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DEPARTAMENTO DE OCEANOGRAFIA
PROGRAMA DE PÓS-GRADUAÇÃO EM OCEANOGRAFIA

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# INFLUÊNCIA DAS CONDIÇÕES OCEANOGRÁFICAS SOBRE A ESTRUTURA DA COMUNIDADE FITOPLANCTÔNICA NO ATOL DAS ROCAS, ATLÂNTICO SUL EQUATORIAL, BRASIL

**Recife**
**2015**

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# INFLUÊNCIA DAS CONDIÇÕES OCEANOGRÁFICAS SOBRE A ESTRUTURA DA COMUNIDADE FITOPLANCTÔNICA NO ATOL DAS ROCAS, ATLÂNTICO SUL EQUATORIAL, BRASIL

**Tese apresentada ao Programa de Pós-Graduação em Oceanografia da Universidade Federal de Pernambuco como parte dos requisitos para obtenção do título de doutor (a) em Oceanografia.**

**Orientador: Prof. Dr Fernando Antônio do Nascimento Feitosa**

**Coorientadora: Prof[a]. Dr[a]. Maria Luise Koening**

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Marina Cavalcanti Jales

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***À minha família, que me apoia em todas as minhas escolhas, fazendo com que eu sempre siga em frente com muita paz e orgulho das minhas conquistas.***

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**Resumo**

O conhecimento da composição e distribuição dos produtores primários é fundamental para uma melhor compreensão da dinâmica trófica de regiões oceânicas. A composição do fitoplâncton no Oceano Atlântico Sul ainda está sendo explorada e em algumas regiões esta diversidade nunca foi descrita, como é o caso da Reserva Biológica do Atol das Rocas. O atol situa-se ao sul do equador (3°51'S e 33°49'W), distante 143 milhas náuticas da Cidade de Natal, Estado do Rio Grande do Norte (Brasil). Este estudo teve como principal objetivo caracterizar a estrutura da comunidade fitoplanctônica do entorno e nas piscinas naturais do Atol das Rocas correlacionando com as variáveis ambientais. As amostras foram coletadas no entorno do atol em julho de 2010, utilizando o navio Oceanográfico da Marinha do Brasil, Cruzeiro do Sul. Dois transectos foram estabelecidos de acordo com a corrente superficial, um transecto em direção sudeste (SE) e o outro, em direção noroeste (NO) do atol. Nestes transectos foram determinados três pontos de coleta para cada um. As amostras foram coletadas em diferentes profundidades (superfície e PMC – Profundidade Máxima de Clorofila) e diferentes períodos do dia (dia e noite). Nas piscinas naturais analisadas (Barretinha, Cemitério, Tartarugas, Rocas e Barretão), as coletas ocorreram em períodos climáticos distintos nos anos de 2012 e 2013. Os parâmetros oceanográficos os quais foram empregados para analisar a influência sobre a estrutura do fitoplâncton foram salinidade, temperatura da água, oxigênio dissolvido, teores de nutrientes inorgânicos dissolvidos e clorofila *a*. Foram realizadas coletas para a análise do microfitoplâncton utilizando rede com malha de 20 µm e densidade fitoplanctônica utilizando garrafa de Niskin. No entorno do atol, a maioria das variáveis ambientais apresentou aumento significativo em função da turbulência no transecto NO. Pode-se observar que houve aumento dos teores de clorofila *a* e nutrientes, e redução da temperatura e oxigênio na camada de mistura em função da influência da ACAS (Água Central do Atlântico Sul). No transecto NO a comunidade fitoplanctônica correlacionou-se fortemente com os parâmetros salinidade e temperatura, devido a uma instabilidade termohalina decorrente da interação das massas d'água Água Tropical e a Água Central do Atlântico Sul. As amostras apresentaram variação espacial horizontal, com maior participação do filo Ochrophyta próximo ao atol e Dinophyta nos pontos mais distantes, enquanto que na distribuição vertical não houve diferença. Espécies mais abundantes foram *Prorocentrum balticum* (Lohmann) Loeblich 1970, *P. compressum* (Bailey) Abéex Dodge 1975 e *P. gracile* Böhm 1933 e *Coccolithus* sp.. Já nas piscias naturais, apesar do filo Ochrophyta ter sido o mais evidenciado, as espécies mais representativas encontradas de acordo com a densidade foram *Prorocentrum balticum* (Lohmann) Loeblich 1970, *P. lima* (Ehrenberg) F. Stein 1878, *Pyrophacus* sp. e *Ostreopsis ovata* Fukuyo 1981. De um modo geral, quatro diferentes filos foram identificados com um total de 195 taxa. No entorno do Atol das Rocas, o aumento de biomassa fitoplanctônica no transecto NO, foi provocado pelo "efeito ilha" e não pela ressurgência. Além disso, as condições oceanográficas influenciaram na distribuição da comunidade fitoplanctônica. Nas piscinas naturais, apesar da composição apresentar diferença espacial, nenhum parâmetro hidrológico foi determinante. No entanto, pode-se observar um padrão sazonal, havendo um aumento quali-quantitativo do fitoplâncton no período chuvoso, no qual, o hidrodinamismo local, proporcionou condições mais favoráveis para o enriquecimento da diversidade, com ênfase nas espécies que compõem a microflora bentônica.

**Palavras chave: Fitoplâncton. Clorofila *a*. Hidrologia. Atol das Rocas. Efeito ilha**

**Abstract**

Knowledge of the composition and distribution of primary producers is essential to understand the trophic dynamics of ocean food webs. The composition of phytoplankton in the South Atlantic Ocean is still being explored, and in some regions this diversity has never been described, as in the case of Biological Reserve of Atol das Rocas. The atoll is located in south of the equator (3°51'S and 33°49'W), some 143 nautical miles from the city of Natal, in the state of Rio Grande do Norte (Brazil). The aim of this paper is to characterize the phytoplankton community structure in the natural pools of Atol das Rocas and its surrounding area by correlating environmental variables. The samples were collected around the atoll in July 2010 on board the Brazil Navy Oceanographic ship, the Cruzeiro do Sul. Two transects were established according to the surface current; a transect oriented southeast (SE) and a transect oriented northwest (NW) of atoll. Three collection points were established for each of the transects. The samples were collected at different depths (surface and DCM - Deep Chlorophyll Maximum) and during different periods of the day (daytime and nighttime). Sampling occurred at the pools Barretinha, Cemitério, Tartarugas, Rocas and Barretão in different climate periods of 2012 and 2013. Oceanographic parameters which were used to analyze the influence on phytoplankton structure were salinity, water temperature, dissolved oxygen, dissolved inorganic nutrients content and chlorophyll *a*. Samples were collected to analyse microphytoplankton using mesh net of 20µm and phytoplankton density using bottle Niskin. Around the atoll, most of the environmental variables increased significantly due to turbulence in NW transect. Increased contents of chlorophyll *a* and nutrients and a reduction of temperature and oxygen in the mixing layer were also detected due to the influence of the SACW (South Atlantic Central Water). In the NW transect, the phytoplankton community corresponded strongly with the salinity and temperature parameters due to thermohaline instability resulting from the interaction of Tropical Water masses and Central Water masses of the South Atlantic. The samples presented a horizontal spatial variation, with highest participation of the phylo Ochrophyta closer to the atoll and Dinophyta further from the atoll, while vertical distribution patterns were not observed. The most representative species were *Prorocentrum balticum* (Lohmann) Loeblich 1970, *P. compressum* (Bailey) Abéex Dodge 1975 and *P. gracile* Böhm 1933, and *Coccolithus* sp.. The predominant group in the natural pools was Ochrophyta. In spite of the predominance of this group, the most representative species found in the pools in terms of density were *Prorocentrum balticum* (Lohmann) Loeblich 1970, *P. lima* (Ehrenberg) F.Stein 1878, *Pyrophacus* sp. and *Ostreopsis ovata* Fukuyo 1981. In general, four different phyla were identified with a total of 195 taxa. In the area surrounding Atol das Rocas, an increase in phytoplankton biomass in transect NW was caused by the "island effect" and not by the upwelling. Furthermore, the oceanographic conditions influenced the distribution of the phytoplankton community. Despite the spatial difference of the composition found in the natural pools, there was no determinant hydrological parameter. However, a seasonal pattern was observed, with a qualitative and quantitative increase of phytoplankton during the rainy season when the local hydrodynamics provides more favourable conditions for the enrichment of diversity, especially among species that compose the benthic microflora.

**Key words: Phytoplankton; Chlorophyll *a*. Hydrology. Atol Das Rocas. Island mass effect**

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# SUMÁRIO

# 1. INTRODUÇÃO GERAL

Os oceanos constituem um biociclo, onde processos químicos, físicos e biológicos interagem entre si, influenciando todas as comunidades marinhas. Os parâmetros abióticos mais importantes nos oceanos são luz, temperatura, salinidade e nutrientes, uma vez que tem influência direta ou indireta em toda a circulação oceânica, determinando a distribuição dos organismos vivos e interligando os diversos processos biológicos e geológicos (Macêdo et al., 2009).

O Oceano Atlântico apresenta um complexo sistema de correntes e subcorrentes que fluem principalmente na direção Leste-Oeste, promovendo trocas de massas e de energia em diferentes níveis da coluna d'água (Araújo e Cintra, 2009). Segundo Góes (2006), o Atol das Rocas recebe influência da Corrente Sul Equatorial (CSE), que se desloca da costa africana para costa brasileira paralelamente ao equador geográfico. Esta corrente segue o sentido de Fernando de Noronha para o Atol das Rocas e subsequentemente para o Litoral Nordeste do Brasil (Moraes et al., 2003).

Nos oceanos, podem-se encontrar formações recifas classificadas como atóis, onde, segundo Kikuchi (1994), atualmente foram registrados 425 atóis, dos quais 27 estão inseridos no Oceano Atlântico, onde 26 são localizados no Mar do Caribe e um único atol do Atlântico Sul, o Atol das Rocas. Apesar de muitas pesquisas realizadas em ambientes recifais, pouco se sabe sobre a comunidade fitoplanctônica desses ambientes e uma série de aspectos necessita ser mais bem elucidada.

A importância ecológica, social, e econômica do ambiente coralino são indiscutíveis, pois são considerados um dos mais antigos e ricos ecossistemas da Terra, juntamente com as florestas tropicais, uma das mais diversas comunidades naturais do planeta. Essa enorme diversidade de vida pode ser medida quando constatamos que uma em cada quatro espécies marinhas vive neste ambiente, incluindo 65% das espécies de peixes (Ferreira, 2007).

Segundo Gherardi and Bosence (1999), os recifes do Atol das Rocas apresentam em sua composição, principalmente, algas calcárias incrustantes e moluscos vermetídeos. Sendo esta composição uma das principais características dos recifes localizados na costa brasileira, além de serem estruturas similares às cristas algais dos recifes Indo-Pacíficos (Laborel, 1967).

Os organismos planctônicos são a base da teia alimentar dos mares e oceanos, sendo assim de importância fundamental para todos os níveis tróficos desses ambientes. Havendo alterações nesta base, pode-se esperar sucessivas mudanças em toda biota marinha.

De acordo com monitoramento da NASA, o fitoplâncton, através da fotossíntese, dependendo da estação do ano, contribui entre 50 e 90% da produção de todo o oxigênio do ar que respiramos. Neste processo de produção de oxigênio, o fitoplâncton, é um dos maiores sumidouros de $CO_2$ da atmosfera e é um fator importante na manutenção de um ecossistema equilibrado essencial para a vida e um planeta saudável (Hoppenrath et al. 2009).

Estima-se que 45 Gt (gigaton) de carbono orgânico particulado sejam produzidos anualmente pelo fitoplâncton nos oceanos. Desse total, cerca de 16 Gt são exportados para as camadas mais profundas do oceano servindo de alimento para organismos que habitam essas regiões. Esse processo conhecido como bomba biológica atua diretamente sobre a concentração de $CO_2$ atmosférico que é retirado da atmosfera por um período prolongado (Gianesella e Saldanha-Corrêa, 2010), sendo um fator de importância mundial para a regulação do clima e dos ciclos biogeoquímicos (Winder e Sommer, 2012). O destino desses processos é criticamente dependente da composição da comunidade do fitoplâncton, pois as alterações das condições climáticas podem modificar estes fatores ambientais e alterar a estrutura da composição taxonômica desses organismos (Winder e Sommer, 2012).

A comunidade planctônica apresenta um caráter muito dinâmico, com elevadas taxas de reprodução e perda, respondendo rapidamente às alterações físicas e químicas do meio aquático e estabelecendo complexas relações intra e interespecíficas na competição e utilização do espaço e dos recursos (Valiela, 1995). As respostas dos organismos fitoplanctônicos podem ser tanto diretamente, através da sua fisiologia, e indiretamente mediadas através de efeitos nos fatores ambientais limitando a produção primária (Winder e Sommer, 2012). Além do citado acima, segundo Fernandes e Brandini (1999), os estudos sobre a composição e distribuição do plâncton em diferentes regiões dos oceanos demonstram a formação de assembléias em função das características hidrográficas das massas de água.

Portanto, o presente trabalho trata-se da primeira investigação oceanográfica sobre a caracterização da comunidade fitoplanctônica tanto no entorno quanto em algumas piscinas naturais do Atol das Rocas. Este estudo faz parte do projeto multidisciplinar intitulado: *Camadas finas oceânicas ao largo do Nordeste do Brasil*, desenvolvido pelo Departamento de Oceanografia da Universidade Federal de Pernambuco com o apoio da Marinha do Brasil e com o financiamento do CNPq.

## 2. HIPÓTESE

As variáveis ambientais e a estrutura da comunidade fitoplanctônica no entorno e nas piscinas naturais do Atol das Rocas apresentam instabilidade horizontal, vertical e sazonal.

## 3. OBJETIVOS

### 3.1. OBJETIVO GERAL

Caracterizar a estrutura da comunidade fitoplanctônica do entorno e nas piscinas naturais do Atol das Rocas (Atlântico Tropical) correlacionando com os parâmetros ambientais.

### 3.2. OBJETIVOS ESPECÍFICOS

- ✓ Identificar a composição florística do plâncton;
- ✓ descrever a distribuição espacial (horizontal e vertical) no entorno e a distribuição espacial e sazonal (estiagem e chuvoso) nas piscinas naturais da densidade e biomassa fitoplanctônica (clorofila *a*) no Atol das Rocas;
- ✓ caracterizar a estrutura das assembleias fitoplanctônicas;
- ✓ analisar os principais parâmetros hidricos (temperatura, salinidade, sais nutrientes, oxigênio dissolvido).
- ✓ analisar as relações entre os parâmetros ambientais e biológicos determinantes da estrutura da comunidade fitoplanctônica;
- ✓ verificar a ocorrência de ressurgência topográfica na região de estudo.

## 4. FUNDAMENTAÇÃO TEÓRICA

Regiões oceânicas de zonas tropicais são consideradas normalmente oligotróficas, uma vez que, apresentam um fluxo mínimo vertical de sais nutrientes e consequentemente uma baixa produtividade biológica (Longhurst e Pauly, 2007).

Estudos realizados com modelos matemáticos de circulação oceânica global descrevem a influência da temperatura no desenvolvimento de microalgas, enfatizando que com o aumento da temperatura também aumenta a estratificação (Thomas et al., 2012), efetivamente cria uma termoclina permanente, tendendo a inibir o fluxo das camadas mais profundas ricas em sais nutrientes, restringindo a produção primária nas águas superficiais nos oceanos (Feitosa e Passavante, 2004). No entanto, estes estudos restringem-se a apenas algumas espécies e assim subestimando os efeitos nos ecossistemas (Thomas et al., 2012).

Pesquisas realizadas anteriormente nas águas superficiais do Nordeste brasileiro por Costa (1991), Medeiros et al. (1999) e Mafalda Jr. et al. (2009), através das Expedições Oceanográficas Nordeste III, pelo JOPs II e REVIZEE respectivamente, apresentaram baixos teores de sais nutrientes e consequentemente baixa biomassa.

O termo "efeito ilha" foi cunhado por Doty e Oguri (1956) para ajudar a explicar observações de produção primária perto das ilhas havaianas (Elliot et al., 2012), a qual chamou a atenção devido ao aumento da produtividade primária a montante das ilhas banhadas por águas oceânicas pobres em nutrientes (Hamner and Hauri, 1981).

O "efeito ilha" é um evento que faz referência a uma maior produção que ocorre em torno de ilhas oceânicas em comparação com as águas circundantes. Existem vários fatores físicos que podem facilitar um "efeito ilha", sendo um deles, o fluxo de maré que aumenta verticalmente, promovendo uma mistura local e consequentemente a quebra da picnoclina e nutriclina, além de formar redemoinhos no lado jusante da ilha. Portanto, em ecossistemas oligotróficos, como por exemplo, os ambientes recifais, o "efeito ilha" pode causar blooms fitoplanctônicos e consequentemente, pode causar um aumento em abundância do zooplâncton (Elliot et al., 2012).

Elliot et al. (2012), mencionam eventos de "efeito ilha" foram observadas em torno de diversos sistemas insulares como Barbados (Sander e Steven 1973), das ilhas Canárias (Hernández-Léon 1988, Hernández-Léon et al., 2001), Galápagos (Palacios 2002), Maldivas (Sasamal 2006), Marquesas (Jones 1962, Martinez e Maamaatuaiahutapu 2004), Mare (Ilhas Lealdade) e Nova Caledônia (Le Borgne et al., 1985), e as Ilhas Kerguelen no Oceano Antártico (Blain et al., 2001).

Nas ilhas do Nordeste brasileiro como o Arquipélago de São Pedro e São Paulo e Frenando de Noronha, também foi constatado que os teores de clorofila *a* apresentaram um aumento nas áreas adjacentes (Mafalda Jr. et. al. 2009; Melo et al., 2012; Lira et al. 2014).

As variações nas características hidrográficas e as interações do fluxo topográfico revelaram evidência de aumento da disponibilidade de nutrientes nas águas subsuperficiais e um aumento no crescimento de fitoplâncton. Isto mostrou que ressurgência topográfico pode ser um mecanismo importante que contribui para a produtividade das águas brasileiras do Nordeste, uma vez que em torno de montes submarinos e ilhas ao largo do Nordeste do Brasil, a relação entre clorofila *a* e nutrientes inorgânicos é estatisticamente significativa (Souza et al., 2013).

Os principais nutrientes inorgânicos utilizados pelo fitoplâncton no meio aquático são o nitrogênio, o fósforo e o silício. Este último, por fazer parte da estrutura de diatomáceas e silicoflagelados (Macêdo et al., 2004).

O estudo da morfodinâmica revelou que o Atol das Rocas apresenta uma dinâmica sedimentar bastante intensa com modificações sazonais, fato que pode estar correlacionado ao aumento na produção de partículas biogênicas ou a fatores hidrodinâmicos locais ainda desconhecidos (Lino et al., 2014).

Os baixos teores de clorofila *a* na camada de mistura, indicam baixas concentrações de fitoplâncton no Atol das Rocas, acredita-se que as fontes alternativas de alimentos podem auxiliar a teia alimentar pelágica ao redor do atol. É provável que a matéria detrital perto do atol, como "muco" e "agregados orgânicos" produzidos pelas comunidades bentônicas (especialmente corais) formem a principal fonte de alimento da microzooplâncton local (Nogueira e Sassi, 2011).

Em estudo sobre a estrutura da comunidade zooplanctônica no Atol das Rocas, apesar de apresentar uma riqueza de taxa elevada, a diversidade pelo índice de Shannon foi relativamente baixa em consequência da pequena equitatividade obtida nas estações (Pinto et al., 1997). Para a comunidade de Tintinnina, esta diversidade variou de média a alta (Nogueira et al., 2008).

Em ambientes recifais como os atóis, em geral, as menores frações da comunidade fitoplanctônica são as que mais contribuem com a síntese da matéria orgânica (Feitosa e Passavante, 2004).

Um dos pontos básicos para o entendimento da estrutura e do funcionamento dos ecossistemas aquáticos é o estudo destas espécies de microalgas, podendo sua diversidade ser analisada através da riqueza de espécies e do conhecimento taxonômico (Wetzel, 1993). A análise da composição de espécies do fitoplâncton traz informações importantes sobre as mudanças que ocorrem na relação desta composição e as mudanças ambientais (Stanca et al, 2013).

Na ilha de Fernando de Noronha, em estudo sobre a estrutura do fitoplâncton, a diversidade foi classificada de muito baixa a baixa, sendo Ochrophyta o grupo mais representativo (Lima, 2012). Enquanto que, no Arquipélago de São Pedro e São Paulo por

Koening e Oliveira (2009), Tiburcio et al. (2011) e Queiroz (2014) constataram a presença de uma flora bem diversificada, composta em sua maioria de dinoflagelados e com maior abundância de uma cianobactéria.

No Atol Faffu nas Maldivas, um total de 140 taxa de fitoplâncton foram identificados onde a maioria é do grupo dos dinoflagelados (Stanca et. al., 2013). No Arquipélago de Tuamotu na Polinésia Francesa, as diatomáceas foram o grupo de maior diversidade, porém o grupo mais abundante foi o dos dinoflagelados (Delesalle et al., 2001).

Estudos realizados em oceanos distintos indicam que há uma diferente distribuição e composição do fitoplâncton, podendo mostrar uma classificação de diversidade variada além de apresentar diferentes grupos como microflora mais representativa da área.

Levando-se em consideração a importância ecológica da Reserva Biológica do Atol das Rocas para diversas espécies em diferentes níveis tróficos, sente-se a necessidade de um conhecimento sobre os organismos representantes da base da teia trófica. Este estudo apresenta um importante e pioneiro levantamento sobre a estrutura da comunidade fitoplanctônica (composição, abundância, frequência, diversidade específica) tanto no entorno como em algumas piscinas naturais do Atol das Rocas e sua interação com o meio abiótico. Portanto, poderá ser utilizado, juntamente com os outros trabalhos que vêm sendo realizados no local, como uma ferramenta para posteriores pesquisas.

## 5. MANUSCRITO I

# Phytoplankton biomass dynamics and environmental variables around the Atol das Rocas, Equatorial South Atlantic

**Abstract**

The Atol das Rocas Biological Reserve is located in the Atlantic Ocean, at 3° 51' S and 33° 49' W. It lies distant 143 nautical miles from the City of Natal, Rio Grande do Norte (Brazil). The purpose of this study was to analyze the hydrology, water masses, currents and chlorophyll *a* content to determine the dynamics of phytoplankton biomass around the Atol das Rocas. Samples were collected in July 2010 in the area around the Atoll, using the Research Vessel Cruzeiro do Sul, from the Brazilian Navy. Two transects were established according to the surface current, which one was bathing the Atoll (Southeast - SE) and other after the island (Northwest- NW). In these transects, collection points were determined for each one. Samples were collected at different depths (surface and DCM - Deep Chlorophyll Maximum) and different times (day and night). According to the PCA (Principal Component Analysis), the nutrients analyzed, DIN (dissolved inorganic nitrogen), DIP (dissolved inorganic phosphorus) and silicate, were inversely correlated with the temperature and dissolved oxygen. Most environmental variables showed a significant increase due to the turbulence in the Northwest transect. It could be noticed that there was an increase in the concentration of chlorophyll *a* and nutrients while the temperature and oxygen in the mixed layer was reduced due to the influence of the SACW (South Atlantic Central Water). Despite the increase observed in some variables as nutrient salts and chlorophyll *a*, the temperature in the mixing layer was reaching a mean value of 23.23 °C due to the predominance of Tropical Water. Therefore, the increase of phytoplankton biomass on the NW transect was caused by "island effect" and not by upwelling.

**Key words: Chlorophyll *a*. Hydrology. Nutrients. Surface current**

**Resumo**

A Reserva Biológica do Atol das Rocas situa-se no Oceano Atlântico, a 3 ° 51 'S e 33 ° 49' W, distante 143 milhas náuticas da cidade de Natal, estado do Rio Grande do Norte (Brasil). Este estudo teve como objetivo analisar a hidrologia, massas de água, correntes e o teor de clorofila *a* para determinar a dinâmica da biomassa fitoplanctônica em torno do Atol das Rocas. As amostras foram coletadas em julho de 2010 na área em torno do atol, usando o navio Oceanográfico da Marinha do Brasil, Cruzeiro do Sul. Dois transectos foram estabelecidos de acordo com a corrente superficial, um transecto em direção sudeste (SE) e o outro, em direção noroeste (NO) do Atol das Rocas. Nestes transectos foram determinados três pontos de coleta para cada um. As amostras foram coletadas em diferentes profundidades (superfície e PMC – Profundidade Máxima de Clorofila) e diferentes períodos do dia (dia e noite). De acordo com a ACP (Análise de Componentes Principais), observou-se que os nutrientes analisados, NID (nitrogênio inorgânico dissolvido), PID (fósforo inorgânico dissolvido) e silicato, correlacionaram-se inversamente com a temperatura e oxigênio dissolvido. A maioria das variáveis ambientais apresentou aumento significativo em função da turbulência no transecto NO. Pode-se observar que houve aumento dos teores de clorofila

*a* e nutrientes, e redução da temperatura e oxigênio na camada de mistura em função da influência da ACAS (Água Central do Atlântico Sul). Apesar do aumento observado em algumas variáveis como sais nutrientes e clorofila *a*, a temperatura na camada de mistura esteve com valor médio de 23.23°C, devido ao predomínio da Água Tropical. Portanto, o aumento de biomassa fitoplanctônica no transecto NW foi provocado pelo "efeito ilha", e não pela ressurgência.
**Palavras chave: Clorofila *a*. Hidrologia. Nutrientes. Corrente superficial**

## INTRODUCTION

Tropical oceans, in general, can be considered as "blue deserts", or areas of low productivity and biomass, but high planktonic diversity (Longhurst and Pauly, 2007). However, the submarine relief with mountains and islands, as well as local currents, can influence the hydrological processes and also the physical processes such as transport and mixing, which reflects on the concentration of chlorophyll *a* in surface water (Souza et al., 2013). According to Leite et al. (2008), this increase in planktonic biomass around these areas, makes these islands and seamounts the main targets of ocean fisheries in the Northeast of Brazil.

