classe.
Palavras-chave: Microzooplâncton tropical, Protista planctônico, Bioindicador, Variação temporal

Introduction

The oceans beget high biological diversity (LONGHURST; PAULY, 2007), mainly in tropical oligotrophic areas close to islands and atolls, where the availability of resources is increased and higher productivity occurs due to the "island mass effect" (DOTY; OGURI, 1956; MUNK et al., 1995; GONZÁLEZ-QUIRÓS et al., 2003). This nutritional increment locally affects the structure of the communities (BOEHLERT; GENIN, 1987; ROGERS, 1994; GENIN, 2004). Because of these features, the Rocas Atoll becomes of great importance for maintaining the marine biodiversity of this region, despite being considered one of the smallest atolls in the world and unique at the southern Atlantic (SOARES; LEMOS; KIKUCHI, 2009).

The planktonic Phylum Radiozoa is among the microorganisms benefiting from these areas. They are dominant in oligotrophic regions (AFANASIEVA et al., 2005) where they act as an important link in the microbial fin, providing energy and nutrients across a range of size fractions. They can feed on prey in size fractions from nano to macro planktonic (Swanberg and Caron 1991), being considered one of the main primary producers/consumers in these areas (SIOKOU-FRANGOU et al. 2010).

Paleontological records show that the phylum represents one of the first microscopic groups to inhabit oceanic regions from the Cambrian to the present day (AFANASIEVA et al., 2005; BRAUN et al., 2007). Its long history of life and wide distribution, both vertical and horizontal, are consequences of its ecological plasticity (DE WEVER et al., 2003; AFANASIEVA et al., 2005; BOLTOVSKOY et al., 2010). The richness of fossil records of the Radiozoa causes most of the work on this phylum to be directed to the paleontological area, with few studies focused on current groups (WEVER; FRANCE, 2001; DE WEVER et al., 2003; SUZUKI; OBA, 2015; SANDIN et al., 2019).

Radiozoa is a phylum of single-celled Protozoa with an average size of 100 to 800 µm, solitary or colonial, predominating in salinity between 32 and 38 PSU and a planktonic way of life (NAZAROV; PETRUSHEVSKAYA, 1995). The reproduction of the phylum is still inconclusive, however Itaki and Bjorklund (2007) suggested that Radiolaria have an asexual binary fission reproduction. They are formed by an internal skeleton composed of hydrated silica ($SiO_2.nH_2O$) (SUZUKI; NOT, 2015). Its skeleton assumes a range of forms, with varying numbers of spines and a central capsule that is destroyed immediately after his death; in Polycystine, for example, the presence of 98% of $SiO_2.nH_2O$ amorphous (NAZAROV; PETRUSHEVSKAYA, 1995) with small amounts (1 to 4%) of Mg, Ca, Al, Na (ANDERSON, 1983) was observed. Its spines assist in motor function, providing an axis to the pseudopods; moreover, the position and quantity of the spines are fixed and distinct within each taxon (DE WEVER et al., 2003). However, recent phylogenetic studies have found no pattern in the initial spicular system that allows separating clades in Nassellaria (SANDIN et al., 2019).

The most current taxonomic classification of the phylum Radiozoa, formerly Radiolaria, is subdivided in three classes, Acantharia, Polycystine and Sticholonchea (WORMS EDITORIAL BOARD, 2019), all of them marine.

In general, the phylum Radiozoa occurs from central oceanic regions to estuaries (BOLTOVSKOY et al., 2003), and can be abundant in areas close to the coast, mainly in the upper part of the water column (BOLTOVSKOY; ALDER; ABELMANN, 1993; BOLTOVSKOY, 1998, 1999). Its vertical distribution is wide (AFANASIEVA et al., 2005), with maximum populations of Radiozoa in tropical and subtropical waters concentrated in the upper layers of the water column, mainly between 50-100 m of depth (KLING; BOLTOVSKOY, 1995; ABELMANN; GOWING, 1997). This fact is related to symbiotic associations commonly found between Radiozoa and chlorophyllate microorganisms that are closely related to luminous intensity (ZASKO; RUSANOV, 2005; ZHANG et al., 2018). The class Polycystine, focus of this study, is highly diversified holoplanktonic protists, with more than 300 recent species registered (BOLTOVSKOY et al., 2010; LAZARUS et al., 2015). Its predominance occurs in the range of 50 to 400 m of depth (BOLTOVSKOY, 1998, 1999; ZASKO; RUSANOV, 2005), typically pelagic and rarely found in coastal waters, especially where salinity falls below normal values of the open ocean (35 PSU) (ANDERSON, 1983; BOLTOVSKOY, 2017).

Studies show that in addition to the carbon increment offered by the chlorophyllate, the Radiozoa also benefit from these as a nutritional reserve (direct source of food) and structural (source of silica), increasing its adaptive capacity and resistance to unfavorable environments (ANDERSON, 1983). However, the main sources of food in this phylum are still bacteria, unicellular algae, ciliates, copepods, larvae and other microscopic items living or dead (ZASKO; RUSANOV, 2005). It was also verified that the Radiozoa species present food preference, and this factor reduces competition for resources (AFANASIEVA et al., 2005).

