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UNIVERSIDADE FEDERAL FLUMINENSE
PROGRAMA ASSOCIADO DE PÓS-GRADUAÇÃO EM BIOTECNOLOGIA MARINHA

FÁBIO CONTRERA XAVIER

ASSINATURA BIOACÚSTICA DE COSTÕES ROCHOSOS: CARACTERIZAÇÃO, MODELAGEM E APLICAÇÕES BIOTECNOLÓGICAS

ARRAIAL DO CABO/RJ

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Tese de doutorado apresentada ao Instituto de Estudos do Mar Almirante Paulo Moreira e à Universidade Federal Fluminense, como requisito parcial para a obtenção do grau de Doutor em Biotecnologia Marinha.

Orientador: Prof. Dr. Leandro Calado
Coorientador: Prof. Dr. Sérgio M. Jesus
Coorientador: Prof. Dr. Alexandre Dias Kassuga

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Arraial do Cabo/RJ, **10 de Maio de 2021**.

À todas as vítimas do negacionismo espalhadas pelo Brasil,
em especial, ao meu amigo Daniel Campbell (*in memoriam*).

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RESUMO

A Paisagem Acústica Submarina (PAS) tem sido estudada por diversas instituições de pesquisa ao redor do mundo. A PAS é dividida em três parcelas: biofonia (sons de origem biológica, ex: golfinhos, peixes, camarões, etc), geofonia (sons de origem ambiental, ex: ondas, vento, chuva, etc) e antropofonia (sons de origem humana, ex: barcos, plataformas, etc). A biofonia é uma parcela que contempla sons complexos que ocupam uma faixa de frequência muito larga. Em áreas costeiras, os sons produzidos por invertebrados bentônicos podem ser bastante representativos. Assim, quando muitos organismos estão ativos em um determinado ambiente marinho, os sons se fundem em um sinal cadenciado, formando um coro bioacústico. Porém, cada ambiente marinho possui assinatura acústica local, que é importante para os processos ecológicos locais. Entretanto, os fatores abióticos podem modular essa assinatura ao longo do dia. Nesse sentido, a modelagem dessa assinatura fornece uma visão mais detalhada sobre os efeitos causados pelo meio, tornando possível a avaliação mais detalhada da mesma. Assim, este estudo investiga a influência de fatores abióticos sobre a assinatura bioacústica de costões rochosos da região da Ilha do Cabo Frio, Arraial do Cabo – RJ. Esta investigação parte de fatores abióticos mais representativos na área de estudo, como a Ressurgência, aos fatores que governam a vida marinha, como luz, marés e ciclos circadianos. Usando os conjuntos de dados acústicos existentes, e relacionando-os aos fatores abióticos disponíveis, foi desenvolvido um modelo que explica aproximadamente 62% da variância da assinatura bioacústica local a partir da contribuição dos fatores abióticos. Este modelo pode facilitar o desenvolvimento de aplicações biotecnológicas ambientais, usando técnicas de bioacústica, para medição de dados abióticos, estimação de densidade populacional de organismos bentônicos e monitoramento eficiente de ecossistemas marinhos.

Palavras-chaves: Paisagem acústica, monitoramento acústico passivo, ecologia acústica, modelagem acústica, biotecnologia ambiental.

ABSTRACT

The marine soundscape has been studied by several research institutions around the world. This soundscape is divided in three parts: biophony (sounds of biological origin, e.g. dolphins, fishes, shrimps, etc.), geophony (sounds of environmental origin, e.g. waves, wind, rain, etc.), and anthropophony (sounds of human origin, e.g., ships, platforms, etc.). Biophony is a part that includes complex sounds that take a very wide frequency range. In coastal areas, the sounds produced by benthic invertebrates might be quite representative. Thus, when many organisms are active in a given marine environment, the sounds merge into a timed signal, forming a bioacoustic chorus. However, each marine environment has its own acoustic signature, also important for local ecological processes. This signature might suffer a strong influence from abiotic factors throughout a day. In this sense, the modeling of this signature provides a more detailed view of the effects caused by the environment, making it possible to make a more detailed assessment of it. Thus, this study investigates the influence of abiotic factors on the bioacoustic signature of rocky shores off the Cabo Frio Island, Arraial do Cabo - RJ. This investigation starts from abiotic factors more representative in the study area, such as the upwelling phenomenon, to factors that drive marine life, as light, tide, and circadian cycles. Using the acoustic datasets and relating them to the available abiotic factors, a model was developed relating acoustics data to main abiotic factors, and it explained approximately 62% of the local bioacoustic signature variance. This model might have several applications, such as developing of environmental biotechnological techniques using bioacoustic approach to estimate benthic organisms population density as well as provide efficient monitoring of marine ecosystems.

Key-words: Marine soundscape, passive acoustic monitoring, acoustic ecology, acoustic modelling, environmental biotechnology.

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SUMÁRIO

1 INTRODUÇÃO

Os oceanos são peças-chave para a vida no planeta. Eles regulam o clima, fornecem alimento, energia, além de diversos materiais. Cobrindo cerca de 70% da superfície terrestre, eles atuam como uma das principais vias de transporte do mundo (MOONEY et al., 2020). Porém, fatores como as mudanças climáticas, a poluição e a degradação dos habitats têm ameaçado bastante este ambiente (CLAUDET et al., 2020). Com o intuito de minimizar e solucionar tais problemas, a comunidade científica e outros setores organizaram um movimento social que culminou na proclamação da Década da Ciência Oceânica para o Desenvolvimento Sustentável de 2021 a 2030, pela Organização das Nações Unidas (VISBECK, 2018). Dentre os objetivos principais da "Década do Oceano", destaca-se o incentivo para o desenvolvimento de sistemas de monitoramento ambiental marinho sustentáveis que facilitem o aumento do conhecimento sobre os oceanos (CLAUDET et al., 2020).

O monitoramento ambiental é essencial para conservação, preservação e restauração dos ecossistemas marinhos (COSTELLO et al., 2017). De acordo com Bean et al. (2017), existem duas categorias básicas de monitoramento do ambiente marinho: (1) utilizando uma plataforma para realizar a medição, como: navios de pesquisa ou veículos autônomos; ou (2) utilizando um sensor ou método para realizar a medição, como uma câmera no fundo do mar ou um censo visual realizado por um mergulhador, entre outras. Entretanto, grande parte das tecnologias utilizadas para o monitoramento ambiental não são sustentáveis ou são bastante invasivas, o que pode, em muitos casos, ser mais um custo do que um benefício para determinado habitat (WYNSBERGHE; DONHAUSER, 2018). Logo, é crucial o desenvolvimento de ferramentas menos invasivas para monitorar o meio ambiente e, principalmente, os ecossistemas marinhos.

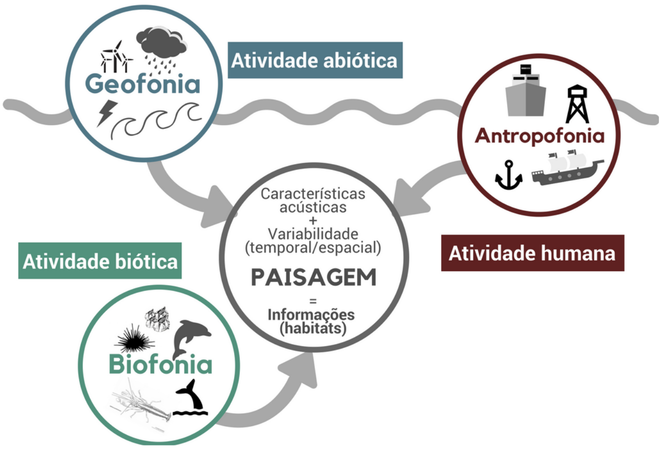
Neste contexto, o monitoramento com foco na proteção do meio ambiente se torna uma ferramenta importante e inovadora para conservação e preservação dos oceanos. Este tipo de monitoramento está dentro de uma área emergente chamada Biotecnologia Ambiental que consiste no desenvolvimento, uso e regulação de sistemas biológicos para aplicações (produtos ou serviços) nas áreas de biorremediação, produção de biopesticidas, biofertilizantes, bioplásticos e monitoramento ambiental (SINGH, 2017). As aplicações desta área servem tanto para ambientes terrestres como aquáticos. A Biotecnologia Ambiental Marinha está presente em várias atividades de pesquisa quando se faz uso de um sistema biológico marinho para obter informações sobre o meio em que ele vive. Por exemplo, no ambiente marinho existem organismos bioindicadores de poluição, de biodiversidade, ecológicos e ambientais (PARMAR;

RAWTANI; AGRAWAL, 2016) que são recorrentemente utilizados pela comunidade científica. Porém, o processo de coleta de tais organismos pode ser bastante invasivo. Uma alternativa a estas coletas é o uso de técnicas de monitoramento remoto (sem contato) destes organismos.

Atualmente, diversos estudos têm mostrado que a observação de ecossistemas marinhos a partir do monitoramento acústico passivo (somente com gravações, sem emissões acústicas) é uma forma inovadora, menos invasiva e promissora de monitorar a saúde do ambiente marinho (MERCHANT et al., 2015; MIKSIS-OLDS; MARTIN; TYACK, 2018; HOWE et al., 2019). De acordo com Mooney et al. (2020), o baixo custo é uma importante vantagem frente aos outros métodos de monitoramento, pois permite que observações contínuas sejam realizadas em uma escala de tempo suficientemente grande para explicar determinados padrões do habitat. Ainda, de acordo com os autores, este tipo de monitoramento possui papel importante para a avaliação da biodiversidade marinha e sua conservação. Mas como o monitoramento acústico passivo e a biotecnologia ambiental marinha estão relacionados?

O ambiente marinho é rico em sons assim como o ambiente terrestre. Estes sons podem ser classificados como de origem abiótica (Ex: sons de chuva, ondas e ação dos ventos), biótica (Ex: crustáceos, cetáceos e peixes) e humana (navios, plataformas e outras atividades portuárias) (CAMPBELL, 2018). A união dos sons destas três componentes é chamada de Paisagem Acústica Submarina (Fig. 1). Essa paisagem acústica possui padrões temporais, sazonais, espectrais e espaciais que permitem extrair informações do ambiente em questão. Os sons de origem biológica, especificamente, refletem diversos processos vitais para os organismos, como: competição, alimentação, forrageamento e desova (FARINA, 2013; MOONEY et al., 2020). O monitoramento acústico pode avaliar o comportamento desses organismos para extração de informações sobre eles e sobre o meio em que vivem. Consequentemente, podem ser desenvolvidos produtos e serviços (baseados em características bioacústicas) para medição de parâmetros abióticos e bióticos que auxiliem na avaliação da saúde do ambiente marinho (FARINA, 2019). Logo, pode-se dizer que esta aplicação faz parte da área de Biotecnologia Ambiental Marinha de acordo com sua definição.

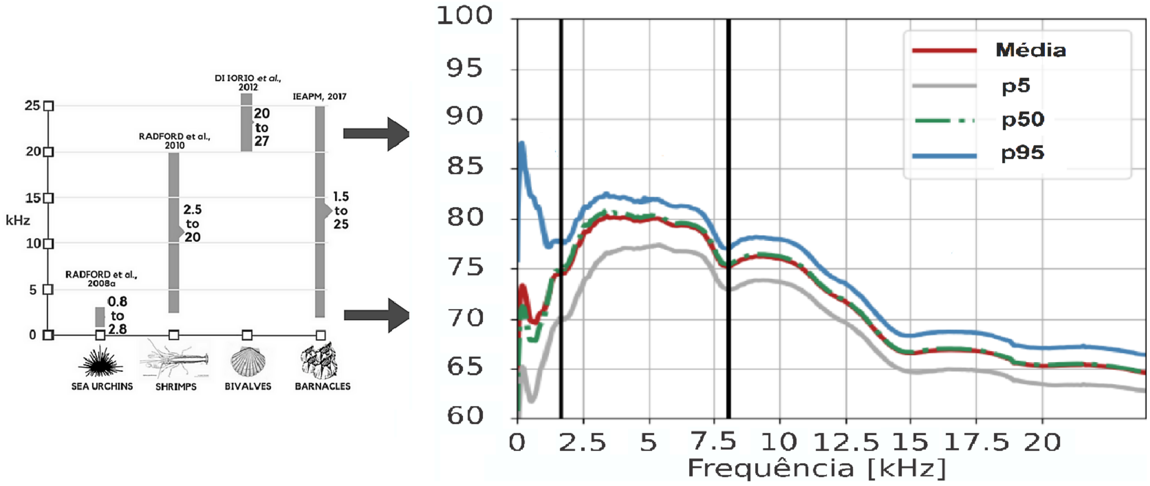
FIGURA 1 – Elementos da Paisagem Acústica Submarina e suas principais características [Retirada de (CAMPBELL, 2018)].



Em zonas costeiras, por exemplo, sons como cliques e estalos produzidos pela fauna bentônica (como crustáceos, equinodermos, bivalves) podem ser bastante representativos na paisagem acústica (BUTLER; BUTLER IV; GAFF, 2017). Estes sons podem ser provocados simplesmente pelo movimento dos organismos sobre o substrato, pela estridulação/fricção das partes duras dos seus corpos ou pela circulação da água por eles (SIMMONDS; MACLENNAN, 2008; LILLIS; PERELMAN et al., 2017). Assim, quando muitos organismos estão ativos em um determinado ambiente marinho, os sons se fundem em um sinal cadenciado, formando um coro bioacústico (FARINA, 2013). De acordo com Radford, Stanley, Tindle et al. (2010) e Radford, Stanley e Jeffs (2014), os ambientes marinhos têm diferentes assinaturas acústicas e essas assinaturas são importantes para os processos ecológicos. De forma análoga, nesta tese, refere-se ao coro bioacústico da fauna bentônica como Assinatura Bioacústica do Costão Rochoso ou Assinatura Bioacústica Local (Fig. 2).