According to Macêdo et al. (2009), at low latitudes, the temperature variation is not very sharp, which does not cause marked changes in biological rhythms of the organisms. The thermocline, which forms an ecological barrier, reduces nutrient turnover between deep and superficial layers, limiting primary production. The waters found beneath this "barrier" exhibit more stable physical and chemical variables and are deeper and colder. This is due to the fact that they do not suffer direct interference from environmental factors such as wind, rain, sunlight and evaporation. In tropical regions this thermocline is located at a depth of between 50 and 170 m (Souza et al., 2013).

While nutrients are limiting in the surface layer, the vertical penetration of light is the limiting factor for primary productivity below the thermocline. Thus, only the strata near the thermocline is not limited by light and nutrients, favoring photosynthesis. This explains the existence of a characteristic Deep Chlorophyll Maximum (DCM), close to the base of the mixed layer (Metzler et al., 1997). Cordeiro et al. (2013) reported that these mixing processes between the water masses above and below the thermocline may occur on a scale of dozens of meters.

Some studies suggest that the significant increase of plankton biomass and nutrient mixture near ocean islands are associated with the "island mass effect." This term refers to the effects of turbulence which changes the dynamics of ocean circulation around these areas, causing moderate depth water, rich in nutrients, to rise into the photic zone (Doty and Oguri, 1956). Some studies, such as Gilmartin and Revelante (1974) in Hawaii; Palacios (2002) in Galapagos; Martinez and Maamaatuaiahutapu (2004) in French Polynesia; Melo et al. (2012) in Archipelago of São Pedro and São Paulo and Lira et al. (2014) in Fernando de Noronha Archipelago, reported these occurrences and the ecological influence that the "island mass effect" can have.

However, despite the recognized ecological importance of the island ecosystem, the papers on plankton in the Atol das Rocas are still scarce, and may be mentioned Pinto et al. (1997); Feitosa and Passavante (2004); Mafalda Jr. et al. (2009); Chaves et al. (2008); Nogueira and Sassi (2011) and Souza et al. (2013). This demonstrates the need for further investigations on the dynamics of plankton and oceanographic variables around the Atol das Rocas in the South Atlantic Ocean.

The present study aims to analyze the hydrology, water masses, currents and chlorophyll *a* content to determine the dynamics of phytoplankton biomass around the Atol das Rocas Biological Reserve. The null hypothesis to be tested was, the chlorophyll *a* content and the nutrients analyzed in the study area are very low, showing no upwelling, but a significant difference between the transects analyzed regarding the predominant surface current.

## MATERIALS AND METHODS

The Atol das Rocas is located in the Atlantic Ocean, south of the equator, at 3° 51' S and 33° 49' W. It lies 143 nautical miles from the city of Natal, Rio Grande do Norte, Brazil (Gherardi and Bosence, 2001). It was formed into a flattened top of a volcano and its base lies at 4000 m depth on the seafloor (Kikuchi and Leão 1997; Gherardi and Bosence, 2005).

According to Medeiros et al. (2009), the fracture process that lead to the creation of the Fernando de Noronha Archipelago, also created the Atol das Rocas and a series of banks found along the coast of Ceará and Rio Grande do Norte States.

The temperature may reach 42° C in the tidal pools, with the surface salinity ranging between 35 and 39 (Pinto et al. 1997). The mesotide regime is semidiurnal, with a maximum variation of 2.7 m, exposing the reef flat at low spring tide (Gherardi and Bosence, 1999).

The climate is considered hot and tropical with a mean annual temperature of 26°C, with a maximum absolute temperature of 32 °C and a minimum of 18 °C. The annual rainfall varies between 1250 and 1500 mm, and the rainy season occurs between March and July. The most intense rainfall occurs in April while October is considered the driest month. There is a high relative humidity of 80% or more all year round (Andrade, 1960; IBAMA, 1989) apud Schulz-Neto (2004).

The east and southeast winds are abundant throughout the year, with an average frequency of 45%. Between June and August, winter in the southern hemisphere, it is observed 35% for SE winds and 15% for E winds. During summer in the Southern Hemisphere, between December and April, the SE wind occurrence is about 20%. The wind speed varies from 6 to 10 m/s, dominant throughout the year. Therefore, during the winter, wind speeds between 11 and 15 m/s are common. Speeds exceeding 20 m/s were recorded more frequently during the summer months (Kikuchi and Leão, 1997).

The water masses reported for the study area are as follows: Tropical Water (TW), South Atlantic Central Water (SACW), Antarctic Intermediate Water (AIW), North Atlantic Deep Water (NADW) and Antarctic Bottom Water (ABW) (Medeiros et al. 2009).

The Atol das Rocas Biological Reserve (ReBio) was established in June 5, 1979 and is comprised of the atoll itself and the surrounding waters up to the 1.000 m isobath. Prior to the creation of ReBio, the atoll was a target of intense fishing activity and extraction of coral and sand (Moraes et al., 2003). Currently the reserve is used strictly for scientific and educational activities.

The field work was conducted in July 2010, around the Atol das Rocas Biological Reserve. Data was collected both day and night at each sampling point. For this was used the Research Vessel Cruzeiro do Sul (NH 38), belonging to the Brazilian Navy.

At all stations, water-column profiling was performed with a conductivity, temperature and depth system (CTD); in addition to these sensors, a fluorescence sensor was also connected to the CTD. Water samples were collected with 5 L Niskin bottles coupled to a rosette system at previously determined levels.

In the insular oceanic area, two transects were made with three sampling points in each one (Figure 1): one SE (Southeast) and one NW (Northwest) transect, in relation to the prevailing surface current. Therefore, before starting the sampling in the study area, it was determined the predominant direction of the currents from 0 m to 350 m through a hull ADCP.

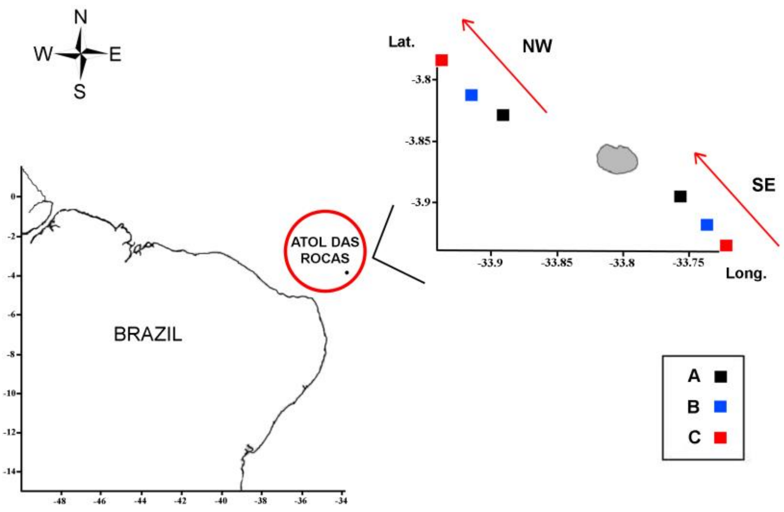


Fig. 1 – Map of the study area with sampling points and direction of the surface current, Southeast (SE) and Northwest (NW) in the Atol das Rocas (South Atlantic).

The thermocline depth and DCM were used as references for the sampling. For these in situ measurements, a CTD coupled with a fluorometer was used. However, in shallow areas, the deepest sample occurred at 75% of the location depth.

The rainfall data for the month of July during the last 10 years were acquired through the meteorological station of Fernando de Noronha and provided by Pernambuco State Agency for Water and Climate (APAC).

Niskin bottles and a rosette coupled to CTD were used for the water samples taken for the analysis of dissolved oxygen, salinity and dissolved inorganic nutrients such as ammonia, nitrite, nitrate, phosphate and silicate.

While the water samples were still on board, the dissolved oxygen content was determined by the modified Winkler method described by Strickland and Parsons (1972). The saturation rate was calculated by correlating the temperature and salinity data using the UNESCO Table (1973).

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).

Samples for phytoplankton biomass analysis were taken on the surface and DCM (80 to 100 m), where 3 L of water were filtered for each depth. Membranous filters of cellulose acetate 47mm in diameter with porosity of 0.45 µm from Schleicher and Schüll were used. After drying, the filters were wrapped in aluminum foil, packed in paper envelopes properly identified and kept in the freezer at -18°C until their analysis. The method for determining the chlorophyll *a* was the spectrophotometric analysis of UNESCO (1966).

In order to extract chlorophyll *a*, test tubes of 10 ml were used, with 90% acetone, leaving them in a freezer at a temperature of -18° C for 24 hours in order to make it possible to extract the these pigments. After this period, the material was centrifuged for 10 minutes at 3000 rpm and the supernatant was placed in optical cuvettes of $1cm^3$, and the respective absorbance readings were made on a spectrophotometer. To calculate the concentration of chlorophyll *a*, Parsons and Strickland (1963) equation was applied.

***Data Analysis***

For the significance test, the data was assessed for normality using the Shapiro-Wilk test, and normal data were tested by factorial ANOVA, in which were considered significant the values of $p \leq 0.05$. A comparison was made between the environmental variables using the following factors: transects SE and NW; time, comparing the diurnal and nocturnal data, and depth, comparing the concentration of chlorophyll *a* on the surface and at DCM. For these univariate analyses, the program STATISTICA 8.0 was used. For multivariate analysis, Principal Component Analysis (PCA) was performed, using the software Plymouth Routines in Multivariate Ecological Research (PRIMER 6).

## RESULTS

For the rainfall analysis, the data from a meteorological station at Fernando de Noronha Archipelago were used. The ten years mean value (from 2003 to 2012), for the month of July, is 170.05 mm of rainfall. However, in July 2010, an above average value of 396 mm of rainfall was observed.

The direction of the currents in this region during the campaign period followed the direction of Southeast (SE) to Northwest (NW). In these vertical profiles the deepening of the mixed layer was observed at the stations on the NW transect, with respect to the SE transect (Figure 2 to 4), where the region, with a depth between approximately 70 and 150 m, appears more mixed due to the turbulence generated by the currents as they cross the Atoll.

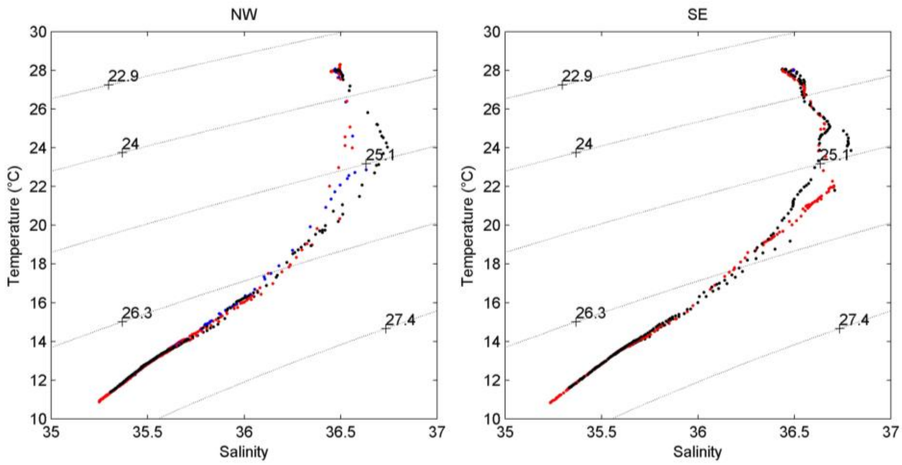


Fig. 2 – TS curve (Temperature–Salinity) around the Atol das Rocas (South Atlantic) in 2010.

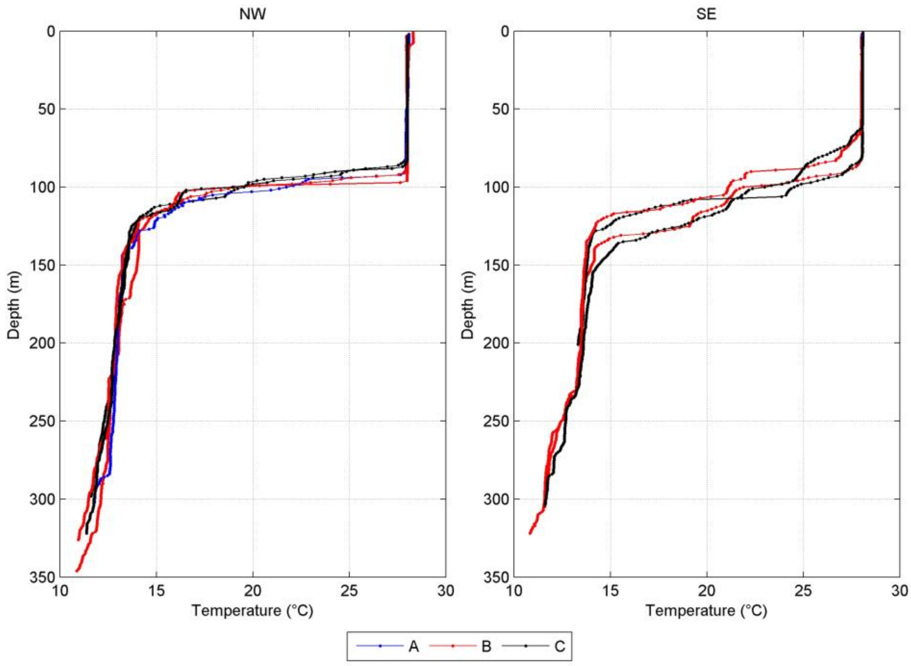


Fig. 3 – Vertical pattern of temperature (°C) at points A, B and C around the Atol das Rocas (South Atlantic) in 2010.

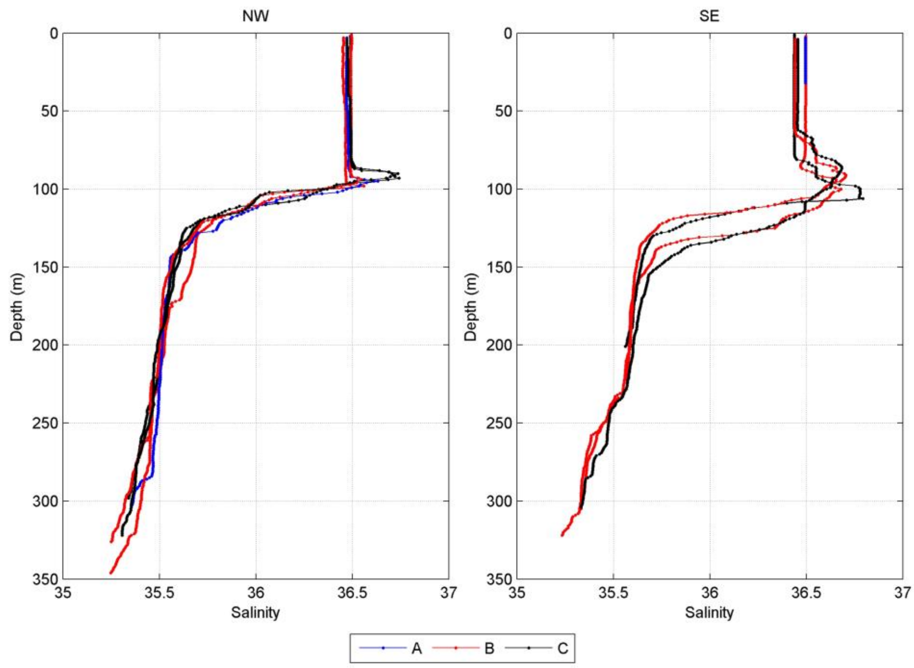


Fig. 4 – Vertical pattern of salinity at points A, B and C around the Atol das Rocas (South Atlantic) in 2010.

Regarding the temperature, a significant difference could only be observed in the analyzed depth (Figure 5). On the SE transect, the mean temperature ranged from 26.23 to 27.84 ºC. On the NW transect, the temperature decreased significantly, exhibiting lower values in the depth of the DCM, reaching a mean value of 23.23°C.

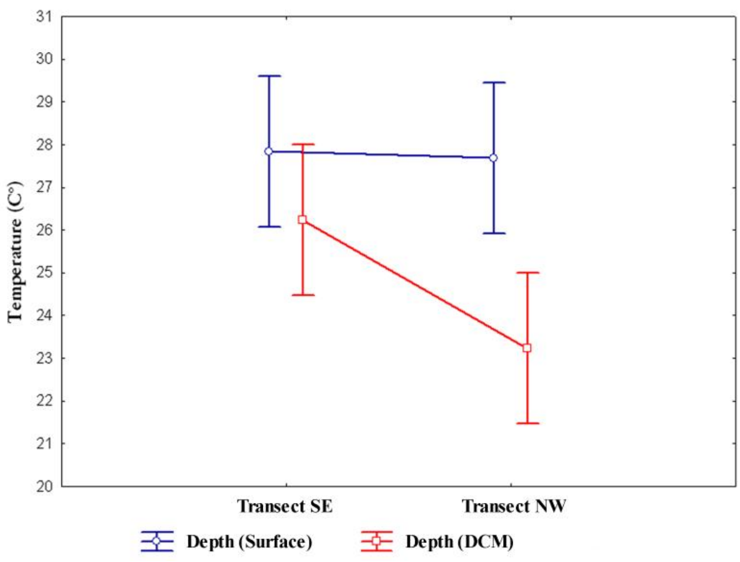


Fig. 5 – Spatial and vertical variation of temperature (°C) around the Atol das Rocas (South Atlantic) in 2010.

The salinity showed no significant difference in any of the factors analyzed. The means of the SE and NW transects were 36.1 and 36.2, respectively (Figure 6).

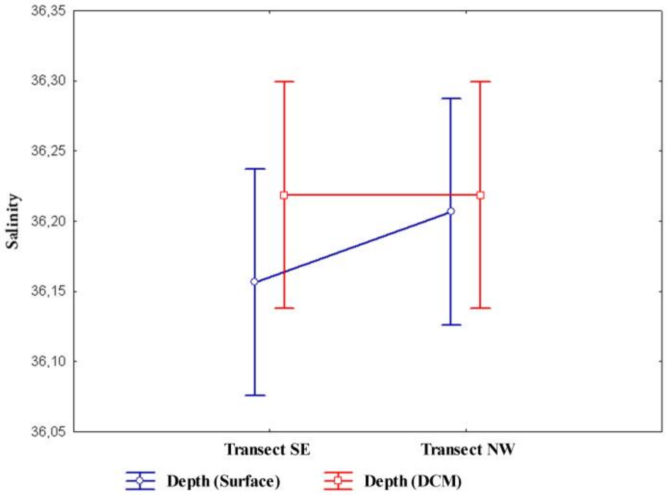


Fig. 6 – Spatial and vertical variation of salinity around the Atol das Rocas (South Atlantic) in 2010.

The dissolved oxygen showed significant differences in terms of depth. On both transects, the values of dissolved oxygen and its saturation rate were lower in the depth of DCM (Figure 7). On the NW transect lower values was more evident. The mean was 3.95 ml.$L^{-1}$ with a saturation of 81.7% at the DCM, whereas in the SE transect, the mean was 4.47 ml.$L^{-1}$ with a saturation of 92.8%.

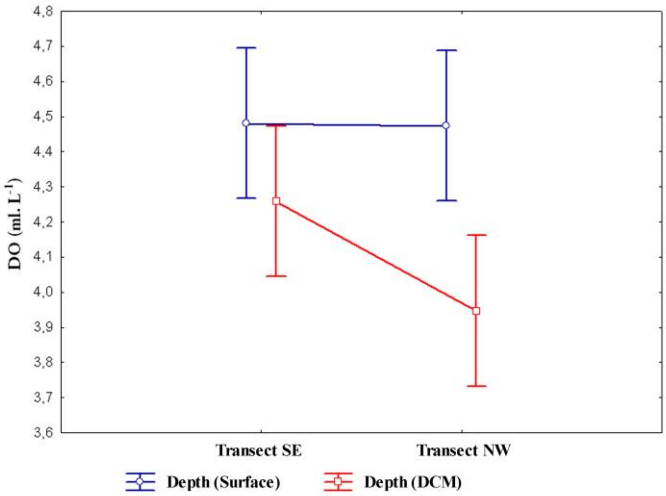


Fig. 7 – Spatial and vertical variation of dissolved oxygen (ml.$L^{-1}$) around the Atol das Rocas (South Atlantic) in 2010.

The research showed significant difference in the DIN (dissolved inorganic nitrogen) in the depths as well as in the transects (Figure 8). The highest mean concentration were found in the NW transect and in the depth of DCM, with a mean of 4.26 µM. Although no significant difference in surface waters was observed, the mean content of DIN was also higher in the NW transect with the value of 0.84 µM, while in the SE transect, the mean value was 0.56 µM.

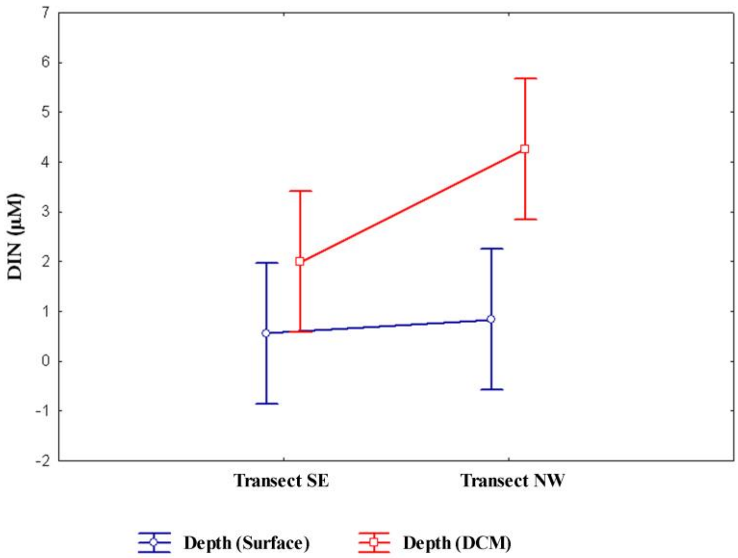


Fig. 8 – Spatial and vertical variation of DIN nitrite, nitrate and ammonia (µM) around the Atol das Rocas (South Atlantic) in 2010.

The contents of DIP were higher on both transects at the depth of DCM than at the surface. Mean values on the SE transect ranged from 0.16 to 0.18 µM while the difference in mean values was more evident on the NW transect with 0.06 and 0.36 µM at the surface and DCM, respectively (Figure 9).

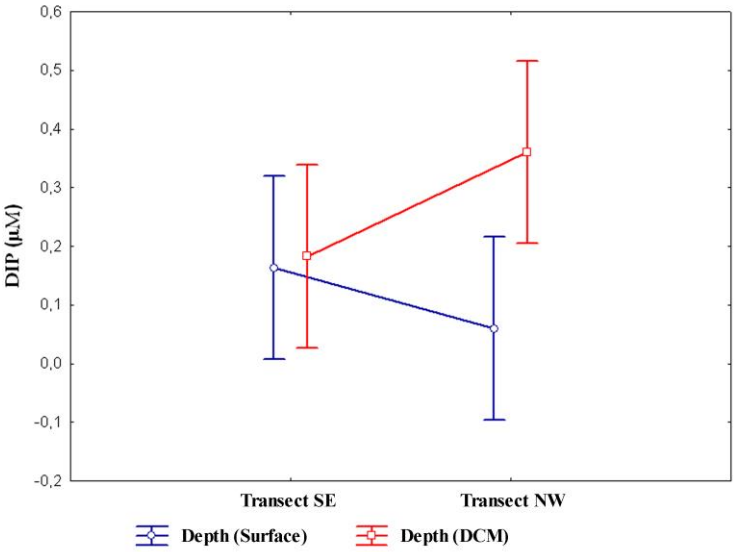


Fig. 9 – Spatial and vertical variation of DIP (µM) around the Atol das Rocas (South Atlantic) in 2010.

The SiO2 (Silicate) content showed no significant difference between depths or transects (Figure 10). Besides the depth and transect factors, the difference in the concentration between the daytime and nighttime periods (time factor) was also analyzed. Regarding this factor, a significant difference was noted only in variable SiO2, with mean values of 1.62 and 1.02 µM during the day and night, respectively (Figure11).

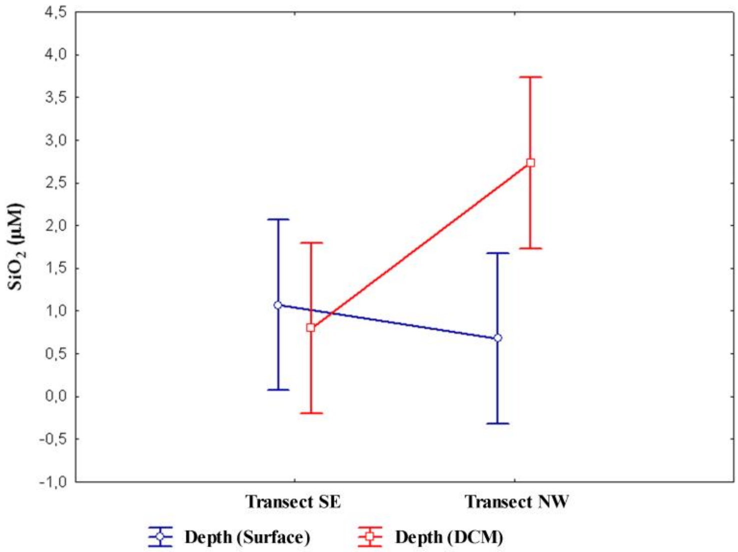


Fig. 10 – Spatial and vertical variation of silicate (µM) around the Atol das Rocas (South Atlantic) in 2010.

