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# Use of Ecoacoustics to Characterize the Marine Acoustic Environment off the North Atlantic French Saint-Pierre-et-Miquelon Archipelago

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**Abstract:** Visual observations of the marine biodiversity can be difficult in specific areas for different reasons, including weather conditions or a lack of observers. In such conditions, passive acoustics represents a potential alternative approach. The objective of this work is to demonstrate how information about marine biodiversity can be obtained via detailed analysis of the underwater acoustic environment. This paper presents the first analysis of the Saint-Pierre-and-Miquelon (SPM) archipelago underwater acoustic environment. In order to have a better knowledge about the marine biodiversity of SPM, acoustic recordings were sampled at different time periods to highlight seasonal variations over several years. To extract information from these acoustic recordings, standard soundscape and ecoacoustic analysis workflow was used to compute acoustic metrics such as power spectral density, third-octave levels, acoustic complexity index, and sound pressure levels. The SPM marine acoustic environment can be divided into three main sound source classes: biophony, anthrophony, and geophony. Several cetacean species were encountered in the audio recordings including sperm whales (which were detected by visual observations and strandings of 3 males in 2014), humpback, and blue whales.

**Keywords:** underwater; acoustic environment; ecoacoustics; noise levels

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## 1. Introduction

Characterizing an underwater acoustic environment can provide insight on the status of the ocean ecosystem at a particular location. Underwater acoustic environments [1,2] are a valuable source of information to describe marine ecosystems as they are the result of complex interactions between biophony, geophony, and anthrophony at various spatiotemporal scales. Describing the acoustic environment and then understanding relationships between these different types of sounds provides information that can be used in developing conservation strategies for marine ecosystems to mitigate the constantly increasing disturbance from anthropogenic activities [3–6]. Anthropogenic sound pollution is a threat to the marine fauna, especially marine mammals [7]. This is also true for fish and invertebrates [8–12]. Indeed, sound is one of the key elements of vital activities in marine life. For example, cetaceans, fish, and crustacean species perceive and generate sounds for foraging, social interactions, mating, escaping from predators, and navigating [8–13].

Moreover, it has been shown that marine mammals, fish, and invertebrates are affected by the deterioration of sound underwater environments, mainly resulting from increasing marine traffic but also local high-power noise sources such as naval sonars and seismic surveys [8–12,14–16].

Underwater acoustic environments can also provide information about marine fauna, which complements visual surveys [17]. Sometimes, because of the lack of access to the ocean (due to bad weather conditions, lack of observers, or the expense of field work), Passive Acoustic Monitoring (PAM) becomes an attractive option. Moreover, marine spatiotemporal trends that can be identified at different scales and acoustic variations in this environment can be recognized using PAM [18].

Ecoacoustics is an emerging field of research. It needs to be based on relevant, accurate assessments of the acoustic environment [19]. Several ecoacoustic methods have been developed to characterize the underwater acoustic environments. Acoustic indices is one of them, they aim at quantifying different aspects of an acoustic environment using a single value for a specific time period. They were first used in the assessment of terrestrial acoustic environments [20] and then for marine ones [21–24]. However, whilst these methods have demonstrated utility in some marine environments, e.g., coral reefs [25], this is not universally true [26]. Whilst there is currently no consensus on the relevance of acoustic indices for marine acoustic environments, it is generally accepted that they should not be used in isolation but in conjunction with other descriptive metrics such as long-term spectrograms (a map that depicts the signal strength in different frequencies over a given time period) [27]. Probabilistic methods with different factorization methods, e.g., Principal Latent Component Analysis (PLCA) [26] or Non-negative Matrix Factorization (NMF) [28], have been proposed to take into account both time and frequency variations, these approaches can be regarded as extending existing acoustic indices that only consider one of these.

Furthermore, to enhance the analysis of large-scale acoustic environment variations, environmental variables such as wind speed and rainfall are often used in the analysis. Trends in sound level across years and seasonality patterns can be revealed by correlating descriptive metrics such as sound pressure level (SPL) and power spectral density with wind speed [29–33], moon phase [34], temperature [33,35], day/night variations [33,36,37], and ship traffic [32,33,38,39]. In addition to these auxiliary variables, intersite studies were carried out to observe seasonality or sound patterns [33,40–44].

In this study, we propose an ecoacoustic analysis of the marine acoustic environment off the Saint-Pierre-and-Miquelon (SPM) islands (French islands close to Newfoundland, Canada), with a special focus on the presence of vocal cetaceans in relation to anthropogenic activities. We deployed a semipermanent acoustic observatory off the SPM Archipelago for three reasons: Firstly, this geographic site is a hot-spot for a wide range of cetacean species, especially the migratory species that come to these feeding grounds between June and October, including humpback whales, fin whales, and blue whales. Secondly, the weather conditions (cold, fog, rain) restrict the ability to conduct recurrent vessel-based observations. Thirdly, human activities are present, including fisheries and marine traffic for economic activities of France, Canada, and the US, which are forecast to increase over the next decade.