In addition to biotic factors, radiolarians feeding and its symbiosis with algae, the population dynamics of Radiolarians is also governed by abiotic factors. The most important ones are temperature, salinity, hydrodynamics and depth (CHUVASHOV et al., 1999), light penetration and the availability of natural silica (SUZUKI; NOT, 2015). Due to the above and in view of the importance of the area in question, this paper aims to evaluate the composition and temporal dynamics of Radiozoa Polycystine found close to Rocas Atoll, Brazil.

Material and Methods

The Rocas Atoll is located 148 km west of the Fernando de Noronha Archipelago (03052" S; 33049" W) (Figure 1). It is placed at the top of a series of undersea mountains based on 4000 meters deep,

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and is characterized as an elliptic, almost circular calcareous algal reef covering approximately 5.5 km^2, with an opening connecting its central lagoon to the open sea; the longest axis (E-W) covers 3.7 km and the shortest axis (N-S) 2.5 km (SOARES; LEMOS; KIKUCHI, 2009).

An equatorial warm climate prevails in the study area, with a cool trade wind from the southwest. The average air temperature varies between 28°C to 32°C throughout the year (PINTO; MAFALDA; SANTOS, 1997) and the surface water temperature is approximately 27.7ºC. The rainy season is between March and July, with a monthly average of 860 mm (SOARES; LEMOS; KIKUCHI, 2009). The relative humidity is high during the year (usually above 80%). The study area is within the Rocas atoll and Fernando de Noronha Biological Reserve Archipelago, the first marine protected area created by Federal Law in 1979 (BRASIL; MMA, 2007), currently managed by the Brazilian Institute for the Environment and Natural Resources (IBAMA).

The Rocas Atoll surrounding waters have low nutrients concentration and fluorescence not exceeding 50 mg-2 (MEDEIROS et al., 1999). The South Equatorial Current (CSE), which presents an average speed of 30 $cm.s^{-1}$, influences the atoll and has a constant westward direction (GOES, 2006). In mid-June to September during the southern hemisphere's winter season, southeast winds are more frequent and range in speed from 11 to 15 $m.s^{-1}$ (KIKUCHI, 2002).

The Rocas Atoll is of geological, paleontological and ecological importance, harboring many migratory shorebirds and residents, with structures that ensure leaching of nutrients available to the planktonic organisms of the area (KIKUCHI, 2002).

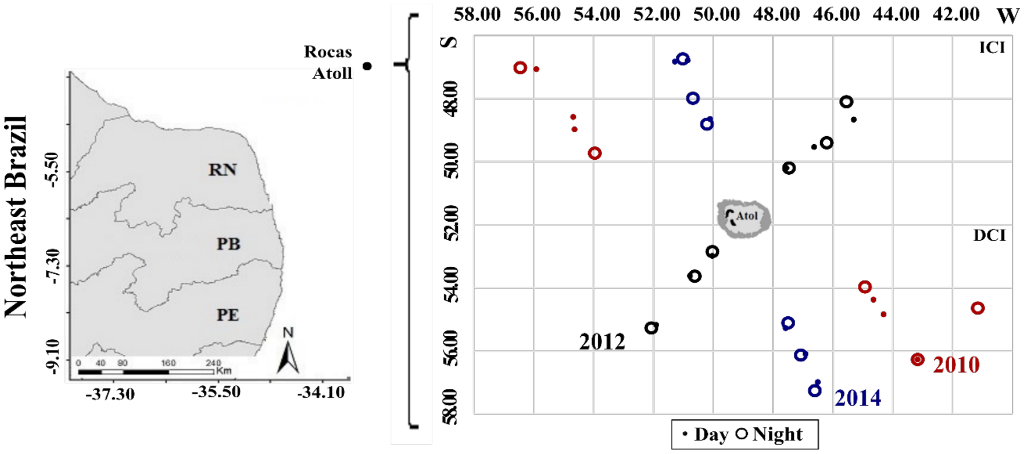

Figure 1. Study area with the three transects at Rocas atoll (Brazil), equatorial Southwest Atlantic. DCI=Direct Current Influence; ICI- Indirect Current Influence

Three oceanographic campaigns were carried out in the Rocas Atoll (July and August of 2010, September and October of 2012 and July and September 2014), aboard of the NHO Cruzeiro do Sul from the Brazilian Navy. Two transects with three points each were made per year, one of the direct current incidence side (IDC) and the other on the indirect current incidence side (IIC), both with day and night collections (Figure 1).

Environmental data, Dissolved Oxygen (mg. L^{-1}), salinity (PSU), fluorescence and temperature (°C) were acquired using a CTD profiler. This data comes from using the average of the acquired values in the most superficial layer of the water column. For analysis of dissolved inorganic nutrients, the water samples were stored in plastic bottles (300ml) and were immediately frozen and transported to the Chemistry Laboratory of the Oceanography Department of UFPE. In the laboratory, analyses were performed as described by Strickland and Parsons (1972) and Grasshoff et al. (1983).