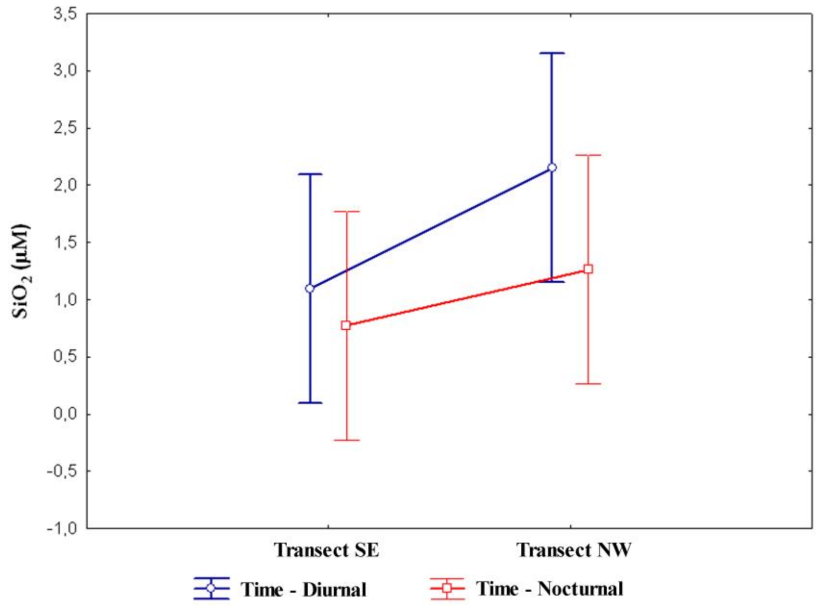


Fig. 11 – Temporal and vertical variation of silicate (µM) around the Atol das Rocas (South Atlantic) in 2010.

The contents of chlorophyll *a* showed no significant difference in any of the factors analyzed (Figure 12). However, mean values were highest at the depth of DCM, with values ranging from 0.79 to 0.87 mg.m-3, on the NW and SE transects, respectively.

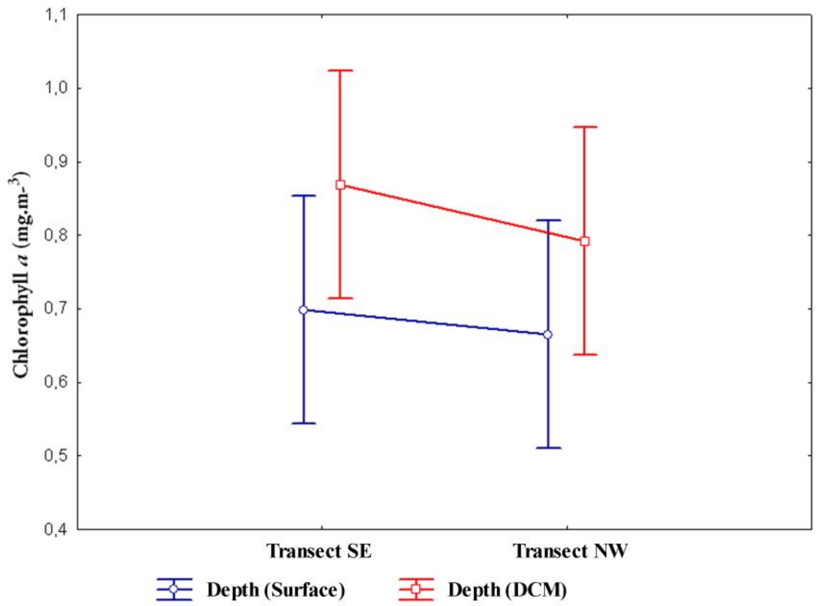


Fig. 12 – Spatial and vertical variation of chlorophyll *a* ($mg.m^{-3}$) around the Atol das Rocas (South Atlantic) in 2010.

PCA - Principal Components Analysis

Based on the data a PCA was performed, where it was found that three factors explained 86 % of environmental variables variation, with each factor being represented by 58; 15 and 13 % respectively (Tab. 1).

Tab. 1 – Principal Component Analysis around the Atol das Rocas (South Atlantic) in 2010.

| ENVIRONMENTAL VARIABLES | Factor 1 (58%) | Factor 2 (15%) | Factor 3 (13%) |
|---|---|---|---|
| Dissolved Oxygen (ml.$L^{-1}$ ) | **0,472** | -0,035 | 0,160 |
| Temperature (°C) | **0,476** | -0,130 | 0,060 |
| Salinity | -0,166 | **0,836** | 0,285 |
| DIN (µM) | **-0,432** | 0,131 | -0,145 |
| DIP (µM) | **-0,421** | -0,220 | 0,110 |
| $SiO_2$ (µM) | **-0,351** | -0,347 | -0,272 |
| Chlorophyll a (mg.$m^{-3}$) | -0,190 | -0,312 | **0,885** |

The factor 1 showed a direct correlation between the variables dissolved oxygen and temperature, and an inverse correlation of these variables with the nutrients DIP, DIN and SiO2. Factor 2 evidenced the salinity and factor 3, the chlorophyll a. However, the variables found in factors 2 and 3 were not correlated with any others (Figure 13).

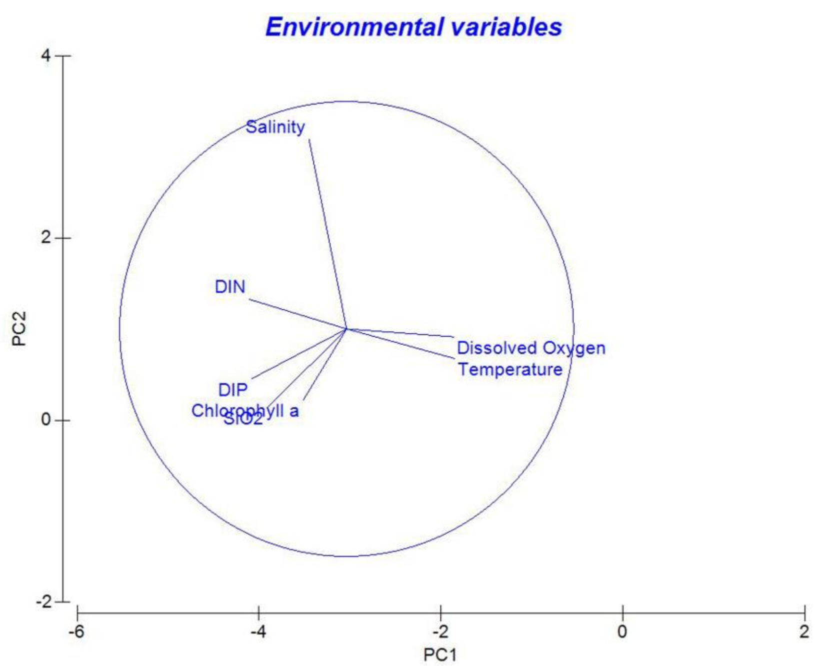


Fig. 13 – Principal Component Analysis made on environmental variables around the Atol das Rocas (South Atlantic) in 2010.

**DISCUSSION**

The surface layer of the tropical Atlantic is dominated by the Tropical Surface Water (TSW) (Stramma and Schott, 1999), with low concentration of dissolved inorganic nutrients and low biological productivity, which is a characteristic of the tropical oceans (Sampaio, 1998).

According to Stramma and Schott (1999), the South Atlantic Central Water (SACW) is transported mainly within the South Equatorial Current (SEC) to the Brazilian Continental Shelf and it is found below the TWS. Two types of SACW are found: the less dense type from the southwest subtropical South Atlantic that circulates in the subtropical gyre, and the denser type that probably originated in the southern South Atlantic.

Therefore, the oceanic current that most influences the study area is the SEC, and through the TS curve diagram (temperature and salinity) the direction of this current which was bathing the Atoll (Southeast - SE) and other after the island (Northwest- NW), was determined.

In the Atoll a greater disruption of the thermohaline structure and the vertical displacement of isotherms in the NW transect were registered, and an increase with the depth of the variables temperature and salinity was observed. This was due to the process of turbulence generated after the passage through the Atoll, ie, the factor known as "island mass effect".

In studies conducted by the Evaluation of the Sustainable Potential of Life’s Resources in the Exclusive Economic Zone Program (REVIZEE), Medeiros et al. (2009) also observed differences in the thermohaline structure and the change in depth of isotherms, particularly close to the Seamounts of the North Chains and along the slope.

Despite the identification of mixture in the water mass, there was no evidence of a cold spot in the surface waters surrounding the atoll, the temperature was always over 26°C. This indicates an improbable occurrence of the upwelling of deeper waters, rich in nutrients. In a study conducted by Souza et al. (2013), a similar result was observed in the Fernando de Noronha Archipelago and in the Seamounts of the North Chains. However, in the same study, the Archipelago of São Pedro and São Paulo presented colder waters on the surface, which probably caused an enrichment of surface waters. Only the depths of the DCM that range from 83 to 100m showed temperatures below 20°C, thus showing that they are very close to the barrier between the TSW and SACW water masses.

Surface temperatures are similar to those reported by Medeiros et al. (1999) and Souza et al. (2013) in the Tropical Atlantic and Feitosa and Passavante (2004) in the Atol das Rocas, but slightly below the values found by Pinto et al. (1997), where the authors found a thermal variation from 28.00 to 32.20 °C. The same happened with salinity, where Pinto et al. (1997) found values between 35 and 39 whereas in the present study the salinity remained above 36 but did not exceed the value of 36.43.

Temperature is however, according to the results of PCA, directly correlated with the concentration of dissolved oxygen. In the surface layer, a greater dissolution of oxygen can be observed due to the influence of wind and thus it presents a similar pattern to most of the ocean. The same happens with the saturation rate, with lower values at the DCM.

Despite of the fact that generally the decrease in temperature causes an increase of the dissolving capacity of gases, this study showed a decrease in the rate of dissolved oxygen below the surface layer. This fact can be explained by the consumption of dissolved oxygen by the biological activity of organisms and organic matter oxidation. Similar patterns occurred in the study performed in the JOPS (Joint Oceanographic Projects) by Medeiros et al. (1999).

All nutrients showed significant differences in some of the factors analyzed and were higher at the DCM, a fact also observed by Souza et al. (2013) in the Tropical Atlantic.

However, the contents of the DIN presented the greatest differentiation, as they showed not only differences as between depths but also between the transects, thus emphasizing the disturbance of the thermohaline structure and the vertical displacement of isotherms on the NW transect, as quoted above. On the other hand, the DIP showed no differentiation between transects, but like most other parameters, it presented differences between depths.

Both DIN and DIP attained a higher concentration in the Rocas Atoll, reaching a maximum of 5.72 and 0.61 µM, respectively, when compared with the Tikehau Atoll, Tuamotu Archipelago, French Polynesia (Charpy and Charpy-Roubaud, 1990) and the Tyrrhenian Sea in the Mediterranean (Misic et al., 2012). In the Tikehau Atoll, the authors observed maximum values of 0.14 and 0.38 µM and in the Tyrrhenian Sea, values of 4.40 and 0.20 µM for nitrogen and phosphorus, respectively.

In a study conducted in waters of Northeastern Brazil by Medeiros et al. (1999), the distribution pattern of nutrients was similar, with lower concentrations in the surface layer but increasing with depth. However, the values were higher, reaching concentrations greater than 10 and 1 µM for nitrogen and phosphorus, respectively.

In the Atol das Rocas, the maximum value of silicate was 5.49 µM, being slightly higher than at the Tyrrhenian Sea in the Mediterranean, which showed a maximum value of 4.18 µM (Misic et al., 2012). In other studies conducted in the Atol das Rocas, the maximum values of silicate were 16.51 and 17.52 µM, by Feitosa and Passavante (2004) and Souza et al. (2013), respectively. The silicate was the only parameter that showed a significant difference between the time periods, with the lowest values during the night. This fact is probably due to the consumption of silicate by the nanoplankton. As observed by Kochhann (2011), zooplanktonic radiolarians have broad spatial and temporal distribution in the ocean basins. The skeleton of radiolarians is impregnated by silicate and their vertical distribution in the water column of the Central Pacific is maximum in the layer between 70-110 m depth.

According to the results of the PCA, the DIN, DIP and silicate showed inverse correlations to the temperature. This can be explained by the fact that the samplings were performed in the DCM, which coincided with the meeting of the water masses.

In oceanic areas, the processes that occur in the first hundred meters are essential for the heat exchanges with the atmosphere and for the organic production. In this layer, the search for light and nutrients simultaneously occurs by the producers.

According to Margalef (1978) the characteristics of planktonic organisms that do not change easily, as far as the morphological, mechanical and general physiological properties of the cells are concerned, are less sensitive to temperature, salinity and shades of light, and much more dependent on turbulence and general nutrient availability. However, according to Goldman (1988), turbulence and other small scale physical processes may be limiting a wide range of biological processes, such as the absorption of nutrients by the phytoplankton.

One of the best known phytoplankton features is the maximum subsurface chlorophyll a, which develops during periods of stratification in different regions of the ocean (Gianesella, 2000).

According to Lalli and Parson (2006), regions with low concentrations of essential nutrients, and therefore, low primary productivity, are called oligotrophic. These areas typically have chlorophyll *a* concentrations lower than 0.05 $mg.m^{-3}$ at the surface and a maximum of 0.10 to 0.50 $mg.m^{-3}$ at a depth of 100 to 150 m. Eutrophic waters contain high concentrations of nutrients and high phytoplankton densities that are expressed by chlorophyll concentrations from 1.0 to 10 $mg.m^{-3}$ in the surface layer. Mesotrophic is a term sometimes applied to intermediate waters with concentrations ranging from 0.60 to 0.90 $mg.m^{-3}$).

However, chlorophyll *a* concentrations and macronutrients cannot be the unique factors to define oligotrophic or eutrophic areas. Over 20% of the world's open-ocean surface waters are characterized by the presence of adequate nitrate, phosphate and silicate in the euphotic zone, but a have a relatively low corresponding phytoplankton biomass. Thus, biological productivity is often limited by a lack of micronutrients, such as iron (Martin et al., 1994).

The DCM are common in situations of oligotrophy, such as those found in the large gyre of the Atlantic and Pacific oceans and in temperate areas during the summer. The upper layers of the photic zone have nutritional depletion and a subsurface maximum of chlorophyll *a* occurs within the pycnocline associated with the nutricline (Gianesella, 2000).

The chlorophyll *a* around the Atol das Rocas showed low concentrations, with values ranged from 0.48 to 1.07 $mg.m^{-3}$ and the same pattern occurred in studies conducted in oceanic regions by Feitosa and Passavante (2004); Misic et al. (2012) and Souza et al. (2013), with values from 0.64 to 1.10 $mg.m^{-3}$, 0.01 to 0.93 $mg.m^{-3}$ and 0.46 to 1.65 $mg.m^{-3}$, respectively.

In Southeastern Brazil, Gianesella (2000) cites that the greater variability between the depth of maximum chlorophyll *a* and nitracline was mainly due to the high nitrate concentrations observed in surface, without a corresponding increase in phytoplankton biomass. Turbulent processes in the mixed layer or the unavailability of any micronutrient due to the presence of chelating agents in water were hypotheses to explain this low biomass.

Regarding the water surrounding the Atoll, there was a relative increase in the chlorophyll a content in the mixed layer due to the influence of a nutrient rich water mass, the SACW. Most of the environmental variables analyzed showed a significant increase due to turbulence. Therefore, the content of chlorophyll a, in spite of presenting an increase, was not significant. This could possibly be due to the negative effect of turbulence, as explained by Goldman (1988), or to the lack of any micronutrient corroborating with Gianesella (2000) and Martin et al. (1994).

The present study indicates that low concentrations of chlorophyll a in the study region show that the productivity of phytoplankton is low and that the most plentiful food supply for the next link in the trophic web (zooplankton) is provided by the productivity of phytobenthos, mucus and aggregate organic matter produced by the benthic community of the Atoll, just as in the study undertaken by Nogueira and Sassi (2011). According to Mitra et al. (2014), the microbial loop surely makes its contribution due the existence of protist mixotrophs. However, the realisation that these organisms are major players in the planktonic food web, contributing substantially to the flow of carbon and other nutrients in aquatic ecosystems, is new and requires more research for the adequate simulation of these events.

Despite the increase observed in some variables such as nutrient salts and chlorophyll a, the temperature in the mixed layer reached a mean value of 23.23 ºC due to the predominance of Tropical Water. The increase of phytoplankton biomass on the NW transect was, therefore, caused by the “island effect” and not by upwelling.

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## 6. MANUSCRITO II

# Oceanographic conditions and spatial variability of phytoplankton in the areas surrounding the Atol das Rocas (South Atlantic)


### Abstract

Knowledge of the composition and distribution of primary producers is essential to better understand the trophic dynamics of ocean food webs. The composition of phytoplankton in the South Atlantic is still being explored and in some regions this diversity has never been described, as in the case of Atol das Rocas (3° 51'S and 33°49'W). Therefore, in order to understand and characterize the phytoplankton community in the atoll, the main objective of this study was to explore the composition of phytoplankton and its spatial variability (horizontal and vertical), and to investigate the relationship between this composition and oceanographic conditions. Samples were collected in the areas surrounding the atoll in July 2010, in two transects with three points each, according to the local surface current. The analysed environmental parameters were salinity, temperature, dissolved oxygen, and dissolved inorganic nutrient content, silica and chlorophyll *a.* For the composition, samples were collected using vertical hauls and Niskin bottles connected to the CTD (*Conductivity, Temperature and Depth).* A total of 150 taxa of four different phyla were identified, with dominance of the phylum Dinophyta being observed. Samples showed horizontal spatial variation with diatoms closest to the atoll and dinoflagellates at the furthest points, whereas vertical distribution patterns were not observed. Most abundant species, considered key species here, were *Prorocentrum balticum* (Lohmann) Loeblich 1970, *P. compressum* (Bailey) Abéex Dodge 1975 and *P. gracile* Böhm 1933 and *Coccolithus* sp.. Distribution of these species correlated with inorganic nutrient concentrations. In the NW transect, phytoplankton community structure correlated strongly with salinity and temperature due to a thermohaline instability arising from the interaction of tropical waters with central water masses of the South Atlantic. Although dominant phytoplankton species are characteristic of oceanic waters of north-eastern Brazil, nonetheless oceanographic conditions influenced phytoplankton distribution in the areas surrounding Atol das Rocas.


**Key words: Phytoplankton. Physic-chemical variables. Reef**



### Resumo

O conhecimento da composição e distribuição dos produtores primários é fundamental para uma melhor compreensão da dinâmica trófica que ocorre na teia alimentar de regiões oceânicas. A composição do fitoplâncton no Atlântico Sul ainda esta sendo explorada e em algumas regiões esta diversidade nunca foi descrita, como é o caso do Atol das Rocas (3°51’S e 33°49’W). Portanto, com o intuito de conhecer e caracterizar a comunidade fitoplanctônica no Atol, este estudo teve como principal objetivo explorar a composição do fitoplâncton e a sua variabilidade espacial (horizontal e vertical), e investigar a relação entre esta composição e as condições oceanográficas. Foram realizadas coletas no entorno do Atol no período de julho de 2010 em dois transectos, com três pontos cada, de acordo com a corrente local

superficial. Os parâmetros ambientais analisados foram salinidade, temperatura, oxigênio dissolvido, teores de nutrientes inorgânicos dissolvidos, sílica e clorofila *a*. Para a composição, foram realizadas coletas através de arrastos verticais e garrafas de Niskin acopladas ao CTD. Um total de 150 taxa de quatro diferentes filos foram identificados, com o predomínio do filo Dinophyta As amostras apresentaram variação espacial horizontal, com diatomáceas mais próximas ao atol e dinoflagelados nos pontos mais distantes, enquanto que os padrões de distribuição verticais não foram observados. Espécies mais abundantes, considerados aqui como espécies chave, foram *Prorocentrum balticum* (Lohmann) Loeblich 1970, *P. compressum* (Bailey) Abéex Dodge 1975 e *P. gracile* Böhm 1933 e *Coccolithus* sp.. A distribuição dessas espécies está correlacionada com concentrações de nutrientes inorgânicos. No transecto NW a comunidade fitoplanctônica correlacionou-se fortemente com os parâmetros salinidade e temperatura, devido a uma instabilidade termohalina decorrente da interação das massas d’água Água Tropical e a Água Central do Atlântico Sul. Portanto, além das espécies mais representativas do fitoplâncton serem características de águas oceânicas do Nordeste do Brasil, as condições oceanográficas influenciaram na distribuição da comunidade fitoplanctônica no entorno do Atol das Rocas.
**Palavras chave: Fitoplâncton. Variáveis físico-químicas. Ambiente recifal**

## INTRODUCTION

In general terms, tropical oceans can be considered "blue deserts" or areas of low productivity and biomass, but high planktonic diversity (Longhurst and Pauly, 2007). This characteristic can be explained by the presence of a hot surface layer above a colder and denser subsurface layer that creates a permanent thermocline (Souza et al., 2013).

Occurrences of mountains and islands in the sub floor are common at irregular frequencies in the entire ocean basins. Although it is still considered one of the lesser-known habitats on Earth (Wessel, 2007), these ecosystems are known to have local currents that can influence hydrological processes, and physical processes like transport and mixing, that alter the concentration of chlorophyll *a* in surface waters (Santos and Morato, 2010; Souza et al., 2013), and consequently the dynamics of local plankton (Genin and Dower, 2007). According to Leite et al. (2008), planktonic biomass increase in these areas renders the oceanic islands and banks the main targets of ocean fishing in north-eastern Brazil.

Knowledge of the composition and distribution of primary producers is essential to better understand the trophic dynamics of oceanic regions. Studies conducted in islands of north-eastern Brazil, such as the studies of Souza et al. (2013); Cordeiro et al. (2013) and Feitosa and Passavante (2004), chiefly address phytoplanktonic biomass and productivity. Available information on the floristic composition of phytoplankton in waters of the South Atlantic is still scarce, and species diversity has not been explored in some regions, as in the case of Atol das Rocas.

Therefore, the aim of this study was to explore the phytoplankton composition and spatial variability (horizontal and vertical) of the Atol das Rocas and to investigate the relationship between phytoplankton community structure and oceanographic conditions.

## MATERIALS AND METHODS

Atol das Rocas (or Rocas Atoll) is located in the Atlantic Ocean, south of the equator (3°51'S and 33°49'W), 143 nautical miles from the state of Rio Grande do Norte (Gherardi and Bosence, 2001), is a volcanic pedestal rising 4000m from the sea floor (Kikuchi and Leão 1997, Gherardi and Bosence, 2005). Similar to a series of ocean banks along the coast of Ceará and Rio Grande do Norte, the atoll originated from a fracturing process that created the island of Fernando de Noronha (Medeiros et al. 2009).

The Atol das Rocas Biological Reserve, ReBio, was created on June 5$^{th}$, 1979, and includes the atoll and the surrounding waters to the 1000 m isobath. Prior to the creation of the ReBio, the atoll was the target of intense fishing activity and the extraction of coral reefs and sand (Moraes et al., 2003). Today, the reserve is used for scientific research and educational activities.

The samples were collected in the areas surrounding the Atol das Rocas in July 2010. Two transects were established (SE) and (NW), each of which contained three collection points, according to the local surface current (Figure 01). The predominant direction of surface currents, 0 m to 100 m, was checked using a ADCP (Acoustic Doppler Current Profiler) mounted on the ship´s hull.

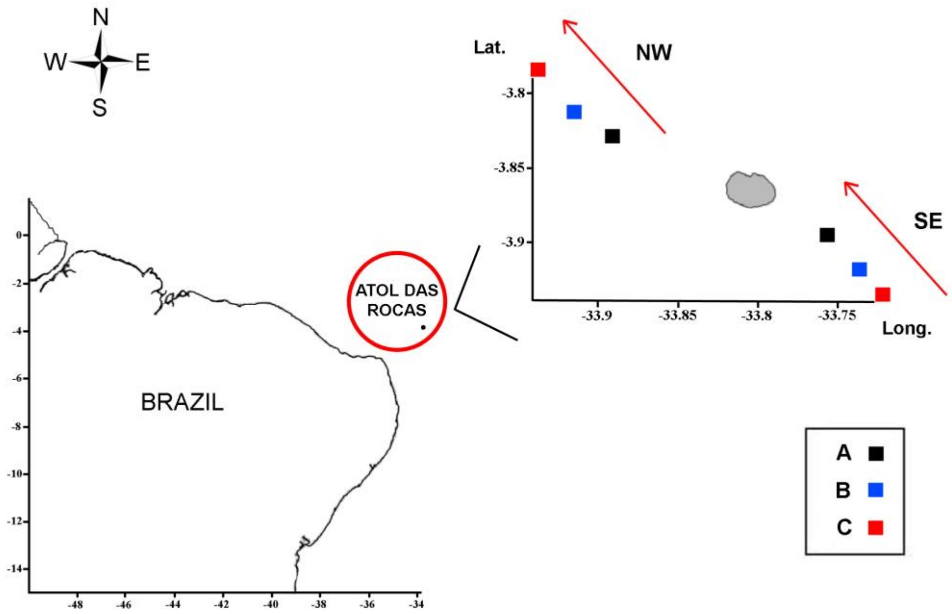


Figure 01 - Map of the study area with collection points and direction of the surface current, southeast (SE) and northwest (NW) in the Atol das Rocas (South Atlantic).

The vessel was a NH 38 (Hydro-oceanographic ship Cruzeiro do Sul) of the Brazilian Navy, equipped with a data collection and water sampling system, a conductivity, temperature and depth (CTD) profiler coupled to a rosette with 5 L oceanographic Niskin-type bottles that were used for collecting water samples at the selected depths.