A assinatura bioacústica de ecossistemas marinhos pode ser útil desde a estimativa de densidade populacional de crustáceos (BUTLER; BUTLER; GAFF, 2016) à avaliação da biodiversidade de peixes e outros invertebrados marinhos (MOONEY et al., 2020). Entretanto, essa assinatura é bastante influenciada por fatores abióticos, como variações de temperatura, luminosidade, maré, fases da lua e estações do ano (BOHNENSTIEHL; LILLIS; EGGLESTON, 2016; MCWILLIAM et al., 2017; LILLIS; MOONEY, 2018). Esses fatores podem alterar essas assinaturas e dificultar o uso das mesmas como parâmetro para avaliação de habitats por métodos acústicos. Além disso, em águas rasas, essas assinaturas podem ser afetadas por pequenas mudanças nas condições de propagação acústica. Por exemplo, a mudança de temperatura provocada pelo fenômeno da ressurgência costeira (afloramento de águas frias na superfície) pode influenciar a propagação do som causando zonas de sombra e, consequentemente, grandes atenuações (CALADO et al., 2018). Mooney et al. (2020) frisam em seu

FIGURA 2 – Exemplo, meramente ilustrativo, de composição do coro bioacústico (esquerda) e de assinatura bioacústica local (direita).



trabalho que ,para evolução das técnicas de avaliação de biodiversidade baseadas em métodos acústicos, é necessário um maior entendimento sobre a variabilidade temporal e principais influências que este coro bioacústico sofre, além de outros aspectos relacionados à propagação acústica.

Assim, este estudo pretende investigar a influência de fatores abióticos sobre a assinatura bioacústica de costões rochosos da região da Ilha do Cabo Frio, Arraial do Cabo – RJ. Esta investigação parte de fatores abióticos mais representativos na área de estudo, como a Ressurgência, chegando aos fatores que governam a vida marinha, como luz solar, marés e ciclos circadianos. Usando os conjuntos de dados acústicos existentes e relacionando-os aos dados disponíveis destes fatores abióticos, pretende-se compreender melhor a assinatura bioacústica de costões rochosos, assim como suas variações ao longo do tempo. Para isso, é necessária a proposição de um modelo que explique a contribuição dos fatores abióticos e suas periodicidades. E, ainda, que permita o desenvolvimento de aplicações biotecnológicas que possam ser utilizadas no monitoramento ambiental marinho baseadas em bioacústica.

Este trabalho está dividido em 5 capítulos: o primeiro faz uma introdução geral sobre o monitoramento acústico passivo como ferramenta biotecnológica, o segundo capítulo apresenta os objetivos do trabalho, o terceiro e quarto capítulo estão em formato de artigo e avaliam a influência da ressurgência na assinatura bioacústica local e o desenvolvimento de um modelo baseado em fatores abióticos para assinatura bioacústica e, por fim, o quinto capítulo apresenta as principais conclusões deste estudo, assim como algumas sugestões para trabalhos futuros.

2 OBJETIVOS

2.1 OBJETIVO GERAL

Propor um modelo temporal para a paisagem acústica submarina, com ênfase na assinatura bioacústica de costões rochosos da região da Ilha do Cabo Frio, Arraial do Cabo – RJ.

2.2 OBJETIVOS ESPECÍFICOS

- Caracterizar a assinatura bioacústica local em termos espectrais e temporais;
- Avaliar a influência dos fatores abióticos na assinatura bioacústica local;
- Avaliar o padrão de variação diária da assinatura bioacústica local;
- Propor um modelo temporal para a assinatura bioacústica local.

3 THE INFLUENCE OF UPWELLING EVENTS ON BIOACOUSTIC SIGNATURE IN SUBTROPICAL ROCKY SHORES

Abstract: In rocky shores, snaps, clicks, and crackles produced by benthic fauna yield a rocky shore bioacoustic signature that can be quite representative of the soundscape. This work aims at characterizing this signature and evaluating its relationship with a sustained upwelling regime. A sound propagation model was utilized to evaluate the transmission loss from biological sources distributed along the rocky shore during upwelling events. A hydrophone and a temperature sensor were installed near Cabo Frio Island, Brazil, continuously recording data for three months. The results show that the bioacoustic signature decreases during upwelling due to both a lowering of source level caused by a diminishing of the bioacoustic activity and an increase of transmission loss due to the acoustic barrier formed by cold water. There is significant difference of bioacoustic activity between upwelling and non-upwelling moments. The relationship between temperature and rocky shore bioacoustic signature can contribute to the understanding of the organisms' behavior concerning the upwelling and the development of novel passive biological sensing techniques.

Keywords: Upwelling, Acoustic ecology, Marine soundscape, and Environmental biotechnology.

3.1 INTRODUCTION

Rocky shores are ecosystems formed by outcrops of crystalline rocks and are considered the transition zone between land and the marine environment. Although rock formations can be found along practically the entire Brazilian coast, true rocky shores (rocky structures that extend from the seabed to just above the water surface) occur almost exclusively in the South and Southeast regions (COUTINHO et al., 2016). According to local characteristics, these environments have a distribution pattern of organisms in horizontal bands, due to the influence of biotic (e.g. predation, competition) and abiotic (e.g. temperature, tides, wave exposure) factors. Furthermore, rocky shores are dynamic environments and sustain a high richness of species (ZAMPROGNO; FERNANDES; FERNANDES, 2012; COUTINHO et al., 2016), mainly in upwelling regions, due to nutrient-rich outcropped waters (BOSMAN; HOCKEY; SIEGFRIED, 1987).

The rocky shore sustains organisms of ecological and economic importance, such as urchins, shrimps, mussels, barnacles, and reef fishes (AUED et al., 2018). For instance, the urchin is one of the main herbivores inhabiting these ecosystems (SUSKIEWICZ; JOHNSON, 2017). Also, these organisms can provide microhabitats, influencing on the abundance and distribution of several species of reef fishes (GIGLIO et al., 2018). During feeding, they produce sounds that resonate in their calcareous skeletons and can be considered one of the organisms with the highest contribution to bioacoustic choruses (RADFORD, C. et al., 2008). Snapping shrimps (Alpheidae Family) are other common inhabitants in rocky shores. Snapping shrimp clicks are a persistent sound in the shallow water habitat of temperate and tropical regions (AU; BANKS, 1998; MCWILLIAM et al., 2017). Although there is little variation during the day, this sound can significantly increase or decrease with water temperature and seasonal events (BOHNENSTIEHL; LILLIS; EGGLESTON, 2016; MCWILLIAM et al., 2017).

In coastal zones, snaps, clicks, pops and crackles produced by benthic fauna (as crustaceans, echinoderms, bivalves) can be quite representative of the soundscape (BUTLER; BUTLER IV; GAFF, 2017). This sound can be caused simply by their movement on the substrate, by the stridulation/friction of the hard parts of their bodies or by water circulation (SIMMONDS; MACLENNAN, 2008; LILLIS; PERELMAN et al., 2017). Thus, when many organisms are active in a given marine environment, the sounds merge into a timed signal, forming a bioacoustic chorus (FARINA, 2013). According to Radford, Stanley, Tindle et al. (2010) e Radford, Stanley e Jeffs (2014), marine environments have different acoustic signatures and these signatures are important for ecological processes. Likewise, in this work, we refer to the rocky shore benthic fauna bioacoustic chorus as Rocky Shore Bioacoustic Signature (RSBS).

In shallow water, the RSBS can be highly affected by small changes in acoustic propagation conditions. Shallow water propagation is influenced mainly by the sound speed profile, sea surface roughness and the geometric and geoacoustic characteristics of the seabed. According to Calado et al. (2018), upwelling may influence acoustic propagation causing shadow zones and consequently large sound attenuation.

Thereby, to understand the relationship between water temperature and bioacoustic patterns, this work aims at characterizing the RSBS and at evaluating its relationship with a sustained upwelling regime. An interesting relationship between the upwelling phenomenon and the RSBS is presented together with sound propagation analysis based on three months of acoustic and temperature data recordings from Cabo Frio Island, Brazil. It is shown that the RSBS level is strongly transmission loss dependent due to upwelling which, in turn, also decreases biological activity. These results are significant to a better understanding of the organisms' behavior and to the development of novel passive biological sensing techniques. Therefore, the RSBS can be used to monitor the marine environment's health, since it represents the natural pattern, based on *in situ* measurements, in the region of interest.

This paper is structured as follows: section 3.2 introduces the phenomenon of Cabo Frio coastal upwelling and its local importance; section 3.3 describes the material and methods used to evaluate the relationship between the RSBS and upwelling; section 3.4 presents the results obtained and section 3.5 closes with a discussion and conclusions.

3.2 THE CABO FRIO COASTAL UPWELLING

The study area is located in the Marine Extractive Reserve of Arraial do Cabo (Cabo Frio region, 22° 58'46"S, 42° W), state of Rio de Janeiro, Brazil. It is considered the point of greatest frequency and intensity of coastal upwelling in Brazil (MIRANDA, 1985). Coastal upwelling is an oceanographic process, which consists in the outcrop of deeper and cooler water to the surface of the ocean.

Cabo Frio coastal upwelling occurs due to coastal geomorphological characteristics and local wind regimes (Fig. 3). The persistence of northeast winds (continuously blowing parallel to the coast for a few days), mainly during spring and summer, leads to the withdrawal of the Coastal Water and the outcrop of the South Atlantic Central Water (CALADO et al., 2018; CASTELAO; BARTH, 2006). This water mass, characterized by temperatures lower than 20°C and salinity range of 34.3-36 (MIRANDA, 1985), is rich in nutrients and increases the primary productivity in the region (VALENTIN; COUTINHO, 1990).

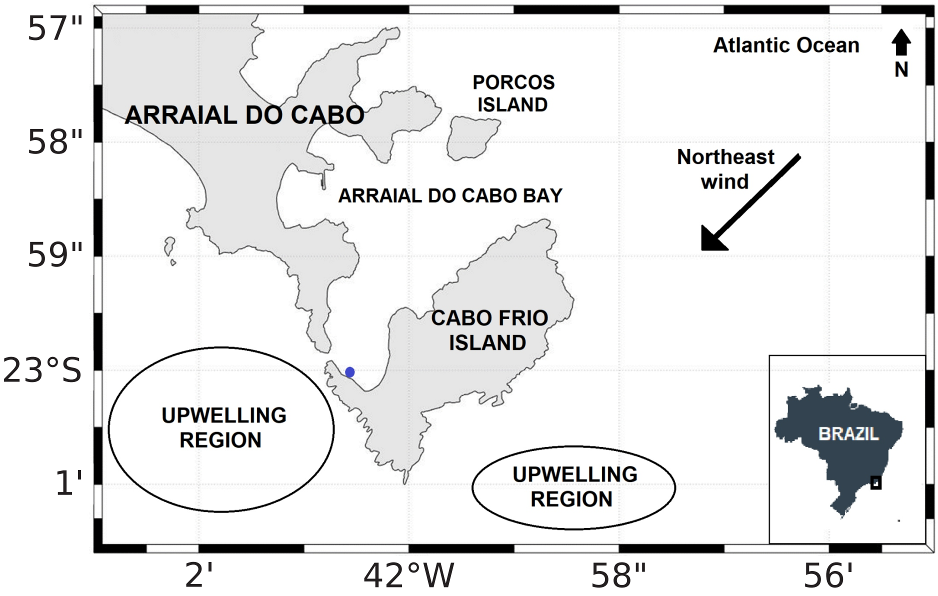
Due to geomorphological characteristics, the Cabo Frio region sustains a unique reef system favored by the hydrodynamic regimes (FERREIRA, 2003). As shown in Fig. 3, the inflection of Arraial do Cabo coast (RODRIGUES; LORENZZETTI, 2001), Cabo Frio and Porcos islands separate the region into two environments of distinct features. The external environment, exposed to the cold waters from the upwelling phenomenon, supports a subtropical community. The internal part of the coast (Arraial do Cabo Bay) suffers influence from upwelling and, therefore, supports a tropical fauna and flora (FERREIRA, 2003; GUIMARAES; COUTINHO, 1996).

3.3 MATERIAL AND METHODS

3.3.1 Experimental setup

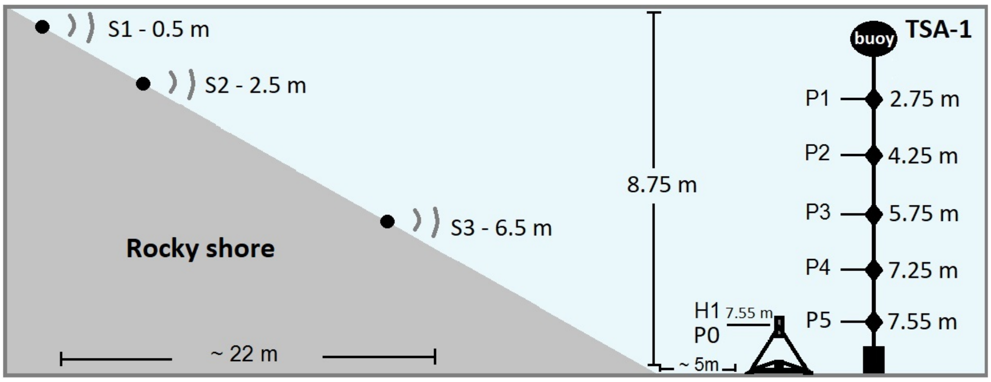
Fig. 4 shows the experimental setup, including an artistic drawing of the rocky shore with approximate dimensions. An acoustic recorder system (H1) (digitalHyd TP1-4A Marsensing Lda) was deployed on a bottom stand at 7.55 m depth, near Cabo Frio Island. The recording stand was at a distance of 5 m from the rocky shore base, where local water depth was 8.75 m. The acoustic recorder was configured with a sampling frequency of 52,734 Hz, has a resolution of 24 bits and a sensitivity of -174.9 dB re 1V/1μPa with a flat response between 100 Hz and 40 kHz. Acoustic recordings were performed from February 8 to April 30, 2018, totaling 82 days at a duty cycle of 20% (1

FIGURA 3 – The study area is located in the Arraial do Cabo Bay, state of Rio de Janeiro, in southeastern Brazil. The map shows the region of upwelling occurrence, and the acoustic acquisition system position, in a bay of Cabo Frio Island (blue dot).



every 5 minutes). Power and data transmission were provided through a cable to a shore facility. A temperature sensor (P0) (Hobo Pendant from Onset Computer Corporation) was deployed on the acoustic recorder structure, collecting data at a rate of 1 sample every 10 minutes. To better understand the relationship between the RSBS and the upwelling regime, from January 16 to 18, 2019, a Temperature Sensor Array (TSA-1) was installed nearby the acoustic monitoring station, as shown in Fig. 4. The TSA-1 was composed of 5 data-loggers (P1-P5) (Hobo Pendant) with a 1/15 min sampling rate,

FIGURA 4 – Drawing of the experimental setup near the rocky shore: a 1 m height stainless steel tripod holds one hydrophone (H1) and one temperature sensor (P0) at approximately 5 m from the base of the rocky shore; and a vertical temperature recording chain (TSA-1) with five sensors (P1-P5) distributed between 2.75 and 7.55 m depth. The three dots S1-S3 represent biological sound sources for acoustic propagation modelling purpose (see section 3.3.4).



and distributed along the water column at the depths indicated.