Although scientific literature on underwater acoustic environments is very large now, this work is the first analysis of the SPM underwater acoustic environment over multiple years. Ref. [16] have presented marine acoustic environment results from different sites, from Labrador to Nova Scotia (Canada), over 2016 and 2017 in order to analyze the impact of seismic surveys on marine life. Our results are specific to the SPM shore and the analyzed time period is previous to theirs. However, this work is complementary to [16] and provides another sampling site to better characterize the Newfoundland (Canada) marine acoustic environment.

The main goal of our analysis reported in this paper was two-fold:

- Characterizing the biophony contributions within the SPM acoustic environment based on standard metrics and usual ecoacoustic tools;
- Investigating the interactions between biophony and anthrophony, and discussing the important question of the impact of anthropogenic activities on marine mammal presence, as the Laurentian Channel and the surrounding of the archipelago are suggested to be protected areas for some cetaceans [45] and have now been a marine protected area since 2019 [46]. However, this is still not the case for the French water zone around the archipelago.

Section 2 describes the study area, data collection, and the methodology to analyze the underwater acoustic environment off the SPM archipelago, including acoustic recordings and environmental data. Section 3 shows the contribution and interactions of the anthrophony, geophony, and biophony, and presents the results of the Acoustic Complexity Index (ACI) on our audio data. In Section 4, results are discussed and compared to reference work by [16] and previous shallow water studies.

## 2. Materials and Methods

### 2.1. Study Area

The archipelago of SPM (46°47′ N 56°10′ W) is located at the South of the Canadian island of Newfoundland. The archipelago consists of eight islands, the two largest being Saint-Pierre and Miquelon-Langlade. The last is composed of two peninsulas linked together by a sandy tombolo. The SPM archipelago is of great interest for cetacean monitoring as it is both a feeding ground and it is situated near several migration corridors as well as shipping lanes and fishing grounds. This site is also characterized by being near both deep and shallow waters but also experiencing a large water temperature gradient [47], which are favorable oceanographic conditions for different cetaceans and marine life.

### 2.2. Acoustic Data

Passive acoustic data were collected using two AURAL-M2 (Autonomous Underwater Recorder for Acoustic Listening, Model-2, by Multi-Electronique Inc., Rimouski, QC, Canada) recorders, owned by the SPM Frag-îles association. These recorders were located at two sites off the archipelago: one was to the North (AURAL-B) and the other to the South (AURAL-A), as shown in Figure 1.

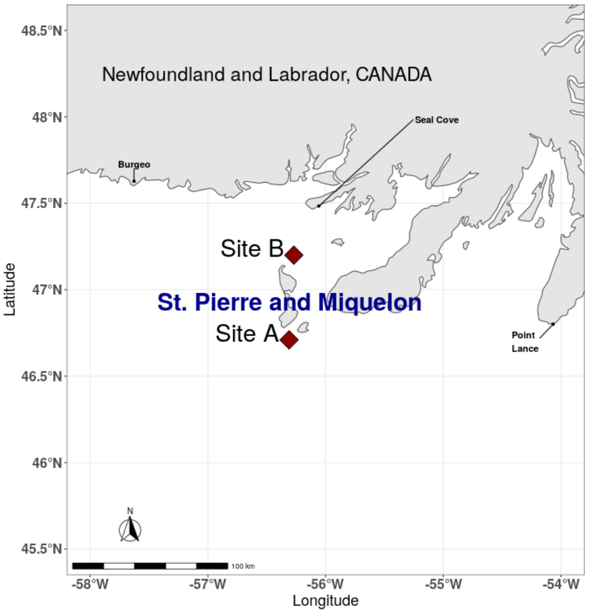

**Figure 1.** Deployment locations.

AURAL-A was moored at a mean depth of 60.5 m, whereas AURAL-B was anchored at a mean depth of 59 m. Both recorders were moored close to the seabed. These two recorders were fitted with a HTI-96-MIN hydrophone (High Tech Inc., Long Beach, MS, USA) with a sensitivity of −165 dB re V/µ Pa and set with a gain of 22 dB. The acoustic surveys were carried out during two different seasons, which allowed some assessments of the seasonal effects. In 2010, site B was acoustically sampled for 45 min, continuously followed by a pause of 15 min (75% duty cycle, sampling rate of 32,768 Hz at 16 bits), and measurements took place in late summer and autumn, see Table 1 for specific dates. Then, in 2011, the duty cycle was modified to 50% (30 min ON, 30 min OFF) to allow longer durations of deployments. The equipment was deployed in spring and summer. Only site A recorded during the winter season, running for 6 months from October 2011 to April 2012 with a duty cycle of about 25% (17 min ON, 43 min OFF). The other configuration settings were unchanged from 2010. A summary is given in Table 1. The different seasons also matched the different seasonality patterns found in the literature [16].