The sampling was performed by oblique hauls (made in "V") with a cylindrical-conical plankton net with mesh openings and mouth diameters of 64 µm and 30 cm, respectively. The hauls extended to a depth of 80% of the local depth, or, at most, up to 200 m. After the hauls, the samples were transferred to plastic bottles and immediately fixed in formaldehyde solution (4%), buffered with sodium tetraborate.

For the qualitative and quantitative analysis of the organisms, each sample was diluted according to the density of organisms. Then, 1 ml aliquote was dropped into a "Sedgwick-Rafter" chamber and analyzed under a compound microscope and at least 300 individuals counted. Three aliquots of each sample were analyzed. The taxa identification was based on the smallest taxonomic unit possible.

Densities were calculated ($org.m^{-3}$) for all identified species. The community structure was described using the Whittaker diagram, which relates the relative abundance with the species richness. With them we can infer the evenness. The ANOSIM was used to test the statistical differences of species density between periods (day and night) and years (2010, 2012 and 2014). To show the difference in density between the years, a multidimensional non-metric scaling (nMDS) was used. The variation of the environmental parameters between the years was evaluated through Principal Component Analysis (PCA). An indicator value analysis (IndVal), which computes a single value for each species, was performed based on the fidelity and specificity of the species in relation to groups of sites, and statistically tests the significance of the relations by permutation (CHEW et al., 2015). The IndVal of a species has been used to express species importance as indicators in community categorizations. All the tests were made using the R language (R Core Team 2017) and the RStudio environment version 1.1.42 (RStudio Team 2016).

Results

A total of 76 Radiozoa Polycystine were identified, distributed in two orders, Nassellaria with 12 families and 45 species and the Spumellaria with 9 families and 31 species. All the taxa identified occurred in the year 2014, being 65.8% of these exclusive of this year. Most of the taxa (49) occurred in both periods (day and night) (Table 1).

The order Spumellaria, despite having lower richness, showed higher density (1217.02 org.m^{-3}). Most of the families of this order presented density greater than 200 org.m^{-3}. Spongodiscidae more specifically the species Dictyocoryne truncatum was the most representative with 646.69 org.m^{-3}, and it occurred only in the year 2014 and was registered in the day and night periods. The Family Actinommidae showed the highest richness within this order (12) and 83% of them occurred only in the year 2014 (Table 1; Figure 2).

The families of lower representativeness were Artostrobiidae, Cannobotryidae, Carpocaniidae, with less than 14 org.m^{-3}, the three are part of the order Nassellaria (Table 1; Figure 2).

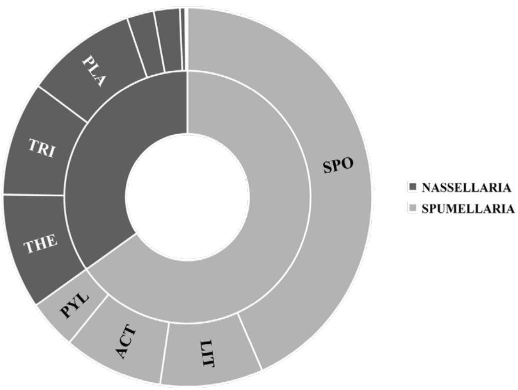

Figure 2. Density of Polycystine (Radiozoa) by order (Nasselaria and Spumellaria) and families in the vicinity of the Rocas Atoll (Brazil). Legend families: ART – Artostrobiidae, CAN- Cannobotryidae, CAR – Carpocaniidae, COL – Collozoidae, PLA – Plagiacanthidae, PTE – Pterocorythidae, THE - Theoperidae, TRI – Trissocyclidae, ACT – Actinommidae, LIT – Litheliidae, PYL – Pyloniidae and SPO – Spongodiscidae.

The year in which the highest total density was observed was 2014 with 1871.3 org.m^{-3}, followed by 2012 (1256.1 org.m^{-3}) and 2010 (841.0 org.m^{-3}). In 2014 the densities were higher in the area of direct incidence of the current (1404.8 org.m^{-3}) and the day period (1127.9 org.m^{-3}) had higher densities than night (743.3 org.m^{-3}). This year was different from what was observed in 2010 and 2012, when the densities in the area of indirect incidence and the night period were higher than those of the day, 273.3 org.m^{-3} (day); 982.7 org.m^{-3} (night), and 191.4 org.m^{-3} (day) and 649.5 org.m^{-3} (night), respectively (Figure 3).

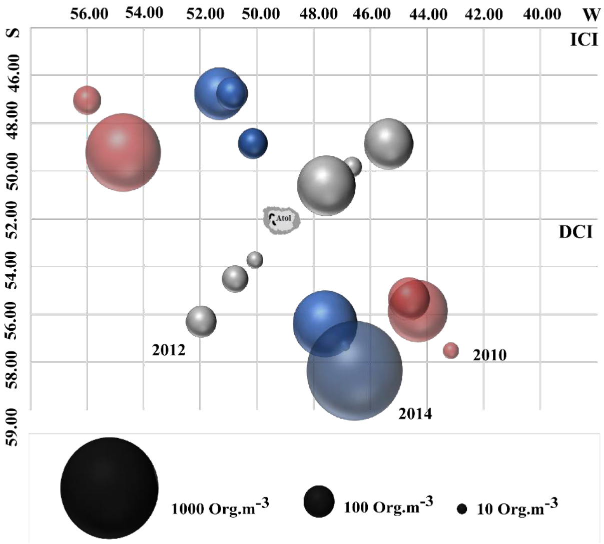

Figure 3. Total density (org.m^{-3}) per site and year of the taxa Polycystina (Radiozoa) in Rocas Atoll (Brazil).