3.3.2 Acoustic analysis

The signals were filtered through an elliptic (Cauer) filter in [0.1, 1.5] kHz (band A), [1.5, 8] kHz (band B) and [8, 24] kHz (band C). The Power Spectral Density (PSD) $P_{d,m}(f_n)$ is estimated by the Welch's method (W), for each minute m as:

$$P_{d,m}(f_n) = W\{y_{d,m}[k]\}, \tag{3.1}$$

where $y_{d,m}[k]$ is the recorded time series for minute m and day d, and f_n is the n-th frequency bin. The spectral parameters were: discrete Fourier Transform block size of 2048, an overlap of 50%, and a Hanning window. The RSBS PSD for each band b, day d and minute m, is given by:

$$P_b(d, m) = 10 \log_{10} \sum_{n=1}^{N} P_{d,m}(f_n), \tag{3.2}$$

where, b represents the frequency band (A, B or C) and N is the number of frequency bins in a given band. Also, in order to characterize the RSBS PSD over the full frequency band (0.1 Hz to 26,367 kHz), a PSD estimate was calculated as the average and percentiles (5th, 50th, and 95th) received power over the entire monitoring period (82 days).

3.3.3 Statistical analysis

The RSBS and the water temperature data were checked for their normal distribution and eventual linear relationship. Since the RSBS and the temperature data did not meet these criteria (based on the Shapiro-Wilk test), they were correlated using the Spearman method.

For RSBS analysis during upwelling, a detector and a counter of upwelling events were developed, based on a threshold for upwelling presence, as proposed in (MIRANDA, 1985). Whenever the water temperature was lower than 20°C for at least one hour, one event was counted. For each upwelling event, acoustic data were used to calculate the RSBS amplitude during the same period, i.e., for 10 upwelling events, we have 10 RSBS datasets. Then, the maxima, minima, mean and standard deviation of these RSBS PSD datasets were calculated.

In order to investigate whether the influence of the upwelling in the RSBS was significant, the Mann-Whitney U test was used between upwelling and non-upwelling moments, because the datasets did not meet the normal distribution and homoscedasticity of error assumptions. As upwelling moments (840 minutes) were less numerous than non-upwelling moments ($>$ 16,000 minutes), a Monte Carlo method for calculating the p-value was applied. This calculation was based on one million random subsamples of 840 minutes in the RSBS data during non-upwelling and thereafter the mean p-value was determined. This method provides greater consistency in the p-value calculation, especially when the samples are of different sizes. All calculations in this paper were performed using Python language and its scientific computing modules.

3.3.4 Bioacoustic propagation modelling

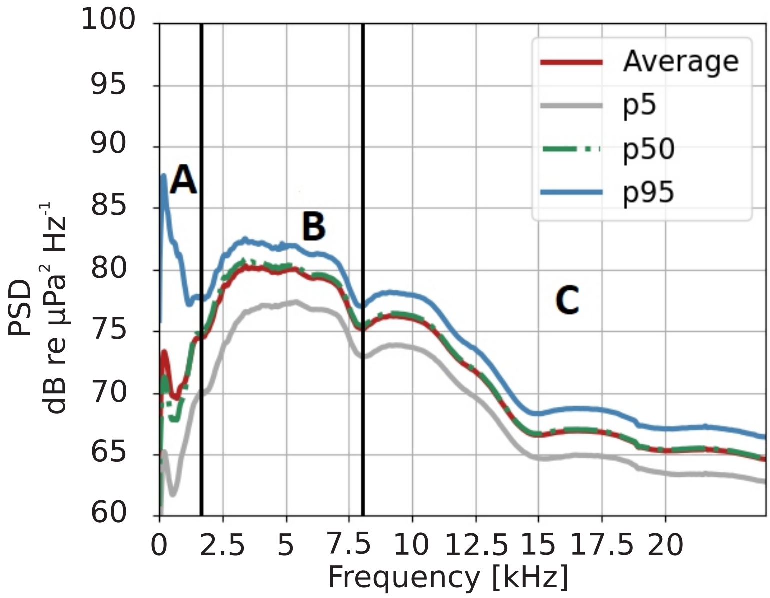
The simulated Transmission Loss (TL) was performed to evaluate the propagation conditions during the upwelling regime. The BELLHOP acoustic propagation model (PORTER, 2011) was used in the simulation scenario depicted in Fig.4. Three sources (S1-S3) were considered to represent RSBS sources, positioned at the middle intertidal 0.5 m depth and at the the sublitoral 2.5 m and 6.5 m depth. As shown in Fig. 4, the range between the sources and the hydrophone were 26.8 m (S1), 20.3 m (S2) and 7.3 m (S3) and the distance from the water line to the hydrophone was 27 m. The sound speed profile was calculated from temperature collected by the TSA-1 array and a salinity value of 35 (MIRANDA, 1985), using the Chen-Millero equations (CHEN; MILLERO, 1977). For the bottom formed by the rocky shore, the geoacoustic properties for basalt based on (HAMILTON, 1980), where density is 2.7 g/cm^3, compressional velocity and attenuation are 5300 m/s and 0.02 dB/m, respectively, were used. The estimated TL endured by the RSBS, is given as the coherent summation of the transmission loss of each individual source S1, S2 and S3, at the hydrophone location.

3.4 RESULTS

3.4.1 Bioacoustic signature characteristics

The acoustic monitoring covered 82 days with a duty cycle of 20% resulting in 17,453 snapshots of one minute, totaling approximately 291 hours of data. The average RSBS PSD, *i.e.*, the PSD estimate taking into account the whole recording period, is shown in Fig. 5. This figure also shows the PSD level corresponding to the 5th, 50th and 95th percentiles, *i.e.*, the level under which the signal lies 5, 50 and 95% of the time, respectively. One can easily distinguish three frequency bands, named as A, B and C. In band A, the average RSBS PSD level is 70.9 dB with a standard deviation of 4.5 dB, and a minimum level of 53.2 dB and a maximum of 97.7 dB. This band is characterized by the highest signal level variability of the whole RSBS band. Fig. 5 also shows that most of the signal energy is concentrated in band B, between 2.5 and 7.5 kHz. The maximum occurs approximately at 3.5 kHz, and from there it only decreases through band C up to the maximum frequency of 24 kHz. For bands B and C, the average RSBS level is [77.8 dB, 67.8 dB] with [1.5 dB, 1.2 dB] of standard deviation, maxima of [85.8 dB, 72.3 dB] and minima of [69.9 dB, 59.7 dB], respectively. The statistical analysis through

FIGURA 5 – Average RSBS PSD level for the whole recording period and its 5th, 50th and 95th percentiles, where band A is 0.1 to 1.5 kHz, band B is 1.5 to 8 kHz and band C is 8 to 24 kHz.



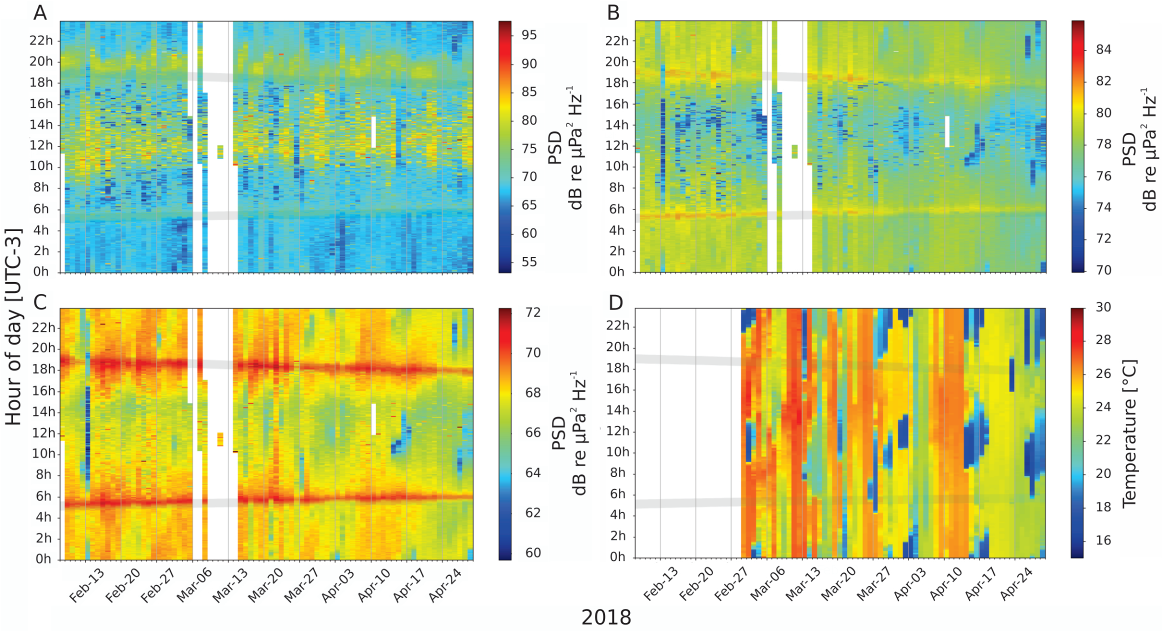
percentiles shows that from $\sim$ 1.5 kHz up the end of the frequency range, the difference between percentiles is small (approximately 5 dB between 5th and 95th percentiles), when compared to band A.

Fig. 6 shows the 24 hour daily pattern of the RSBS PSD along the y-axis for every day of the recording period for bands A, B and C in plots (A), (B) and (C), respectively, while plot (D) shows the same daily evolution of temperature in °C as recorded in sensor P0. In band A (Fig. 6-A) it is clear that the RSBS PSD increases around twilight (after dawn and dusk) possibly due to fish choruses, although at dusk this acoustic power increase is more intense than at dawn. In this band, most of the energy is concentrated during day hours due to boat movement in the bay and, therefore, band A is named the anthropogenic noise band. As shown in Figs. 6-B and 6-C, for bands B and C, the RSBS PSD also presents a daily pattern (dusk/dawn peaks) with a power increase in the night time and decrease during the day.

3.4.2 Upwelling effects in bioacoustic signature

The correlation observed between RSBS PSD and temperature was of 0.09, 0.33 and 0.51 with a p-value $<$ 0.05, for bands A, B and C, respectively. Moreover, in Figs. 6-A, 6-B and 6-C, one can observe that the RSBS PSD decays abruptly at several moments along time, *e.g.* on April 14th, between noon and 23:00. These moments coincide with upwelling events, as it can be seen by visually superimposing Fig. 6-D with any of the Figs. 6-A, B or C. Considering 20°C as the lower threshold and a minimum

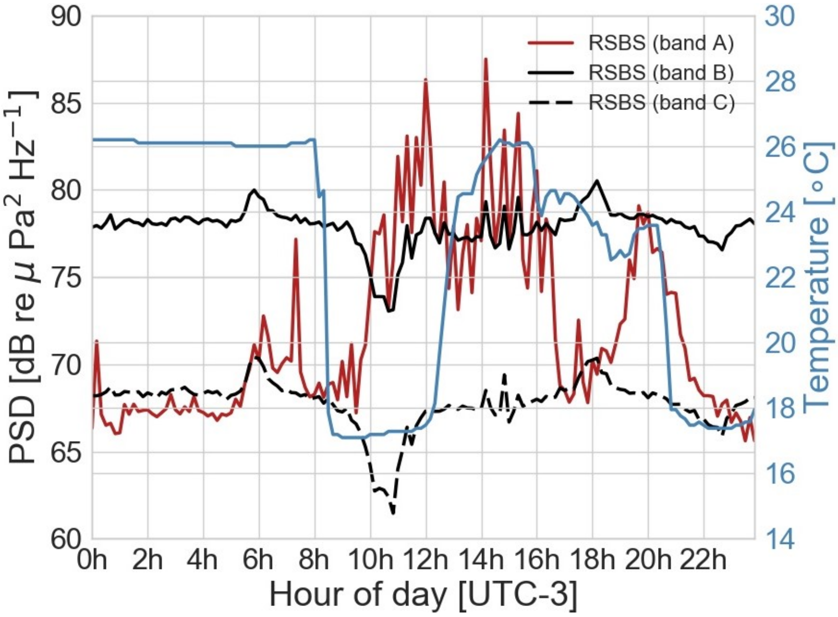
FIGURA 6 – RSBS PSD where y-axis represents hour of day [UTC-3] and x-axis represents the day over the 82 days for band A [0.1 to 1.5 kHz] (A), for band B [1.5 to 8 kHz] (B), for band C [8 to 24 kHz] (C), and for water temperature variation measured by temperature data-logger sensor attached to the acoustic system (D). Tuesdays are marked by vertical lines, dusk and dawn periods by gray stripes and data missing by white areas.



duration of 1 hour for upwelling occurrence, 36 upwelling events were recorded during 82 days. During these events, the RSBS PSD amplitude showed an average of [10.4 dB, 3.0 dB, 2.8 dB] with [5.8 dB, 1.9 dB, 1.8 dB] standard deviation and maxima of [22.9 dB, 8.7 dB, 7.0 dB], for bands A, B, and C, respectively. In these cases, upwelling occurrence is related to tidal current triggered by the low tide onset. This phenomenon occurs during light wind regime (soon after several days with strong Northeast wind) and it controls upwelling water in-out passage out from the Arraial do Cabo Bay.