**Table 1.** Summary of the characteristics of recordings performed in each site for each year.

| Recorder | Mooring Periods (dd/MM/YYYY, hh) | Duty Cycle (mins ON/mins OFF) |
|---|---|---|
| Site B | 19/08/2010, 18:00–02/11/2010, 23:00 | 45/15 |
| | 25/04/2011, 20:00–16/08/2011, 18:00 | 30/30 |
| Site A | 23/04/2011, 13:00–23/07/2011, 12:00 | 30/30 |
| | 15/10/2011, 01:00–30/04/2012, 18:00 | 17.03/42.57 |

### 2.3. Open Science Meets Ocean Sound Explorers (OSmOSE) Project

OSmOSE is a scientific interest group centered around the processing of PAM data and its applications related to the sustainable development of the oceans. Driven by the principles of open science, its ambition is to develop big data oriented and web-based tools with extensive documentation. The aim of this group is to respond collectively to needs in terms of scientific expertise and innovative technological developments of the PAM community's research. This study is a case study of the big data system developed within this project. All the implementations of the big data system are available at https://github.com/Project-ODE/FeatureEngine (accessed on 23 September 2019).

### 2.4. Self-Generated Noise

In 2010, 1016 audio files on 1806 of site B were corrupted by a low-frequency noise that needs to be taken into account in the analysis of acoustic levels and other metrics. In 2011, 726 audio files on 2184 and 1116 on 2711 were corrupted by this noise for site A and B, respectively. The precise source of the noise is not known but it is believed that it relates to the motion of the batteries within the recorder, with motion being induced by the flow of water over the recorder. Visual inspection of the data suggests it is the frequency band from 0 Hz to 3 kHz that is affected by this noise. No clear temporal variation pattern was found for this noise. No correlation between files containing the self-generated noise and hourly wind or daily precipitation values was found (point-biserial correlation coefficient to correlate binary—i.e., presence or absence of the self-generated noise in a file—and continuous variables, i.e., the hourly wind speed was lower than 0.49, $n = 9170$, and Spearman's correlation coefficient $\rho$ was lower than 0.5 too, $p = 0.011$a, $n = 481$, for daily precipitation).

### 2.5. Environmental Data

Wind speed data were included in this study so that the impact of surface generated noise on the data could be assessed. No weather buoy was linked to our recorders. However, wind speed and daily precipitation data were obtained from the National Oceanic and Atmospheric Administration database (https://www.ndbc.noaa.gov/, accessed on 23 September 2019). Weather buoy 44,235 is moored and equipped with a surface-mounted buoy anemometer at 10 m above the surface that provides hourly reports on wind speed. This buoy is approximately 81 km and 110 km from sites B and A, respectively. Daily-averaged precipitation data were collected from an onshore station (SBM00071805). When these data are unavailable, the corresponding observations were removed from the analysis. No wind data were retrieved from the onshore station.

### *2.6. Data Analysis*

#### 2.6.1. Visual and Aural Inspection of Audio Files

All audio files from sites A (2011, 2011–2012) and B (2010, 2011) were aurally and visually assessed by an analyst (OA) in Adobe Audition software (Adobe Audition CS6 v.5.0). No specific software or detection algorithm was employed. Each audio recording was given one or more tags depending on the identified acoustic sources. Tags were given to each audio recording when it contained mysticete (baleen whale) calls (mysticeti label on Figure 2), odontocete (toothed whale) calls (for both whistles and clicks, odontoceti label on Figure 2), all kinds of ships (ship label on Figure 2, no automatic identification system data were used), rain (rain label on Figure 2), self-generated noise (self-noise label on Figure 2), or the absence of such acoustic sources (abs label on Figure 2). For example, if an audio file recorded some mysticete calls and a ship, this file was given the labels mysticeti, ship. The mean number of hours per day by month for both sites was computed for each category and shown on Figure 2.

