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***Abstract*—One of the best ways of studying animals that produce signals in underwater environments is to use passive acoustic monitoring (PAM). Acoustic monitoring is used to study marine mammals in oceans, and gives us information for understanding cetacean life, such as their behaviour, movement or reproduction. Automated analysis for captured sound is almost essential because of the large quantity of data. A deep learning approach was chosen for this task, since it has proven great efficiency for answering such problematics. This study focused on the orcas (*Orcinus orca*) of northern Vancouver Island, Canada, in collaboration with the NGO Orcalab which developed a multi-hydrophone recording station around Hanson Island to study orcas. The acoustic station is composed of 5 hydrophones and extends over 50 km^2 of ocean. Since 2016 we are continuously streaming the hydrophone signals to our laboratory at Toulon, France, yielding nearly 50 TB of synchronous multichannel recordings. The objective for this research is to do a preliminary analysis of the collected data and demonstrate influence of environmental factors (tidal, moon phase and daily period) on the orcas' acoustic activities.**

***Index Terms*—Ethoacoustics, Deep Learning, Convolutional Neural Networks, Orcas, Killer whales, Cetaceans, Bioacoustics, Environmental factors, Soundscape, Big data**

I. Introduction

Orca (*Orcinus orca)* is a top-predator of the marine food chain [1]. The Northern Resident Killer Whale community is composed of several "pods" composed of matrilines [2]. Several of those visit the area surrounding Hanson Island (Canada, north of Vancouver) due to the concentration of salmon [3]. For a more accurate description we suggest: The Northern Resident Killer Whale community is composed of more than 300 individuals (in 2018) organized into several pods comprised of matrilines, each of which possess their own dialect (a repertoire of 7-17 discrete calls). Pods that share similar call types are classified into one of three acoustic clans. There are no shared calls between clans. This odontocete can produce 3 different types of signals: clicks, whistles and pulsed calls [4]. This study focuses only on vocalizations (pulsed calls).

Some biological studies describe the communication of orcas [5]–[8], based on manual methods. Related work [9] compared dialects of orca using artificial neural networks and showed that acoustic similarities are significantly correlated with the group association patterns.

In order to analyze animal communication in different spacial and temporal contexts, automated analysis for captured sound is crucial. For that purpose, the field of bioacoustics has proposed numerous approaches using neural networks and deep learning [10]. We therefore investigated the latter methods to automatically detect orca calls emitted throughout 3 years of continuous recording from 2015 to 2017. The data collection system was built over years of fruitful collaboration between Orcalab and DYNI LIS CNRS Toulon University, that we call 'OrcalabToulon'.

II. Material

For 20 years, the NGO Orcalab developed and has maintained a unique multi-hydrophone recording station around Hanson Island (Northern Vancouver Island, Canada) to study orcas. This acoustic station is composed of 5 hydrophones and extends over 50 km^2 of ocean (Fig. 1).

A previous database from Orcalab called Orchive [11] was compiled from these recordings in 2013, congregating selected and segmented orca calls extracted from their context. It was the first open corpus allowing large scale analysis, but cannot be used to compute spatial long term behaviors of the orcas, or to link voicing with typical spatio-temporal events.

To help with solving this paradigm, in 2015 we have set up a continuous recording of all the hydrophones of this station. The aim is to allow observations and modelling bioacoustic activities of various species, at large spacial and temporal scales, including all details of their ecoacoustic niche, under various

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geophysical and anthropophonic conditions, more particularly in order to build new knowledge about orcas.

The architecture of the global system is shown on Fig. 2. The hydrophones record the soundscape continuously. The recordings are transmitted to the OrcaLab station in real time via very high frequency (VHF) radio. Each analog signal is received by a radio receiver at Orcalab, then digitized on a Presonus analog-to-digital converter (ADC) and sent to a Linux OS portable DELL Latitude PC running continuously. The recordings are then compacted in segments of 2 minutes including all 5 channels, using lossless flac compression, with a sampling rate of 22050 Hz and resolution of 16 bits. Each segment is then sent to DYNI Toulon University big data NAS (Network Attached Storage) of 300 TB via wifi to Alert Bay, and then via the Internet. A buffer of 7 days on our local laptop in Orcalab allows to dealing with interruptions of the local or intercontinental Internet connection. The data transmission is automatically continued as soon as the connection is stabilized. The sampling rate of the ADC is chosen low enough so the system has spare bandwidth to transfer the buffer after a connection failure. In total, from July 2015 to 2017, around 50 TB of sound (about 14,500 h) was stored on our server.