Fig. 7 shows the detail of the RSBS PSD level and temperature variation on April 14th, 2018. In this day, at noon, it is possible to observe a decay of approximately 5 dB of the measured RSBS PSD on bands B and C during the upwelling event, which represents a variation twice as large as that observed in twilight periods. In opposite, the RSBS PSD in band A, shows a positive variation of about 10 dB which is linked to the contamination by anthropogenic noise (nautical tourism boats). The hypothesis that the RSBS PSD is upwelling-dependent for bands B and C was tested. The normality test (Shapiro-Wilk) evidenced that the data had a non-normal distribution (p-values $<$ 0.01). The Mann-Whitney U test (p-value $<$ 0.01 and freedom degree of 839) showed that there is a significant difference between the RSBS PSD acquired during upwelling and non-upwelling periods, for both bands B and C.

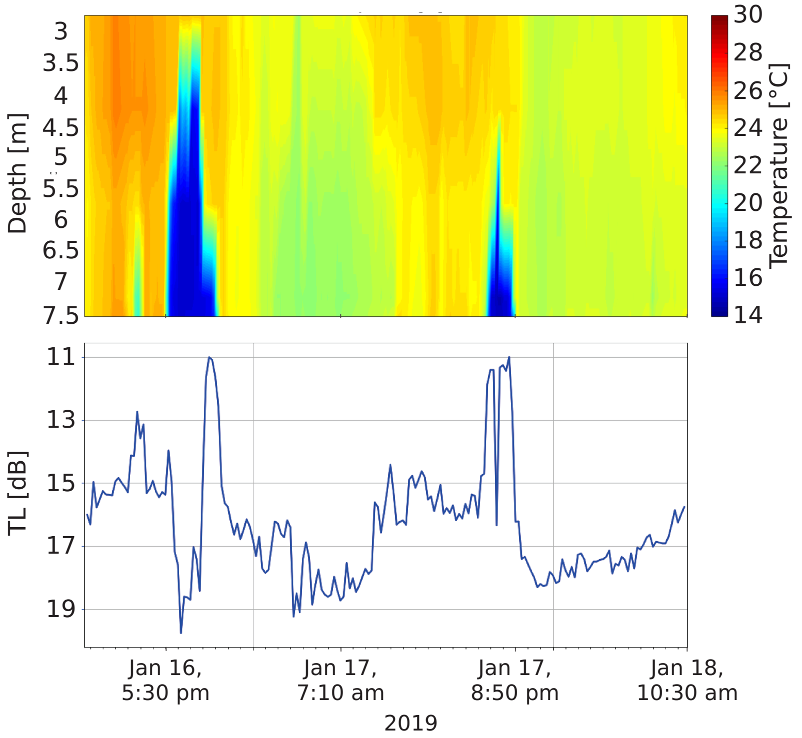
FIGURA 7 – RSBS PSD and temperature variation along hour of the day on April 14th, 2018: for band A (red line), for band B (black line), band C (dashed black line) left y-axis scale, and temperature (blue line) right y-axis scale.



3.4.3 Upwelling effects in sound propagation

As shown in Fig. 8, for January 16th to 18th, 2019, two upwelling events were recorded. The first event started Wednesday, January 16th at 5:30 pm, and lasted for 3.5 hours, with a minimum temperature of 15.1°C and 10°C of amplitude. The second event started Thursday, January 17th at 6:45 pm, and lasted for 2 hours, with a minimum temperature of 14.8°C and 9°C of amplitude. The two events occurred during low tide, at 5:23 pm and at 6:15 pm, respectively. As already seen in the previous analysis, upwelling in the bay is driven by tidal current. Fig. 8 (top) shows that these upwelling events stratified the water column in two layers: 3 m warm and 5 m of cold water in the first event, and 6 m warm and 2 m of cold water in the second event. The simulation shows that in the experiment time interval, the calculated TL (Fig. 8 bottom) between the rocky shore and the receiver location, has a maximum value of approximately 19.3 dB with a variation of approximately 4 dB, and was clearly modulated by the onset of cold water in the lower portion of the water column due to the water circulation in Arraial do Cabo Bay. After the first event, the water temperature increased in almost the entire water column, and at dawn/morning of day 17th, it dropped slightly (from approximately 25°C to 22°C) enough to lower the TL again. In the morning of January 17th (at 10 am, approximately), the water temperature turned back to 25°C and TL consequently decreased 2 dB (from approximately 18 dB to 16 dB). Before the second upwelling event, TL decreased by another 5.3 dB and during this second event (at 6.45 pm of January 17th), two layers are formed again and the TL increase was estimated to approximately

FIGURA 8 – Temperature collected by TSA-1 (Temperature Sensor Array with 5 elements) during January 16 to 18, 2019 (top). Transmission Loss calculated with the BELLHOP acoustic propagation model, initialized with the data collected by TSA-1 during January 16 to 18, 2019 (bottom), assuming 3 biological sources distributed along the rocky shore (see Fig. 4 for scenario details).



to 16.2 dB and it had a variation amplitude of approximately 5 dB.

3.5 DISCUSSION AND CONCLUSIONS

The term RSBS is introduced in this work to designate the sound produced by organisms that live in rocky shore. The RSBS has a daily pattern that decreases during daytime and increases in the nighttime, with peaks at dawn and dusk. A similar pattern was observed in Pacific coral reefs and it is attributed to snapping shrimp (BERTUCCI et al., 2016; KAPLAN; LAMMERS et al., 2018). However, from tropical to subtropical regions the abundance of sessile filter-feeders like barnacles and mussels increase in percent coverage in intertidal habitats (COUTINHO et al., 2016). This occurs especially because cold water from coastal upwelling seasonally influences the subtropical coast. Urchins are also very abundant and an important component of the subtropical coast (CORDEIRO; HARBORNE; FERREIRA, 2014). Thus, it is expected that these organisms have a major contribution to the RSBS in the Cabo Frio Island.

The activity of these benthic fauna components are significantly linked to water temperature changes because it regulates the speed of metabolic processes, presenting a positive correlation (BOHNENSTIEHL; LILLIS; EGGLESTON, 2016; BROTHERS;

MCCLINTOCK, 2015). For example, barnacles produce sounds by moving their calcareous plates to expose their cirrus for feeding and reproduction, and its cirrus activity is directly linked to temperature (SKINNER; NEVES SIVIERO; COUTINHO, 2007).

The RSBS PSD measured over 82 days of monitoring showed evident separation between the analyzed bands. In band A, below 1.5 kHz, the correlation between RSBS and water temperature was not significant due to the high interference caused by anthropogenic noise (CAMPBELL et al., 2019). As can be seen in Fig. 5 below 1.5 kHz, the 50th and 95th percentiles suggest that the high sound level variability occurs in lower than half of a day, i.e., sounds of high intensity (*e.g.* boat noise) are present in the soundscape during periods less than 12 hours. For example, at 170 Hz, there is a difference of 16 dB between the 50th and the 95th percentiles that is related to the fishing activity and the touristic boats traffic in the Arraial do Cabo Bay (CAMPBELL et al., 2019). There is another sound level increase around noon, that occurs due to the peak of nautical tourism traffic in the region (Fig. 6-A) (CAMPBELL et al., 2019). Furthermore, during the weekend there is also an increase in RSBS PSD level. For example, on February 12, there is a rise in RSBS level due to the Brazilian carnival period, where the number of nautical touristic trips to the beaches in the bay triples.

The RSBS PSD in bands B and C had higher correlations with temperature than band A. Band C has the highest correlation also due to the highest predominance of marine invertebrate related sound. This occurs because the main contributors near to coastal zones (LILLIS; MOONEY, 2018; KAPLAN; MOONEY et al., 2015) (invertebrates, as shrimps and urchins) to this signal produce the loudest and more frequent sound in this band (AU; BANKS, 1998; BORIE et al., 2015). In these bands, the RSBS is frequently characterized by an impulsive timed signal, i.e., signal rhythmic and quasi-continuous in time, frequently named as snapping shrimp noise (BOHNENSTIEHL; LILLIS; EGGLESTON, 2016; LILLIS; MOONEY, 2018). In addition, it is possible to observe several changes in the RSBS pattern that are probably related to changes in abiotic factors. Fig. 6-C shows that in March 23rd, the RSBS shows a high acoustic intensity for most of the day, this is related to luminosity because the day was cloudy and with a light pattern similar to twilight moments.

This study demonstrates that there is a significant impact of upwelling and non-upwelling moments on the RSBS. Fig. 7 clearly shows although with a time lag, that the RSBS decreases together with the temperature, but the RSBS does not remains at low levels for the whole period in which the upwelling cold water is present. During these upwelling periods, the availability of food increases and the water temperature decreases (VALENTIN; COUTINHO, 1990). These two factors represent the major influence on the behavior and physiology of marine invertebrates (BROCKINGTON; CLARKE, 2001). However, each benthic fauna component responds differently to water temperature changes, which may explain the time lag and the nonlinear relationship between the RSBS and the temperature decay, shown in Fig. 7.

Another interpretation is related to the high-density gradient caused by the upwelling phenomenon. For instance, in Fig. 8, the main difference between the two upwelling events was the water column extent of the cold water layer. This occurs because the relative TL in the second event was higher than in the first event, as shown by the simulations in Fig. 8. In addition, in the second event the cold water layer was smaller, resulting in a more stratified water column. These results evidence the presence of the cold water as an acoustic barrier forced by the high-density gradient between the two layers. Based on simulations, one can demonstrate that the RSBS decays are caused by 2 factors: (a) the acoustic barrier imposed by two-layer formation (CALADO et al., 2018), and (b) the interference pattern caused by biological sources position along the rocky shore and hydrophone position (on the seabed).

This work showed an interesting relationship between the upwelling phenomenon and RSBS, where the RSBS is modulated by the water temperature, decreasing level during cold water events. This level decrease occurs due to both the decrease of the RSBS source level and a high transmission loss. The low source level is caused by a decrease in the bioacoustic activity of benthic organisms probably due to metabolic rate decrease induced by cold water. The high TL is caused by an acoustic barrier generated by the stratification caused by the upwelling phenomenon. This relationship between temperature and RSBS may help to understand biologic patterns and their variation, as an important step towards the understanding of the organism's behavior. Also, it may help to the development of bioacoustic inversion applications for abiotic data measuring, the population density of benthic organisms and efficient marine health monitoring.

4 MODELLING THE BIOACOUSTIC SIGNATURE OF A SUBTROPICAL ROCKY SHORE

Abstract: Different coastal marine habitats have distinct acoustic signatures and might suffer a strong influence by the invertebrate bioacoustic chorus. This local bioacoustic signature and its patterns may reveal a core information about the ecosystem health. However, the local bioacoustic signature is strongly influenced by abiotic factors, such as temperature, light, sea level, and circadian, circatidal, circalunar cycles, and even seasonal variations. Thus, this study proposes a model for bioacoustic signature, based on data collected from a subtropical rocky shore off Cabo Frio Island, Brazil. Acoustic and abiotic data (temperature, light, sea level, wind speed and precipitation) were acquired near a rocky shore during 82 days. The bioacoustic signature model was based on a multiple regression using a mathematical model for bioacoustic circadian rhythm and the abiotic factors. Regression analysis show that temperature, light, sea level and bioacoustic circadian model explain approximately 62% of the bioacoustic signature variance. This model proved to be a good fit to investigate these patterns and their variations, and can also be applied to marine ecosystem health monitoring using bioacoustic inversion associated with abiotic data and population densities of benthic organisms.

Keywords: Temporal patterns, Bioacoustic modelling, Marine soundscape, Passive acoustic monitoring, and Environmental biotechnology.

4.1 INTRODUCTION

Most of marine benthic fauna produce sounds from behavioral characteristics, like movement, foraging, feeding, or reproduction (HAWKINS; POPPER, 2017; COQUEREAU et al., 2016). When several of these organisms, fish or invertebrates, produce sounds at the same time, the benthic bioacoustic chorus is formed (ERBE et al., 2015). Fish choruses occur approximately at dawn and dusk moments (PARMAR; RAWTANI; AGRAWAL, 2016). The choruses produced by invertebrates, like snapping shrimps, urchins, bivalves, and other groups unidentified, take place throughout the day, also with increasing close to dawn and dusk (FREEMAN et al., 2014; RADFORD, C. et al., 2008).

As different coastal marine habitats have distinct acoustic signatures and can be strongly influenced by invertebrate choruses, these sounds may reveal important information about the ecosystem health (KENNEDY et al., 2010; RADFORD; STANLEY; JEFFS, 2014). For instance, benthic bioacoustic chorus (or local bioacoustic signature) has ecological importance to the reef organisms, as an important orientation mechanism for fish and invertebrate larvae, to locate the appropriate environment for settlement (TOLIMIERI; JEFFS; MONTGOMERY, 2000; SIMPSON et al., 2011; LILLIS; BOHNENSTIEHL; EGGLESTON, 2015).

Due to its temporal, spatial, spectral, and seasonal features, each habitat worldwide has unique but similar bioacoustic patterns. For example, McWilliam et al. (2017) reported six different patterns of fish choruses on coral reefs in the Great Barrier Reef, in each one was also reported in the southern Atlantic Sanchez-Gendriz e Padovese (2017). Similarly, several acoustical surveys show two patterns of benthic invertebrates, one with more active at nighttime than at daytime in Pacific corals and Atlantic rocky shores (FREEMAN et al., 2014; KAPLAN; LAMMERS et al., 2018; CAMPBELL et al., 2019), and an opposite trend in the Caribbean coral reefs (LILLIS; MOONEY, 2018; STAATERMAN et al., 2014; BOHNENSTIEHL; LILLIS; EGGLESTON, 2016). These patterns might be useful from estimating the population crustaceans density (BUTLER; BUTLER; GAFF, 2016) to assessing of fish and marine invertebrates biodiversity (MOONEY et al., 2020), and as an indicator of habitat type and quality information for dispersion of organisms (LILLIS; EGGLESTON; BOHNENSTIEHL, 2014).