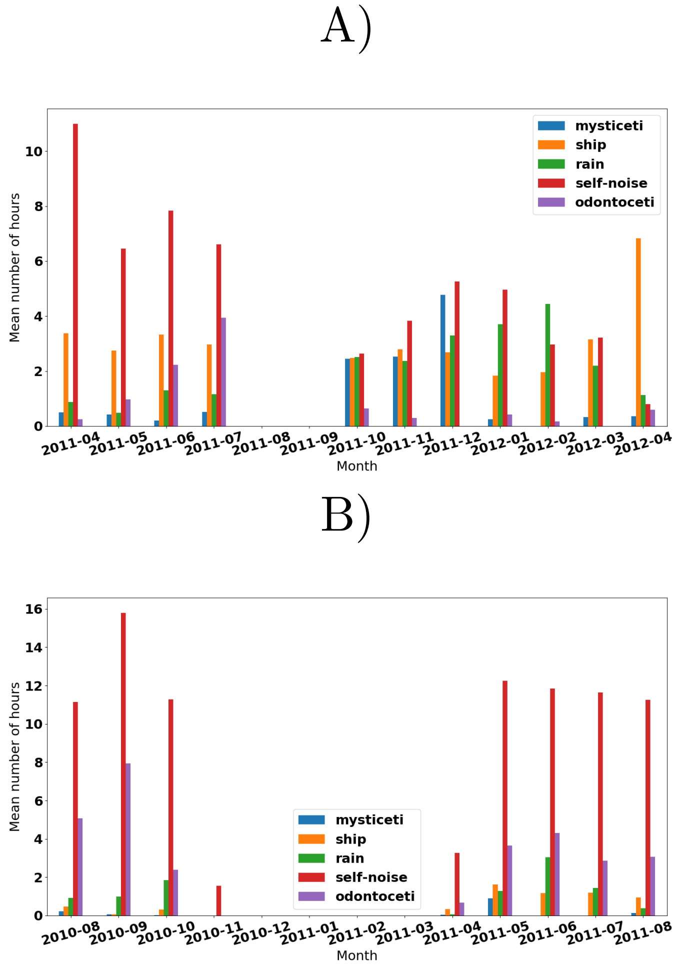

**Figure 2.** Mean number of hours per day by month for site (**A**) (**upper**) and site (**B**) (**lower**) campaigns for mysticetes, odontocetes, rain, ships, and the self-generated noise. Blank periods indicate that no data were available for that period.

#### 2.6.2. Overall Sound Levels

Quantitative methods to characterize the spatial, temporal, and spectral contents of the SPM underwater acoustic environment were used.

In order to correlate SPL with geophony, SPL was computed in 8 octave bands: 0–500 Hz, 500–1000 Hz, 1–2 kHz, 2–4 kHz, 4–8 kHz, and 8–16 kHz.

#### 2.6.3. Anthrophony: Shipping Noise

Third octave band levels (TOL) were evaluated to characterize shipping noise. The workflow used to compute the quantitative metric follows that of [48].

The Marine Strategy Framework Directive (MSFD) of the European Union Indicator 11.2.1 requests the monitoring of the 63- and 125-Hz centered TOL to describe low-frequency anthropogenic noise [49]. As a consequence, these two TOL were set as a measure of anthrophony and evaluated every minute.

Since the data generally have nonzero means, the mean of each TOL band was subtracted before running a point-biserial correlation between expert annotations of ships and the two TOL bands to determine if these bands are good proxies for ship presence.

#### 2.6.4. Biophony

First, expert annotations were used as a reference for identifying seasonal trends in biophony. Interactions between anthrophony, biophony, and geophony were also studied based on the annotations.

Then, the ACI [50,51] was computed every minute and averaged either hourly or daily to estimate biophony in our long-term recordings. The ACI is an estimation of the amount of information contained in an audio spectrogram based on the intensities. To compute the ACI, the difference between two contiguous intensities in a same frequency bin is calculated [21,50,51]. This ecoacoustic index is one of the most widely used for assessing the presence of biophony [24]. Even though this ecoacoustic index was firstly tuned for transient signals [21], it was used in this study to describe all types of cetacean sounds. No standardized frequency band and time resolution [27] for ACI was found in literature, as it heavily depends on the studied species [21,52]. The ACI was computed over the whole frequency range (i.e., 0 to 16,384 Hz, 50% overlap, frequency resolution = 8 Hz, Hamming window).

We also investigated the robustness of ACI to other abiotic sounds, i.e., anthrophony and geophony [25]. For correlations between anthropogenic activities and ACI, the point-biserial correlation coefficient between files with and without ships were compared to the ACI. In order to assess the robustness of ACI to wind, we computed hourly averaged ACI values to match the time resolution of the hourly wind speed data and these metrics were compared with Spearman's correlation coefficient. To assess the robustness of ACI to the acoustic interference of rain, hourly averaged ACI values were compared to the rain annotations with a point-biserial correlation.

In this work, only the cetacean acoustic contribution to the marine acoustic environment of SPM was analyzed even if other contributors such as fish or invertebrates were present.

## 3. Results

### *3.1. Anthropogenic Noise*

The anthrophony in our recordings consisted of vessels traveling to and from SPM along with distant ship traffic and fishing vessels, as site A and B are near shipping lanes and fishing grounds [16]. Tonal components of ship noise were found at various frequencies depending on their propeller blade rate, engine tones and overtones ranged from 100 Hz to 7 kHz in our data. Both TOL bands showed a high degree of variation, with the largest variation in the 63-Hz TOL for the campaign on site A with values ranging from 63 dB re 1 µPa to 138 dB re 1 µPa. On average, the 63-Hz TOL experienced the greatest level variations with about 75.3 dB re 1 µPa, whereas for the 125-Hz TOL, these levels were about 63.1 dB re 1 µPa. TOL were louder in the 63-Hz bands compared to the 125-Hz by about 2 dB in mean levels but only 1 dB in terms of the median. In 2010 for site B and 2011 for both sites, sound levels in the 63-Hz and 125-Hz TOL bands remained similar, around 88 dB re 1 µPa and 87 dB re 1 µPa, respectively, as shown Figure 3. For the 2011–2012 site A campaign, the 125-Hz TOL was louder than the 63-Hz.