III. Data Analysis

A. Automatic acoustic event extractor

We designed an automatic acoustic event extractor (inspired from [12]). The main steps of the algorithm (shown in Figure 3) are: (i) calculating the spectrogram (time frequency representation) of the recording using an STFT with a Tukey window of 1024 samples and 20% overlap; (ii) computing a binary image by comparing against the median over frequency band and time slice: if the value of a pixel is greater than 3 times the median plus 3 times the standard deviation of its row, and greater than 3 times the median plus 3 times the standard deviation of its column, it is set to 1, otherwise to 0; (iii) applying a "closing" and "dilation" filter for each pixel to remove the noise; (iv) finding connected components and removing small components and isolated pixels; (v) computing bounding boxes for remaining components.

Merging nearby boxes (with a gap of at most 0.2 s), and filtering out irregular ones (vertical boxes with a frequency range in Hz larger than 5000 times the time range in seconds, or boxes with a maximum spectral magnitude higher than 25 dB, too high to be orcas) helped us to get rid of a large amount of non-orca acoustic events. The remaining 3.5k (out of 14k) boxes were annotated as orca or noise manually.

B. Orca detector using deep learning

We built a dataset (resulting mainly from the above experiment) composed of 872 orca vocalization samples and 6801 noise samples (boats, rain, void...), which we split randomly with 20% for the test set, 60% for the training set and 20% for the validation set. [1] With that in hand, we trained a CNN [13] (originally designed for a bird detection task) to distinguish orca vocalizations (not clicks) from boats and background noise.

[1] A random split may sample train and test segments from nearby locations, giving an overly optimistic test error. We did not have enough annotated data for a chronological split avoiding this.

Table I
Test set performance of deep learning model for orca detection

	Accuracy	Area Under Curve
Training	0.97	0.88
Validation	0.96	0.89
Test	0.97	0.89

After training, when computing predictions, a threshold of 0.9 is applied to the output of the model. This reduces the risk of false positives. Table I and Figure 4 show the performance of the detector on our labeled test set, demonstrating that it produces reasonable results.

IV. Results

A. Large scale statistics

Once trained, the model was run on 3 years of recordings (2015, 2016 and 2017) in 2 days of computation on an Nvidia Titan X Pascal GPU. The results in Figure 5 show the proportion of files with orca detections among all the recordings of each month, for each hydrophone. Orcas are present (acoustically) mostly during summer (June, July, August and September). This migration is confirmed by [14], orcas are abundant in Johnstone Strait between July and October, when salmon migrate into it.

Hydrophone 5 (Johnstone Strait) is the busiest location in every year. The second (smaller) peak, encompassing October-December, may additionally reflect the presence of vocal Humpback Whales [15] and/or other cetaceans in the area, that are often classified as orcas by our model.

B. Trajectography

In order to get an idea of animal trajectories, one can estimate the acoustic activity of orcas in the range of each hydrophone over time. This idea was applied for the 24th of August 2017 with several techniques. First we used the automatic acoustic event extractor (Section III-A), taking the number of detected events as a proxy for estimating the acoustic activity of orcas (Fig. 6). The trajectory from H5 to H1 can be deduced by the succeeding high detection rates of the hydrophones, but the signal is very noisy since this detector is not specific to orcas.

A second method was to use our deep learning model (Section III-B) trained for orca call detection, thus giving a much better estimate on orca activity over time and hydrophone (see Figure 7). The results confirm the primary deduction from the acoustic event detector (Fig. 6, trip from H5 to H1 at 5:30 am), but with a much cleaner signal.

C. Voicing statistics

In order to better understand the orcas' voicing activities, we have located them in zones (Fig. 1) using the detection of voicing by hydrophone(s) (note that in the statistics, we