***Environmental Variables***

To correlate phytoplankton species distribution patterns, environmental variables such as salinity (CTD), temperature (CTD) and dissolved oxygen were monitored (Winkler modified, described by Strickland and Parsons, 1972). Other analyses were levels of dissolved inorganic nutrients, such as ammonia, nitrate, nitrite, phosphate (Strickland and Parsons, 1972), silica (Grasshoffet al., 1983) and chlorophyll *a* (spectrophotometric analysis of UNESCO, 1966). The equation of Parsons and Strickland (1963) was applied to calculate chlorophyll *a* concentration.

***Phytoplankton Composition***

Samples of the phytoplankton structure were collected using the Maximum Depth of Chlorophyll *a* (DCM) as reference and a CTD profiler equipped with fluorometers. To analyse phytoplankton composition, samples were collected using two methods.

Conical-cylinder nets with a 20 µm mesh opening were used for the hauls, totalling 12 samplings. The hauls were vertical, starting at 10 m under the recorded DCM depths. The maximum sampling depth was 110 m. In shallower areas, where it was not possible to establish the DCM, samples were collected at 75% of the local depth, for example for the sampling point nearest to the atoll in the SE transect. Hauled samples were transferred to 500 mL plastic bottles and immediately fixed on board in formaldehyde solution (4%) buffered with sodium tetraborate (pH ~7).

The samples were mixed to homogeneously suspend the organisms, then 1 mL aliquots were qualitatively and quantitatively analyzed using a phase contrast 400x optical microscope (Olympus XB). Two subsamples were studied for each analysis.

Samples were also collected for analysis of phytoplankton density using 5 L Niskin bottles coupled to the CTD. A total of 63 samples were collected at the following depths: surface, 25 m, 50 m, DCM, 10 m above and 10 m below the DCM, and some samples at 100 m. Considering daytime and spatial variation of the depth of the DCM, the depths of the collections varied accordingly.

One litre of water was collected per sample, transferred to plastic containers and fixed in Lugol´s solution. The collected phytoplankton was concentrated using reverse filtration (Dodson and Thomas, 1978), using membranous filters of cellulose acetate 47mm in diameter with a porosity of 0.45 µm from Schleicher and Schüll and analysed on an inverted microscope (ZeissAxiovert), using the Utermöhl method (Hasle, 1978; Edler, 1979; Ferrario et al., 1995), consisting of 10 $cm^3$ sample sedimentation chambers. The total volume was counted at 400x magnification, and phytoplankton population size is expressed in cells per litre ($cell.L^{-1}$). Rose bengal was used for contrast enhancement. Phytoplankton genera and species were identified using Peragallo e Peragallo (1897-1908), Hustedt (1930, 1959, 1961-1966), Cupp (1943), Desikachary (1959), Balech (1988), Silva-Cunha e Eskinazi-Leça (1990), Licea et. al. (1995), Tomas (1997). The identification refinement criteria and scientific names of species followed the rating system Guiry and Guiry (2015).

***Data Analysis***

Frequency of occurrence, the number of samples in which each taxon occurred in the total number of analysed samples, was calculated as described by Mateucci and Colma

(1982). The relative abundance of taxa was calculated according to Lobo and Leighton (1986).

Frequency, abundance and diversity indexes were analysed for samples collected using the trawl net method.

The Shannon (1948) index was used to calculate specific diversity, and the obtained values were referenced using the classification of Valentin et al. (1991). This index was calculated using the statistical software PRIMER 6.0 (Plymouth Routines as outlined for Multivariate Ecological Research).

For the significance test of environmental variables, comparisons were made between transects (SE and NW), time (night and day) using factorial ANOVA. P-values ≤ 0.05 were considered significant. Univariate analyses were conducted using STATISTICA ® 8.0 StatSoft.

Multivariate MDS analysis was used to analyse the impact of physico-chemical parameters on phytoplankton community structure and abundance patterns. Correlations between transects (SE and NW) and horizontal distribution (A, B and C) were used for the samples collected in trawl nets, while correlations were analysed for population density between transects (SE and NW) and vertical distribution (depths 1 to 7). Multivariate BIOENV analysis (PRIMER®6.0) was used to explore relationships between environmental variables and phytoplankton community structure.

## RESULTS

### *Environmental Variables*

Dissolved oxygen levels varied between 3.15 and 4.71 ml. $L^{-1}$ in the SE transect and 2.81 and 4.58 in the NW transect. Average temperatures were slightly higher in the SE transect (~26°C). Average salinity (~36) was highest in the NW transect. In relation to inorganic nutrients, DIN (Dissolved Inorganic Nitrogen) and $SiO_2$ showed considerable variation within each transect. DIN ranged from 0.02 to 10.32 µM and 0.07 to 19.70 µM in the SE and NW transects, respectively, while $SiO_2$ ranged from not detectable (ND) to 13.21 µM. DIP (Dissolved Inorganic Phosphorous) values were low, 0.21 and 0.37 µM on average in the SE and NW transects, respectively. Contents of chlorophyll *a* ranged from 0.38 (NW) to 1.07 mg $m^{-3}$ (SE), but average values were similar for the SE and NW transects (0.77 and

0.63 mg m$^{-3}$, respectively). Except for temperature and DIN, physico-chemical differences between transects were insignificant for all other parameters (Table 01).

Table 01 - Data of environmental variables collected in Atol das Rocas for the different transects and degree of significance correlation (p).

| Environmental Variables | Transect (SE) | | | Transect (NW) | | | ($p \leq 0,05$) |
|---|---|---|---|---|---|---|---|
| | Min. | Max. | Average | Min. | Max. | Average | |
| **Dissolved Oxygen (ml.L$^{-1}$)** | 3.15 | 4.71 | 4.27 | 2.81 | 4.58 | 3.99 | 0.08 |
| **Temperature (°C)** | 18.02 | 28.11 | 26.34 | 14.51 | 28.04 | 23.59 | **0.04** |
| **Salinity** | 35.93 | 36.35 | 36.18 | 35.12 | 36.47 | 36.09 | 0.19 |
| **NID (µM)** | 0.02 | 10.32 | 1.82 | 0.07 | 19.70 | 5.12 | **0.01** |
| **PID (µM)** | 0.04 | 0.83 | 0.21 | 0.04 | 1.23 | 0.37 | 0.14 |
| **$SIO_2$ (µM)** | ND | 4.44 | 1.22 | 0.01 | 13.21 | 2.40 | 0.67 |
| **Chlorophyll *a* (mg.m$^{-3}$)** | 0.41 | 1.07 | 0.77 | 0.38 | 1.00 | 0.73 | 0.63 |

### *Phytoplankton Composition*

A total of 150 taxa were identified belonging to the phyla Cyanobacteria, Dinophyta, Ochrophyta and Haptophyta. The Dinophyta showed the greatest contribution with 86 species (57.33%), followed by the Ochrophyta with 56 species (37.33%), Cyanobacteria with 5 species (3.34%) and Haptophyta with 3 species (2.00%) (Table 02).

Table 02 - Composition of the phytoplankton community in natural pools of the Atol das Rocas.

| Phytoplankton Composition | Transect SE | | | | | | | | | Transect NW | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Net | Density (cell.L$^{-1}$x10$^{2}$) | | | | | | | | Net | Density (cell.L$^{-1}$x10$^{2}$) | | | | | | |
| | 20 µm | Surf. | 25m | 36m | 50m | DCM -10 | DCM | DCM +10 | 100m | 20µm | Surf. | 25m | 50m | DCM -10 | DCM | DCM +10 | 100m |
| **Cyanobacteria** | | | | | | | | | | | | | | | | | |
| Cyanobacteria 1 | | | | | 4 | | 1 | | | | 1 | 1 | 1 | | 4 | | |
| Cyanobacteria 2 | | | | | | 1 | | | | | 2 | 3 | | 1 | | | |
| *Oscillatoria* sp. [r, S] | | | | | | | | | | X | | | | | | | |
| *Trichodesmium thiebautii*. [a, VC] | X | 1 | | 1 | 1 | 4 | | | | | | | | | | | |
| *Richelia intracellularis* J.Schmidt in Ostenfeld & J. Schmidt 1901 [a, VC] | X | | | | | | | | | | | | | | | | |
| **Dinophyta** | | | | | | | | | | | | | | | | | |
| *Amphisolenia bidentata* Schröder 1900 [r, S] | | | | | | | | | | X | | | | | | | |
| *Ceratocorys armata* (Schütt) Kofoid 1910 [r, I] | X | | | | | | | | | X | | | | | | | |
| *Ceratocorys horrida* Stein 1883 [r, VC] | X | | | | | | | | | X | | | | | | | |
| *Corythodinium constrictum* (Stein) F.J.R.Taylor 1976 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Corythodinium elegans* (Pavillard) F.J.R.Taylor [r, C] | X | | | | | | | | | X | | | | | | | |
| *Corythodinium tesselatum* (Stein) Loeblich Jr. &Loeblich III 1966 [r, C] | X | | | | | | | | | X | | | | | 1 | | |
| *Dinophysis hastata* Stein 1883 [r, I] | X | | | | | | | | | X | | | | | | | |
| *Dinophysis exigua* Kofoid & Skogsberg 1928 [r, VC] | X | | | | | | | | | X | | | | | | | |
| *Dinophysis minuta* Cleve) Balech [r, S] | | | | | | | | | | X | | | | | | | |
| *Dinophysis schuettii* Murray &Whitting 1899 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Dinophysis* sp. [r, S] | X | | | | | | | | | | | | | | | | |
| *Gymnodinium* sp. [r, S] | X | 1 | | | | | | | | | | | | | | | |
| *Goniodoma polyedricum* (Pouchet) Jørgensen 1899 [r, VC] | X | | | | | | | | | X | | | | | | | |
| *Gonyaulax birostris* Stein 1883 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Gonyaulax digitalis* (Pouchet) Kofoid 1911 [r, S] | | | | | | | | | | X | | | | | | | |
| *Gonyaulax polyedra* F.Stein 1883 [a, VC] | X | | | | | | | | | X | | | | | | | |
| *Gonyaulax polygramma* Stein 1883 [a, VC] | X | | | | | | | | | X | | | | | | | |
| *Gonyaulax spinifera* (Claparède & Lachmann) Diesing 1866 [r, S] | | | 1 | | 2 | | | | | X | | | | | | | 2 |
| *Heterodinium minutum* Kofoid & Michener 1911 [r, I] | X | | | | | | | | | X | | | | | | | |
| *Histioneis dolon* Murray &Whitting 1899 [r, S] | X | | | | | | | | | | | | | | | | |
| *Histioneis hippoperoides* Kofoid & Michener 1911 [a, VC] | X | 1 | | 1 | | | | | | X | | 2 | | | | | |
| *Histioneis panaria* Kofoid & Skogsberg 1928 | | | | | | | | | | | | | 1 | | | | |
| *Histioneis rotundata* Kofoid & Michener 1911 [r, S] | | | | | | | | | | X | | | | | | | |
| *Histioneis striata* Kofoid & Michener 1911 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Histioneis* sp. [r, S] | X | | | | | | | | | | | | | | | | |
| *Neoceratium arietinum* (Cleve) F.Gómez, D.Moreira & P.López-Garcia 2010 [r, S] | X | | | | | | | | | | | | | | | | |
| *N. azoricum* (Cleve) F.Gómez, D.Moreira & P.López-Garcia 2010 [r, S] = *Tripos arietinus* (Cleve) F.Gómez 2013 | X | | | | | | | | | | | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *N. candelabrum* (Ehrenberg) F.Gómez, D.Moreira & P.López-Garcia 2010 [r, VC] = *Tripos candelabrus* (Ehrenberg) F.Gómez 2013 | X | | | | | X | | | | | | |
| *N. contortum* (Gourret) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r,I] = *Tripos contortus* (Gourret) F.Gómez 2013 | X | | | | | | | | | | | |
| *Neoceratium declinatum* (Karsten) F. Gomez, D. Moreira & P. Lopez-Garcia 2010 [a, VC] = *Tripos declinatus* (G. Karsten) F.Gómez 2013 | X | 1 | | 3 | | X | 2 | 3 | 1 | | | |
| *N. extensum* (Gourret) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r, I]= *Tripos extensus* (Gourret) F.Gómez 2013 | X | | | | | | | | | | | |
| *N. fusus* (Gourret) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [a, VC] = *Tripos fusus* (Ehrenberg) F.Gómez, 2013 | X | | | | | X | | | | | | |
| *N. gibberum* (Gourret) F.Gómez, D.Moreira & P.López-García 2009 [r, C] = *Tripos gibberus* (Gourret) F.Gómez 1883 | X | | | | | X | | | | | | |
| *N. horridum* (Gran) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r, I]= *Tripos horridus* (Cleve) F. Gómez, 2013 | X | | | | | X | | | | | | |
| *N. lineatum* (Ehrenberg) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r, VC] = *Tripos lineatus* (Ehrenberg) F. Gómez, 2013 | X | | | | | X | | | | | | |
| *N. longirostrum* (Gourret) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r, S] = *Ceratium longirostrum* Gourret 1883 | | | | | | X | | | | | | |
| *N. macroceros* (Ehrenberg) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r, C] = *Tripos macroceros* (Ehrenberg) F.Gómez, 2013 | X | | | | | X | | | | | | |
| *N. massiliense* (Gourret) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r, S] = *Tripos massiliensis* (Gourret) F.Gómez 2013 | X | | | | | | | | | | | |
| *N. pentagonum* (Gourret) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [a, VC] = *Tripos pentagonus* (Gourret) F.Gómez, 2013 | X | 2 | | | 2 | X | 1 | 1 | | 1 | | |
| *N. teres* (Kofoid) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [a, VC] | X | 1 | 1 | 1 | 2 | X | 1 | 2 | 3 | | | |
| *N. tripos* (Kofoid) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r, VC] = *Tripos muelleri* Bory de Saint-Vincent, 1824 | X | | | | | X | | | | | | |
| *N. vultur* (Cleve) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r, S] = *Tripos vultur* (Cleve) F.Gómez 2013 | X | | | | | | | | | | 2 | |
| *Ornithocercus magnificus* Stein 1883 [r, VC] | X | 1 | 2 | 1 | 1 | X | | | 1 | | 1 | 2 |
| *Ornithocercus quadratus* Schütt 1900 [r, C] | X | 1 | | | | X | | | | | | |
| *Ornithocercus steinii* Schütt 1900 [r, C] | X | | | | | X | | | | | | |
| *Ornithocercus thumii* (Schmidt) Kofoid & Skogsberg 1928 [r, C] | X | | | | | X | | | | | | |
| *Ornithocercus* sp. | | | | 1 | | | | | | | | |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Oxytoxum crassum* Schiller 1937 | | 1 | | | | | | | | | | | | | | | |
| *Oxytoxum gracile* Schiller 1937 | | 1 | | | | 1 | | 1 | | | | | | | 1 | | |
| *Oxytoxum laticeps* Schiller 1937 [r, S] | | | | | | | | | | X | | | 2 | | | | |
| *Oxytoxum mediterraneum* Schiller | | | 2 | | | 1 | | | | | | | | | | | |
| *Oxytoxum obliquum* Schiller 1937 | | 3 | | | | 1 | | | | | | | | | 1 | | |
| *Oxytoxum scolopax* Stein 1883 [r, C] | X | 1 | | | | 1 | | | | X | 2 | | 1 | | | | |
| *Oxytoxum subulatum* Kofoid [r, S] | | | | | | | | | | X | | | | | | | |
| *Oxytoxum viride* Schiller 1937 | | 10 | | 3 | | | | | | | | | | | | | |
| *Oxytoxum* sp. | | 2 | 1 | | | | 1 | | | | 1 | 1 | 3 | 4 | | | |
| *Parahistioneis reticulata* (Kofoid) Kofoid & Skogsberg 1928 [r, S] | X | | | | | | | | | | | | | | | | |
| *Phalacroma argus* Stein 1883 [a, VC] | X | | 1 | | | | | | | X | | | | | | | |
| *Phalacroma cuneus* F.Schütt 1895 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Phalacroma doryphorum* Stein 1883 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Phalacroma favus* Kofoid & Michener 1911 [r, I] | X | | | | | | | | | X | | | | | | | |
| *Phalacroma rapa* Jorgensen 1923 [r, VC] | X | | | | | | | | | X | | | | | | | |
| *Phalacroma rotundatum* (Claparéde & Lachmann) Kofoid & Michener 1911 [a, VC] | X | | | | | | 1 | | | X | | | | | 1 | | |
| *Podolampas bipes* Stein 1883 [r, S] | X | | 1 | | | | | | | | | | | | | | |
| *Podolampas elegans* Stein 1883 [r, S] | X | | | | | | | | | | | | | | | | |
| *Podolampas palmipes*Schütt 1895 [r, VC] | X | 2 | 1 | | 2 | 1 | | | 1 | X | | 2 | | | | | |
| *Podolampas reticulata* Kofoid 1907 [r, S] | X | | | | | | | | | | | | | | | | |
| *Podolampas spinifera* Okamura 1912 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Prorocentrum balticum* (Lohmann) Loeblich 1970 [a, VC] | X | 12 | 5 | | 6 | 3 | 1 | 1 | | X | 3 | 5 | 11 | 1 | 4 | | 1 |
| *Prorocentrum compressum* (Bailey) Abéex Dodge 1975 [r, VC] | X | | 3 | | 2 | | 2 | | | X | | 2 | 2 | 2 | 3 | | |
| *Prorocentrum gracile* Böhm 1933 [a, VC] | X | 10 | | | 2 | 2 | 1 | | | X | 3 | 2 | 3 | 1 | 1 | | 2 |
| *Prorocentrum hoffmannianun* M. A. Faust 1990 [r, I] | | | | | | | | | | X | | | | | | | |
| *Prorocentrum micans* Ehrenberg 1834 [r, I] | X | 1 | | | | 1 | | 2 | | X | | | | | | | |
| *Prorocentrum vaginulum* (Ehrenberg) Dodge [r, VC] | X | | 1 | | 1 | | | | | X | 1 | 1 | 1 | 2 | | | |
| *Prorocentrum* sp. [r, I] | | | | | | | | | | X | | | | | | | |
| *Protoceratium reticulatum* (Claparède & Lachmann) Butschli 1885 [r, C] | X | | | | | | | | | X | | | 1 | | | | |
| *Protoperidinium conicum* (Gran) Balech 1974 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Protoperidinium depressum* (Bailey) Balech 1974 [r, S] | | 2 | 1 | 2 | | 1 | | | | X | | 1 | 1 | | | | |
| *Protoperidinium* sp. [a, VC] | X | 1 | | | | | | | | X | | | | | | | |
| *Protoperidinium* sp. 1 [a, VC] | X | | | | 1 | | | | | X | | 2 | | | 1 | | |
| *Protoperidinium* sp. 2 | | | | | 1 | | | | | | | | | | | | |
| *Pyrocystis fusiformis* C. W. Thomson in Murray &Whitting 1876 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Pyrocystis lunula* (J.Schütt) J.Schütt in Engler & Prantl 1896 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Pyrocystis obtusa* Pavillard 1931 [r, S] | X | | | | | | | | | | | | | | | | |
| *Pyrocystis robusta* Kofoid 1907 [r, I] | | 1 | | | | | | | | X | | | | | | | |
| *Pyrophacus* sp. Stein 1883 [a, I] | | | | | | | | | | X | | | | | | | |
| **Ochrophyta** | | | | | | | | | | | | | | | | | |
| *Actinoptychus* sp. [r, S] | X | | | | | | | | | | | | | | | | |
| *Amphora arenaria* Donkin 1858 [r, C] | X | | | | | | | | | X | | | | | | | |
| *Amphora fluminensis* Grunow 1863 [r, S] | | | | | | | | | | X | | | | | | | |

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|---|---|---|---|---|---|---|---|
| *Amphora* sp. [r, I] | X | | X | | | | |
| *Amphora* sp. 1 [r, S] | X | | | | | | |
| *Asterionellopsis glacialis* (Castracane) Round in Round, R. M. Crawford & D.G.Mann 1990 [a, C] | X | | X | | | | |
| *Bellerochea malleus* (Brightwell) Van Heurck 1885 [a, VC] | X | 1 | X | | | | |
| *Campylodiscus clypeus* Ehrenberg) Ehrenberg ex Kützing 1844 [r, S] | | | X | | | | |
| *Chaetoceros lorenzianus* Grunow 1863 [r, C] | X | | | | | | |
| *Chaetoceros peruvianus* Brightwell 1856 [r, S] | X | | | | | | |
| *Chaetoceros* sp. [r, I] | X | | X | | | | |
| *Climacosphenia elongata* Mereschkowsky [r, C] | X | | X | 1 | | | |
| *Cocconeis scutellum* Ehrenberg 1838 [r, I] | X | | X | | | | |
| *Cocconeis* sp. [r, C] | X | | X | | | | |
| *Coscinodiscus* sp. | | 1 | | | | | |
| *Dictyocha fíbula* Ehrenberg 1839 [a, VC] | X | | X | | | | |
| *Dictyocha speculum* Ehrenberg 1839 [r, S] | X | | | | | | |
| *Diploneis splendida* Cleve 1894 [r, I] | X | | X | | | | |
| *Diploneis* sp. [r, C] | X | | X | | | | |
| *Grammatophora serpentina* Ehrenberg 1844 [a, C] | X | | X | | | | |
| *Hemiaulus* sp. [r, I] | X | | X | | | | |
| *Hemidiscus* sp. [r, C] | X | | X | | | | |
| *Isthmia enervis* Ehrenberg 1838 [r, C] | X | | X | | | | |
| *Isthmia* sp. [r, S] | | | X | | | | |
| *Lampriscus orbiculatum* (Shadbolt) Peragallo & Peragallo 1902 [a, VC] | X | | X | | | | |
| *Licmophora lyngbyei* (Kützing) Grunowex Van Heurck 1867 [r, C] | X | | X | | | | |
| *Licmophora remulus* Grunow 1867 [r, S] | | | X | | | | |
| *Licmophora* sp. [r, I] | X | | X | | | | |
| *Lyrella lyra* (Ehrenberg) Karajeva 1978 [a, I] | | | X | | | | |
| *Melchersiella hexagonallis* C. Teixeira [a, VC] | X | | X | | | | |
| *Navicula splendida* Gregory 1856 [r, S] | X | | | | | | |
| *Navicula* sp. [r, S] | | | X | | 1 | | |
| *Nitzschia incerta* (Grunow) M. Peragallo 1903 [r, S] | X | | | | | | |
| *Nitzschia longissima* (Brébisson) Ralfs in Pritchard 1861 [r, C] | X | | X | | | | |
| *Nitzschia pacifica* Cupp 1943 [r, I] | | | X | | | | |
| *Nitzschia sigma* (Kützing) W.Smith 1853 [r, I] | X | | X | | | | |
| *Nitschia* sp. [r, I] | X | | X | | | | |
| *Nitschia* sp. 1 [r, I] | | | X | | | | |
| *Odontella aurita* (Lyngbye) C.Agardh 1832 [r, I] | X | | | | | | |
| *Paralia sulcata* (Ehrenberg) Cleve 1873 [a, I] | | | X | | | | |
| *Planktoniella sol* (C. G. Wallich) Schütt 1892 [a, VC] | X | | X | | | 1 | 1 |
| *Podocystis adriatica* (Kützing) Ralfs in Pritchard 1861 [a, VC] | X | | X | | | | |
| *Rhabdonema adriaticum* Kützing 1844 [a, C] | | | X | | | | |
| *Rhabdonema* sp. [r, I] | | | X | | | | |
| *Rhizosolenia setigera* Brightwell 1858 [a, VC] | X | | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Skeletonema costatum* (Greville) Cleve 1873 [a, I] | X | | | | | | X | | | | | |
| *Striatella interrupta* (Ehrenberg) Heiberg 1863 [a, C] | X | | | | | | X | | | | | |
| *Striatella unipunctata* (Lyngbye) C. Agardh 1832 [a, VC] | X | | | | | | X | | | | | |
| *Surirella fastuosa* Ehrenberg [r, S] | | | | | | | X | | | | | |
| *Synedra formosa* Hantzsch 1863 [r, C] | X | | | | | | X | | | | | |
| *Synedra undulata* (J. W. Bailey) Gregory 1857 [r, C] | X | | | | | | X | | | | | |
| *Synedra* sp. [r, I] | | | | | | | X | | | | | |
| *Thalassiosira* sp.[a, VC] | X | | | | | | X | | | | 1 | |
| *Trachyneis aspera* (Ehrenberg) Cleve 1894[r, I] | X | | | | | | X | | | | | |
| *Triceratium pentacrinus* (Ehrenberg) Wallich 1858 [r, S] | X | | | | | | | | | | | |
| *Triceratium repletum* Greville [r, S] | X | | | | | | | | | | | |
| **Haptophyta** | | | | | | | | | | | | |
| *Coccolithus* sp. [r, I] | X | 1 | | 2 | 3 | 1 | X | 2 | 1 | 2 | 1 | 2 |
| *Scyphosphaera apsteinii* Lohmann 1902[r, I] | | | | | | | X | | | | | |
| *Syracosphaera* sp. [r, I] | X | | | | | | | | | | | |

Legend: Relative abundance: d - dominant; a - abundant; r - rare. Frequency of occurrence: VC - very common; C - common; I - infrequently; S - sporadic. Conc. - Concentration. Surf. - surface; DCM -10m – DCM under 10 meters; DCM - Deep Chlorophyll Maximum; DCM + 10m - DCM over 10 meters deep.