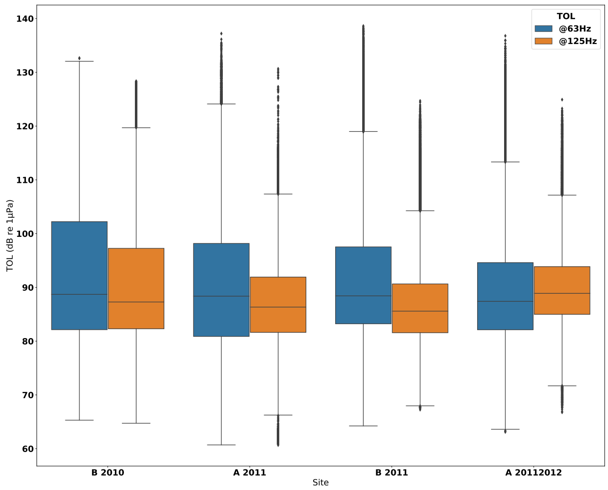

**Figure 3.** Boxplots representing the 63-Hz and 125-Hz centered Third octave band levels (TOL).

More vessel passages were acoustically observed at site A with a mean of almost 4 h per day of acoustic vessel presence for each month of the deployments (cf. Figure 2). At site A, April 2012 was the month that experienced the highest mean number of hours a day of anthropogenic pressure with more than 6 h when ships were present. A point-biserial correlation was run to determine the relationship between files containing ship sounds, the 63-Hz TOL, and the 125-Hz TOL. A very small effect size was identified between these variables ($0.02 < r < 0.14$, $n = 11{,}474$, $p < 0.05$ for the correlation between ship annotations and the two TOL bands). No clear time pattern was found across the recording campaigns.

### 3.2. *Geophony*

The geophony is dominated by surface, wind-dependent noise and rainfalls.

#### 3.2.1. Wind Speed

The mean wind speed measured across the whole campaign is greater than 14 m/s. Therefore, wind is a major contributor in the underwater acoustic environment.

Table 2 shows Spearman's correlation coefficient for wind speed with different SPL bands for each of the different measurement campaigns. The 2–16-kHz SPL bands are strongly correlated to wind speed. Table 2 shows that wind is a major contributor to frequencies ranging from 2 to 16 kHz on both sites.

**Table 2.** Spearman's correlation coefficient for daily-averaged wind data versus different sound pressure level (SPL) bands. Characters in bold indicate $p < 0.05$, $\rho > 0.49$.

| SPL Bands (Hz) Sites | 0–500 | 500–1000 | 1000–2000 | 2000–4000 | 4000–8000 | 8000–16,000 |
|---|---|---|---|---|---|---|
| A2011 ($n = 72$) | 0.0735 | 0.2807 | 0.4883 | **0.6101** | **0.6369** | **0.6207** |
| A20112012 ($n = 197$) | 0.3215 | **0.6531** | **0.7650** | **0.7966** | **0.7842** | **0.7864** |
| B2010 ($n = 75$) | 0.3317 | 0.4915 | **0.7787** | **0.8809** | **0.8879** | **0.8794** |
| B2011 ($n = 95$) | 0.1512 | 0.3623 | 0.4861 | **0.7142** | **0.7501** | **0.7248** |

#### 3.2.2. The Contribution of Precipitation

The SPM archipelago witnesses sparse rainfall that often occurs simultaneously with strong winds. However, the effect size was small based on a low Spearman correlation coefficient ($0.01 < \rho < 0.25$; $n = 93$ for A 2011; $n = 199$ for A 20112012; $n = 76$ for B 2010; $n = 114$ for B 2011; $p < 0.05$ for all sites). A small effect size was also identified between SPL bands and precipitation ($0 < \rho < 0.23$; $n = 93$ for A 2011; $n = 199$ for A 20112012; $n = 76$ for B 2010; $n = 114$ for B 2011; $p < 0.05$).

From the expert annotations, site A was the location with the most rainfall. The rainiest season was winter at site A. Spring and summer experienced the least rainfall at both sites.

### 3.3. *Biophony*

The marine acoustic environment in the SPM archipelago is rich in sounds produced by various and concurrent biologic acoustic sources. Although present for only a few months of the year, in certain frequency bands, cetaceans are the dominant contributors to the average noise level.

We identified a few time periods of intense vocal activity and manually extracted some samples for analysis. They were further aurally and visually checked by a cetacean expert (OA) to identify the species. In the following, we report a short catalog of the most commonly encountered vocal sounds per species, from the lowest to the highest frequency bands. Note that other marine mammal species may be present, as we only focused on the signatures that had the most influence on the long-term averaged representations.

#### 3.3.1. Blue Whales

It is known that blue whales generate stereotyped calls that are used to discriminate subspecies groups in different geographic locations. For example, Antarctic Blue whale vocalizations [5,53] differ from those encountered near SPM.

#### 3.3.2. Humpback Whales

Even in feeding seasons, but less rare than in breeding seasons, humpback whales are an active sound source for several months, resulting in a spectral peak near 300 Hz. Humpback whales produce complex tonal and pulsed sounds between 20 Hz and several kHz [30,54–56]. Figure 4B shows a distant humpback vocalization spanning frequencies from about 50 Hz to 2 kHz, with the most intense components between 100–400 Hz. Some sound units of this are repeated and organized in the same order in the reproduction phrase. The humpback whale sounds are typical of those used in social and foraging activities [57].