Local bioacoustic signature is strongly influenced by abiotic factors, such as variations in temperature, light, sea level, and circadian, circatidal, circalunar cycles, and even seasonal variations (TESSMAR-RAIBLE; RAIBLE; ARBOLEDA, 2011; BOHNENSTIEHL; LILLIS; EGGLESTON, 2016). These factors may influence the signatures (LILLIS; MOONEY, 2018), making more complex to use for habitats assessment through passive acoustic methods. Also, in shallow water, these signatures may also be affected by abrupt changes in acoustic propagation conditions (CALADO et al., 2018). According to Mooney et al. (2020), for the evolution of the techniques for assessing biodiversity based on acoustic methods, a greater understanding of the temporal variability and of the main influences over the bioacoustic chorus are required, in addition to other aspects related to acoustic propagation.

Therefore, to better understand the local bioacoustic signature, as well as its variations over time, it is necessary to explain the contribution of abiotic factors and their periodicities. The fit of the model for these patterns is important and may allow the development of biotechnological applications for in monitoring marine health based on bioacoustic inversion.

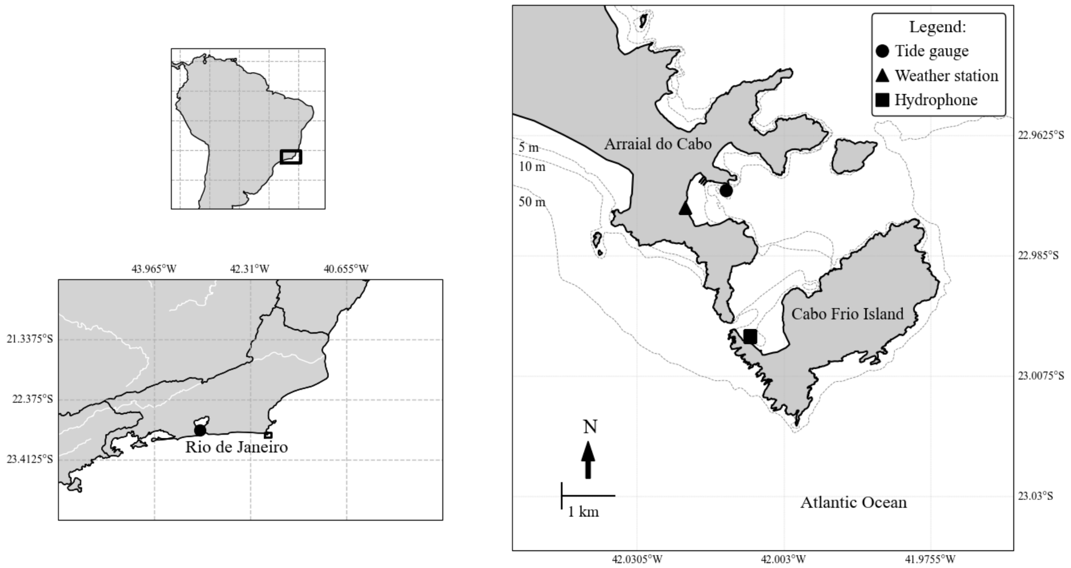
This work aims to investigate the relationship between abiotic factors and bioacoustic signature of a subtropical rocky shore in Cabo Frio Island, southeastern Brazil. It also aims to examine more closely how each abiotic factor contributes to the temporal bioacoustic signature pattern, and how to propose a model for this signature based on statistical and time series analysis.

4.2 MATERIAL AND METHODS

4.2.1 Soundscape monitoring

The marine soundscape monitoring started in February 2018 to support the benthic bioacoustic choruses characterization of a subtropical rocky shore in Cabo Frio Island, Arraial do Cabo, RJ, Brazil (Fig. 9). A structure containing one hydrophone (digitalHyd TP1-4A Marsensing Lda) was installed at the bottom, at 7.55 meters depth and 5 meters from rocky shore base, and the local is 8.75 meters depth. Acoustic data of 82 days (291 hours) from February 8 to April 30, 2018, was obtained from this monitoring. The acoustic recorder was configured with to record a 20% of duty cycle (1 minute sample every 5 minutes) and at a sampling frequency of 52,734 Hz. The instrument has a resolution of 24 bits, and a sensitivity of -174.9 dB re 1V/1μPa with a flat response between 100 Hz and 40 kHz.

FIGURA 9 – The study area is located in the Arraial do Cabo Bay, state of Rio de Janeiro, in southeastern Brazil. The map shows positions of the acoustic acquisition system (black square), tide gauge (black dot), and meteolorogical station (black triangle), in the bay of Cabo Frio Island.



The abiotic data used to evaluate the temporal trends and relationships with the RSBS were temperature/light (from datalogger deployed with the acoustic system, a HOBO Pendant, Onset Computer Corporation), sea level (tide gauge from Brazilian Navy), and meteorological dataset (precipitation, wind, solar radiation) from National Institute of Meteorology (Fig. 9). These abiotic data were measured once every 1 min, 10 min, and 1 hour for sea level, temperature/light, and meteorological data, respectively. Unfortunately, due to vandalism action, the data from HOBO pendant were only retrieved between March 4 and April 30, 2018, while the acquisition of remaining abiotic data follow the period of acoustic monitoring.

4.2.2 Data analysis

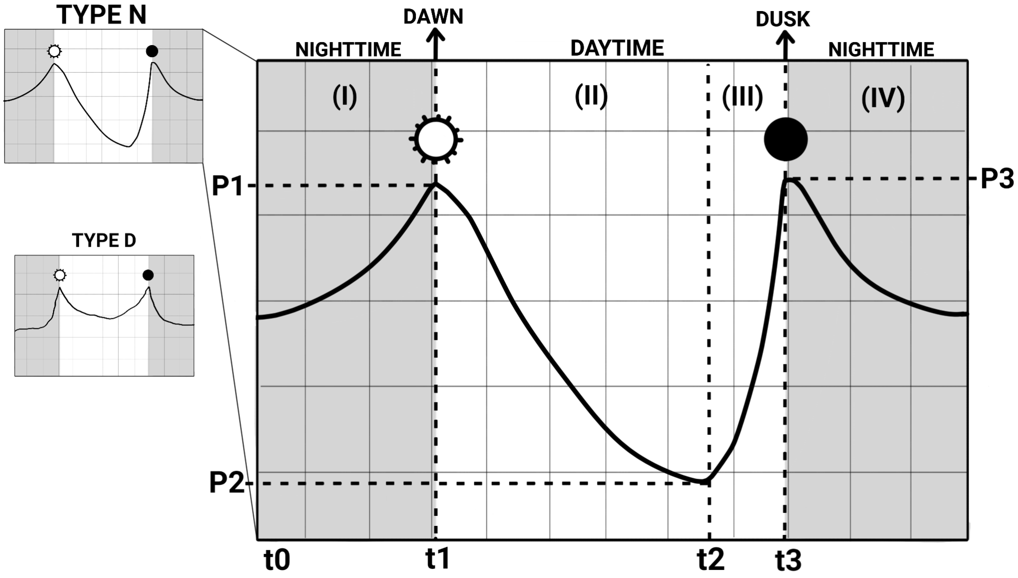
RSBS PSD (Power Spectral Density) was estimated using the Welch periodogram method from the Scipy Python module. This procedure was applied to two band-passed signals: 1.5 to 8 kHz (band B) and 8 to 24 kHz (band C). These bands are usually used as a proxy for benthic invertebrate's sound production (COQUEREAU et al., 2016; LILLIS; MOONEY, 2018). RSBS and abiotic datasets were assessed for normal distribution (Shapiro-Wilk) and linear relationship. As these assumptions weren't meet, the following correlations were performed (based on Spearman method): RSBS *versus* water temperature (T), light (L), sea level (TD), wind speed (WS), and precipitation (R).

To detect temporal periodicities in the RSBS data and relate them to the periodicity of the abiotic data (temperature, sea level, and light), a time series analysis based on wavelets (Continuous Wavelet Transform) was performed using Matlab® wavelet toolbox (GRINSTED; MOORE; JEVREJEVA, 2004). The power spectrum was calculated using the Morlet function, as it is generally an appropriate choice when it is intended to extract contributions from other variables (GRINSTED; MOORE; JEVREJEVA, 2004). The sampling time used was 1/24 with 8 sub-octaves per octave, from March 4 to April 30, 2018. The results are presented using scalograms with periods of 0.125 (3h), 0.25 (6h), 0.5 (12h), 1, 2, 4, and 8 days.

4.3 ROCKY SHORE BIOACOUSTIC SIGNATURE MODEL

From collections carried out in different areas around the world, it is possible to observe that the bioacoustic signature produced by benthic invertebrates has two types of daily variation patterns (STAATERMAN et al., 2014; KAPLAN; LAMMERS et al., 2018). These patterns are related to circadian cycles (TESSMAR-RAIBLE; RAIBLE; ARBOLEDA, 2011), the behavior of benthic fauna, and abiotic factors (LILLIS; MOONEY, 2018). Although the circadian cycle modulates this pattern, increasing the signature level during the twilight (Fig. 10), it's complex to explain RSBS only based on abiotic factors, such as temperature and light. On the other hand, the two patterns differ with opposite patterns, one has the highest level at nighttime (Type N), and the other at daytime (Type D). In the area surveyed in this study, the invertebrates RSBS follows the characteristics of this first pattern (Type N), with a higher RSBS at night than during the day, as shown in Fig. 10. In this figure, it's possible to observe that there are three critical points: two maxima representing the moments of twilight, and one minimum when the total solar radiation is greater. Understanding and modeling this pattern is

FIGURA 10 – Graphical representation of Bioacoustic Circadian Model (BCM), where p_n represent amplitudes at t_n moments, and t_0 represents midnight, t_1 and t_3 are, respectively, dawn and dusk moments (civilian twilight), and t_2 represents the approximate moment of greater total solar radiation. Type N (Pacific corals and Atlantic rocky shores) and D (Caribbean Sea) present two different daily patterns for invertebrate benthic organisms that produce sounds above 1.5 kHz, and the numerals I, II, III and IV represent BCM formulation given by Eq.(4.14).



core challenge to evaluate the contributions from abiotic factors and also how they drive the RSBS.

Based on that, we proposed a mathematical model of the RSBS daily pattern. As shown in Fig. 10, it is possible to divide the type N curve into four parts: (I) midnight to dawn, (II) dawn to the minimum of the day, (III) minimum of the day to dusk, and (IV) dusk to midnight. Supposing that (I) and (IV) may be represented by two exponential functions, and that (II) and (III) may be represented by two quadratic functions, there is that:

$$BCM_b[h] = \begin{cases} A_1 e^h + B_1, & \text{if } t_0 \leq h < t_1 \\ A_2 h^2 + B_2, & \text{if } t_1 \leq h < t_2 \\ A_3 h^2 + B_3, & \text{if } t_2 \leq h < t_3 \\ A_4 e^h + B_4, & \text{if } t_3 \leq h < t_0 \end{cases} \tag{4.1}$$

For this model, called Bioacoustic Circadian Model (BCM), b represents the frequency band, h represents any moment throughout the day, t_0 represents midnight, t_1 and t_3 are, respectively, dawn and dusk moments (civilian twilight provided by the National Observatory of Brazil), and assuming that t_2 represents the approximate instant for the moment of greater total solar radiation (established for the study area as 3 pm), we have to:

$$h = t - t_n + 1, \quad \text{if } n = 1, 3 \tag{4.2}$$

$$h = t - t_n, \quad \text{if } n = 2 \tag{4.3}$$

where n represents one of the three critical points on the curve. Thus, when t equal to $t_{1,3}$ we add one so that the curve coincides with the amplitudes p_1 and p_3, and when t equal to t_2 it coincides with the amplitude p_2 that is equivalent to parabola vertex (Fig. 10). Assuming also a standardized curve concerning the y-axis, ranging from -1 to 1, soon:

$$p_1 = p_3 = 1, \tag{4.4}$$

$$p_2 = -1. \tag{4.5}$$

Then, the linear coefficients B_n are given by:

$$B_2 = B_3 = p_2 = -1, \tag{4.6}$$

$$B_1 = B_4 = 0. \tag{4.7}$$

Regarding the angular coefficients A_n, we have to:
For $t = t_1$:

$$A_1 = e^{-1}, \tag{4.8}$$

$$A_2 = \frac{2}{(t_1 - t_2)^2}. \tag{4.9}$$

(4.10)

For $t = t_3$:

$$A_3 = \frac{2}{(t_3 - t_2)^2}, \tag{4.11}$$

$$A_4 = e. \tag{4.12}$$

(4.13)

Thus, the BCM can be defined as:

$$BCM_b[t] = \begin{cases} e^{t-t_1}, & \text{if } t_0 \leq t < t_1 \\ \frac{2(t-t_2)^2}{(t_1-t_2)^2} - 1, & \text{if } t_1 \leq t < t_2 \\ \frac{2(t-t_2)^2}{(t_3-t_2)^2} - 1, & \text{if } t_2 \leq t < t_3 \\ e^{t_3-t}, & \text{if } t_3 \leq t < t_0 \end{cases} \tag{4.14}$$

Considering Eq.(4.14) and the main abiotic contributors (temperature, light, and sea level), a multiple regression analysis was performed, based on the least-squares method, to assess how much each abiotic factor explains the variance of RSBS data, and to create a model for RSBS pattern Eq.(4.15). However, for all assumptions (linear relationship, normality of residues, multicollinearity, and homoscedasticity) to be met, the light data were transformed, that is, their base was changed from linear to logarithmic:

$$RSBS_b = a_0 + a_1T + a_2\ln(L+1) + a_3TD + a_4BCM, \tag{4.15}$$

where b is frequency band, T is temperature, L is light, TD is sea level, BCM is bioacoustic circadian model, a_0 are residues, and a_1-a_4 are regression coefficients.