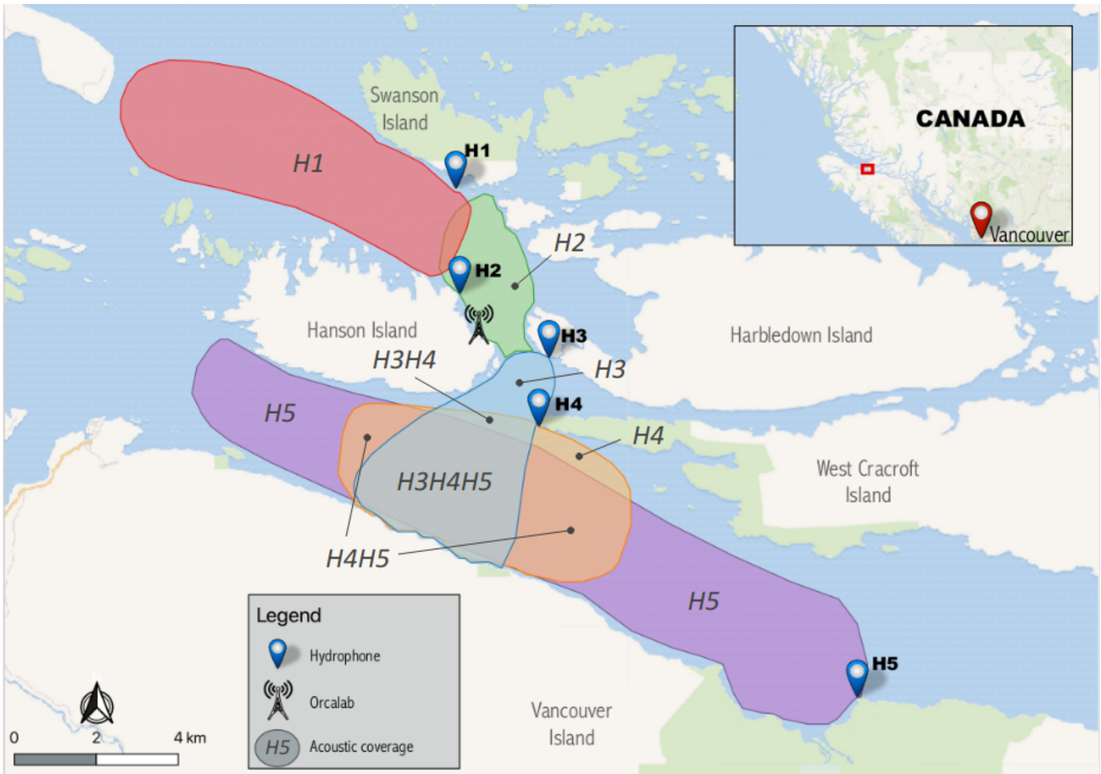

Figure 1. Map of the area and the listening range of the 5 hydrophones. Map pins with H1 to H5 in bold print denote the hydrophone locations. Detection zones indicate which hydrophones can capture orca calls in a particular area, according to experience of ten years of audio-visual observations of the orcas by the OrcalabTeam. Map generated by QGIS software (version 2.14 Essen).

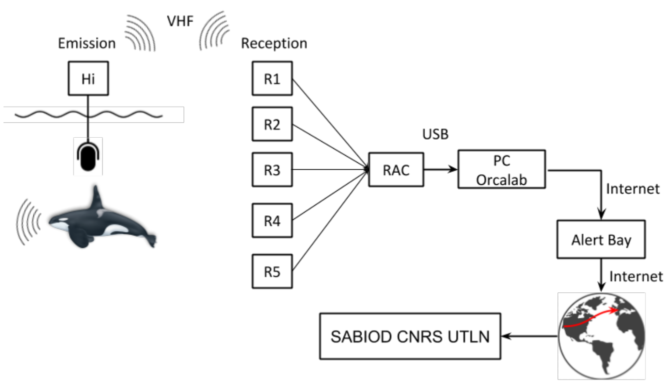

Figure 2. Representation of the data acquisition, from recording until storage on SABIOD CNRS UTLN server.

remove any intersection zone from each individual area, so that they are disjoint). The model described in III-B is used to determine if a recording contained orca calls or not. We use a simple heuristic to map each two-minute recording period to a detection zone in Fig. 1: If a period has orcas detected for a single hydrophone only, we assume they are in the zone covered by this hydrophone exclusively. If there are detections for multiple hydrophones that have overlapping ranges (e.g., H4 and H5), we assume they are in their joint

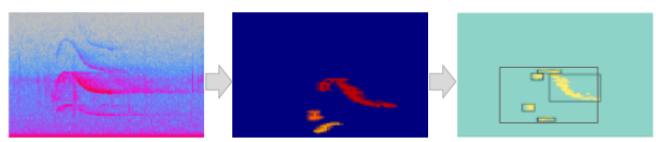

Figure 3. Main steps for the acoustic events extraction: Binarization and detection of connected components. The spectrogram shows frequencies from 0 to 6.5 kHz during 2.5 s.

detection zone. Simultaneous detections for hydrophones with non-overlapping ranges (e.g., H1 and H5) are discarded – we need a single zone to compute transitions, and this affected less than 1% of recordings. Using those zones not only gives us an idea of the common localization of the animals, but also of their most common trajectories (studying zone transition probabilities). We applied this study to the available recordings of June, July and August of 2015, 2016 and 2017, corresponding to 72109 5-channel recordings of 2 minutes (approximately 100 continuous days).