#### 3.3.3. Sperm Whales

Sperm whales were identified by their regular clicks and buzzes (Figure 4C) with peak energy ranging from 2 to 25 kHz [58,59]. These are easily identifiable with no ambiguity from clicks emitted by other odontoceti species, because of their acoustic intensities, time duration, and peak frequencies. Creaks were also recorded corresponding to foraging activity [60]. In our recordings, it seems by visual and aural inspection that the northern site recorded more sperm whale activity than the southern site. The presence of sperm whales normally generates a peak in the percentile plots close to 7 kHz [61].

#### 3.3.4. Killer Whales

A large repertoire of sounds are emitted by killer whales including whistles and clicks [62,63]. Resident killer whales are actively vocal, and are often recorded in this area [64]. Figure 4D depicts some killer whale calls found in the data sets.

#### 3.3.5. Delphinids

Common dolphins, striped dolphins, Atlantic white-sided dolphins, and long-finned pilot whales are the primary contributors to the SPM acoustic environment in the high-frequency bands with whistles and clicks. Groups were often detected in audio recordings when high energy was observed in the long-term spectral averages. Ships were also frequently identified at the same times.

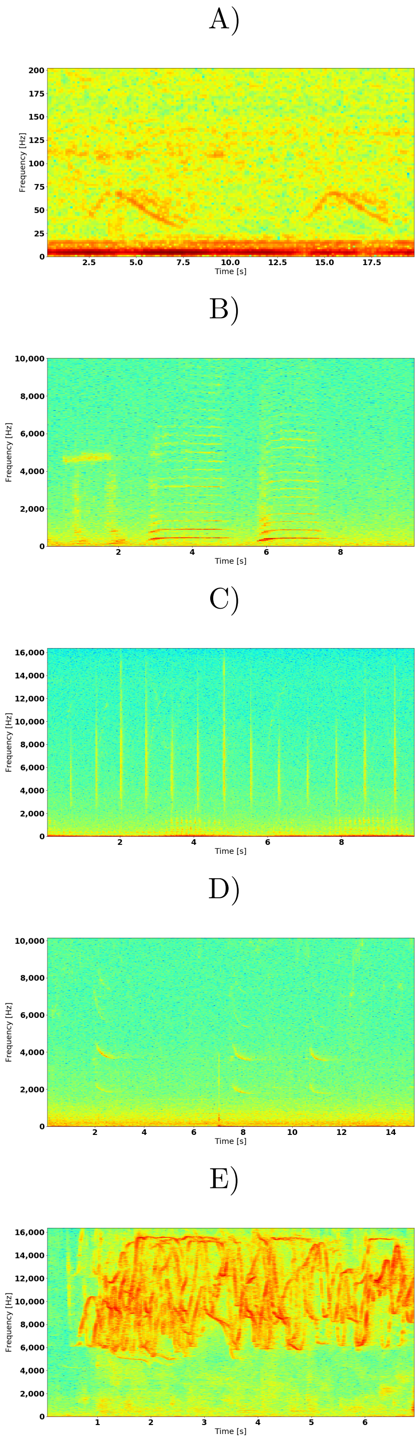

**Figure 4.** Spectrograms of different species encountered near Saint-Pierre-and-Miquelon (SPM) archipelago: (**A**) blue whale vocalization (frequency resolution = 2 Hz, time resolution = 0.5 s); (**B**) humpback whale vocalization (frequency resolution = 8 Hz, time resolution = 0.125 s); (**C**) sperm whale click train (frequency resolution = 16 Hz, time resolution = 0.0625 s); (**D**) killer whale (frequency resolution = 8 Hz, time resolution = 0.125 s); (**E**) delphinids (frequency resolution = 8 Hz, time resolution = 0.03 s).

### 3.3.6. Seasonality

Odontocetes were identified mostly during summer and autumn in both sites. In 2011, more odontocetes were observed at site B for April, May, and June. From these three months, an increase in the mean number of hours per day of odontocetes' presence was identified. In July 2011, odontocetes were more present at site A than at site B, with twice the mean number of hours per day (4 h for site A against 2 h for site B).

There was a small difference between 2010 and 2011 in the times when the greatest abundance of odontocetes were observed. In 2011, it was the first half of August when the peak occurred, whereas that peak happened in the second half of August in 2010.

Mysticetes were rare at site B in the spring, summer, and autumn. At site A, the most favorable season to hear mysticetes was winter. Moreover, a diurnal pattern could be observed for December 2011 for site A, with more detections during the night from 19:00 to 04:00 (cf. Figure 5).

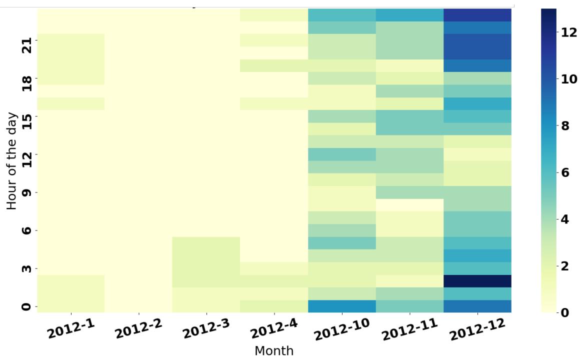

**Figure 5.** Hourly number of detections of mysticetes by month for the 2011–2012 site A campaign.

### 3.3.7. Assessing Biophony with ACI

A point-biserial correlation was computed between ACI values and files with annotations. A small effect size between the ecoacoustic indices and the presence of mysticetes or odontocetes was found ($r < 0.25$, $p < 0.05$, $n$ = 11,474).