The similarity analysis (ANOSIM) indicated significant difference in density only in relation to the year (2010; 2012; 2014) R= 0.1884, p = 0.001, but not for the period (day/night) R=-0.04862, p = 0.956.

With the analysis of the Whittaker diagram (Figure 4), the superiority of richness presented in the year 2014 is clear. It is also possible to visualize that few species were highlighted in terms of relative abundance in the three years. In 2010, *Dictyocoryne* sp., *Spongodiscus resurgens*, *Discopyle* sp. and *Zygocircus productus* were the most abundant. In 2012, outranked *Dictyocoryne* sp., *Discopyle* sp., *Carpocanistrum* sp. and *Plegmosphaera* sp.; and, in 2014 *Dictyocoryne* sp., *Lophophaena hispida*, *Spongotrochus* sp. and *Dictyocoryne profunda* were dominant. In 2014, the distribution pattern of individuals among species was intermediated concerning 2012 which was higher and 2010 which was lower. That is, the relative abundance percentages were better distributed in 2012, while 2014 had a high number of rare species, see Figure 4.

With the construction of the nMDS we can observe 3 groupings of points based on the density difference of the organisms in the stations between the years, the distance between the points of 2014 and 2010 is greater comparatively than any other association. This means that these were the least similar years. It

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Table 1. Total Density and occurrence per period and year of the taxa Polycystina (Radiozoa) identified in Rocas Atoll (Brazil).

TAXONOMIC CLASSIFICATION		TOTAL DENSITY (Org.m^{-3})	OCCURRENCE	
			PERIOD	YEAR
PHYLUM RADIOZOA				
CLASS POLYCYSTINA				
ORDER NASSELLARIA				
Family Artostrobiidae	*Spirocyrtis scalaris*	2,36	D/N	2014
Family Cannobotryidae	*Botryopyle dictyocephalus*	3,13	N	2014
Family Carpocaniidae	*Carpocanistrum sp.*	64,27	D/N	ALL
	Carpocanium sp.	2,31	N	2014
Family Collozoidae	*Collosphaera macropora*	2,50	D/N	ALL
	Collosphaera sp.	1,66	N	2014
	Collosphaera tuberosa	0,65	D	2014
	Siphonosphaera polysiphonia	0,65	N	2014
	Siphonosphaera sp.	3,99	D/N	2012/2014
	Solenosphaera sp.	2,96	D/N	2014
	Solenosphaera zanguebarica	2,91	N	2014
	*Collozoidae**	48,45	N	2014
Family Plagiacanthidae	*Amphiplecta sp.*	6,24	D/N	2014
	Clathrocorys sp.	11,70	D/N	2014
	Enneaphormis rotula	3,32	N	2014
	Lampromitra sp.	4,74	D/N	2014
	Lophophaena buetschlii	3,05	D/N	2014
	Lophophaena hispida	215,76	D/N	2014
	Peromelissa sp.	9,77	D/N	2014
	Pseudocubus obeliscus	16,45	D/N	ALL
	Pteroscenium pinnatum	1,25	D	2014
Family Pterocorythidae	*Lamprocyclas sp.*	9,98	D/N	2014
	Pterocorys minythorax	1,66	D/N	2014
	Pterocorys zancleus	1,50	D	2010/2014
Family Theoperidae	*Corocalyptra cervus*	14,77	D/N	2010/2014
	Corocalyptra columba	2,03	D/N	2012/2014
	Corocalyptra sp.	26,59	D/N	2010/2014
	Cycladophora sp.	77,64	D/N	ALL
	Dictyophimus infabricatus	3,32	N	2014
	Dictyophimus sp.	43,65	D/N	2014
	Eucyrtidium acuminatum	11,59	D/N	2014
	Eucyrtidium hexastichum	3,32	N	2014
	Eucyrtidium sp.	26,59	D/N	2010/2014
	Lipmanella bombus	0,70	D	2014
	Litharachnium tentorium	57,76	D/N	ALL
	Pterocanium trilobum	7,98	D/N	2012/2014
	Stichopilidium kruegeri	1,66	N	2014

* Unidentified organisms.

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Table 1. Total Density and occurrence per period and year of the taxa Polycystina (Radiozoa) identified in Rocas Atoll (Brazil). continuation...