4.4 RESULTS

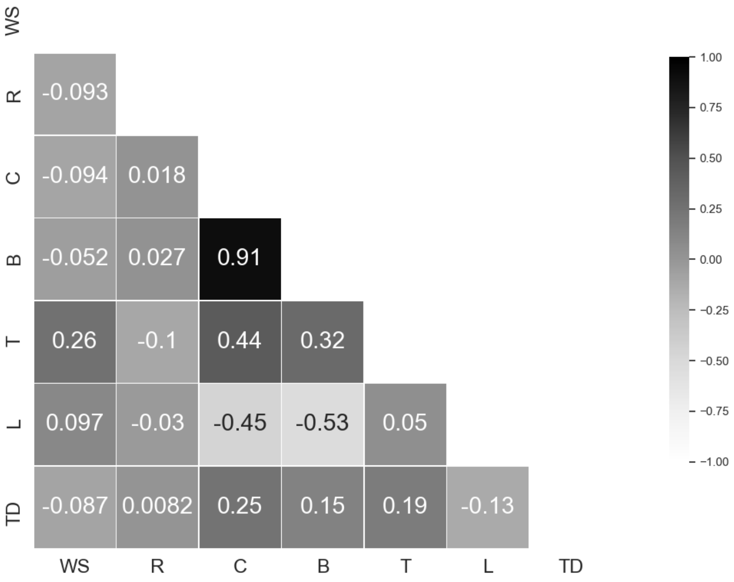
4.4.1 Abiotic contributions and validation of RSBS model

The relationship between RSBS PSD and abiotic factors based on the Spearman correlation, for both B and C bands, is shown Fig. 11. The results show a positive correlation between the sea level/temperature data (Fig. 12), and RSBS PSD for both bands ($r_b^{TD} = 0.15$; $r_c^{TD} = 0.25$; $r_b^{T} = 0.32$; $r_c^{T} = 0.44$, $p < 0.05$), where the correlation is almost twice higher in the C band than B for sea level. Fig. 12 shows that the correlations between light and RSBS PSD are negative for both bands ($r_b^{L} = -0.53$; $r_c^{L} = -0.45$, $p < 0.05$). The wind speed data have a negative correlation with the RSBS PSD for both bands ($r_b^{WS} = -0.052$; $r_c^{WS} = -0.094$, $p < 0.05$), where the correlation coefficient is higher for the C band. The precipitation data have a positive correlation with the RSBS PSD for both bands ($r_b^{R} = 0.027$; $r_c^{R} = 0.018$, $p < 0.05$). The correlations were higher in the C band than B for almost all abiotic factors except for light and precipitation.

Fig. 12 shows the relationship between RSBS PSD and each abiotic factors (L, T, and TD) that had the highest correlations, as well as their total and individual contributions to explain the RSBS PSD data variance, through multiple regression. Using only these three variables, the total contribution of the abiotic factors was about of $r^2_{adj} = 0.39$ and $r^2_{adj} = 0.46$ for B and C band, respectively. In Fig. 12, it possible to observe that the total contribution of the abiotic factors and BCM presents a better variance explanation of data in the C band ($r^2_{adj} = 0.62$) than in the B band ($r^2_{adj} = 0.55$). It is also possible to note that the light is the only abiotic factor that presents a greater variance explanation in Band B than in Band C (B: $r^2_{adj} = 0.26$, C: $r^2_{adj} = 0.19$), as well as the bioacoustic circadian model (B: $r^2_{adj} = 0.40$, C: $r^2_{adj} = 0.33$). In contrast, band C is better explained than band B based on temperature (B: $r^2_{adj} = 0.13$, C: $r^2_{adj} = 0.28$) and sea level data (B: $r^2_{adj} = 0.03$, C: $r^2_{adj} = 0.08$).

Based on the least-squares method, it was possible to obtain the regression and residual coefficients for each analyzed band. Then, the models proposed for RSBS

FIGURA 11 – Diagonal matrix of Spearman correlation between RSBS (B and C bands) and abiotic factors (temperature T, light L, sea level TD, wind speed WS and precipitation R), where black and white indicate positive and negative correlation, respectively. The used data were acquired from February 8th to April 30th, 2018.



PSD in bands B and C, respectively, are given by:

$$RSBS_B = 73.11 + 0.19T - 0.10\ln(L+1) + 0.11TD + 1.35BCM, \tag{4.16}$$

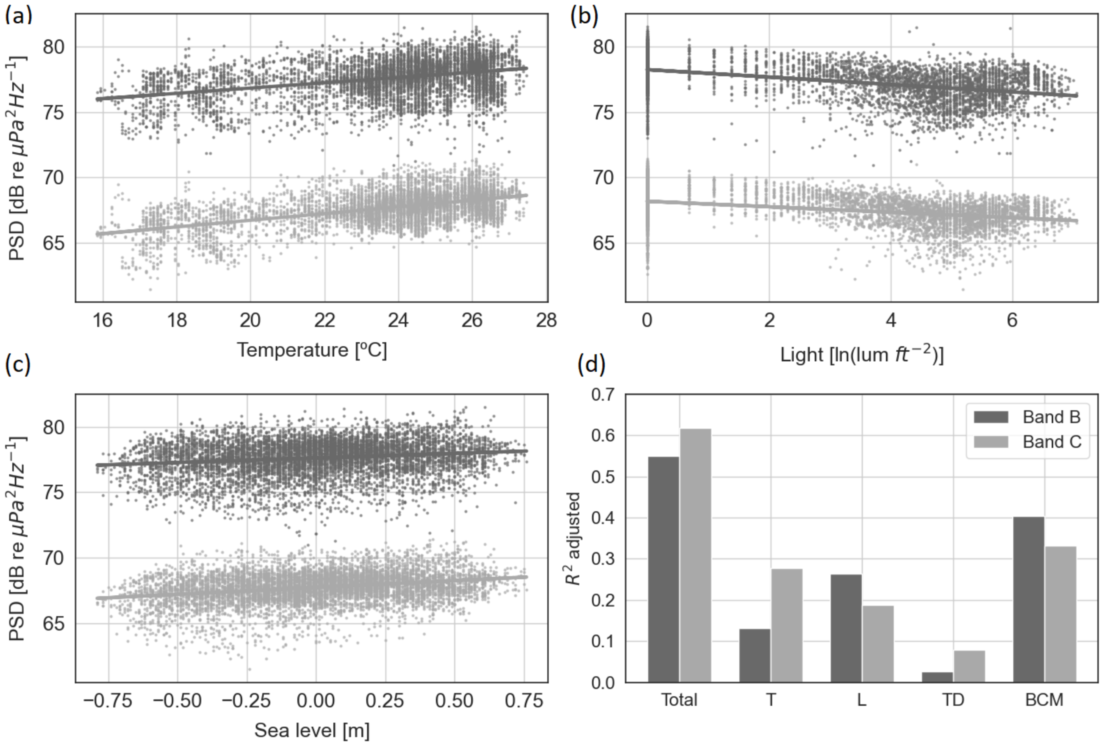
$$RSBS_C = 61.21 + 0.23T - 0.06\ln(L+1) + 0.41TD + 1.14BCM. \tag{4.17}$$

Fig. 13 and Fig. 14 show a comparison between the collected data and the model output data for both bands. These models explain approximately 55% (band B) and 62% (band C) of the total RSBS data variance. On the band B (Fig. 14) is possible to note that the model differs from the real data, mainly during daytime, with an average error rate between 1 and 2 dB, and maximum values of approximately 6.5 dB at several moments. On band C (Fig. 14), the model output show differs from real data mainly at upwelling moments (outcropping of cold waters lower than 20°C, as reported by Miranda (1985)), with greater errors at dusk, with an average error rate also between 1 and 2 dB, and a slightly lower maximum error of approximately 5 dB.

4.4.2 Temporal patterns

This section presents scalograms and average power spectra based on wavelet analysis, evaluating the periodicity of the RSBS PSD (B and C bands) and abiotic factors (temperature, light and sea level) (Fig. 15). The band B scalogram highlights two significant periods (12h and 24h), with the 24h period presenting more powerful, and also with some significant variations in shorter periods ($<$ 12h) and accentuated variations in the period of approximately 3 days. Band C also presents significant periods

FIGURA 12 – Water temperature (a), light (b) and sea level (c) and Bioacoutic Circadian Model (BCM) contributions to RSBS PSD variance, and (d) shows the RSBS least-square multiple regression adjusted r^2. The used data were acquired from March 4th to April 30th, 2018.



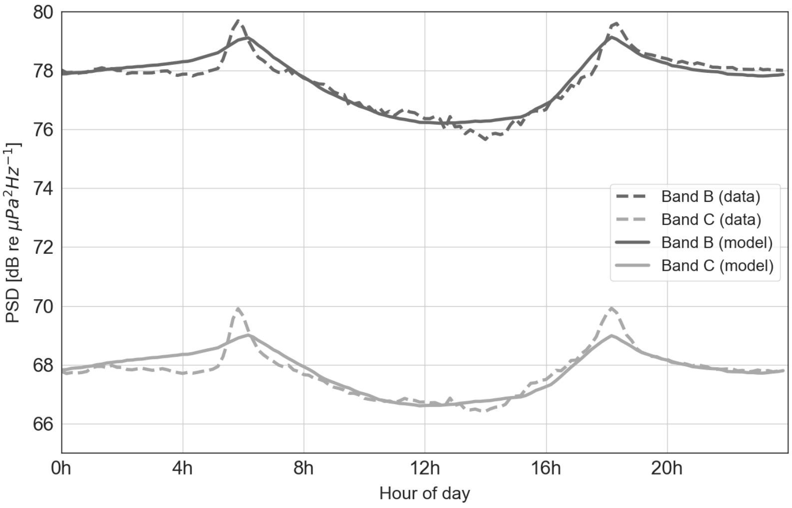
(6h, 12h, and 24h), but the 12h period is more powerful in this case (Fig. 15). Also, it presents some significant variations in shorter periods ($<$ 12h), but they are less numerous than in band B. There are also two marked variations in the periods between 2 and 4 days and 4 and 8 days.

The temperature data (Fig. 15) show three significant periods (12h, between 2 and 4 days, and between 4 and 8 days), and with upwelling moments.The light scalogram (Fig. 15) shows three significant periods (12h, 24h, and 8 days), with the 24h period being the most powerful. It is also possible to observe daytime and nighttime moments, as well as moments of greater and lesser total solar radiation. The sea level data (Fig. 15) also present three significant periods (12h, 24h and between 4 and 8 days), with some moments when spring and neap tides occurred.

4.5 DISCUSSION AND CONCLUSIONS

Acoustic recordings were collected during 82 days at a subtropical rocky shore and used along with abiotic factors to investigate their relationship. The discovered relationships demonstrate that RSBS from high frequency ($>$1.5 kHz) sounds are mainly driven by water temperature, light, sea level, and circadian rhythm. The RSBS model

FIGURA 13 – Average RSBS PSD daily pattern for the recorded data, and the modeled data in both bands. The used data were acquired and modelled from March 4th to April 30th, 2018.

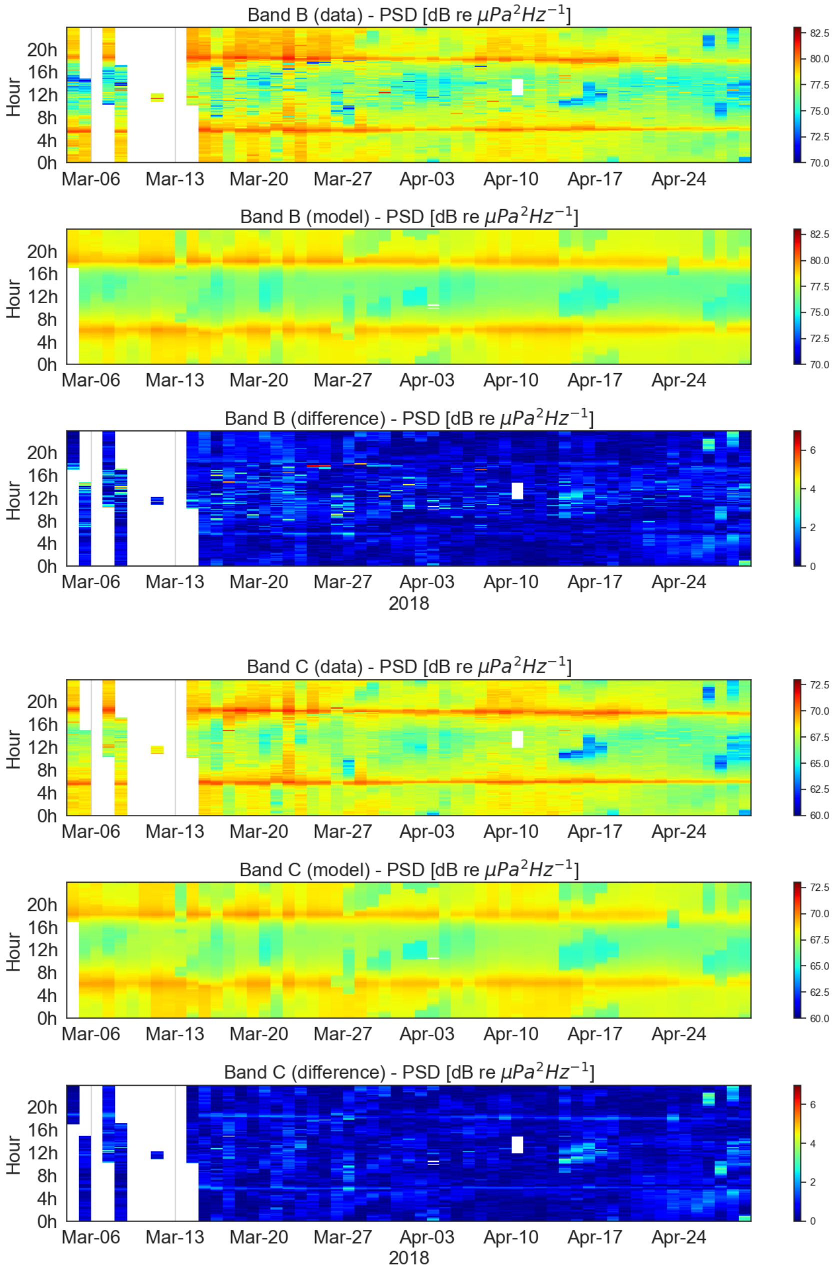


proposed from these factors explained approximately 55% (band B) and 62% (band C) of the RSBS data variance (Fig. 12). Sea level, temperature, and light have already been pointed out by other studies as important invertebrate chorus drivers (MOONEY et al., 2020). In contrast, wind speed and precipitation had lower correlations than the others and did not appear to relate to RSBS data, as also evaluated by Kaplan, Lammers et al. (2018).