### 3.3.8. Anthrophony and Geophony Interferences in ACI Values

The effect size was very small between boat annotations and ACI values ($r < 0.1$, $p < 0.05$, $n$ = 11,474).

To assess the interactions between biophony and wind speed, hourly averaged ACI values were compared to hourly wind speed with Spearman's correlation coefficient. A small effect size was found ($\rho < -0.3$, $p < 0.05$, $n$ = 11,474). Hourly summed ACI values were also compared to the rain annotations with a point-biserial correlation. Similarly, a small effect size was found ($r < -0.03$, $p < 0.05$, $n$ = 11,474).

### 3.3.9. Manual Analysis of Biophony and Anthrophony Interactions

The number of files containing both cetaceans (either mysticete or odontocete calls) and ship sounds was computed. On 11,474 audio files, 1130 contained ship noise and 1265 contained cetacean sounds. A total of 459 audio recordings contained both cetacean and ship sounds, which is more than a third of the audio files containing only cetacean sounds. On these 459 audio files, all the files containing mysticete sounds in December 2012 also contained ship noise.

Finally, only 2 audio recordings for both sites in September 2010 contained both cetacean and ship sounds, while this month experienced the highest number of audio recordings containing only cetacean sounds (213 files).

# 4. Discussion

## 4.1. Geophony

Wind was shown to be the dominant abiotic source. Its correlation with underwater noise was substantial at 200 Hz–16 kHz. The North-West Atlantic Ocean is an active cyclonic zone, especially in September and October, and some annual data recorded 2010 as being an especially active year. On 20 September 2010, for both sites, hydrophone saturation was observed in the audio files. This coincides with the end of Hurricane Igor (8 September 2010–12 September 2010) with the resulting swell, rainfall, and wind overloading the underwater recorders. Note that wind records were retrieved from a station further from the hurricane's eye than the SPM archipelago, which implies stronger winds at the archipelago. This was not the only storm in 2010 that could have affected SPM recorders during the deployment (e.g., hurricane Earl in the end of August of 2010). PAM has been shown to be a good proxy to gather weather data [30,65,66].

Moreover, ACI was shown to be robust against geophony interferences in the acoustic data set [25,67], as shown by the low point-biserial correlation coefficient between annotations of files containing rain and ACI values. Geophony will generate an overall increase in the spectral levels across a wide range of frequencies. The underlying signal remains broadly Gaussian, so the ACI is unaffected.

## 4.2. Anthrophony Noise

This study focused on distant traffic noise following the guidelines of the MSFD Descriptor 11 [49] in the SPM archipelago. Even if offshore Eastern Canada is a place where seismic surveys are regularly conducted, no such events were retrieved in our acoustic data. Noise levels were provided, serving as a baseline for future studies at this site. The TOL were found to be steady from 2011 and 2012 (only for the AURAL-A). The 63-Hz and 125-Hz median and mean TOL bands remained under 100 dB re 1 µPa. For AURAL-A, for mid-autumn 2011 to spring 2012, these TOL values reached the same levels as in 2010 and 2011.

By comparing the two TOL median values for our sites, they were more than 10-dB-less than those observed by [68], where their moorings were 15 km from a shipping lane and at a mooring depth of about 40 m. Our values for the two TOL median level were also more than 20 dB lower than those reported by [69] for a mooring at 80 m depth in the Celtic sea. Ref. [69] also cautioned that a mooring environment such as shallow waters could result in erroneous estimation of the MSFD TOLs.

By correlating these TOL with expert annotations (excluding files containing self-generated noise), a small effect size was found, meaning that the MSFD TOL might not be adequate for shallow waters [69].

A very small effect size between ACI values and annotations of ship files was found, suggesting that ACI is robust to the inclusion of ship noise in the acoustic recordings [25]. One reason could be that the ACI computation implies the removal of sounds with limited variations of amplitudes over time and frequency [23,51].

## 4.3. Biophony

Multiple baleen whale species potentially migrate annually along the SPM archipelago coasts. While we do not have a exhaustive catalog with the sounds emitted by all the cetacean species, we provided an overview of some of them that could be encountered near the SPM archipelago.

Regarding mysticetes, they were rarely found in spring, summer, and autumn. This result is unexpected compared to [16]. However, for December 2011 season of site A, a diurnal pattern of mysticete vocalizations was identified. More vocalizations were observed during the night than during the day. Moreover, the limited presence of mysticetes in spring, summer, and autumn could be due to mysticetes that stay around the area for feeding or breeding [16].

Summer and autumn seemed to be the seasons where odontocetes were the most frequently recorded, as the highest number of hours containing detections were found to peak in summer and autumn months for both sites. This result can be explained by the high concentrations of chlorophyll-a in these seasons [45], which attract aggregations of prey species. Moreover, this seasonality was also identified in [17] for the closest stations to SPM.