Family Trissocyclidae	*Acanthodesmia viniculata*	47,21	D/N	2014
	Amphispyris reticulata	0,70	D/N	2014
	Amphispyris sp.	41,44	D	2014
	Ceratospyris sp.	3,61	N	2014
	Clathrocircus stapedius	4,98	N	2014
	Tholospyris sp.	7,69	D/N	2014
	Zygocircus productus	104,60	D/N	2010/2014
	Zygocircus sp.	64,19	D/N	ALL
ORDER SPUMELLARIA				
Family Actinommidae	*Acanthosphaera actinota*	6,68	D/N	2014
	Acanthosphaera dodecastyla	3,97	N	2014
	Acanthosphaera pinchuda	22,51	D/N	2014
	Acanthosphaera sp.	11,72	D/N	2014
	Actinomma sp.	3,24	D	2014
	Centrocubus sp.	1,66	N	2014
	Hexacontium aristarchi	1,17	N	2014/2014
	Hexacontium armatum-hostile	4,98	N	2014
	Hexacontium sp.	7,33	D/N	2014
	Hexastylus phaenaxonius	0,70	D	2014
	Plegmosphaera sp.	86,42	D/N	ALL
	Spongosphaera streptacantha	93,29	D/N	ALL
Family Litheliidae	*Discopyle sp.*	194,63	D/N	ALL
	Larcopyle buetschlii	53,19	D/N	2010/2014
	Lithelius minor	1,99	N	2014
	Lithelius spp.	3,32	D	2014
Family Pyloniidae	*Octopyle sp.*	23,02	D/N	2014
	Octopyle stenozona	6,64	D/N	ALL
	Phorticium clevei	46,44	D	2014
	Phorticium sp.	3,97	D/N	ALL
	Pylolena sp.	30,20	D/N	2014
	Pylonidae	6,23	D/N	ALL
	Tetrapyle octacantha	3,65	D/N	2014
Family Spongodiscidae	*Dictyocoryne profunda*	92,87	D/N	ALL
	Dictyocoryne sp.	17,98	D/N	ALL
	Dictyocoryne truncatum	646,69	D/N	2014
	Euchitonia elegans-furcata	1,39	D	2014
	Spongaster tetras	166,12	D/N	ALL
	Spongodiscus resurgens	150,45	D/N	2010/2014
	Spongotrochus sp.	133,23	D/N	ALL
	Spongurus pylomaticus	8,30	D/N	2014
TOTAL DENSITY			2807,23	

* Unidentified organisms.

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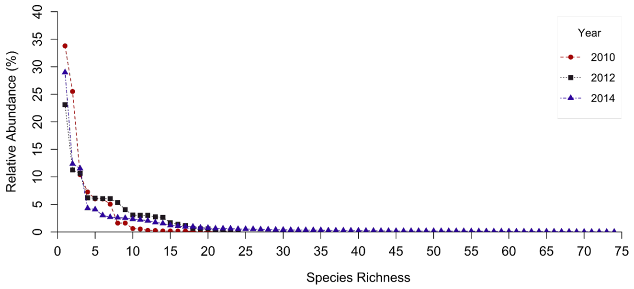

Figure 4. Whittaker diagram showing the relative abundance of the species (Y axis) of Polycystine (Radiozoa) by species richness, ordered in the abscissa in descending sequence of importance for the three years of collection in the vicinity of the Rocas Atoll (Brazil).

can be observed that all points referring to 2012 are superimposed on those of 2010 or 2014, showing that this year is statistically like the other two years sampled. 2014 shows greater variation between their points, while in 2012 the points are closer, suggesting that the variation of Radiozoa density of the stations was lower than in the other years (Figure 5).

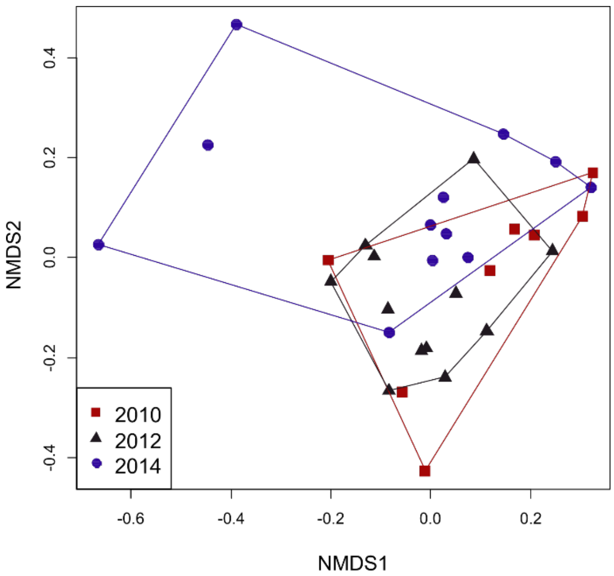

Figure 5. Non-metric multidimensional scaling (nMDS) showing groupings based on Polycystine density difference between the years in the Rocas Atoll (Brazil).

Table 2 shows the average variation of the environmental parameters between the years compared to the average density of Radiozoa Polycystine. The average density of the order was higher in the year 2014, and in this year the nutrients NO3, PO4 and SiO2 also had the largest medias, mainly SiO2 that ranged from 1.04 µM in 2010 to 3.76 µM in 2014. The parameters temperature and fluorescence were higher in the year 2010, as well as the highest chlorophyll-*a* value (0.68 mg.m^{-3}) (Table 2).

The Principal Component Analysis shows the grouping of the stations according to the discrepancy between the values of the environmental variables. We can observe therefore that, the confidence intervals of 95% in relation to the mean of the years 2012 and

Table 2. Environmental parameters (mean ± SD) and Total Radiolaria Polycystine in the vicinity of the Rocas Atoll (Brazil).