Here, the sea level and RSBS data had a positive correlation for both bands with a greater contribution to band C (Fig. 11 and 12), which can be related to the number of submerged organisms increasing when the tide rises. Furthermore, according to Tessmar-Raible, Raible e Arboleda (2011), the circatidal cycles (sea level variation) influence tidal zone organisms' activity. This occurs because zones as rocky shores are impacted by fall and rise of water that cause environmental changes in habitat, like salinity, temperature, oxygen levels, sun irradiation, and food availability disturbances (COUTINHO et al., 2016). Also, several species can anticipate the tidal change due to circatidal clock mechanisms (TESSMAR-RAIBLE; RAIBLE; ARBOLEDA, 2011).

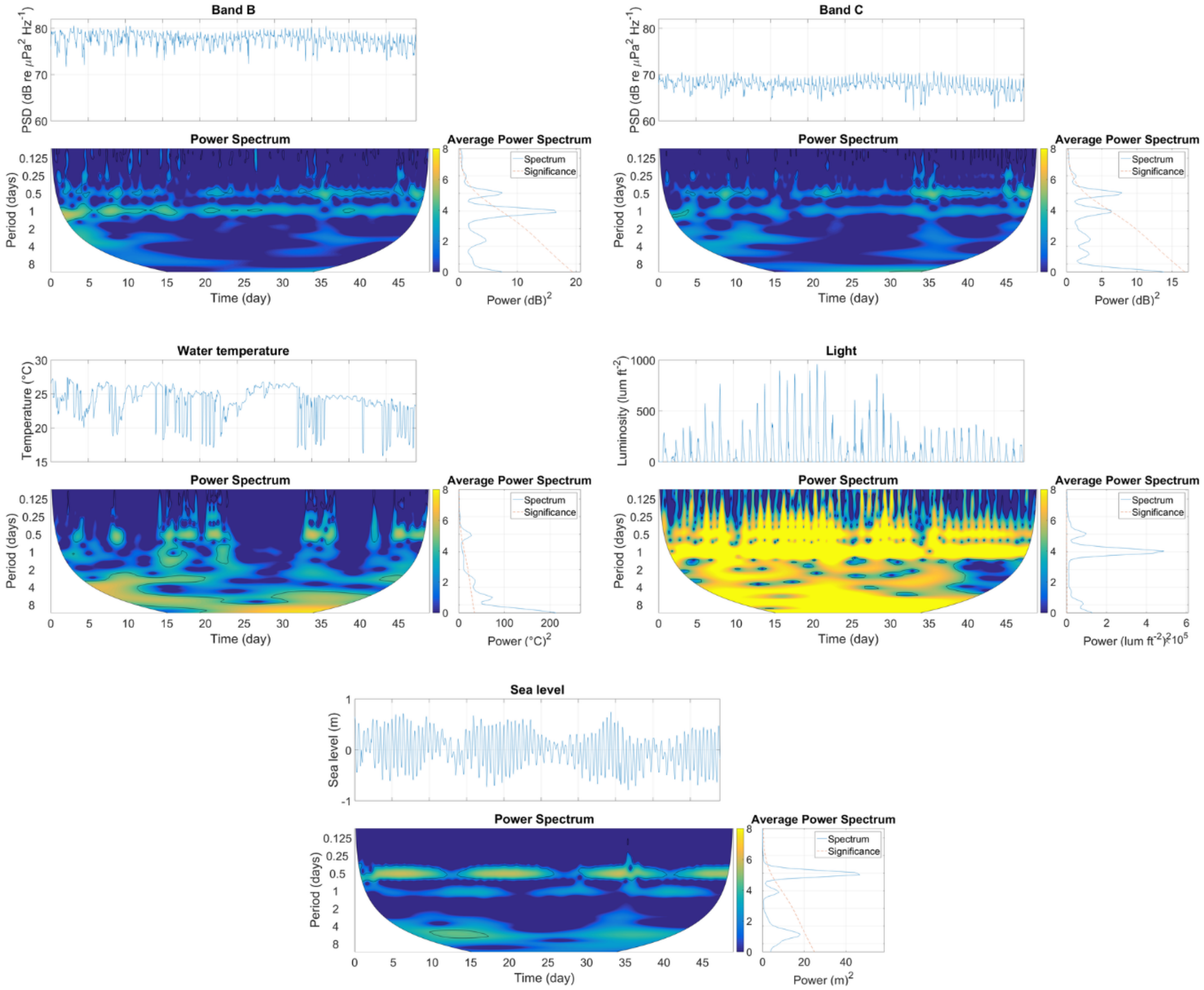
Similarly as the sea level, temperature and RSBS data also had a positive correlation, and higher contribution to band C than B (Fig. 11 and 12). When the temperature rises, the RSBS data follow the same pattern, which indicates a relationship with the metabolic activity of the organisms that tend to increase with temperature (SKINNER; NEVES SIVIERO; COUTINHO, 2007; BROTHERS; MCCLINTOCK, 2015), and also with seasonal changes in the crustacean population size (BOHNENSTIEHL; LILLIS; EGGLESTON, 2016). Yet, the magnitude of this relationship varies among coastal marine habitats (KAPLAN; LAMMERS et al., 2018; STAATERMAN et al., 2014),

FIGURA 14 – Least-square regression model for RSBS (bands B and C) based on temperature data T, light L, sea level TD, and bioacoustic circadian model BCM. For each band, the recorded data (top), the modeled data (center) and the absolute difference between the recorded and modeled data (bottom). The used data were acquired from March 4th to April 30th, 2018.



suggesting that local characteristics may influence this bioacoustic signature. Besides, the study area is strongly influenced by the upwelling phenomenon (CALADO et al., 2018), which can modulate benthic fauna behavior and change acoustic propagation conditions. In general, the relationship between temperature and bioacoustic signature could have important implications for soundscape studies in climatic changes scenarios (LILLIS; MOONEY, 2018),in addition to ocean acidification possibly decreasing level of

FIGURA 15 – Time series, wavelet-based scalogram, average power spectrum, for RSBS PSD bands B and C, water temperature, light and sea level. These scalograms show the periodicity between March 4th and April 30th, 2018.



invertebrate bioacoustic signature due to its response to lower pH (ROSSI; CONNELL; NAGELKERKEN, 2016).

As for light, the opposite happens, we had a negative correlation, with a higher contribution to band B than C (Fig. 11 and 12), which indicates that during the nighttime (RADFORD, C. A. et al., 2008), twilight, and cloudy days the RSBS levels are higher than on sunny days (LILLIS; MOONEY, 2018). However, around dawn and dusk moments, the light intensity is almost the same as that very cloudy day, but the RSBS PSD level is higher in twilight than daylight hours. This feature can be explained by the evening chorus (or twilight chorus) concept, which describes the moment when large numbers of crepuscular animals are acoustically actives (RADFORD, C. A. et al., 2008; TESSMAR-RAIBLE; RAIBLE; ARBOLEDA, 2011). This twilight bioacoustic activity is related to temporal rhythms resulted from a complex combination of biological rhythm, molecular clock, and abiotic factors (TESSMAR-RAIBLE; RAIBLE; ARBOLEDA, 2011; LILLIS;

MOONEY, 2018).

Here, we proposed a Bioacoustic Circadian Model (Fig. 10) based on the RSBS pattern from the study area aiming its better understanding, since the RSBS pattern is composed of biological rhythm modulated by abiotic factors and other external impacts (like anthropogenic noises) (Fig. 14). The model resumes the biological rhythms from several invertebrate benthic organisms (like snapping shrimps, urchins, bivalves and barnacles) that produce sounds above 1.5 kHz (COQUEREAU et al., 2016). In this case, it represents an average biological rhythm for local species, and the output is similar to the Pacific corals pattern (FREEMAN et al., 2014; BERTUCCI et al., 2016). Applying this model with main abiotic factors, it is possible to observe that for both bands there are at least two types of model error, resulting in a difference between collected and modeled data (Fig. 14). One possible cause of the error is the upwelling occurrence during the last 5 days of the monitoring, with abrupt temperature changes, resulting in errors of approximately 3 to 4 dB (Fig. 14). It is also possible to note daytime errors of approximately 5 to 6.5 dB, mainly in B band, caused by anthropogenic influence from nautical tourism (JESUS et al., 2020).

In addition, it is possible to observe that band B is more influenced by light than temperature and sea level (Fig. 12), while the C band is more influenced by temperature and sea level than by light. These two pieces of evidence, both for band B and C, are corroborated by the wavelet scalogram analysis (Fig. 15). This analysis highlighted that the events that occur in bands B and C have periods of 24h (similar to light) and 12h (similar to sea level and temperature) more accentuated, respectively. This evidence may indicate that band C is more influenced by organisms living in the intertidal zone, since they are more influenced by the sea level, while B band is more influenced by organisms that are below the intertidal zone (infralittoral), however these hypotheses yet to be examined.

The RSBS model was based on a multiple regression using a mathematical model for bioacoustic circadian rhythm, and the main abiotic factors. Regression analysis shows that temperature, light, sea level, and bioacoustic circadian model explain approximately 55% (band B: 1.5 kHz to 8 kHz) and 62% (band C: 8 kHz to 24 kHz) of the RSBS variance. In general, as pointed out by Mooney et al. (2020), the relationship between abiotic factors and local bioacoustic signature can help to understand bioacoustic patterns and their temporal variation, being an important step towards understanding the behavior of the organisms. Also, RSBS model proved to be a good fit to investigate these patterns and their variations and it can help in the development of environmental biotechnological applications using bioacoustic inversion techniques for measuring abiotic data, for estimating the benthic organisms population density, and for efficient marine ecosystem health monitoring.

5 CONSIDERAÇÕES FINAIS

Habitats marinhos possuem assinaturas acústicas distintas compostas por sons de origem antropogênica, abiótica e biótica. Nas zonas costeiras, a assinatura acústica tem uma forte influência de organismos bentônicos que formam o coro bioacústico. No entanto, os padrões dessa assinatura podem ser influenciados pelos ciclos circadiano e lunar, maré, temperatura, luminosidade e outros. Para entender melhor a influência dos fatores abióticos e bióticos no padrão desta assinatura é importante modelar, identificar e quantificar as contribuições de cada um desses fatores.

Além do ritmo diário, que evidenciou um aumento do ruído biológico durante os períodos crepusculares, a Assinatura Bioacústica dos Costões Rochosos (ABCR) próximos à Ilha do Cabo Frio, Arraial do Cabo - RJ também é modulada pela temperatura da água. Em situações de temperaturas mais baixas, o decréscimo da ABCR ocorre com uma defasagem temporal e a ABCR não permanece baixa durante todo período em que as águas ressurgentes estão presentes na região. Essa diminuição da temperatura da água provocada pela Ressurgência apresenta-se como um fator relevante para a ABCR, influenciando principalmente os invertebrados marinhos. Neste trabalho, fica evidente que a ressurgência tem um papel importante na modulação da ABCR na área de estudo.

O modelo para ABCR desenvolvido neste trabalho foi baseado em regressão múltipla, e utilizou um modelo matemático criado para o ritmo circadiano bioacústico em conjunto com parâmetros abióticos. Este modelo evidenciou que a temperatura, a luz, o nível do mar e o modelo circadiano bioacústico explicam aproximadamente 55% (banda B: 1,5 kHz a 8 kHz) e 62% (banda C: 8 kHz a 24 kHz) da variância da ABCR. E como a maioria dos organismos presentes em zonas costeiras respondem diretamente à variação desses fatores abióticos, este estudo pode ter desdobramentos visando um melhor entendimento sobre o comportamento desses organismos. Além disso, o desenvolvimento de ferramentas que permitem a simulação de condições específicas de um determinado processo possibilita uma compreensão mais acurada sobre o assunto. A modelagem da assinatura bioacústica de um determinado habitat marinho permite um estudo mais detalhado da interação entre suas componentes e o meio físico. Além disso, esta modelagem pode ser utilizada no monitoramento da qualidade do ambiente marinho, uma vez que ela representa o padrão natural, baseado em medições *in situ* na região de interesse.

Dessa forma, com base nos estudos realizados neste trabalho, é importante ressaltar que o desenvolvimento de novas pesquisas nessa área deve ser contínuo. Por exemplo, utilizar o modelo desenvolvido para ABCR a partir de bandas de frequências mais estreitas pode indicar como a ABCR está relacionada com os organismos de cada faixa do costão. Com isso, seria possível simular a propagação do som dessas fontes, gerando mapas acústicos para os sons provenientes de invertebrados bentônicos. Além disso, também é importante a avaliação do padrão de atividade acústica diária dos organismos mais representativos na paisagem acústica, para que o modelo pudesse ser refinado e utilizado como ferramenta para análise de biodiversidade. Estes desdobramentos podem facilitar o desenvolvimento de aplicações biotecnológicas ambientais, usando técnicas de inversão bioacústica, para medição de dados abióticos, estimação de densidade populacional de organismos bentônicos e monitoramento eficiente de ecossistemas marinhos.

REFERÊNCIAS

AU, Whitlow WL; BANKS, Kiara. The acoustics of the snapping shrimp Synalpheus parneomeris in Kaneohe Bay. **The Journal of the Acoustical Society of America**, ASA, v. 103, n. 1, p. 41–47, 1998.

AUED, Anaide W et al. Large-scale patterns of benthic marine communities in the Brazilian Province. **PloS one**, Public Library of Science, v. 13, n. 6, e0198452, 2018.

BEAN, Tim P et al. A review of the tools used for marine monitoring in the UK: combining historic and contemporary methods with modeling and socioeconomics to fulfill legislative needs and scientific ambitions. **Frontiers in Marine Science**, Frontiers, v. 4, p. 263, 2017.

BERTUCCI, Frédéric et al. Acoustic indices provide information on the status of coral reefs: an example from Moorea Island in the South Pacific. **Scientific reports**, Nature Publishing Group, v. 6, p. 33326, 2016.