Using the zone transition probabilities, we estimated the most common travels done by the orcas. The numbers on the arrows (Fig. 8) correspond to the probability to arrive to a zone coming from another one (for instance, 52% of the times the orcas left the H3H4H5 zone, it was for the H4H5 area).

Figure 9, describing the proportion of recordings with orca

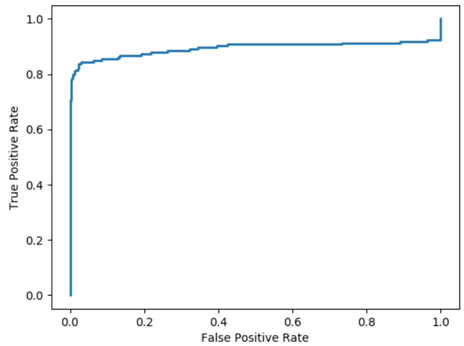

Figure 4. Receiver Operating Characteristics of the trained deep learning detector.

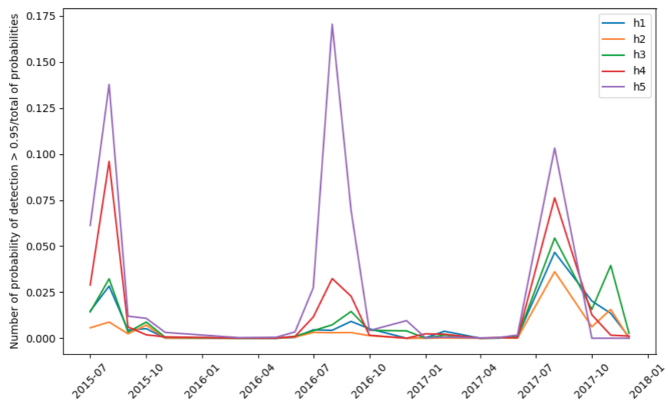

Figure 5. Proportion of two-minutes recordings with detected orca calls per month and hydrophone, from 2015 to 2017.

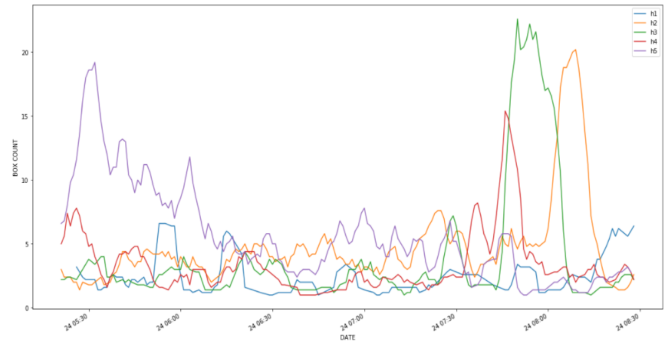

Figure 6. Evolution of the number of detected orca acoustic events from 5:30 to 8:30 am on August 24, 2017

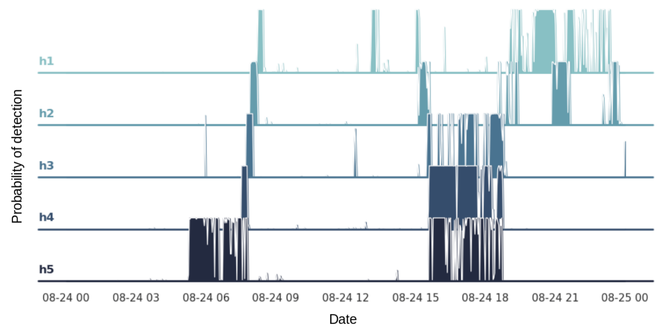

Figure 7. Example of the evolution of the probability of call detection for each hydrophone during one day (August 24, 2017). During the morning, a group of orcas comes from the east (see Figure 1) on H5, and is moving on H4, H3, H2 then on H1. Different round trips are made during the day.

calls per zone, supports the idea that zones' activation times are correlated with their sizes, except for H4. H4 is a small zone (covered only by the H4 hydrophone) through which the orcas pass in close proximity in order to travel to or from the adjacent passageway thus increasing the chances of detection.