In the microphytoplankton composition of the Atol das Rocas, no species was considered dominant, however highly abundant and very frequent species were: *Trichodesmium* sp.; *Richelia intracellularis* J.Schmidt in Ostenfeld & J. Schmidt 1901*; Gonyaulax polyedra* F.Stein 1883*; G. polygramma* Stein 1883*; Histioneis hippoperoides* Kofoid & Michener 1911*; Neoceratium declinatum* (Gourret) F.Gomez, D.Moreira & P.Lopez-Garcia 2010*; N. fusus* (Gourret) F.Gomez, D.Moreira & P.Lopez-Garcia 2010*; N. pentagonum* (Gourret) F.Gomez, D.Moreira & P. Lopez-Garcia 2010*; N. teres* (Kofoid) F.Gomez, D.Moreira & P.Lopez-Garcia 2010*; Phalacroma argus* Stein 1883*; P. rotundatum* (Claparéde & Lachmann) Kofoid & Michener 1911*; Protoperidinium* sp.; *Protoperidinium* sp. 1; *Prorocentrum balticum* (Lohmann) Loeblich 1970*; P. gracile* Böhm 1933*; Bellerochea malleus* (Brightwell) Van Heurck 1885*; Dictyocha fíbula* Ehrenberg 1839*; Lampriscus orbiculatum* (Shadbolt) Peragallo & Peragallo 1902*; Melchersiella hexagonalis* C. Teixeira*; Planktoniella sol* (C. G. Wallich) Schütt 1892*; Podocystis adriatica* (Kützing) Ralfs in Pritchard 1861*; Striatella unipunctata* (Lyngbye) C. Agardh 1832, and *Thalassiosira* sp..

In relation to phytoplankton population density, the most abundant species were *Prorocentrum balticum* (28 cells.$L^{-1}$), *P. gracile (*15 cells.$L^{-1}$), *Prorocentrum compressum* (7 cells.$L^{-1}$) and *Coccolithus* sp. (7 cells.$L^{-1}$) for the SE transects and *Prorocentrum balticum* (25 cells.$L^{-1}$), *P. gracile* (12 cells.$L^{-1}$), *Prorocentrum compressum* (9 cells.$L^{-1}$) and *Coccolithus* sp. (8 cells.$L^{-1}$) for the NW transects. Within transects, however, there was no significant difference in terms of density.

In relation to the diversity index, the samples were classified as medium diversity ($< 3.0 \geq 2.0$) and high diversity ($\geq 3.0$). Diversity varied from 2.25 to 3.37. MDS of the relationship between phyla and transects shows that the Dinophyta and Ochrophyta were the most representative phyla in both transects, whereas the Haptophyta and Cyanobacteria were dispersed without a defined pattern (Figure 02).

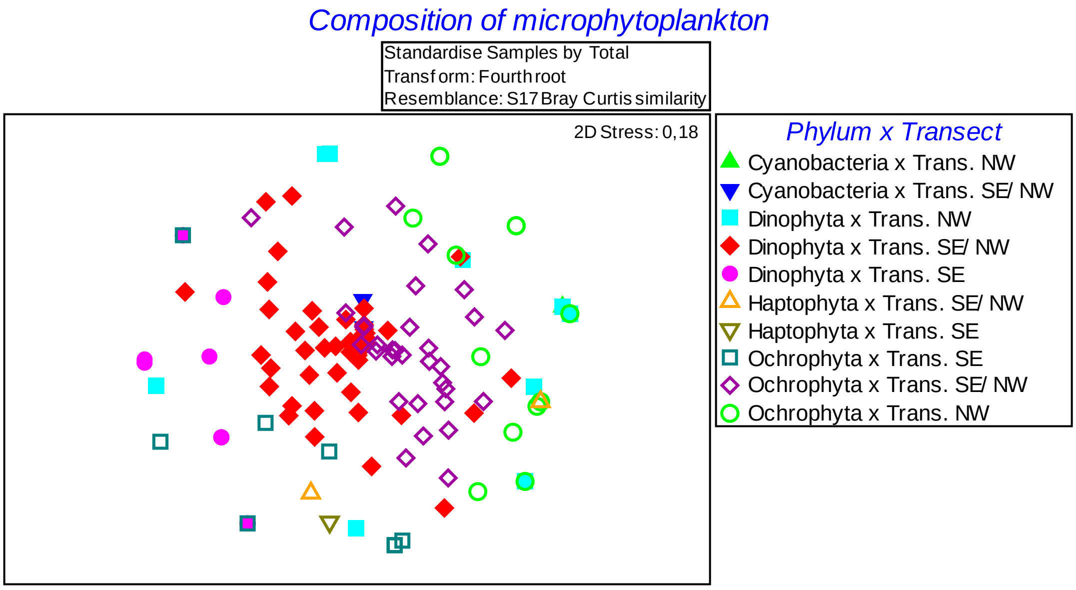


Figure 02 - Association of main phyla of microphytoplankton composition with the southeast (SE) and northwest (NW) transects surrounding the Atol das Rocas (South Atlantic).

The Dinophyta and Ochrophyta were also highly abundant spatial distribution patterns of the microphytoplankton (collection points A, B and C), and a horizontal spatial pattern was evident with the diatoms being closest to the atoll (distances A and B) and the dinoflagellates being in the farthest points (distances B and C) (Figure 03).

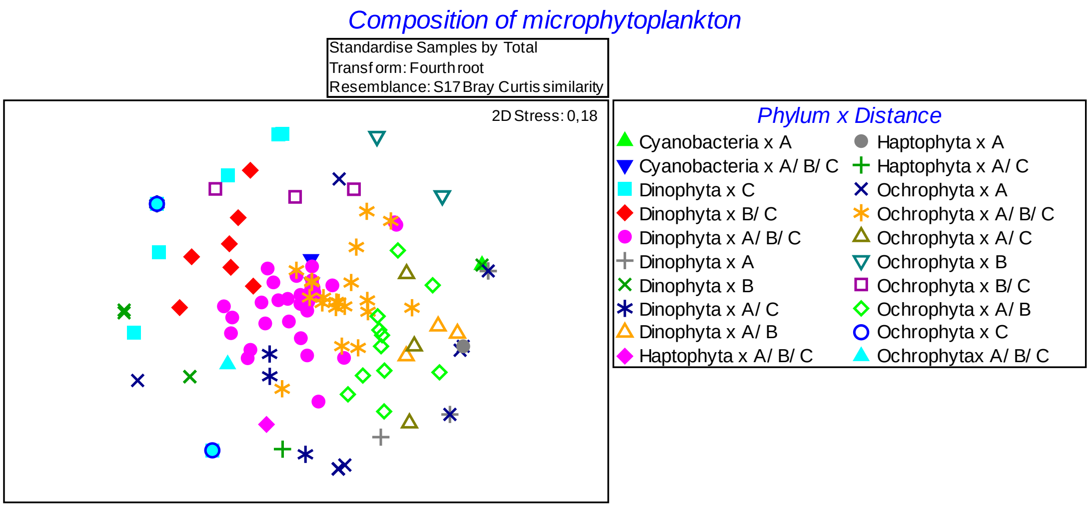


Figure 03 - Association of main phyla of microphytoplankton composition with spatial distribution (A, B and C) surrounding the Atol das Rocas (South Atlantic).

MDS analysis of phyla density patterns within transects showed that the phylum Dinophyta presented distinct abundance patterns in both transects, although this was more apparent for the SE transect than for the NW transect, while the phylum Ochrophyta, Cyanobacteria and Haptophyta, showed no identifiable abundance patterns (Figure 04).

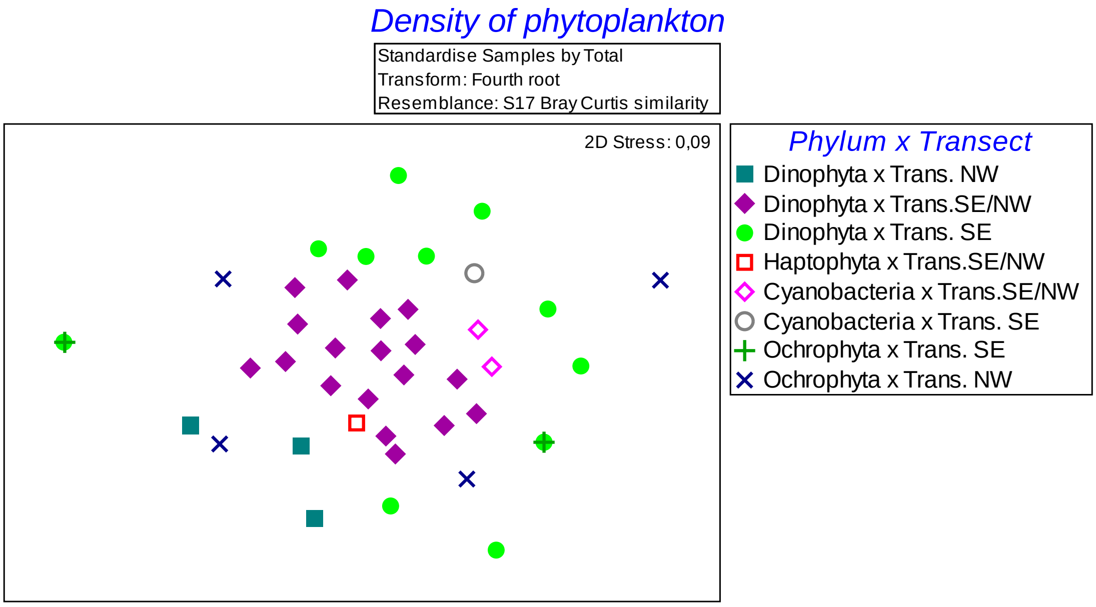


Figure 04 - Association between the main phyla of phytoplankton density with transects southeast (SE) and northwest (NW) surrounding the Atol das Rocas (South Atlantic).

In contrast, population densities showed no apparent grouping patterns with vertical spatial distribution, potentially because of occurrence of all phyla at all depths (Figure 05).

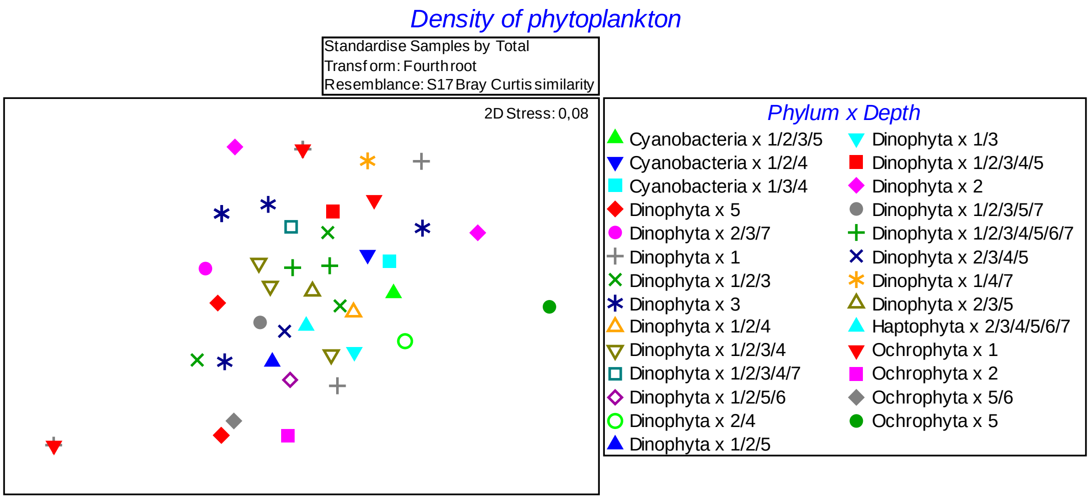


Figure 05 - Association between the main phyla of phytoplankton density and vertical distribution (1-7) surrounding the Atol das Rocas (South Atlantic).

BIOENV was used to explore the relationship between phytoplankton composition and physico-chemical parameters in detail. Correlations between phytoplankton abundance and environmental variables were low (r=0.113) for all samples. The relationship of the variables with the different transects was also analysed. In the SE transect, correlation was lowest for DIN (r=0.375), whereas in the NW transect, a significant relationship between community and temperature and salinity (r=0.504) was detected.

According to Spearman´s correlation using BIOENV analysis, the species classified as key-species of the Atol das Rocas, namely *Prorocentrum balticum; P. compressum; P. gracile* and *Coccolithus* sp. showed a low correlation with DIN and DIP (r=0.231).

**DISCUSSION**

The Atol das Rocas is located in the middle of the Atlantic Ocean showing high taxonomic diversity of microphytoplankton. This small area in the Atlantic protects several organisms and serves as a nursery for different species like *Negaprion brevirostris, Ginglymostoma cirratum, Dasyatis americana, Chelonia mydas* (Freitas et al., 2009; Agra, 2009; Almeida et al., 2011), showing a female dominance of 80% on average for its fauna.

The Atol das Rocas is influenced by the South Equatorial Current that comprises a mass of tropical surface water with low levels of dissolved inorganic nutrients and low biological productivity, which is characteristics of tropical oceans (Sampaio, 1998). According to Ekau and Knoppers (1999), the pelagic systems of northeastern and eastern Brazil should be considered a single system that is mainly controlled by the impact of oligotrophic waters from the South Equatorial Current and derived currents.

According to Travassos et al. (1999), the thermohaline structure of ocean banks and islands of northeastern Brazil does not present evidence of resurgance resulting from the interaction between currents and topography. According to Jales et al. (in press), the Atol das Rocas in particular does not show evidence of the resurgence process, although a thermohaline perturbation was observed in the NW transect.

According to the BIOENV, temperature and salinity in the areas surrounding the Atol das Rocas showed a positive correlation with phytoplankton abundance (as determined by chlorophylla *a* concentrations).

In the Archipelago of São Pedro and São Paulo, mathematical modelling of the oceanic circulation in the equatorial region of the Atlantic Ocean identified an important interaction between the Equatorial Undercurrent and this archipelago capable of reducing upstream velocities and generating a system of sub-surface vortices (50 to 120m in depth) that propagate towards the East (Araújo Filho and Cintra, 2009). These vortices can play an important role in the dynamics of plankton and nutrients of these waters. Although the presence of vortices in the Atol das Rocas was not determined, the presence of thermohaline perturbations affecting phytoplankton abundances was verified.

In the Atol, none of the phytoplankton species was classified as dominant, which could be an indication of stable conditions and high environmental quality favouring the observed high phytoplankton biodiversity.

Dinoflagellates represent one of the most important groups of marine plytoplankton communities and directly and indirectly determine the fertility of the sea, thus playing an important ecological role as primary producers and heterotrophic organisms in the trophic web (Balech, 1988).

The genus *Prorocentrum* is one of the most diverse in tropical marine environments (Delmail et al. 2011; Gul and Saifullah, 2011; Chomérat et al. 2010 and 2012). It belongs to a group of dinoflagellates that consists of 80 species (Guiry and Guiry, 2015) with a highly similar cell structure Witek and Plinski, 2000). In the Atol das Rocas, based on population density, the species *Prorocentrum balticum; P. compressum; P. gracile* were classified as key-species, with none of them producing cysts or exhibiting toxicity according to Avancine (2006).

*Prorocentrum balticum* is a cosmopolitan, but is typically overlooked or biased against in net samples due to its small size (Hoppenrath et al., 2009). This species is classified as marine, neritic, oceanic and planktonic and is usually found in cold to tropical waters (Foust and Gulledge, 2002). Records of this species exist for the north (PA), northeast (RN, BA), southeast (ES, RJ), and south (PR, RS) of the Brazilian coast (Odebrecht, 2010); the Canary Islands (Gil-Rodríguez et al., 2013); the Mediterranean Sea (Gómez, 2003); and Helgoland in the North Sea (Hoppenrath, 2004).

According to Muciño - Marquez et al. (2014), *Prorocentrum compressum* does not produce toxins, but forms harmful algal blooms suffocating aquatic organisms, such as fish and oysters in La Paz Bay (Mexico). In addition to the Atol das Rocas and reports in several states along the Brazilian coast according to Odebrecht, (2010), *P. compressum* was also recorded in waters of the South Pacific Ocean (Gómez et al., 2008), in the Colombian Caribbean Sea by Lozano-Duque et al. (2011), and is considered a very common species in the Arabian Sea by Gul and Saifullah (2011).

Cohen-Fernandez et al. (2006) consider *Prorocentrum gracile* to be a synonym for *P. sigmoides,* although they were classified as different species in works carried out in Mexico by Gárate-Lizárraga et al. (2014), and in the Colombian Caribbean Sea by Lozano-Duque et al. (2011). According to Avancini (2006), it also forms harmful algal blooms. *Prorocentrum gracile* is classified as cosmopolitan and its occurrence has been registered along the Pacific Coast of Mexico (Hernández - Becerril et al., 2000; Cohen-Fernandez et al., 2006); in the

Eastern English Channel, France (Guilloux et al., 2013); and in the Arabian Sea by Gul and Saifullah (2011).

It should be noted that the species of *Prorocentrum* mentioned above have also been recorded in waters of the Archipelago of São Pedro and São Paulo (Koening and Oliveira, 2009), with high frequencies of *P. gracile*.

Another representative group in the atoll were coccolithophorids, which are highly diverse calcified and biogeochemically important nanophytoplankton organisms, given their primary function in the global carbon cycle and role in the alkalinity of photic zones in the world's oceans (de Vargas et al. 2007). The genus *Coccolithus* presents a wide distribution and mainly occurs in oceanic tropical and subtropical environments (Avancini, 2006). This supports its presence in environments such as the Atol das Rocas and the Archipelago of São Pedro and São Paulo, as stated by Koening and Oliveira (2009).

DIN, besides presenting a significant difference among transects, is also an influential factor in the floristic composition of the Atol das Rocas. Although the atoll presents an "island effect" with respect to the increase of DIN (Jales et al. (in press)), the concentration of chlorophyll *a* showed no significant difference among the surveyed transects. This fact can be explained by a lack of micronutrients, such as iron, in most of the oligotrophic regions (Martin et al., 1994).

With regards to horizontal spatial distribution patterns of the floristic community, this research established that diatoms were more represented in collection points closest to the Atol das Rocas due to higher silicate levels and potentially due to a higher general affinity for nutrients (Margalef, 1978; Eskinazi-Leça et al. 2004) and the hydrological regime in the area (Margalef, 1978) allowing for more mixing closer to the atoll due to wave action favouring this group.

In contrast, the dinoflagellates exhibited an opposite pattern, with a transition in terms of species richness that increased with distance of the collection points from shore. This could in part be due to most of the species being oceanic preferring stable salinity levels of higher than 30 but lower than 40 (Taylor, 1987); but it could also be due to the adaptation of these organisms to low nutrient environments (Margalef, 1978). However, vertical spatial community analyses revealed no distinct floristic patterns.

In summary, the most representative phytoplankton species of the Atol das Rocas are characteristic of the oceanic waters of northeast Brazil with oceanographic conditions influencing phytoplanktonic community structure in areas surrounding the atoll.

Identified key species were *Prorocentrum balticum*, *P. compressum*, and *P. gracile* potentially due to low nutrient concentrations. Furthermore, phytoplankton community structure of the NW transect correlated with salinity and temperature patterns arising from a thermohaline instability caused by the interaction of tropical water and central water masses of the South Atlantic.

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## 7. MANUSCRITO III

# Diversity and distribution (spatial and temporal) of phytoplankton in Atol das Rocas (South Atlantic)

**Abstract**

Taxonomic investigations of the phytoplankton community structure are very important to understand the dynamics of these organisms in the reef environment, especially considering that this community can vary depending on the different hydro-biological characteristics of the site. The aim of this paper is to determine and investigate the composition of the phytoplankton community and biomass, and to correlate this community with the environmental variables in different climatic periods and natural pools of Atol das Rocas. This study should provide additional information for further research on the trophic capacity of the atoll and its influence on the South Atlantic. The atoll is located in the Atlantic Ocean, south of the equator (3°51'S and 33°49'W), some 143 nautical miles from the state of Rio Grande do Norte, Brazil. Oceanographic parameters which were used to analyze the influence on phytoplankton structure were salinity, water temperature, dissolved oxygen, dissolved inorganic nutrients content and chlorophyll *a*. Samples were collected to analyse microphytoplankton and phytoplankton density. Sampling occurred at the pools Barretinha, Cemitério, Tartarugas, Rocas and Barretão in different climate periods. A total of 109 species were identified and distributed into four groups. The predominant group was Ochrophyta with a representation of 52.3%, followed by Dinophyta with 37.6%, Cyanobacteria with 7.33% and Haptophyta with 2.75%. The most representative species found in this study in terms of density were *Prorocentrum balticum* (Lohmann) Loeblich 1970, *P. lima* (Ehrenberg) F. Stein 1878, *Pyrophacus* sp. and *Ostreopsis ovata* Fukuyo 1981. Despite the spatial difference of the composition, there was no determinant hydrological parameter. However, according to the statistical analysis, the composition of all pools is primarily associated with nutrient salts. In terms of density, only a seasonal pattern was clearly identified and there was a qualitative and quantitative increase of phytoplankton in the rainy season. This fact is due to the positive relationship between phytoplankton composition and nutrient salts when associated with the local hydrodynamics, providing more favourable conditions for the enrichment of diversity with emphasis on the species that compose the benthic microflora.

**Key words: Atoll. Chlorophyll *a*. Phytoplankton composition. Coral reef**

**Resumo**

Investigações taxonômicas da estrutura da comunidade fitoplanctônica são muito importantes para a compreensão da dinâmica desses organismos no ambiente recifal e esta comunidade irá variar dependendo das diferentes características hidro-biológicas do local. Portanto, este estudo tem como objetivo principal determinar e investigar a composição da comunidade fitoplanctônica e biomassa, correlacionando-as com as variáveis ambientais em diferentes períodos climáticos e piscinas naturais do Atol das Rocas, com o intuito de prover informações para posteriores pesquisas da capacidade trófica do atol e sua influência para o Atlântico Sul. O atol está localizado no Oceano Atlântico, ao sul do equador (3°51'S e 33°49'W), 143 milhas náuticas do estado do Rio Grande do Norte. Os parâmetros oceanográficos os quais foram empregados para analisar a influência sobre a estrutura do fitoplâncton foram salinidade, temperatura da água, oxigênio dissolvido, teores de nutrientes inorgânicos dissolvidos e clorofila *a*. Foram realizadas coletas para a análise do

microfitoplâncton e densidade fitoplanctônica. As coletas ocorreram nas piscinas Barretinha, Cemitério, Tartarugas, Rocas e Barretão em períodos climáticos distintos. Foram identificadas 109 espécies distribuídas em quatro grupos. Ochrophyta com uma representação de 52,3% sendo o grupo predominante, Dinophyta com 37,6%, Cyanobacteria com 7,33% e Haptophyta com 2,75%. Apesar do grupo das Ochrophytas ter sido o mais evidenciado, as espécies mais representativas encontradas neste estudo devido sua densidade foram *Prorocentrum balticum* (Lohmann) Loeblich 1970, *P. lima* (Ehrenberg) F.Stein 1878, *Pyrophacus* sp. e *Ostreopsis ovata* Fukuyo 1981. Apesar de a composição apresentar diferença espacial, nenhum parâmetro hidrológico foi determinante. No entanto, segundo as análises estatísticas, a composição de todas as piscinas está associada principalmente com os sais nutrientes. Na densidade, apenas um padrão sazonal foi bem identificado, havendo um aumento quali-quantitativo do fitoplâncton no período chuvoso. Este fato se deve à positiva relação da composição fitoplanctônica e sais nutrientes quando associados ao hidrodinamismo local, proporcionando condições mais favoráveis para o enriquecimento da diversidade, com ênfase nas espécies que compõem a microflora bentônica.
**Palavras chave: Atoll. Clorofila *a*. Composição fitoplanctônica. Recifes de coral**

## INTRODUCTION

Phytoplankton organisms are unicellular algae. Some of these organisms are able to move with the aid of flagella, while others only drift with currents (Verlecar and Desai, 2004). Marine phytoplankton colonize the upper part of the water column, up to the limit of light penetration (Vaulot, 2001). They are found in a multitude of sizes and shapes and can live as individual cells or colonies. They play an important ecological role as primary producers and as valuable indicators of water quality (Verlecar and Desai, 2004; De Klerk et al., 2008). They also carry a global importance as regulators of climate and biogeochemical cycles (Winder and Sommer, 2012).

Environmental changes, such as physical conditions, nutrient input (bottom up control) and the intense pressure of "grazing" (top down control), affect the diversity, community structure and dynamics of phytoplankton (Winder and Sommer, 2012; Hoppenrath, 2009). This causes phytoplankton organisms to establish an ecological defence by making several adaptations (Hoppenrath, 2009). Understanding the factors that control the dynamics and composition of species is important to prevent environmental impacts in aquatic ecosystems (Winder and Sommer, 2012).

It is common knowledge that productivity in the reef system is greater for phytobenthos than for phytoplankton due to the presence of the symbiotic zooxanthellae of the corals, macroalgae, etc. (Odum and Odum, 1955; Sournia, 1977). However, the plankton community plays a key role in the nutrition and maintenance of numerous sessile and sedentary organisms that are filter feeders and cohabit the same environment, including coral polyps.

From the ecological point of view, taxonomic investigations and investigations of phytoplankton community structure are very important to understand the dynamics of these organisms in the reef environment. This composition can vary depending on the different hydro-biological characteristics of the studied site (Sridha et al., 2010).

As in the case of Atol das Rocas, there is a scarcity of research on the composition and dynamics of phytoplankton in remote locations. Only one study, conducted by Feitosa and Passavante and published in 2004, addresses phytoplankton biomass in the natural pools of the atoll.

Consequently, the aim of this paper is to determine and investigate the composition of the phytoplankton community and biomass, and to correlate this community with the environmental variables in different climatic periods and natural pools of Atol das Rocas. This study should provide additional information for further research on the trophic capacity of the atoll and its influence on the South Atlantic.

## MATERIALS AND METHODS

Atol das Rocas is located in the Atlantic Ocean, south of the equator (3°51'S and 33°49'W), some 143 nautical miles from the state of Rio Grande do Norte, Brazil (Gherardi and Bosence, 2001). Similarly to a series of ocean banks along the coast of Ceará and Rio Grande do Norte, the atoll originates from a fracturing process that created the island of Fernando de Noronha (Medeiros et al. 2009).