BOHNENSTIEHL, DelWayne R; LILLIS, Ashlee; EGGLESTON, David B. The curious acoustic behavior of estuarine snapping shrimp: temporal patterns of snapping shrimp sound in sub-tidal oyster reef habitat. **PloS One**, Public Library of Science, v. 11, n. 1, e0143691, 2016.

BORIE, Alfredo et al. Soundscape of a management and exploitation area of benthic resources in central Chile. **Latin American Journal of Aquatic Research**, Pontificia Universidad Católica de Valparaıso, v. 43, n. 5, 2015.

BOSMAN, AL; HOCKEY, PAR; SIEGFRIED, WR. The influence of coastal upwelling on the functional structure of rocky intertidal communities. **Oecologia**, Springer, v. 72, n. 2, p. 226–232, 1987.

BROCKINGTON, Simon; CLARKE, Andrew. The relative influence of temperature and food on the metabolism of a marine invertebrate. **Journal of Experimental Marine Biology and Ecology**, Elsevier, v. 258, n. 1, p. 87–99, 2001.

BROTHERS, CJ; MCCLINTOCK, JB. The effects of climate-induced elevated seawater temperature on the covering behavior, righting response, and Aristotle's lantern reflex of the sea urchin Lytechinus variegatus. **Journal of Experimental Marine Biology and Ecology**, Elsevier, v. 467, p. 33–38, 2015.

BUTLER, Jack; BUTLER, Mark; GAFF, Holly. Acoustic-based model estimation of snapping shrimp populations and the effects of a sponge die-off. **bioRxiv**, Cold Spring Harbor Laboratory, p. 056986, 2016.

BUTLER, Jack; BUTLER IV, Mark J; GAFF, Holly. Snap, crackle, and pop: Acoustic-based model estimation of snapping shrimp populations in healthy and degraded hard-bottom habitats. **Ecological indicators**, Elsevier, v. 77, p. 377–385, 2017.

CALADO, Leandro et al. Upwelling regime off the Cabo Frio region in Brazil and impact on acoustic propagation. **The Journal of the Acoustical Society of America**, ASA, v. 143, n. 3, el174–el180, 2018.

CAMPBELL, Daniel et al. Underwater soundscape pattern during high season of nautical tourism in Cabo Frio Island, Brazil. In: ASA. PROCEEDINGS of Meetings on Acoustics 5ENAL. [S.l.: s.n.], 2019. v. 37, p. 070003.

CAMPBELL, Daniel Andrade. **Estudo da paisagem acústica submarina na região do Arraial do Cabo, Rio de Janeiro, Brasil**. 2018. Tese (Doutorado) – Dissertação de Mestrado.

CASTELAO, Renato M; BARTH, John A. Upwelling around Cabo Frio, Brazil: The importance of wind stress curl. **Geophysical Research Letters**, Wiley Online Library, v. 33, n. 3, 2006.

CHEN, Chen-Tung; MILLERO, Frank J. Speed of sound in seawater at high pressures. **The Journal of the Acoustical Society of America**, ASA, v. 62, n. 5, p. 1129–1135, 1977.

CLAUDET, Joachim et al. A roadmap for using the UN Decade of ocean science for sustainable development in support of science, policy, and action. **One Earth**, Elsevier, v. 2, n. 1, p. 34–42, 2020.

COQUEREAU, Laura et al. Sound production and associated behaviours of benthic invertebrates from a coastal habitat in the north-east Atlantic. **Marine biology**, Springer, v. 163, n. 5, p. 127, 2016.

CORDEIRO, Cesar Augusto Marcelino Mendes; HARBORNE, AR; FERREIRA, CEL. Patterns of distribution and composition of sea urchin assemblages on Brazilian subtropical rocky reefs. **Marine biology**, Springer, v. 161, n. 10, p. 2221–2232, 2014.

COSTELLO, Mark J et al. Methods for the study of marine biodiversity. In: THE GEO handbook on biodiversity observation networks. [S.l.]: Springer, Cham, 2017. P. 129–163.

COUTINHO, Ricardo et al. Studies on benthic communities of rocky shores on the Brazilian coast and climate change monitoring: status of knowledge and challenges. **Brazilian Journal of Oceanography**, SciELO Brasil, v. 64, spe2, p. 27–36, 2016.

ERBE, Christine et al. The marine soundscape of the Perth Canyon. **Progress in Oceanography**, Elsevier, v. 137, p. 38–51, 2015.

FARINA, Almo. Ecoacoustics: A quantitative approach to investigate the ecological role of environmental sounds. **Mathematics**, Multidisciplinary Digital Publishing Institute, v. 7, n. 1, p. 21, 2019.

_______. **Soundscape ecology: principles, patterns, methods and applications**. [S.l.]: Springer, 2013.

FERREIRA. Non-indigenous corals at marginal sites. **Coral Reefs**, Springer, v. 22, n. 4, p. 498–498, 2003.

FREEMAN, Simon E et al. The origins of ambient biological sound from coral reef ecosystems in the Line Islands archipelago. **The Journal of the Acoustical Society of America**, Acoustical Society of America, v. 135, n. 4, p. 1775–1788, 2014.

GIGLIO, Vinicius J et al. Reef fish associations with sea urchins in an Atlantic oceanic island. **Marine Biodiversity**, Springer, v. 48, n. 4, p. 1833–1839, 2018.

GRINSTED, Aslak; MOORE, John C; JEVREJEVA, Svetlana. Application of the cross wavelet transform and wavelet coherence to geophysical time series. **Nonlinear Processes in Geophysics, European Geosciences Union (EGU)**, 11 (5/6), p. 561–566, 2004.

GUIMARAES, Mariana Alves; COUTINHO, Ricardo. Spatial and temporal variation of benthic marine algae at the Cabo Frio upwelling region, Rio de Janeiro, Brazil. **Aquatic Botany**, Elsevier, v. 52, n. 4, p. 283–299, 1996.

HAMILTON, Edwin L. Geoacoustic modeling of the sea floor. **The Journal of the Acoustical Society of America**, ASA, v. 68, n. 5, p. 1313–1340, 1980.

HAWKINS, Anthony D; POPPER, Arthur N. A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. **ICES Journal of Marine Science**, Oxford University Press, v. 74, n. 3, p. 635–651, 2017.

HOWE, Bruce M et al. Observing the oceans acoustically. **Frontiers in Marine Science**, Frontiers, v. 6, p. 426, 2019.

JESUS, SM et al. Particle motion measurements near a rocky shore off Cabo Frio Island. **The Journal of the Acoustical Society of America**, Acoustical Society of America, v. 147, n. 6, p. 4009–4019, 2020.

KAPLAN, Maxwell B; LAMMERS, Marc O et al. Acoustic and biological trends on coral reefs off Maui, Hawaii. **Coral Reefs**, Springer, v. 37, n. 1, p. 121–133, 2018.

KAPLAN, Maxwell B; MOONEY, T Aran et al. Coral reef species assemblages are associated with ambient soundscapes. **Marine Ecology Progress Series**, v. 533, p. 93–107, 2015.

KENNEDY, EV et al. Spatial patterns in reef-generated noise relate to habitats and communities: evidence from a Panamanian case study. **Journal of Experimental Marine Biology and Ecology**, Elsevier, v. 395, n. 1-2, p. 85–92, 2010.

LILLIS, Ashlee; BOHNENSTIEHL, DelWayne R; EGGLESTON, David B. Soundscape manipulation enhances larval recruitment of a reef-building mollusk. **PeerJ**, PeerJ Inc., v. 3, e999, 2015.

LILLIS, Ashlee; EGGLESTON, David B; BOHNENSTIEHL, DelWayne R. Estuarine soundscapes: distinct acoustic characteristics of oyster reefs compared to soft-bottom habitats. **Marine Ecology Progress Series**, v. 505, p. 1–17, 2014.

LILLIS, Ashlee; MOONEY, T Aran. Snapping shrimp sound production patterns on Caribbean coral reefs: relationships with celestial cycles and environmental variables. **Coral Reefs**, Springer, v. 37, n. 2, p. 597–607, 2018.

LILLIS, Ashlee; PERELMAN, Jessica N et al. Sound production patterns of big-clawed snapping shrimp (Alpheus spp.) are influenced by time-of-day and social context. **The Journal of the Acoustical Society of America**, ASA, v. 142, n. 5, p. 3311–3320, 2017.

MCWILLIAM, Jamie N et al. Patterns of biophonic periodicity on coral reefs in the Great Barrier Reef. **Scientific reports**, Nature Publishing Group, v. 7, n. 1, p. 17459, 2017.

MERCHANT, Nathan D et al. Measuring acoustic habitats. **Methods in Ecology and Evolution**, Wiley Online Library, v. 6, n. 3, p. 257–265, 2015.

MIKSIS-OLDS, Jennifer L; MARTIN, Bruce; TYACK, Peter L. Exploring the ocean through soundscapes. **Acoust. Today**, v. 14, p. 26–34, 2018.

MIRANDA, Luiz Bruner. Forma da correlação TS de massas de água das regiões costeira e oceânica entre o Cabo de São Tomé (RJ) e a Ilha de São Sebastião (SP), Brasil. **Boletim do Instituto Oceanográfico**, v. 33, n. 2, p. 105–119, 1985.

MOONEY, T Aran et al. Listening forward: approaching marine biodiversity assessments using acoustic methods. **Royal Society open science**, The Royal Society, v. 7, n. 8, p. 201287, 2020.

PARMAR, Trishala K; RAWTANI, Deepak; AGRAWAL, YK. Bioindicators: the natural indicator of environmental pollution. **Frontiers in life science**, Taylor & Francis, v. 9, n. 2, p. 110–118, 2016.

PORTER, Michael B. The bellhop manual and user's guide: Preliminary draft. **Heat, Light, and Sound Research, Inc., La Jolla, CA, USA, Tech. Rep**, 2011.

RADFORD, CA; STANLEY, JA; JEFFS, AG. Adjacent coral reef habitats produce different underwater sound signatures. **Marine Ecology Progress Series**, v. 505, p. 19–28, 2014.

RADFORD, CA; STANLEY, JA; TINDLE, CT et al. Localised coastal habitats have distinct underwater sound signatures. **Marine Ecology Progress Series**, v. 401, p. 21–29, 2010.

RADFORD, Craig et al. Resonating sea urchin skeletons create coastal choruses. **Marine Ecology Progress Series**, v. 362, p. 37–43, 2008.

RADFORD, Craig A et al. Temporal patterns in ambient noise of biological origin from a shallow water temperate reef. **Oecologia**, Springer, v. 156, n. 4, p. 921–929, 2008.

RODRIGUES, Regina R; LORENZZETTI, João A. A numerical study of the effects of bottom topography and coastline geometry on the Southeast Brazilian coastal upwelling. **Continental Shelf Research**, Elsevier, v. 21, n. 4, p. 371–394, 2001.

ROSSI, Tullio; CONNELL, Sean D; NAGELKERKEN, Ivan. Silent oceans: ocean acidification impoverishes natural soundscapes by altering sound production of the world's noisiest marine invertebrate. **Proceedings of the Royal Society B: Biological Sciences**, The Royal Society, v. 283, n. 1826, p. 20153046, 2016.

SANCHEZ-GENDRIZ, I; PADOVESE, LR. Temporal and spectral patterns of fish choruses in two protected areas in southern Atlantic. **Ecological Informatics**, Elsevier, v. 38, p. 31–38, 2017.

SIMMONDS, John; MACLENNAN, David N. **Fisheries acoustics: theory and practice**. [S.l.]: John Wiley & Sons, 2008.

SIMPSON, Stephen D et al. Adaptive avoidance of reef noise. **PLoS One**, Public Library of Science, v. 6, n. 2, e16625, 2011.

SINGH, Ram Lakhan. **Principles and applications of environmental biotechnology for a sustainable future**. [S.l.]: Springer, 2017.

SKINNER, Luis Felipe; NEVES SIVIERO, Fernanda; COUTINHO, Ricardo. Comparative growth of the intertidal barnacle Tetraclita stalactifera (Thoracica: Tetraclitidae) in sites influenced by upwelling and tropical conditions at the Cabo Frio region, Brazil. **Revista de Biologia Tropical**, Universidad de Costa Rica, v. 55, Su1, 2007.

STAATERMAN, Erica et al. Celestial patterns in marine soundscapes. **Marine Ecology Progress Series**, v. 508, p. 17–32, 2014.

SUSKIEWICZ, TS; JOHNSON, LE. Consumption rates of a key marine herbivore: a review of the extrinsic and intrinsic control of feeding in the green sea urchin. **Marine Biology**, Springer, v. 164, n. 6, p. 131, 2017.

TESSMAR-RAIBLE, Kristin; RAIBLE, Florian; ARBOLEDA, Enrique. Another place, another timer: marine species and the rhythms of life. **Bioessays**, Wiley Online Library, v. 33, n. 3, p. 165–172, 2011.

TOLIMIERI, Nick; JEFFS, Andrew; MONTGOMERY, John C. Ambient sound as a cue for navigation by the pelagic larvae of reef fishes. **Marine Ecology Progress Series**, v. 207, p. 219–224, 2000.

VALENTIN, Jean Louis; COUTINHO, Ricardo. Modelling maximum chlorophyll in the Cabo Frio (Brazil) upwelling: a preliminary approach. **Ecological Modelling**, Elsevier, v. 52, p. 103–113, 1990.

VISBECK, Martin. Ocean science research is key for a sustainable future. **Nature communications**, Nature Publishing Group, v. 9, n. 1, p. 1–4, 2018.

WYNSBERGHE, Aimee van; DONHAUSER, Justin. The dawning of the ethics of environmental robots. **Science and engineering ethics**, Springer, v. 24, n. 6, p. 1777–1800, 2018.

ZAMPROGNO, Gabriela C; FERNANDES, Flavio C; FERNANDES, Luiz L. Temporal and spatial variation of rocky shores intertidal benthic communities in Southeast Brazil. **Iheringia. Série Zoologia**, SciELO Brasil, v. 102, n. 4, p. 375–383, 2012.