Factors	2010	2012	2014
Temperature (°C)	27.87±0.12	26.28±0.05	26.50±0.03
Fluorescence	0.59±0.18	0.23±0.08	0.19±0.03
Salinity (PSU)	36.04±0.31	36.20±0.01	36.12±0.24
Oxygen (ml.L^{-1})	4,82±0.33	4,10±0.02	3,86±0.03
NO3 (µM)	1.14±0.36	1.57±0.083	2.06±3.73
PO4 (µM)	0.11±0.09	0.09±0.05	0.12±0.08
SiO2 (µM)	1.04±0.59	1.34±0.63	3.76±5.51
Chlorophyll-*a* (mg.m^{-3})	0.68±0.18	0.19±0.11	0.49±0.24
Radiolaria Polycystina total (org.m^{-3})	139.57	70.08	155.94

2014, represented by the circles, are overlapping, suggesting that these years are statistically similar and different from 2010 (Figure 6).

Main component 1 explains 35% of the variation of the data, and in this axis the parameter that best explains this variation is the temperature, which showed greater difference between the years and the highest values were observed in 2010. Other important parameters were oxygen and chlorophyll-*a*, with higher values in 2010 than in the other years. Salinity was slightly higher in 2012 and 2014, but its

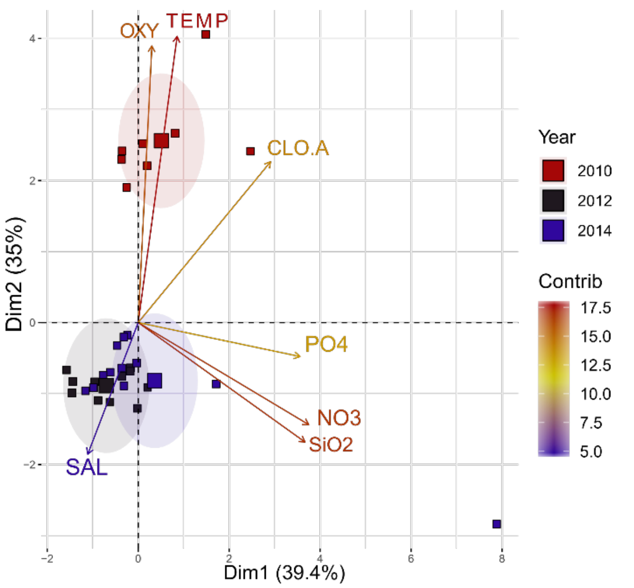

Figure 6. Principal component Analysis (PCA) of environmental parameters between the years in the Rocas Atoll (Brazil).

importance was low in relation to the others, that is, its value does not vary widely between the points and years studied. 2012 and 2014, are better distributed in the lower quadrant. This shows that the values of SiO2, NO3 and PO4 were higher in these years and mainly in 2014 (Figure 6)

The analysis of the indicator value (IndVal) showed that from the 76 species analyzed less than 10% showed significant indication levels. Five of these were exclusive of 2014, and the species *Lophophaena hispida* (indval = 71.6%) was the one that presented the highest indicator value of this year and was indicative of higher levels of nutrients. Only the species *Spongodiscus resurgens* was related to the year 2010, with 75.3% of indicative value of higher temperatures and chlorophyll-*a*, and no species was related to the year 2012. Zygocircus productus (indval = 77.5%) was simultaneously related to the years 2010 and 2014 (Table 3).

Table 3. Individual indication value (IndVal) of Polycystine (Radiozoa) from the surroundings of the Rocas Atoll (Brazil), in the years 2010, 2012 and 2014.

Year	Taxa	A	B	Stat	p.value
2010	*Spongodiscus resurgens*	0.9076	0.6250	0.753	0.009
2014	*Lophophaena hispida*	1	0.5833	0.764	0.002
	Acanthodesmia viniculata	1	0.5000	0.707	0.002
	Dictyophimus sp.	1	0.5000	0.707	0.002
	Amphispyris toxarium	1	0.4167	0.645	0.017
	Tholospyris sp.	1	0.3333	0.577	0.025
2010+2014	*Zygocircus productus*	1	0.6	0.775	0.011

Discussions

The phylum Radiozoa is very representative within the Microzooplankton and important in terms of density and abundance (SHERR; SHERR; PAFFENHÖFER, 1986). The species found in this study were collected in the vicinity of the Rocas Atoll, in the superficial and sub superficial section of the water column. According to Dennett et al. (2002), the greatest abundance and diversity of the phylum Radiozoa, which may present up to 20.000 colonies m-3 of the order Polycystine is concentrated in this layer (CAMACHO; FUNDACIÓN DE HISTORIA NATURAL FÉLIX DE AZARA, 2008). It is also in this layer that we find the greatest complexity in the distribution structure of the species (KLING, 1979), even though some studies also show that they may be more abundant below 200 meters deep (KRŠINIĆ,1998; KRŠINIĆ e GRBEC, 2002). In Polycystine we find a wide range in the vertical distribution, which can occur in greater abundance from 50 to 400 m deep (BOLTOVSKOY, 1998, 1999; ZASKO; RUSANOV, 2005).