Atol das Rocas is a geological site that consists of carbonate sediments. The site is 3.35 km long (E-W axis) and 2.49 km wide (N-S axis), with approximately 6.56 km² and an estimated perimeter of 11 km. It is also one of the smallest atolls in the world (Pereira et al., 2013). The Atol das Rocas reef complex is influenced by the South Equatorial Current, which runs in a westward direction at an average speed of 30 cm $s^{-1}$ (Richardson and Walsh, 1986).

Before becoming the biological reserve of Atol das Rocas, ReBio, in June 5$^{th}$, 1979, the atoll was the target of overfishing and sand and coral extraction (Moraes et al., 2003). Currently, the site is used for conducting scientific research and educational activities.

Atol das Rocas comprises two islets, a large sandy plain which is exposed at low tide, various pools of different shapes and sizes, tide pools, caves, channels, reef front, reef flat, a crest encircling the ring of the reef and a lagoon on the north-northeast side. As a consequence, the atoll encompasses a series of different ecological conditions (Medeiros et al. 2009 and Veer and Jensen 2006).

Samples were collected in five pools of Atol das Rocas (Barretinha, Cemitério pool, Tartarugas pool, Rocas pool and Barretão - Figure 01) in different climatic periods. In the dry season, sampling was performed between 03th and 15th of December, 2012, and in the rainy season sampling was performed between August 26th and September 09th, 2013. Three collections were carried out in each pool, on different days, for each period.

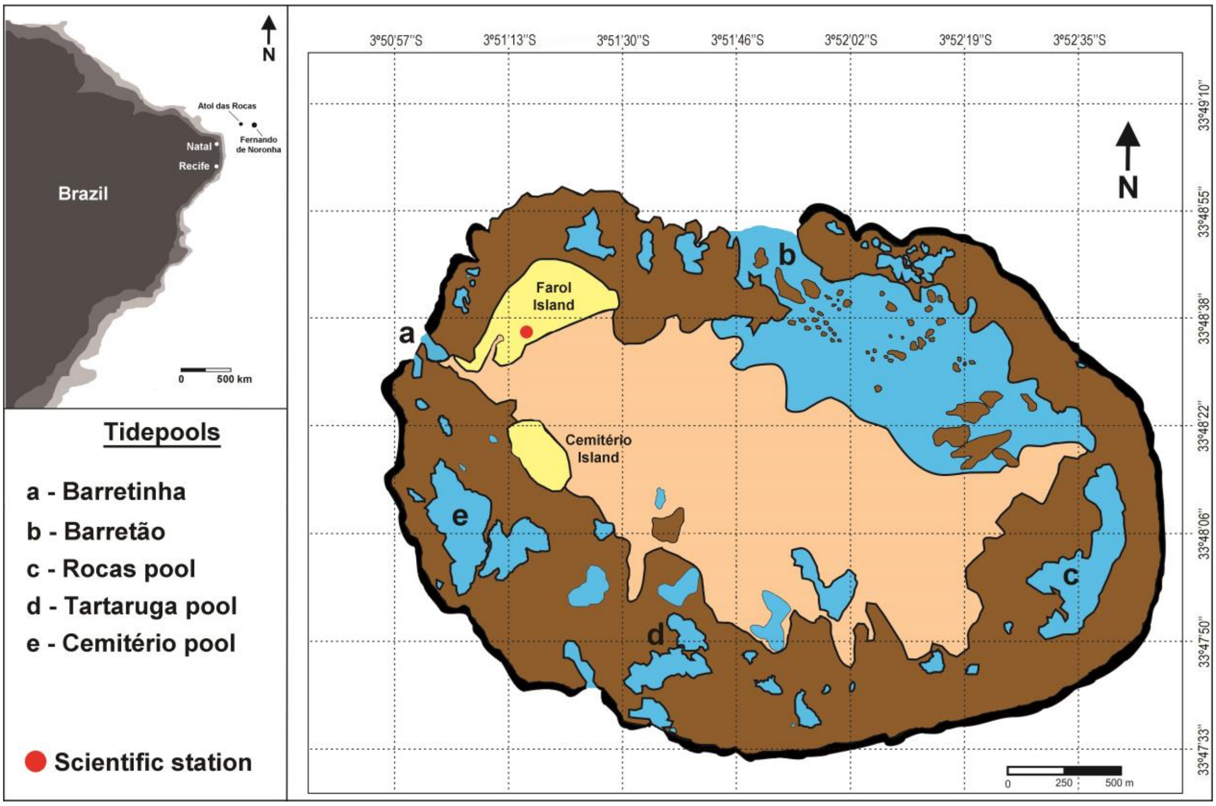


Figure 01 - Map of the study area with collection points. Modified map (Pereira, N. S. 2011)

To monitor the distribution of phytoplankton organisms, environmental variables, such as salinity, were analyzed using a manual Atago refractometer, model S/Mill-E with a scale range of 0 to 100 and an interval of 1. Water temperature was determined *in situ* with the use of a common thermometer (alcohol) with a scale of -10°C to 60°C, and dissolved oxygen was determined using the modified Winkler method described by Strickland and Parsons (1972). Other analyses were levels of dissolved inorganic nutrients, such as ammonia, nitrate, nitrite, phosphate (Strickland and Parsons, 1972), silica (Grasshoff et al., 1983), and chlorophyll *a* (spectrophotometric analysis of the UNESCO, 1966). The Parsons and Strickland (1963) equation was used to calculate the concentration of chlorophyll *a*.

Samples for phytoplankton composition were collected by filtering 200 litres of microphytoplankton concentration for each sample through a PVC tube with a height of 50 cm and a diameter of 10 cm, surrounded by a 20 μm aperture mesh. A total of 30 samples were collected, of which 15 samples corresponded to each climate period where 3 samples corresponded to each analysed pools. After microphytoplankton concentration, the samples were transferred to 250 mL plastic bottles and immediately fixed in formaldehyde solution (4%) buffered with sodium tetraborate. To analyse this composition, the samples were homogenized, and aliquots of 1.0 mL were removed and placed on a slide in order to observe all the organisms. Two quantitative and two qualitative subsamples were analyzed for each sample. This composition was determined by means of observations using a 400x optical microscope.

Additional samples were collected to analyse phytoplankton density. Another 30 samples were collected, as in the case of microphytoplankton concentration. For each sample, one litre of water was collected, conditioned in plastic containers and fixed in Lugol´s solution. The collected phytoplankton was concentrated using reverse filtering and analysed in an inverted microscope, brand ZeissAxiovert, using the Utermöhl method (Hasle, 1978; Edler, 1979; Ferrario et al., 1995). This count included the entire cuvette, analysed with a magnification of 400x, and expressed in number of cells.$L^{-1}$. Rose bengal was used to allow a better view of the species samples. The samples were classified with the help of specialized taxonomic literature as Peragallo e Peragallo (1897-1908), Hustedt (1930, 1959, 1961-1966), Cupp (1943), Desikachary (1959), Balech (1988), Silva-Cunha e Eskinazi-Leça (1990), Licea et. al. (1995), Tomas (1997) and the synonymy was identified using AlgaeBase, which is a global database containing information on all the phyla of algae. The identification refinement criteria and scientific names of species followed the rating system Guiry and Guiry (2015).

The frequency of occurrence was calculated by applying the formula described by Mateucci and Colma (1982) considering the number of samples in which each taxon occurred and the total number of analysed samples. Relative abundance of the taxa was estimated according to Lobo and Leighton's criteria (1986). Raw data of the samples collected using the microphytoplankton concentration method, were considered for the indexes of frequency, abundance and diversity.

The Shannon index (1948) was used to calculate the specific diversity, and the obtained values were classified according to Valentin et al. (1991). The statistical software Plymouth Routines In Multivariate Ecological Research, PRIMER 6.0. was used to calculate this index.

The environmental variables were tested for significance by comparing the different climate periods (dry and rainy season) and the collection points (Barretinha, Cemitério pool, Tartarugas pool, Rocas pool and Barretão) with factorial ANOVA. The variables $p \leq 0.05$

were considered significant. The STATISTICA 8.0 programme was used for the univariate analyses.

To better explore the relationship of the environmental variables and the structure of the phytoplankton community, multivariate analyses, such as PCA (Principal Component Analysis), Cluster and BIOENV, were conducted using the PRIMER 6.0 programme.

**RESULTS**

The temperature in the study area varied from 27.5$^{o}$C to 30$^{o}$C. Both these values were found in the Cemitério pool during the dry season and rainy season, respectively. Salinity varied from 35.33 in the dry season to 36.67 in the rainy seasons in the Tartarugas pool. Dissolved oxygen ranged from 4.74 mL.L$^{-1}$ in Barretinha in the dry season and 6.69 mL L$^{-1}$ in the Cemitério pool during the rainy season. As in the case of temperature, salinity, dissolved oxygen and total and size-fractionated chlorophyll *a* were also higher during the rainy season.

In the dry season, the lowest average of total chlorophyll *a* was 0.10 mg.m$^{-3}$ in the Rocas pool, and 0.01 mg.m$^{-3}$ for size-fractionated chlorophyll *a* in the Tartarugas pool. The highest average in the rainy period was found in the Cemitério pool, ranging from 0.91 mg.m$^{-3}$ and 0.52 mg.m$^{-3}$ for total and size-fractionated chlorophyll *a*, respectively. In relation to fractionation, nanophytoplankton and peal components that corresponded to the fraction < 20µm showed the lowest contribution to the biomass of the environment, with 28,4% in the dry season and 47,5% in the rainy season.

Unlike the variables described above, in terms of average values of all the analysed pools, nutrient salts and silica presented the highest averages during the dry season. The average parameters of DIN (Dissolved Inorganic Nitrogen), DIP (Dissolved Inorganic Phosphorous) and $SiO_2$ in the dry season were 1.79, 0.12 and 2.26 µM, respectively. While, in the rainy season these averages were 1.70, 0.11 and 0.73 µ M.

There was a significant difference for the environmental variables temperature, salinity and total and size-fractionated chlorophyll *a* in relation to the climate periods. The parameters dissolved oxygen and nutrient salts showed no significant difference. With regard to spatiality, there was no significant difference for any of the analyzed parameters (Table 01).

Table 01 - Data of environmental variables collected in Atol das Rocas for the different transects and degree of significance correlation (p).

| Environmental Variables | Average | | | | | Dry Season | Average | | | | | Rainy Season | p< 0,05 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cemitério | Tartarugas | Barretinha | Rocas | Barretão | Average | Cemitério | Tartarugas | Barretinha | Rocas | Barretão | Average | |
| Temperature (C°) | 27,50 | 28,33 | 28,17 | 28,50 | 28,17 | 28,13 | 30,00 | 29,00 | 29,17 | 28,67 | 28,67 | 29,10 | 0,01 |
| Salinity | 35,67 | 35,33 | 36,00 | 36,00 | 35,33 | 35,67 | 36,00 | 36,67 | 36,00 | 36,00 | 36,33 | 36,20 | 0,04 |
| Dissolved Oxygen (ml. $L^{-1}$) | 5,53 | 5,49 | 4,74 | 5,46 | 5,81 | 5,41 | 6,69 | 5,72 | 5,89 | 5,53 | 5,75 | 5,92 | 0,07 |
| Total Chlorophyll a (mg.$m^{-3}$) | 0,13 | 0,25 | 0,12 | 0,10 | 0,19 | 0,16 | 0,91 | 0,29 | 0,70 | 0,32 | 0,52 | 0,55 | 0,00 |
| Fracionate Chlorophyll a (mg.$m^{-3}$) | 0,03 | 0,01 | 0,07 | 0,07 | 0,04 | 0,04 | 0,52 | 0,16 | 0,25 | 0,20 | 0,18 | 0,26 | 0,00 |
| DIN (µM) | 2,26 | 1,51 | 1,51 | 1,96 | 1,69 | 1,79 | 2,05 | 1,69 | 1,53 | 1,52 | 1,69 | 1,70 | 0,95 |
| DIP (µM) | 0,11 | 0,08 | 0,08 | 0,26 | 0,07 | 0,12 | 0,04 | 0,23 | 0,21 | 0,03 | 0,02 | 0,11 | 0,80 |
| $SiO_2$ (µM) | 1,69 | 1,51 | 1,51 | 2,27 | 4,31 | 2,26 | 0,27 | 0,19 | 1,03 | 0,46 | 1,69 | 0,73 | 0,80 |

The PCA data revealed three factors that explain the 71% variation of the environmental parameters in the study area (Figure 02). Each factor is represented by 40%, 16% and 14%, respectively. Factor 1 shows a direct relationship between temperature and total and size-fractionated chlorophyll *a*, and an inverse relationship with SiO2. Factor 2 shows a direct relationship between salinity and dissolved inorganic phosphate (DIP), while factor 3 reveals a direct relationship of the parameters dissolved oxygen and dissolved inorganic nitrogen (DIN). The following graph clearly shows the pattern between the samples according to the season. Where, the rainy season is related to the highest values.

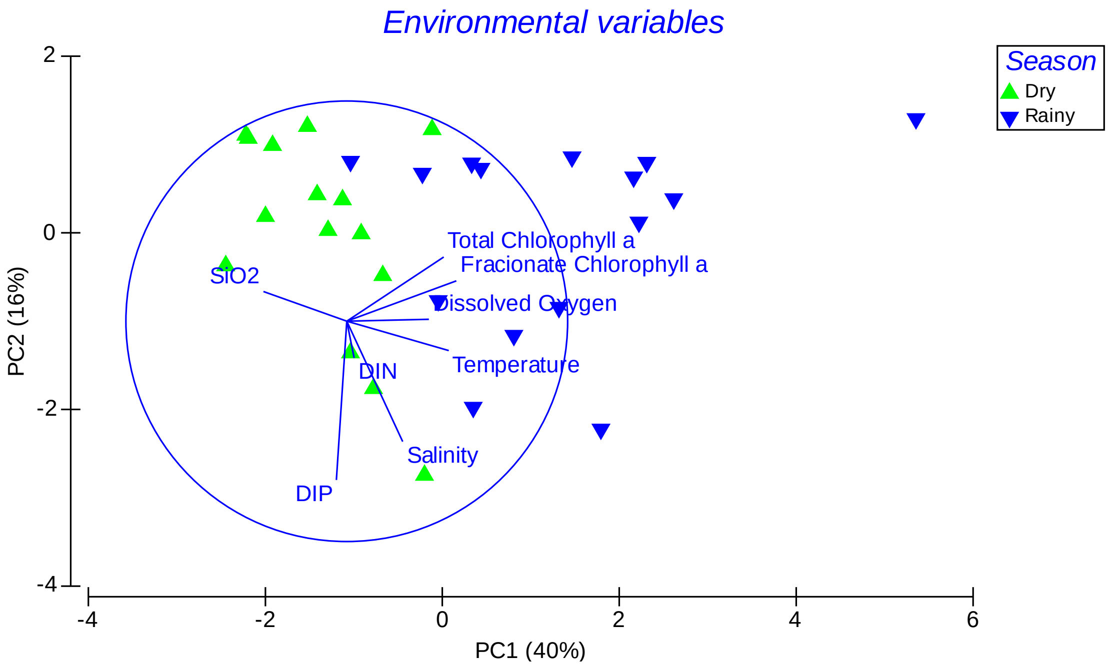


Figure 02 - Principal Component Analysis of the natural pools of Atol das Rocas (South Atlantic) in different climatic periods (dry and rainy seasons).

A total of 109 species were identified and distributed into four major groups. The groups found in the pools of Atol das Rocas were Ochrophyta with a representation of 52.3%, which was the predominant group, followed by Dinophyta with 37.6%, Cyanobacteria with 7.33% and Haptophyta with 2.75% (Table 02).

In the dry season, there was a high density of the species *Protoperidinium* sp. (261 cell.$L^{-1}$), *Prorocentrum balticum* (Lohmann) Loeblich 1970 (389 cell.L-1x$10^2$), *Prorocentrum lima* (Ehrenberg) F. Stein 1878 (932 cell.L-1x$10^2$) and *Pyrophacus* sp. (143 cell.$L^{-1}$). The highest density values, listed above, were found in the Tartarugas pool. However, the species also occurred in the other pools were samples were collected. In addition to the high density of the specie *P.lima* in the Tartarugas pool, this species was also well represented in the Barretão (366 cell.$L^{-1}$).

During the rainy season, the density of most species is higher, with the exception of some taxa, such as the species *P. balticum*. During the rainy season, this species reached the highest value in the Cemitério pool (19 cell.$L^{-1}$), while in the dry season, the density of this species was ten times greater (389 cell.$L^{-1}$).

The species with the highest density in this climate period were *Lyngbya* sp. (127 cell. $L^{-1}$), *Amphora arenari*a Donkin 1858 (113 cell.$L^{-1}$), *Bellerochea malleus* (Brightwell) Van Heurck 1885 (97 cell. $L^{-1}$), *Cylindrotheca closterium* (Ehrenberg) Reimann & J. C. Lewin 1964 (218 cell.$L^{-1}$), *Navicula* sp. (120 cell.$L^{-1}$), *Ostreopsis ovata* Fukuyo 1981 (362 cell.$L^{-1}$), *Protoperidinium* sp. (572 cell.$L^{-1}$), *Prorocentrum compressum* (Bailey) Abéex Dodge 1975 (79 cell.$L^{-1}$), *P. hoffmannianum* M. A. Faust 1990 (89 cell.$L^{-1}$), *P. mexicanum* Osorio-Tafall 1942 (88 cell.$L^{-1}$), *P. lima* (862 cell.$L^{-1}$) and *Pyrophacus* sp. (503 cell.$L^{-1}$). In this case, the species are distributed among the samples of the collection pools, which differs from the dry season where the highest density is in the Tartarugas pool.

With regard to the occurrence and abundance frequency indexes, the species classified as dominant and very frequent were *Pyrophacus* sp. and *Prorocentrum lima*. The species *Ostreopsis ovata*, which was also classified as dominant, is regarded as being frequently present in 40% of the analysed samples.

The specific diversity index showed a wide variation, where the samples ranged from 0.43 to 3.00 bits.$cel^{-1}$ in the Tartarugas pool in the dry season and rainy season respectively. Therefore, the values are included in the very low diversity classification (< 1.0 bits.$cell^{-1}$) and high diversity classification (≥ 3.0 bits.cell-1). However, of the 30 analysed samples, 21 were classified as being of medium diversity (< 3.0 ≥ 2.0 bits.$cell^{-1}$), with indexes of 2 to 2.90 bits.$cell^{-1}$.

Table 02 - Composition of the phytoplankton community in the natural pools of Atol das Rocas.

| Phytoplankton Composition | Dry Season Conc. 20 µm | Dry Season Density (cell.L$^{-1}$) Cemitério | Tartarugas | Barretinha | Rocas | Barretão | Rainy Season Conc. 20 µm | Rainy Season Density (cell.L$^{-1}$) Cemitério | Tartarugas | Barretinha | Rocas | Barretão |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CYANOBACTERIA** | | | | | | | | | | | | |
| Cianofícea 1[a, C] | X | 1 | | | 3 | | X | 7 | | | | |
| Cianofícea 2 | | | | | | | | 2 | | | | |
| Cianofícea 3[r, C] | X | | | | | | X | | | 91 | | |
| Cianofícea 4[r, I] | X | | | | | | X | | | | | |
| *Anabaena* sp. [a, I] | X | | | | | | X | | | | | |
| *Lyngbya* sp. [a, VC] | X | 8 | 3 | | 1 | | X | 48 | 3 | 63 | 4 | 9 |
| *Oscillatoria* sp. [a, VC] | X | 3 | | | 3 | 1 | X | 7 | 1 | 20 | 13 | 14 |
| *Trichodesmium thiebautii* [r, S] | X | | | | | | X | | | | | |
| **OCHROPHYTA** | | | | | | | | | | | | |
| *Amphitetras antidiluviana* Ehrenberg 1840 | | | | | | | | | | | 1 | |
| *Amphiprora alata* (Ehrenberg) Kützing 1844 [r, S] | X | | | | | | X | | | | | |
| *Amphiprora* sp. [r, S] | X | | | | | | X | 1 | | | | 1 |
| *Amphora arenaria* Donkin 1858 [a, VC] | X | 1 | 3 | | 2 | | X | 61 | 2 | 41 | 1 | 8 |
| *Amphora* sp.[a, C] | X | | | 1 | | 3 | X | 1 | | 3 | 2 | 17 |
| *Asterionellopsis glacialis* (Castracane) Round in Round, R.M.Crawford & D.G.Mann 1990 [a, I] | | | | | | | X | | | | | |
| *Asterolampra marylandica* Ehrenberg 1844 [r, S] | | | | | | | X | | | | | |
| *Auricula* sp. [r, S] | | | | | | | X | | | | | |
| *Bacillaria paxillifer* (O. F. Müller) T. Marsson 1901 [r, I] | X | | | | | | X | | 10 | | | |
| *Bellerochea malleus* (Brightwell) Van Heurck 1885 [a, C] | X | | | 4 | | 2 | X | 9 | 8 | 72 | 5 | 3 |
| *Biddulphia biddulphiana* S. F. Gray 1821 [r, I] | X | | | | | | X | | | | | |
| *Biddulphia regia* (Schultze) Ostenfeld 1908 | | | 1 | | | | | | | | | |
| *Campylodiscus clypeus* (Ehrenberg) Ehrenberge x Kützing 1844 [r, S] | | | | | | | X | | | | | 8 |
| *Campyloneis grevillei* (W.Smith) Grunow & Eulenstein in Grunow 1868 [r, S] | X | | | | | | | | | | | |
| *Chaetoceros* sp. [r, S] | X | | | | | | X | | | | | |
| *Climacosphenia elongata* Mereschkowsky [r, C] | X | | | | | | X | | 2 | 1 | | 1 |
| *Cocconeis scutellum* Ehrenberg 1838 [a, VC] | X | | 1 | | | | X | 5 | 2 | 2 | 1 | 4 |
| *Cylindrotheca closterium* (Ehrenberg) Reimann & J.C.Lewin 1964 [a, C] | | | | | | | X | | 192 | | 26 | |
| *Dictyocha fíbula* Ehrenberg 1839 [r, S] | X | | | | | | | | | | | |
| *Dimerogramma* sp. [r, S] | | | | | | | X | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Diploneis bombus* (Ehrenberg) Ehrenberg 1853 | | | | | | | | 1 | 1 | | | |
| *Diploneis* sp. [r, C] | X | | | | | 1 | X | | | | | 1 |
| *Diploneis* sp.1 [r, I] | X | | 2 | | | | X | | | | | |
| *Grammatophora oceanica* Ehrenberg 1840 | | | | | | | | | 1 | | | |
| *Grammatophora* sp. [a, I] | | | | | | | X | | | | | |
| *Isthmia enervis* Ehrenberg 1838 [r, I] | X | | | | | | X | | | | | 2 |
| *Lampriscus* sp. A. Schmidt 1882 [r, I] | X | | | | | | X | | | | 3 | 1 |
| *Licmophora* sp. [r, C] | X | | | | | | | | 17 | 6 | 2 | |
| *Lithodesmium undulatum* Ehrenberg 1839 | X | | | | | | | | | | | |
| *Lyrella lyra* (Ehrenberg) Karajeva 1978 [r, C] | X | 1 | 1 | | | | X | | | 2 | | 1 |
| *Melchersiella hexagonallis* C. Teixeira [r, C] | X | | | | | | X | | | | 2 | 3 |
| *Navicula* sp. [a, C] | X | 3 | 1 | | 7 | | X | 27 | 19 | 33 | 345 | 380 |
| *Navicula* sp.1 [a, I] | | | | | | | X | | 120 | | | |
| *Nitzschia distans* W. Gregory 1857 [r, S] | | | | | | | X | | | | | |
| *Nitzschia longissima* (Brébisson) Ralfs in Pritchard 1861 [a, VC] | X | | | | | | X | | | | | |
| *Nitschia pacifica* Cupp 1943 [r, S] | X | | | | | | | | | | | |
| *Nitzschia punctata* (W.Smith) Grunow 1878 [r, S] | | | | | | | X | | | | | |
| *Nitzschia sigma*(Kützing) W.Smith 1853 [a, C] | | | 1 | | | | X | | 10 | | 16 | 2 |
| *Nitzschia spathulata* W.Smith 1853 [a, C] | X | | | | | | X | | | | 11 | 25 |
| *Nitzschia* sp. [r, VC] | | | | | | | | | | | 16 | 1 |
| *Paralia sulcata* (Ehrenberg) Cleve 1873 [a, I] | X | | | | | | | | | | | |
| *Pleuro/ Gyrosigma* sp. [r, C] | X | | | | | | X | | 9 | 1 | 4 | 5 |
| *Podocystis adriatica* (Kützing) Ralfs in Pritchard 1861 [r, C] | X | | | | | | | 3 | | 3 | | 2 |
| *Psammodictyon panduriforme* (W.Gregory) D.G.Mann in Round, Crawford & Mann 1990 [r, S] | | | | | | | X | | | 1 | | |
| *Rhabdonema adriaticum* Kützing 1844 [r, I] | X | | | | | | X | | | | | |
| *Rhizosolenia imbricata* Brightwell 1858 [r, S] | | | | | | | X | | | | | |
| *Rhizosolenia styliformis* T. Brightwell 1858 [r, S] | | | | | | | X | | | | | |
| *Streptotheca tamesis* Shrubsole 1891 [r, S] | X | | | | | | | | | | | |
| *Surirella fastuosa* Ehrenberg [r, S] | X | | | | | | X | | | | | |
| *Synedra formosa* Hantzsch 1863 [r, C] | X | | | | | | X | | | | | |
| *Synedra* sp. | | | | | | | | | 8 | | | |
| *Thalassiosira* sp. [a, C] | X | | | | | | X | | 1 | | 2 | 5 |
| *Toxarium undulatum* Bailey 1854 [r, I] | | | | | | | X | | | | | |
| *Trachyneis aspera* (Ehrenberg) Cleve 1894 [r, C] | X | 1 | 1 | 1 | | | X | 9 | 5 | 2 | | 6 |
| *Triceratium antediluvianum* (Ehrenberg) Grunow 1868 [r, S] | X | | | | 1 | | | | | | | |
| *Triceratium pentacrinus* (Ehrenberg) Wallich 1858 [r, S] | | | | | | | X | | | | | |
| *Tropidoneis* sp. [r, I] | | | | | | | X | | | | 1 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **DINOPHYTA** | | | | | | | | |
| *Ceratocorys horrida* Stein 1883 [r, S] | | | X | | | | | |
| *Dinophysis caudata* Saville-Kent 1881 [r, S] | X | | | | | | | |
| *Dinophysis* sp. [r, S] | | | X | | | | | |
| *Gymnodinium catenatum* H.W.Graham 1943 [a, C] | X | | X | | | | | |
| *Gymnodinium* sp. [a, VC] | X | | X | 4 | 17 | 3 | 3 | 2 |
| *Gonyaulax birostris* Stein 1883 [r, S] | X | | | | | | | |
| *Gonyaulax minuta* Kofoid & Michener 1911 [r, I] | X | | X | | | | | |
| *Gonyaulax polyedra* F.Stein 1883 [r, S] | | | X | | | | | |
| *Gonyaulax polygramma* Stein 1883 [r, C] | X | 1 | X | | | | | |
| *Gonyaulax spinifera* (Claparède & Lachmann) Diesing 1866 [r, S] | X | | | | | | | |
| *Neoceratium declinatum* (Karsten) F. Gomez, D. Moreira & P. Lopez-Garcia 2010 [r, I] = *Tripos declinatus* (G. Karsten) F.Gómez 2013 | | | X | | | | | |
| *Neoceratium fusus* (Ehrenberg) F.Gomez, D.Moreira & P.Lopez-Garcia 2010 [r, S] = *Tripos fusus* (Ehrenberg) F.Gómez, 2013 | | | X | | | | | |
| *Neoceratium horridum* (Gran) F. Gomez, D. Moreira & P.Lopez-Garcia 2010 = *Tripos horridus* (Cleve) F. Gómez, 2013 | | | | | | | 1 | |
| *Neoceratium lineatum* (Ehrenberg) F. Gomez, D. Moreira & P. Lopez-Garcia 2010 [r, S] = *Tripos lineatus* (Ehrenberg) F. Gómez, 2013 | X | | | | | | | |
| *Neoceratium macroceros* (Ehrenberg) F. Gomez, D. Moreira & P. Lopez-Garcia 2010 [r, S] = *Tripos macroceros* (Ehrenberg) F.Gómez, 2013 | | | X | | | | | |
| *Neoceratium pentagonum* (Gourret) F. Gomez, D. Moreira & P. Lopez-Garcia 2010 [r, I] = *Tripos pentagonus* (Gourret) F.Gómez, 2013 | X | | X | | | | | |
| *Neoceratium teres* (Kofoid) F. Gomez, D. Moreira & P. Lopez-Garcia 2010 [r, C] | X | | X | | | | | |
| *Neoceratium tripos* (O.F.Müller) F. Gomez, D. Moreira & P. Lopez-Garcia 2010 [r, S] = *Tripos muelleri* Bory de Saint-Vincent, 1824 | | | X | | | | | |
| *Ornithocercus magnificus* Stein 1883 [r, S] | | | X | | | | | |
| *Ornithocercus quadratus* Schütt 1900 [r, S] | | | X | | | | | |
| *Ornithocercus* sp. [r, S] | | | X | | | | | |
| *Ostreopsis ovata* Fukuyo 1981 [d, C] | | | X | | 9 | 339 | 4 | 10 |
| *Oxytoxum sceptrum* (F.Stein) Schröder 1906 [r, S] | | | X | | | | | |
| *Oxytoxum scolopax* Stein, F. 1883 [r, S] | X | | | | | | | |
| *Phalacroma rotundatum* (Claparéde & Lachmann) Kofoid & Michener 1911 [r, I] | X | | X | | | | | |
| *Podolampas palmipes* Stein 1883 [r, S] | X | | | | | | | |
| *Podolampas spinifera* Okamura 1912 [r, I] | | | X | 1 | 1 | | 2 | |
| *Protoperidinium obtusum* (Karsten) Parke& Dodge 1976 [r, S] | X | | | | | | | |
| *Protoperidinium pyriforme* (Paulsen) Balech 1974 [a, I] | X | | X | | | | | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Protoperidinium* sp. [a, C] | X | 24 | 174 | 4 | 50 | 9 | X | 270 | 17 | 229 | 2 | 54 |
| *Protoperidinium* sp. 1[a, I] | X | | | | | | X | | | | | |
| *Protoperidinium* sp.2 [r, S] | | | | | | | X | | | | | |
| *Prorocentrum balticum* (Lohmann) Loeblich 1970 [a, C] | X | 2 | 379 | 2 | 1 | 5 | X | 19 | 6 | 4 | 3 | 4 |
| *Prorocentrum compressum* (Bailey) Abéex Dodge 1975 [a, C] | X | 4 | 19 | | | 1 | X | 26 | 8 | 35 | 2 | 8 |
| *Prorocentrum emarginatum* Fukuyo 1981 [r, C] | X | | | | | | X | | | | | |
| *Prorocentrum hoffmannianum* M. A. Faust 1990 [a, VC] | X | 4 | 3 | 1 | | | X | 3 | 23 | 51 | 3 | 9 |
| *Prorocentrum lima* (Ehrenberg) F.Stein 1878 [d, VC] | X | 6 | 474 | 49 | 37 | 366 | X | 375 | 7 | 57 | 14 | 409 |
| *Prorocentrum mexicanum* Osorio-Tafall 1942 [a, I] | | | | | | | X | | 3 | 85 | | |
| *Prorocentrum micans* Ehrenberg 1834 [a, I] | X | | 9 | | 3 | | X | | | | | |
| *Prorocentrum sigmoides* Böhm 1933 | | | | | | | | | | | | 1 |
| *Pyrophacus* sp. [a, VC] | X | 3 | 105 | 14 | 3 | 18 | X | 72 | 97 | 184 | 11 | 139 |
| **HAPTOPHYTA** | | | | | | | | | | | | |
| *Coccolithus* sp.[a, VC] | X | 10 | 8 | 1 | 6 | 13 | X | 14 | 7 | 2 | 5 | 3 |
| *Coccolithus* sp. 1[a, C] | X | | | | | | X | | | | | |
| *Coccolithus* sp. 2 [r, C] | X | | 1 | 1 | | | X | 1 | 1 | | | |