Other cetaceans can be found near the archipelago [16,70]. PAM is of great interest to identify species that are visually cryptic but highly vocal. In this case, sperm whales were rarely visually observed at sea but with strandings on the shores of SPM (https://la1ere.francetvinfo.fr/saintpierremiquelon/saint-pierre-2/miquelon-cachalot-echoue-ses-dents-arrachees-130915.html) and we aurally identified them in our underwater recordings. Other odontoceti, like Kogiidae, are also very discrete and difficult to visually observe, even from boats and from aerial drones. It shows that acoustic observations are an attractive complementary method to visual observations.

The ACI was computed as a way to identify the contribution of biophony in the SPM underwater acoustic environment. We showed that this ecoacoustic index was robust to anthrophony (shipping noise) and geophony (wind and rain). The ACI was initially computed to quantify high-energy acoustic sounds with high variations in time and frequency such as broadband impulsive sounds (e.g., snapping shrimps, echolocation clicks) or harmonic ones (e.g., fish chorus). This ecoacoustic index was created to be relatively unaffected by continuous sounds with small time and frequency variations (e.g., rain, wind, or ship acoustic signatures) [21,24,71]. It was mostly used in underwater acoustic environments for characterizing coral reef biophony such as fish choruses and snapping shrimp sounds [22,24–26,35,36,38,67], which are either transient sounds like echolocation clicks or harmonic ones like cetacean vocalizations. The ACI is known to be sensitive to processing parameters such as the time and frequency resolutions [37,52,71], but also to the underwater biophony diversity and the abundance of the sounds of a specific site [71].

Due to the self-generated noise that mask frequencies from 0 to 3 kHz, cetaceans were not well identified with this ecoacoustic index. The self-generated noise is a transient signal, which generated high values of ACI. A better estimation of the biophony could be the use of several ecoacoustic indices instead of only one [72].

Based on the manual analysis of the biophony and anthrophony interactions, about a third of the audio recordings containing cetacean sounds also recorded ship noise at the same time. This trend shows the need to use PAM for the large-scale monitoring to improve new marine management programs.

Furthermore, it is worth noting that cetaceans are not the only marine animals that can be impacted by anthrophony, fish and invertebrates also are. It would not be surprising that some fish and invertebrate sounds were recorded in the study area. In-depth analysis of such an impact should be carried out because the surroundings of the SPM archipelago seems to be a feeding habitat for several cetaceans identified in our acoustic data set [73]. The research on the effects of anthrophony on fish and invertebrates is gaining importance because they form the basis of the marine food web. For example, one of the main threats for Southern Resident killer whales is the lack of food [74]. By gaining knowledge on these preys, new insights could be used in marine management strategies [75]. In our work, only sound pressure was analyzed, which may be inadequate to study the acoustics of fish and invertebrates as they mostly rely on particle motion [76,77]. Furthermore, some fish and invertebrates might also use substrate vibrations [78] for foraging and another anthropogenic threat for them are anthropogenic substrate vibrations [79] caused by seismic surveys or pile driving, for example. The analysis of particle motion in shallow waters might require specific sensors [76] that were available for this study.

## 5. Conclusions

Although computations of the daily averaged long-term representations is straightforward, they proved to be good descriptive tools to characterize long-term underwater acoustic environments. This paper presents the underwater acoustic environment characterization of the SPM archipelago over multiple years and sites. We were able to extract acoustic events in order to describe the biophony (especially the presence of few cetacean species), the geophony (especially the occurrence of rain and wind), and the anthrophony (especially the routes of motor ships). Mysticeti and odontoceti share waters off SPM archipelago even if some of them are residents while the others are migratory species. This is probably because SPM archipelago is a feeding area for these cetacean species. Furthermore, during these two seasons, the SPM underwater acoustic environment is more likely to experience extreme weather. Mysticetes were mostly vocally active in winter in the southern site. From our data sets, no clear interactions were shown between anthrophony and biophony for the considered recording campaigns even if a substantial number of audio recordings contained both cetaceans and ship sounds. Due to the recent Laurentian Channel marine-protected area, PAM recordings should be continued and further analysis on anthrophony and biophony interactions should be carried out. Ships going in and out of the SPM archipelago do not show a clear time pattern. The southern site was more prone to vessel passage noise disturbance than the northern one. Finally, the ecoacoustic measure ACI was shown not to be a good proxy in our case, for example, because a self-generated noise produced high values of ACI. However, it was shown to be robust to anthrophony and geophony. Any spatiotemporal changes of the different acoustic sources and their distribution can be identified by using PAM. Future studies need to be undertaken to (i) analyze the variability of underwater acoustic environments depending on duty cycle and window size to compute the fast Fourier transform, and to (ii) detect acoustic events for specific species in these data sets to have a better insight of the visitation pattern in the SPM archipelago. Long-term data sets of the same location allows to monitor changes in the underwater acoustic environments over the years, which might contribute to the development of marine life conservation programs.

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