In spite of this, the observed richness (76) was low compared to other studies carried out around the world, including the ones made in nearby areas, also located in the Atlantic Oligotrophic region, such as the archipelago of São Pedro and São Paulo, where it was recorded 72 taxa close to the archipelago (COSTA; SANTANA; NEUMANN-LEITÃO, 2018). Boltovskoy and Riedel (1980) observed 98 taxa in the Southwestern Atlantic. In the current of California, Boltovskoy and Riedel (1987) found 158 species and Kling and Boltovskoy (1995) registered 136 species. Boltovskoy (2017) in a broad review between 30° N and 30° S in the global oceans quoted 151 taxa. Welling et al. (1996) found 109 taxa in Tropical Pacific, while McMillen and Casey (1978) in a study conducted in the Gulf of Mexico and Caribbean Sea identified 92 taxa. For the Adriatic Sea, Kršinić and Kršinić (2012) recorded 78 species.

In this study, the Polycystine class was represented by two orders, Nassellaria and Spumellaria, commonly found in Radiozoa studies. Different from that observed by Vergara et al. (2008) and Zapata and Olivares (2005), the order that presented the greatest richness was Nassellaria. This order presents two forms of feeding, the active form (SUGIYAMA et al., 2008) and symbiotic associations, especially dinoflagellates (ZHANG et al., 2018). Therefore its distribution is related to this behavior, concentrating its greatest abundance and diversity in tropical surface waters (BOLTOVSKOY; CORREA, 2016; BOLTOVSKOY, 2017) where light availability favors the development of symbiotes. In Nassellaria, the family that presented the highest number of taxa was Theoperidae, however, the most representative family in density was Plagiacanthidae with prominence of the species *Lophophaena hispida*. This species was an indicator for the year 2014 (high nutrients), and it is characterized by having wide distribution in tropical oceanic areas (BENSON, 1966).

The order Spumellaria, on the other hand, presented higher density having high adaptive capacity in various environmental conditions (ISHITANI et al., 2012). In the North Pacific, for example, it keeps on the order of 400 cel.m-3 (ISHITANI; TAKAHASHI, 2007). It is a highly diverse order (DE WEVER et al., 2003), that presents specific geographic provinces in tropical regions and is distributed in vertical layers that can be from the surface to very deep regions (YAMASHITA; TAKAHASHI; FUJITANI, 2002; ISHITANI et al., 2008). Studies show that this order is subdivided into two groups based on temperature and habitat; a portion occupies superficial waters (upper surface 0–40 m and lower surface 40–200 m) at high latitudes and are submerged in low latitudes and the other occupies tropical and subtropical surface waters (ISHITANI et al., 2012). In this order, two families were highlighted, Actinommidae that presented the largest number of species, with 83% of them occurring exclusively in 2014; and the Spongodiscidae family with the highest density within the order, where the species *Dictyocoryne truncatum* represented more than 50% of this value and occurred exclusively in the year 2014. Most species of this family occur in tropical surface waters, however, *Spongodiscus resurgens*, that presented high density in this study, resides in subtropical surface waters (KLING, 1979; BOLTOVSKOY; RIEDEL, 1987; KLING; BOLTOVSKOY, 1995).

The total density variation of Polycystine was not statistically significant in relation to the day and night periods but was in relation to the years. The individual indication value (IndVal) of Polycystine (Radiozoa) for the years showed seven indicator species, with five of them from the year 2014, one from 2010 and one from 2010 and 2014. The indicator species of 2014, *Lophophaena hispida* is widely distributed in tropical seas with preference for oceanic waters (BENSON, 1966); *Acanthodesmia viniculata* is cosmopolitan and its highest frequency was observed in a resurgence region, besides having greater affinity for oceanic waters and was not reported in high latitudes (BENSON, 1966). *Amphispyris toxarium* is tropical and may vary in temperate regions of all seas and has not been reported in polar latitudes (BENSON, 1966). In 2010, the indicator species was Spongodiscus resurgens, a species cited as cosmopolitan (HAECKEL, 1887; BOLTOVSKOY; RIEDEL, 1980; BOLTOVSKOY, 1998). The indicator species from the years 2010 and 2014 was the *Zygocircus productus*, it is very rare in the northern third of the Gulf of California (BENSON, 1966). This species is considered cosmopolitan, occurring in surface waters in the Atlantic and Pacific Oceans, as well as in the Mediterranean Sea; and, it was not reported at high latitudes (HAECKEL, 1887).

The year 2014 showed the highest values of density and richness, still, the distribution pattern of individuals among species was intermediated concerning 2012, which was higher and 2010, which was lower. Boltovskoy (1999) declares that there is a high degree of homogeneity of the distribution of organisms among the species close to the tropics. In general, the distribution of phylum is inversely linked to the environmental stability of temperature and salinity.