**Legend**: Relative abundance: d-dominant; a-abundant; r - rare. Frequency of occurrence: VC - very common ; C - common; I - infrequently; S – sporadic; Conc- Concentration.

The dendrogram below, referent to the composition of the microphytoplankton samples, clearly shows the grouping pattern of two large groups associated with seasonality. It can also be observed that during the rainy season, the natural pools establish a strong resemblance, with the exception of a sample of the Rocas pool that is grouped with the Cemitério pool. A clear pattern between the pools cannot be observed in the dry season (Figure 03).

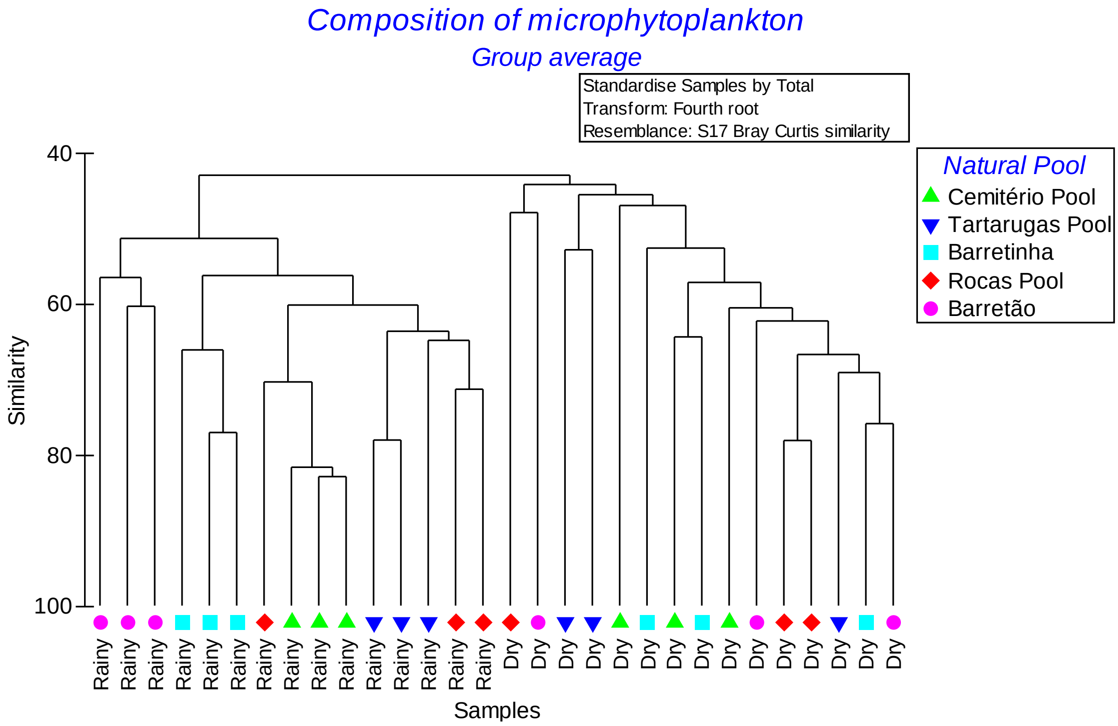


Figure 03 - Associations of samples in different climatic periods, dry and rainy, and natural pools (Cemitério pool, Tartarugas pool, Barretinha, Rocas pool and Barretão) in Atol das Rocas (South Atlantic).

Similarly to the samples of microphytoplankton composition, the density of the phytoplankton of the natural pools follows the same pattern, showing a clear distinction between the seasons. However, in this case, only one sample of the Tartarugas pool in the rainy season is grouped with the samples of the dry season (Figure 04).

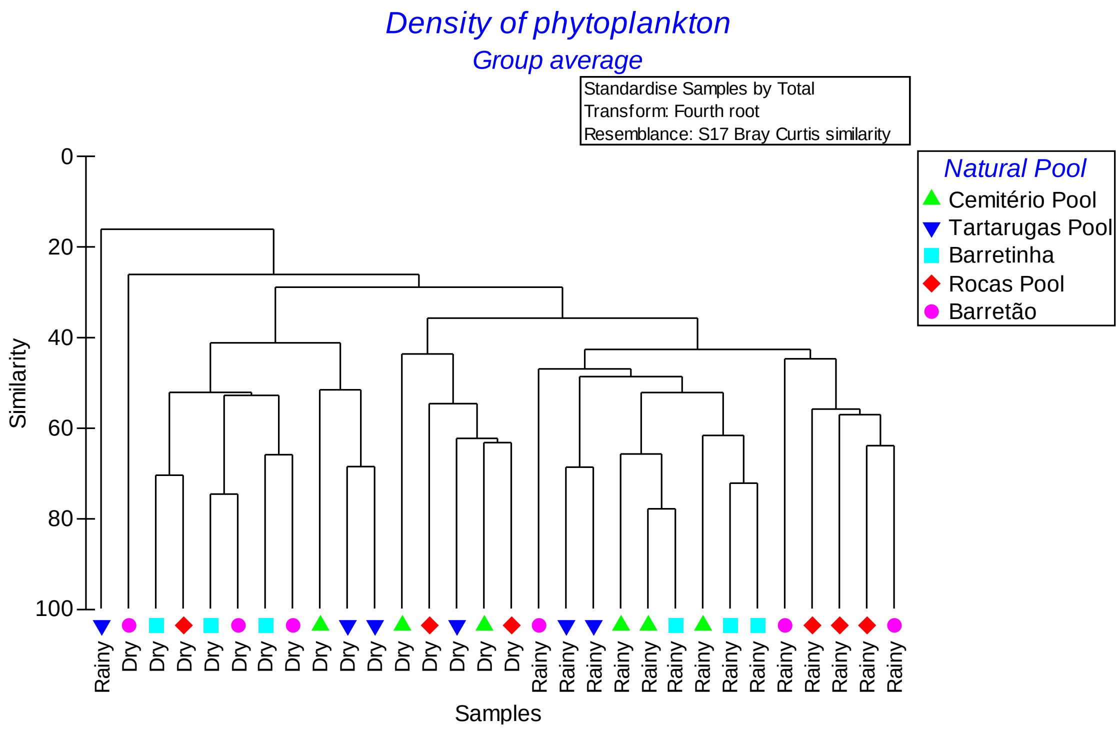


Figure 04 - Associations of samples in different climatic periods, dry and rainy, and natural pools (Cemitério pool, Tartarugas pool, Barretinha, Rocas pool and Barretão) in Atol das Rocas (South Atlantic).

The BIOENV analysis using Spearman´s correlation resulted in different groupings. The correlation between the phytoplankton composition and environmental variables was relatively low (r = 0.337). In this analysis, the composition correlates with salinity and $SiO_2$. The correlations with the climate periods and for each natural pool were also analysed. During the rainy season, this correlation was a little more significant (r = 0.492), where the composition correlated with the variables DIP and $SiO_2$.

Regarding the analyses of biotic and abiotic interaction conducted for each natural pool, the results were more expressive. In the Cemitério pool, phytoplankton composition had a high correlation with the variables salinity, total chlorophyll *a*, DIN, DIP and $SiO_2$ (r = 0.846). In the Tartarugas pool, this correlation was even more significant (r = 0.932), correlating with the temperature, total and size-fractionated chlorophyll *a*, DIN and DIP. In Barretinha, the Rocas pool and Barretão, the correlation of the composition occurred with the same variables, nutrient salts and $SiO_2$. However, in Barretinha and the Rocas pool this correlation was even higher (r = 850) than the correlation found in Barretão (r = 598).

The most representative species found in this study (*Prorocentrum baltricum*, *P. lima*, *Pyrophacus* sp. and *Ostreopsis ovata*), according to Spearman’s correlation and the BIOENV, showed a correlation with size-fractionated chlorophyll *a* and DIN (r = 0.438).

**DISCUSSION**

Oceanic surface waters present a wide temperature variation depending on the latitudes, reaching averages of -1.8°C to 30°C (Toseland et al., 2013). Phytoplankton inhabits all of these different temperature zones, and temperature is an environmental parameter that influences their growth and diversity (Thomas et al., 2012).

According to Pereira (2015), based on a historical average of SST (Sea Surface Temperature) measured by satellite (AVHRR) between 1985 and 2012, the temperature values of Atol das Rocas range from 24°C to 30°C, with an average of 27.4°C and an annual average amplitude of 3°C. In this study, temperature was one of the parameters that showed a significant seasonal difference and a direct relationship with chlorophyll *a* according to PCA. The highest and lowest averages were recorded in the Cemitério pool, 30°C and 27.5°C respectively, which is within the historical average temperature patterns.

However, aside from the historic average, Pereira (2015) also reports a temperature record year in the Cemitério pool and Salão, where the average values found differ from the present study. The average temperature values in the months of August and September in the analysed pools ranged from 28.67°C to 30°C, while the average values that were found by Pereira (2015) in the Cemitério pool and Salão in those same months were 27°C and 27.5°C. This fact can be explained by the daily temperature variation in the pools. Pereira (2015) observes a daily variation throughout the year of up to 3°C and attributes this event to the tidal regime.

In the reef ecosystem of Atol das Rocas, there was a significant seasonal difference for salinity. However, as the alteration is a little more than 1, it is believed that the phytoplankton community adapts to this variation without compromising the community. Similar salinity values were also reported by Feitosa and Passavante (2004).

Ochrophyta are aquatic organisms that substantially contribute to marine productivity and are considered abundant in tropical waters (Silva-Cunha and Eskinazi-Leça 1990; Lacerda *et. al*. 2004). In the pools of Atol das Rocas, this was the most representative group with 57 species. In spite of the greater occurrence of the group of diatoms, the species that were classified as being the most representative were dinoflagellates, such as *Prorocentrum balticum, P. lima, Pyrophacus* sp. and *Ostreopsis ovata*, since, with the exception of the latter species, they are strongly represented in both seasonal periods.

According to Faust et al., (1996), the identification of benthic dinoflagellates is of fundamental importance because they can be toxic to humans. The species of the Ostreopscidaceae family are commonly found in benthic microflora and in pools of reef environments. The genus *Ostreopsis* is widely distributed and a greater quantity of blooms is reported annually, in addition to the identification of new locations (Rhodes, 2011). Similarly to Atol das Rocas, in this study the genus *Ostreopsis* has also been identified in the Archipelago of São Pedro and São Paulo by Nascimento et al. (2012), and in coastal reef environments of north-eastern Brazil, such as Tamandaré by Madureira (2015) and Porto de Galinhas by Machado (2015).

Although the species *Ostreopsis ovata* is mostly found in protected environments (Foust et al., 1996), in the atoll this species was reported only in the rainy season with a greater occurrence in the collection point that is connected to the open sea and is influenced by the local hydrodynamics. A study carried out in 2008 in rocky unprotected areas on the Reserve Beach in Nice by Tichadou et al., (2010) corroborates the condition found in the atoll.

According to Guerrini et al. (2010) and Tichadou et al. (2010), studies in the Mediterranean Sea confirmed the occurrence of blooms of the species O. ovata. This species has been causing health problems for human beings because it produces Palytoxins (PTX) and Ostreocines (PTX-like), which are highly toxic. In tropical environments, these toxins are produced by various marine organisms, including *Ostreopsis,* and can accumulate along the food chain. In Atol das Rocas, this species was widely observed, but its density was not expressive enough for the observance of blooming.

Many times, *O. ovata* is found in association with other potentially toxic dinoflagellates, such as the species *Prorocentrum lima*. These organisms form epiphytic communities associated with coral reefs or with seaweed associated with the surfaces of these corals (Vila et al, 2001).

According to Aligizaki et al. (2009), the species *Prorocentrum lima* varies greatly in size and shape, in addition to being toxic. In spite of the high density of the species *P. lima* found in the rainy season in the Atol das Rocas, its density was slightly higher in the dry season when the lowest values of the parameters temperature and salinity were recorded. Corroborating a study conducted in Greece, despite the broad temperature and salinity ranges in which *P. lima* is found (10.0 – 29.5 °C and 30.7–37.1), the peaks in abundances of this species are reported in lower temperature and salinity conditions (Aligizaki et al., 2009).

Unlike the other representative species found in this study, *Prorocentrum balticum* is also abundant in waters that surround the atoll (Jales et al., in press), and it is not a benthic or toxic species (Foust and Gulledge, 2002), as reported for the other species. This species is classified as marine neritic, oceanic and planktonic and is usually found in cold to tropical waters (Foust and Gulledge, 2002). Its presence in the pools of the atoll is justified by the constant renovation during the high tide.

The genus *Pyrophacus* is widely distributed and presents only three species that are difficult to distinguish (Hoppenrarth et al. 2009). Studies conducted in Jeju Island in Korea (Kim et al., 2013), the Mediterranean (Balkis and Koray, 2001), in the Archipelago of São Pedro and São Paulo (Koenig and Oliveira, 2009), and in the estuary of the Timbo river in Brazil (Silva-Cunha et al., 1989) report the occurrence of this genus.

According to Gherardi and Bosence (2001), the waves that occur in the atoll are concentrated in the SE portion (windward), although the refraction of waves in the basement of the atoll can generate large wave breaks in the W and SW (leeward) portion. Moreover, the high tidal amplitude ensures that a large part of the atoll profile is affected by breaking waves twice a day, where the atoll is exposed at low tide and is bathed by strong tidal currents during the ebb tide. There are historical accounts of storm waves that reach the atoll during September and October (Rodriguez, 1940). Although the frequency of these waves has not yet been determined, they occurred twice in the years 1999 and 2000 (Gherardi and Bosence, 2001).

The microphytoplankton composition of the Atol das Rocas presented a pattern of seasonal and spatial distribution. Despite the spatial difference of the composition, there was no determinant hydrological parameter. However, according to the BIOENV, the compositions of all the pools is chiefly associated with the nutrients DIN, PID and $SiO_2$.

It should be noted that the natural pools analysed in this study are relatively shallow, with average depths of 5m, and the most representative species of the area are part of the benthic microfauna. This shows that the hydrodynamics of the location influences the distribution dynamics of the phytoplankton.

In terms of density, only a seasonal pattern was clearly identified and there was a qualitative and quantitative increase of phytoplankton in the rainy season. This fact is due to the positive relationship between the composition of phytoplankton and nutrient salts when associated with the local hydrodynamics proposed by Gherardi and Bosence (2001) and Rodriguez (1940), thus providing more favourable conditions for the enrichment of diversity with emphasis on the species that compose the benthic microflora.

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## 8. CONSIDERAÇÕES FINAIS

- No entorno do Atol das Rocas houve um aumento da biomassa fitoplanctônica e algumas variáveis ambientais, como os sais nutrientes. Fato este observado através da curva T-S, e assim constatando um evento de "efeito ilha", e não ressurgência.

- As espécies mais representativas do fitoplâncton no entorno do Atol das Rocas são características das águas oceânicas do Nordeste do Brasil e as condições oceanográficas influenciaram na estrutura desta comunidade. No transecto NO, esta estrutura correlacionou-se fortemente com os padrões de salinidade e temperatura provenientes da instabilidade termohalina causada pela interação das massas de água tropical e central do Atlântico Sul.

- No entorno do atol, um total de 150 taxa de quatro diferentes grupos foram identificados. Dinophyta mostrando a maior contribuição com 57,33%, seguido pelo grupo das Ochrophytas com 37,33%, Cyanobacteria com 3,34% e Haptophyta com 2,00%. As espécies de maior representatividade no entorno do atol foram *Prorocentrum balticum*, *P. compressum*, e *P. gracile* devido potencialmente a baixas concentrações de nutrientes.

- As amostras apresentaram variação espacial horizontal, com o filo das Ochrophytas mais próximas ao atol e Dinophyta nos pontos mais distantes, enquanto que verticalmente não houve nenhuma diferença significativa.

- Nas piscinas naturais, foram identificadas 109 espécies distribuídas em quatro grupos. Ochrophyta com uma representação de 52,3% sendo o grupo predominante, Dinophyta com 37,6%, Cyanobacteria com 7,33% e Haptophyta com 2,75%. Apesar do grupo das Ochrophytas ter sido o mais evidenciado, as espécies mais representativas encontradas neste estudo devido sua densidade foram *Prorocentrum balticum*, *P. lima*, *Pyrophacus* sp. e *Ostreopsis ovata*.

- Nas piscinas naturais do Atol das Rocas, a composição do fitoplâncton apresentou um padrão de distribuição sazonal e espacial. O padrão sazonal foi claramente identificado e houve um aumento qualitativo e quantitativo do fitoplâncton na estação chuvosa devido ao fato da relação positiva entre a composição do fitoplâncton e sais nutrientes, quando associada com a hidrodinâmica local, proporcionando assim condições mais favoráveis para o enriquecimento da diversidade com ênfase nas espécies que compõem a microflora bentônica. A diferença espacial desta composição não faz relação com nenhum parâmetro hidrológico determinante.

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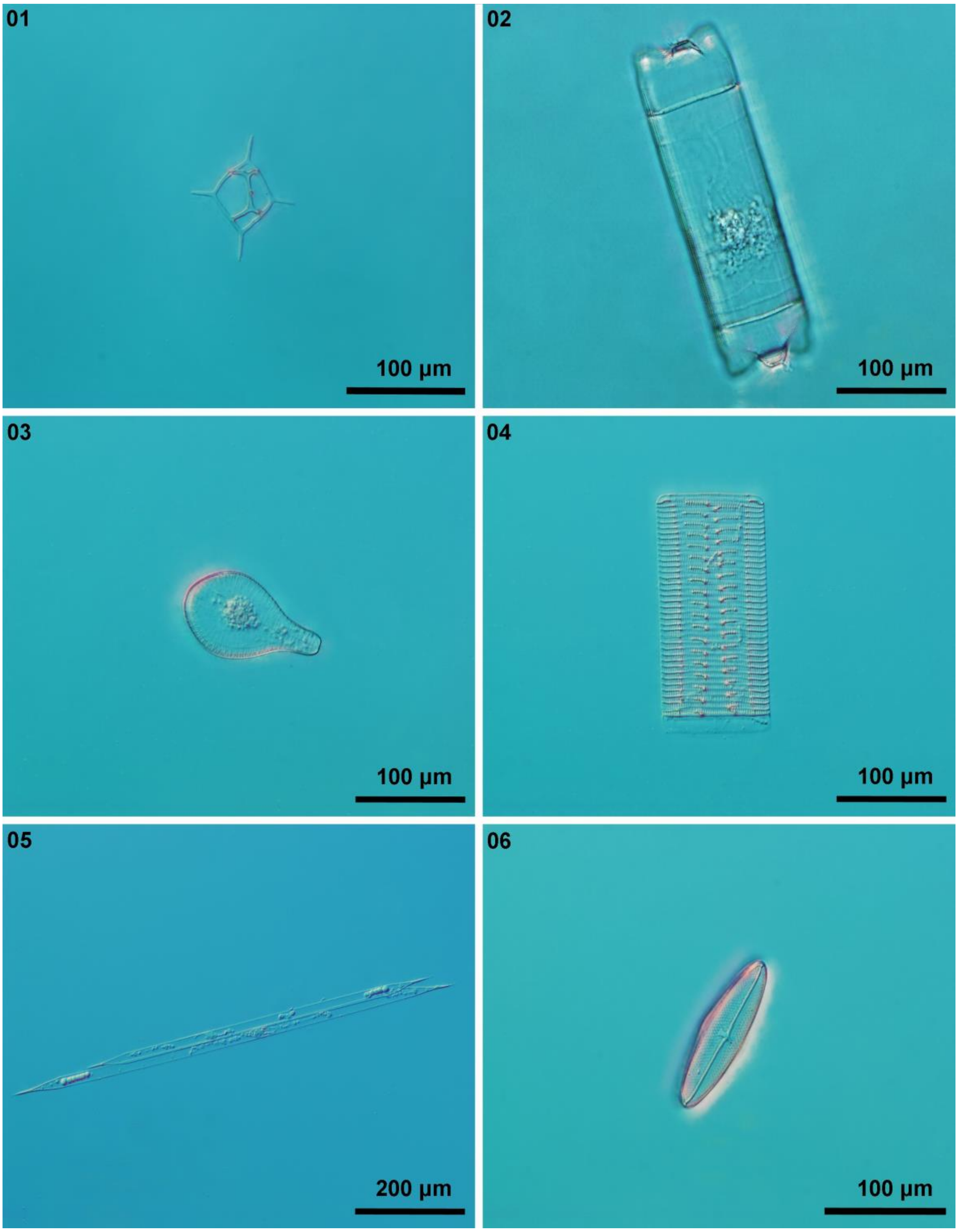
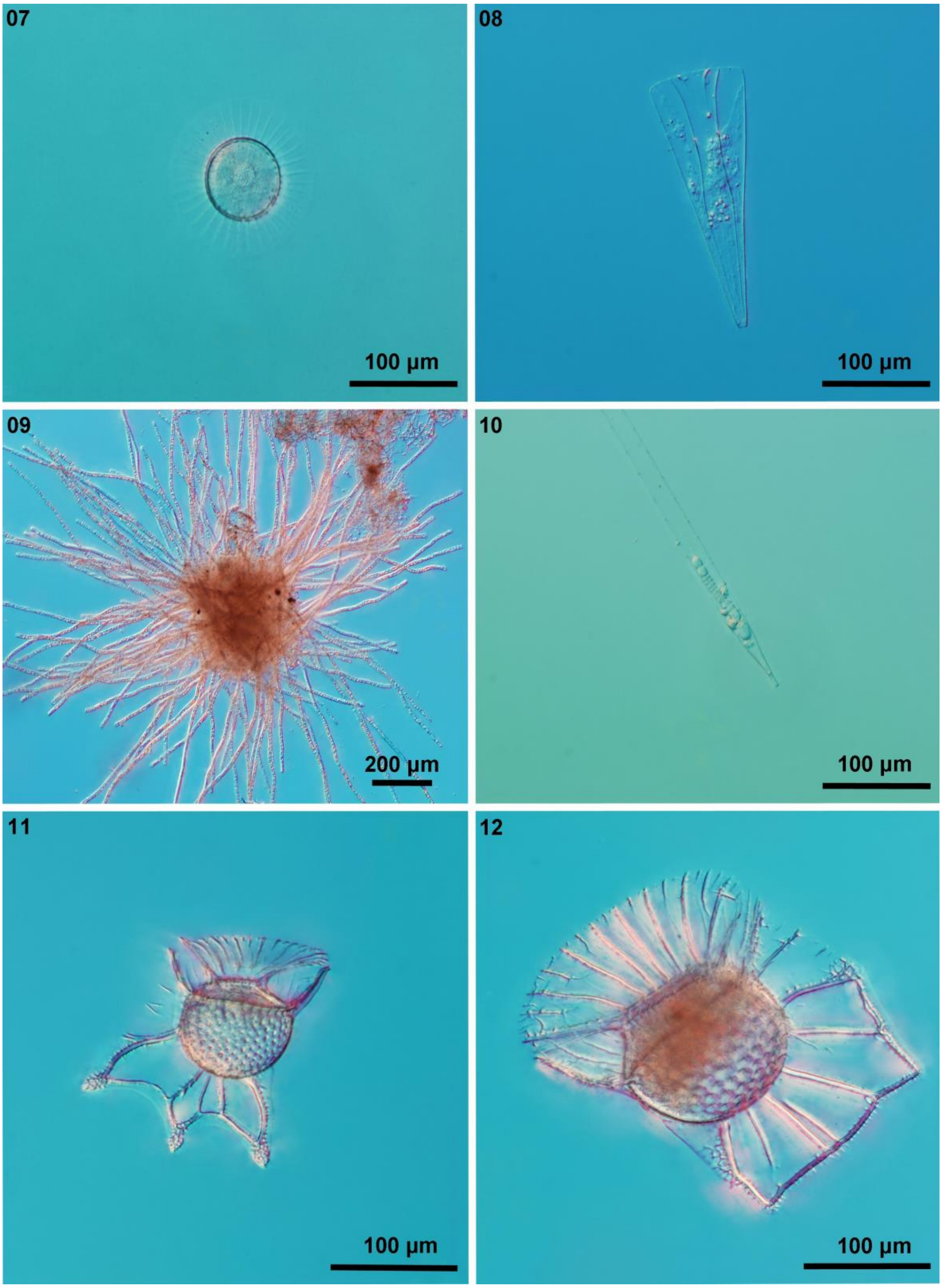
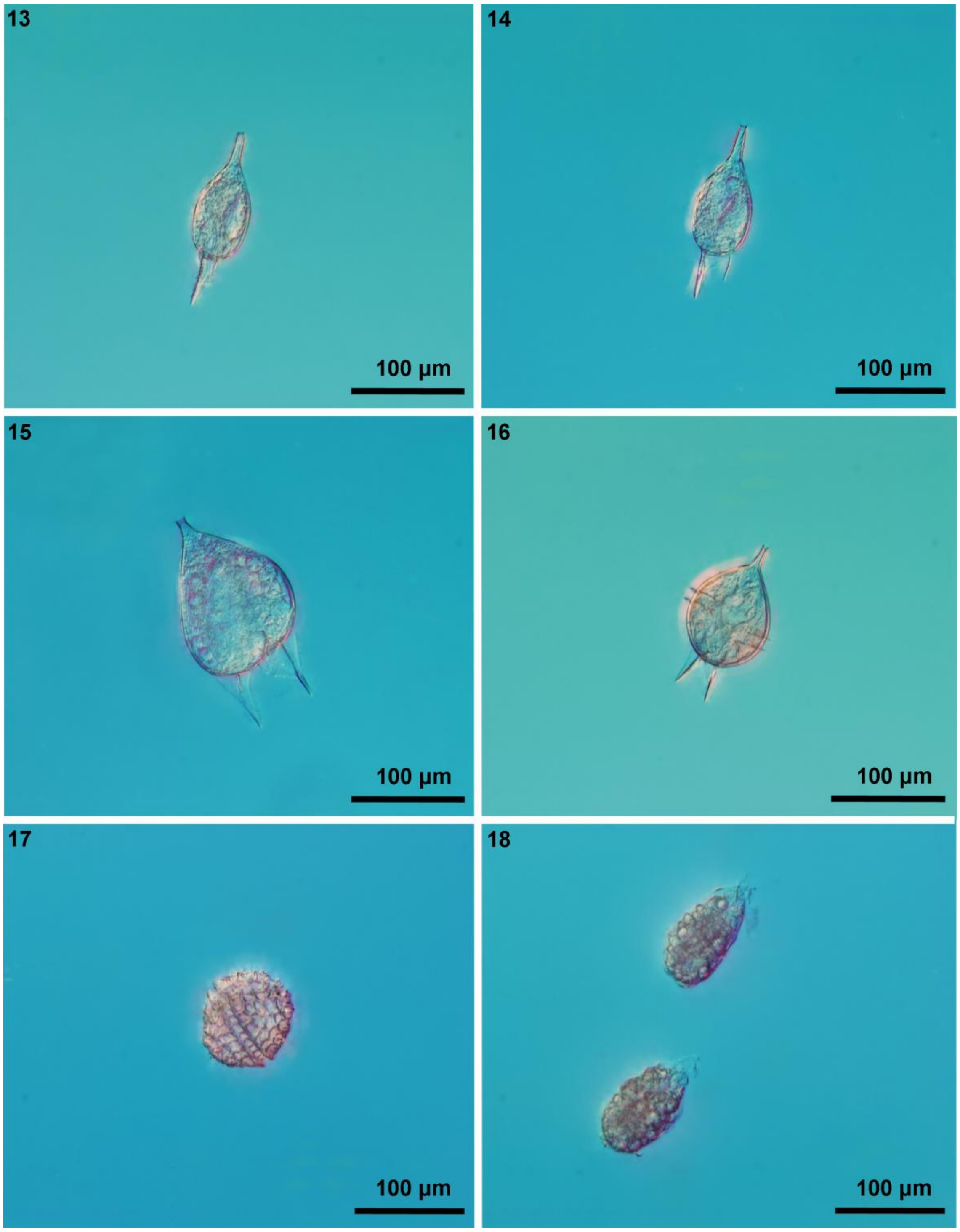
**APÊNDICE** – Ilustrações de algumas espécies representantes da composição do microfitoplâncton do Atol das Rocas (Atlântico Sul).



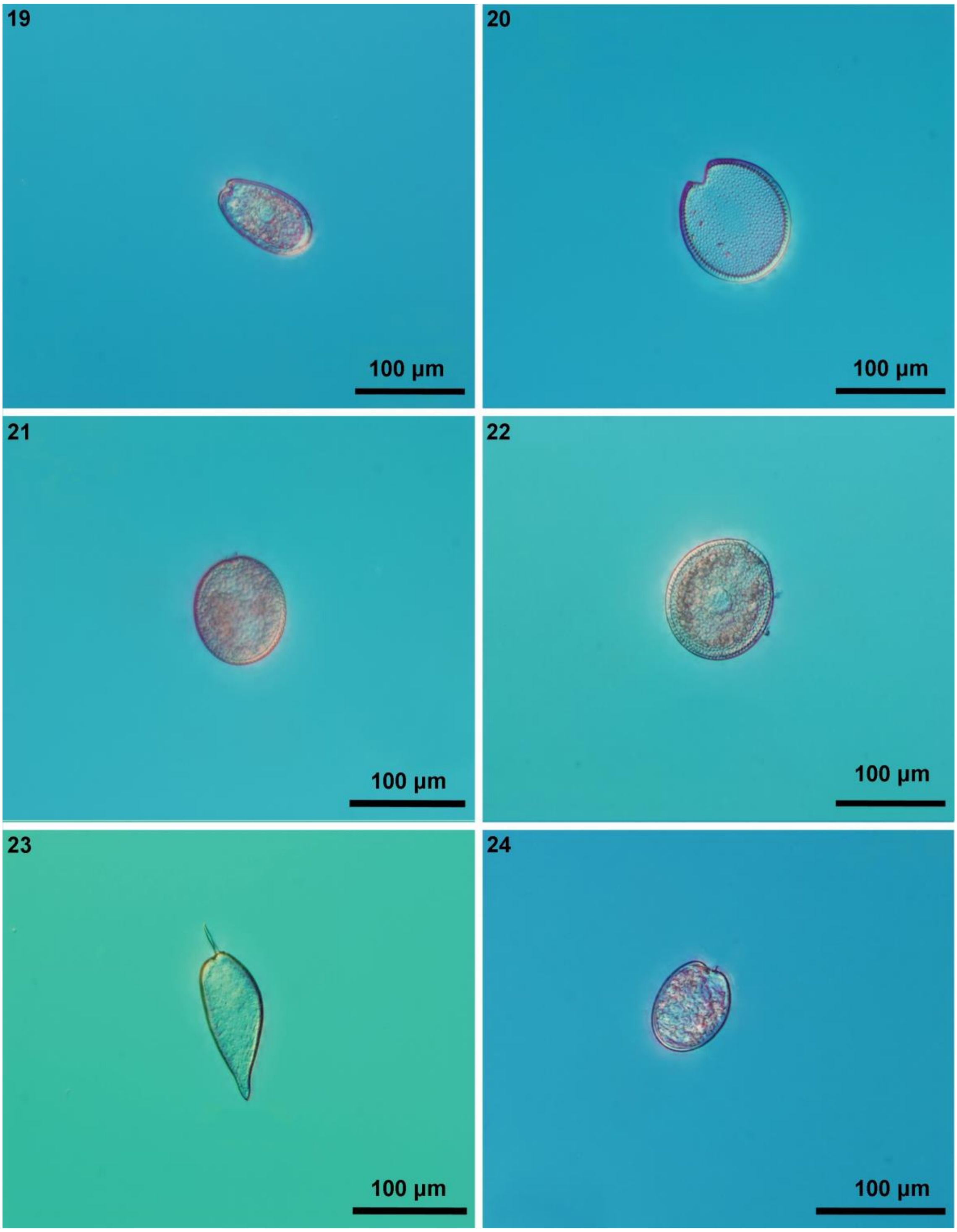

(Ochrophyta) 01 – *Dictyocha fibula*; 02 – *Lampriscus orbiculatum*; 03 – *Podocystis adriatica*; 04 – *Rhabdonema adriaticum*; 05 – *Rhizosolenia* sp.; 06 – *Trachyneis aspera*



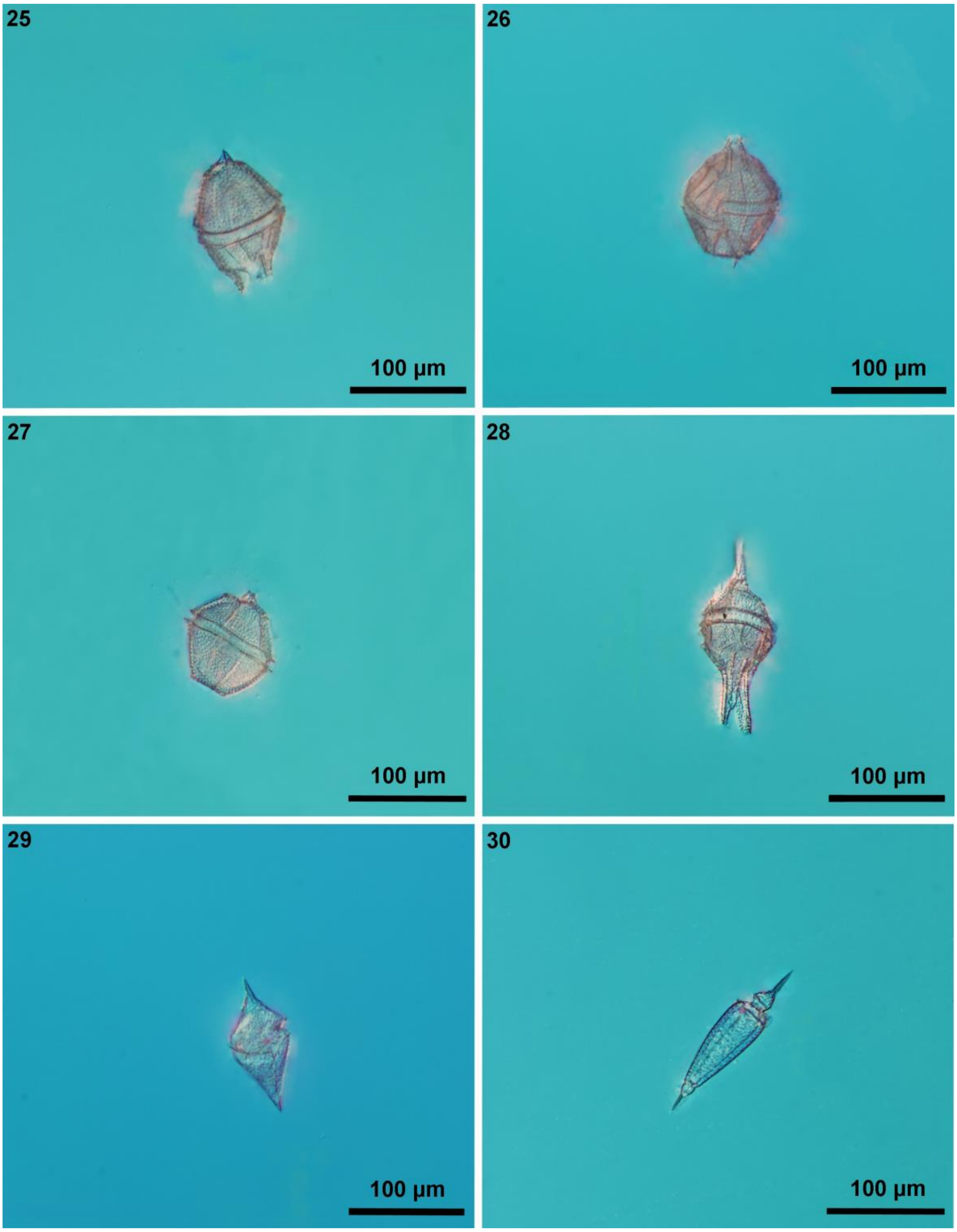

07 – *Planktoniella sol*; 08 – *Climacosphenia elongata*; (Cyanobacteria) 09 – *Trichodesmium thiebautii*; 10 – *Richelia intracellularis*; (Dinophyta) 11 – *Ornithocercus magnificus*; 12 – *Ornithocercus quadratus*



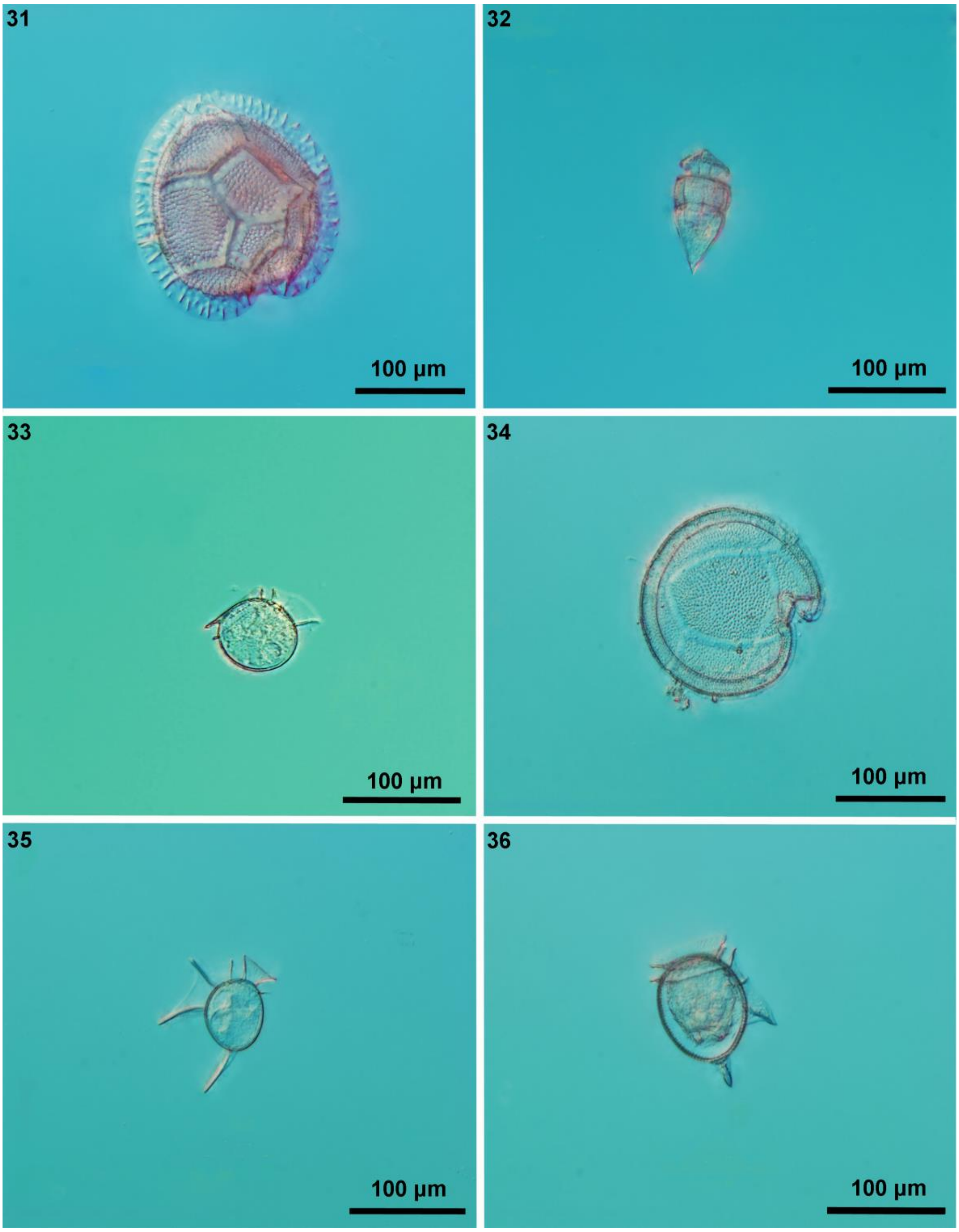

13 – *Podolampas palmipes* (vista lateral); 14 – *Podolampas palmipes*; 15 – *Podolampas bipes*; 16 – *Protoperidinium pyriforme*; 17 – *Protoceratium reticulatum*; 18 – *Ostreopsis ovata*



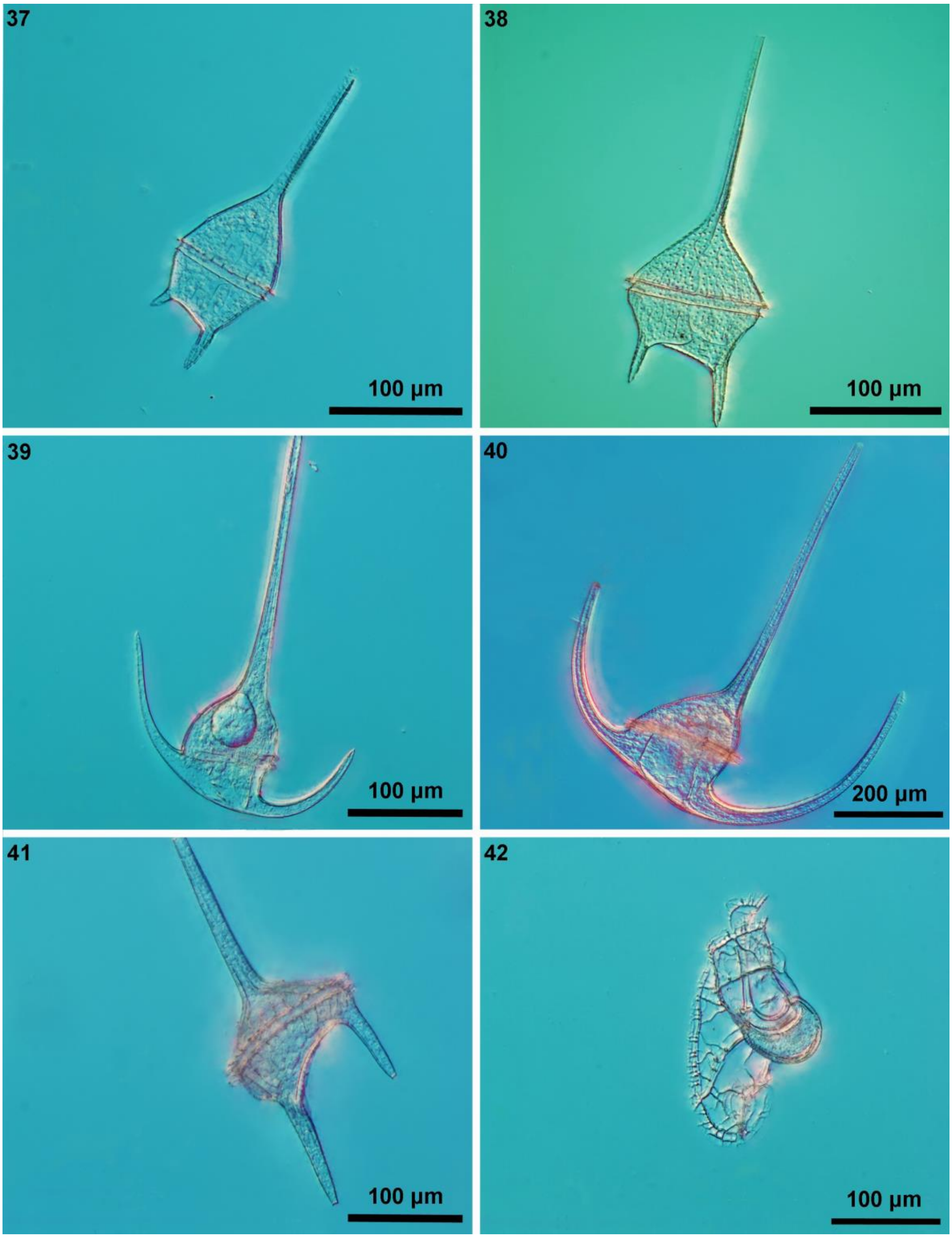

19 – *Prorocentrum lima*; 20 – *P. emarginatum*; 21 – *P. balticum*; 22 – *P. hoffmannianum*;
23 – *P. gracile*; 24 – *P. mexicanum*




25 – *Gonyaulax spinifera*; 26 – *Gonyaulaxpolygramma*; 27 – *Gonyaulax polyedra*;
28 – *Gonyaulax birostris*; 29 – *Oxytoxum milneri*; 30 – *Oxytoxum scolopax*




31 – *Goniodoma polyedricum*; 32 – *Corythodinium constrictum*; 33 – *Phalacroma rotundatum*; 34 – *Pyrophacus* sp.; 35 – *Dinophysis schuettii*; 36 – *Dinophysis hastata*




37 – *Neoceratium teres*; 38 – *N. pentagonum*; 39 – *N. declinatum*; 40 – *N. tripos*;
41 – *N. candelabrum*; 42 – *Histioneis hippoperoides*