In this study, both the density, species richness and the environmental parameters analyzed showed remarkable differences between the years, mainly between 2010 and 2014. The year 2012 was intermediate to the other years, and, in relation to the variation of the environmental parameters indicated in the principal component analysis, it was more like 2014. In this analysis, the temperature was the most explanatory parameter for this temporal discrepancy, with 2010 presenting the highest values. This difference interferes directly in the pattern of distribution of species between the years, since, the influence of physical and biological factors in the phylum Radiozoa acts similarly to most zooplankton groups. For the order Polycystina, factors such as temperature, salinity and primary production are considered the most important ones (CAMACHO; FUNDACIÓN DE HISTORIA NATURAL FÉLIX DE AZARA, 2008).

Therefore, the greatest diversities observed for the group occur in medium-low latitudes, decreasing slightly towards the equator and drastically towards the poles (BOLTOVSKOY; RIEDEL, 1987; BOLTOVSKOY, 1999), achieving maximum diversity in tropical waters (CAMPBELL; HOLM, 1957), where the incidence of solar rays is more direct and the surface temperatures of seawater can overcome the 30°C.

During the study period, we observed a variation of 1.59°C in the average temperature of the surface layer of water between the years 2010 and 2012, 1.37°C between 2010 and 2014 and 0.22°C between 2012 and 2014. This variation, in the average temperature is common in the face of El Niño-South Oscillation phenomena (ENSO). In this period of time it was recorded a phenomenon of positive anomalies (El Niño) that began in 2009 and lasted until 2010, with moderate intensity, that is, the temperature variation on the surface of the Sea (TSM) is in the range of 1.5 and 1°C. After this occurrence, a phenomenon of negative anomalies (La Niña) was also moderate, with a variation of TSM higher than -1.5°C but lower than -1.0°C, which lasted until the beginning of 2012 (DAHLMAN, 2019); 2014 was a neutral year, however, preceded a strong-intensity El Niño event. Jales et al. (2015) observed, in the same area, in the year 2010, a greater rupture of the thermohaline structure. These variations were probably determinant in the population dynamics of Polycystine, since even moderate temperature variations exert an effect on abundances and composition of the microplankton community (CARON; HUTCHINS, 2013).

Other characteristics that differentiated the years and possibly influenced the variability in density and richness were the values of chlorophyll-α and dissolved oxygen that was higher in 2010 and of the nutrients NO3, PO4 and SiO2, higher in 2014. One of the most important nutrients for radiolarians is silica. This component has structural function and is one of the factors that makes this group an important source of oceanographic, biostratigraphy and paleoenvironmental knowledge (VERGARA; MARCHANT S. M; GIGLIO, 2008). Silica is used in the formation of the skeleton of these organisms and is taken directly from the water (KOCHHANN, 2015). Therefore, it is expected that the availability of this resource is conducive to the development of this group. In this sense, the high density and diversity observed in 2014 may be directly related to the highest silica values during this year. According to Abelmann and Gowing (1997), the variability of temperature, silica and other macronutrients can dictate the variation of abundance in the Radiolaria communities, which makes them possible indicators of paleoproductivity (KOCHHANN, 2015).

Although some factors made 2010 favorable to the development of microzooplankton, attested by the high density observed this year (Basílio-Dantas et al., in press), the Radiozoa did not develop as expected; and, similar discrepancy was also observed by Costa et al. (2018)in the Archipelago of São Pedro and São Paulo. One of the factors that may have influenced this response, in addition to the lower availability of silica, was possibly the competition of these with diatomaceous by the same resources (RACKI, 1999).

The presence of Rocas Atoll, as already seen, interferes locally in the structure of currents, which consequently reflects on the availability of resources and increment of chlorophyll-α (SAMPAIO DE SOUZA et al., 2013). This region is bathed by waters of low nutrient concentration, the South Atlantic Central water (SACW) that is transported by the South Equatorial current (SEC) (STRAMMA; SCHOTT, 1999). Jales et al. (2015) observed, for the year 2010, disturbance due to turbulent processes generated by the passage of the current in the Rocas Atoll, despite not having found evidence of resurgence of nutrient-rich waters. In this year, as well as in 2014, the velocity of the SEC was maximal. This fact may have favored the greater nutritional contribution, not by the resurgence, but by the vortices formed on the opposite side of the atoll and by the entrance of the current and greater washing of the submerged areas close to the atoll (NEUMANN-LEITÃO et al., 1999; MORATO et al., 2010; MACEDO-SOARES; CARVALHO; FREIRE, 2011). These areas are rich in nutrients from animal residues abundantly produced in the coralline reefs and surroundings (GOVE et al., 2016), generating an environment favorable to increased productivity. Radiozoa presents greater abundance in oceanic areas rich in nutrients and resurgence (BOLTOVSKOY, 2005). Furthermore, Radiozoa groups have already been described in oligotrophic waters, in associations with water masses that differed in temperature and nutrients (BJØRKLUND et al., 1998; BOLTOVSKOY, 1998, 1999). Thus, fossil debris from Radiolaria can also provide valuable clues to the ecological sceneries (SANDOVAL, 2018).

Observing the values of richness and density presented we can deduce that the Polycystine class was more successful in the year 2014. Intrinsic characteristics of this year, as high values of available nutrients contributed positively to the abundance of this class. Moreover, it is important to emphasize that some characteristics of each species (such as morphological, mechanical and physiological properties) may be more sensitive to nutrient availability than to other environmental parameters, such as salinity and/or temperature.

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