We then analyzed the voicing activities in more detail, in space and within these time ranges:

- Day time is from 11 am to 5 pm (25% of the recordings).
- Night time is from 11 pm to 5 am (25% of the recordings).
- Full Moon time is from 4 days before to 4 days after a full moon (31% of the recordings).
- New Moon time is from 4 days before to 4 days after a new moon (24% of the recordings).
- Rising tide are times with a positive 40 cm differential of sea level (11% of the recordings).
- Falling tide are times with a negative 40 cm differential of sea level (11% of the recordings).

Those intervals were chosen to keep a significant difference for each factor (luminosity, moon phase, and currents).

We show (Fig. 10) the global evolution of voicings of orcas depending on these conditions. We see that the number of vocalizations is higher during the day, full moon and rising tide compared to night, new moon and falling tide respectively. Four times more recordings were including orca calls during full moon (14%) compared to new moon (3%) and 8 times more during rising tides (25%) compared to falling tides (3%). In the second part of Figure 10, proportion of state changes depending on time conditions are described. It lets us get an idea of the periods of times when orcas are more active in terms of travelling.

More precisely, we computed the probabilities to detect orca calls in each zone during a given time interval, shown in Figure 11. This result shows the global patterns of the orcas' voicing activity in time and space, based on the continuous 3 years of recordings. It reveals variations in the voicing activities of up to a factor of four between conditions and zones. The biggest variation concerns the influence of tide and moon in zone H5. In fact, this area is subject to strong currents during tidal hours. The Johnstone Strait is relatively deep (450 m), so the trophic chain can change according to the moon phase [16] and influence the orca acoustic activities.

V. Discussion

To the best of our knowledge, this is the first automatic large scale ethoacoustic analysis on orcas. The results are consistent with [17]–[19] that found that lunar phase is likely to be important in driving behavior of two species of cetaceans, suggesting that it is correlated with preys that migrate vertically [16]. It

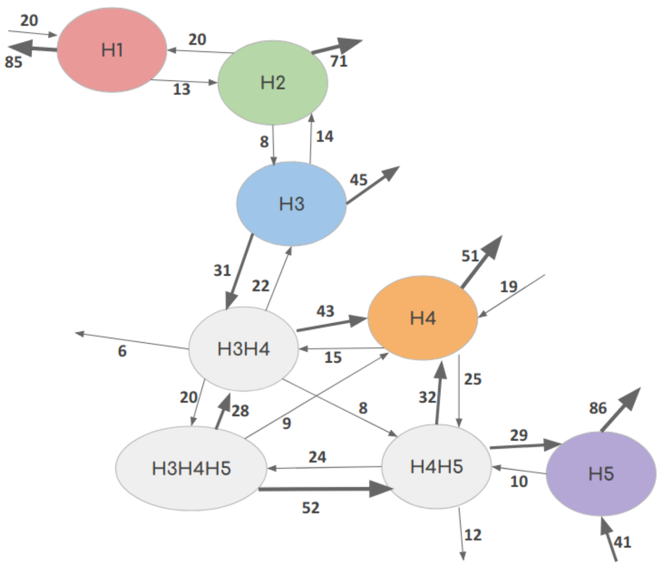

Figure 8. Directed graph of the main transition probabilities (%) between the detection zones of orca calls as defined in Fig 1. We set the transition probability E(Hi,Hj) that an orca voices from the hydrophone zone Hi to zone Hj, such that the sum of E(Hi,Hj) over all j different to i equals one. We only show here E > 5%.

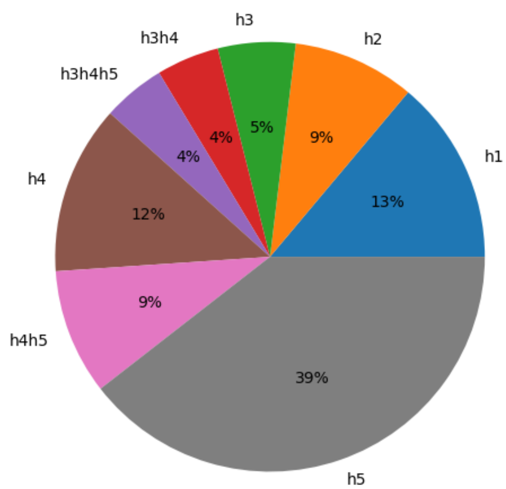

Figure 9. Proportion of recordings including orca calls per zone (%).

is assumed that during full moon, preys are more present in higher layers of water, thus making it easier for the orcas to reach them.

Tides also have an influence on presence (25% vs. 3%) and movement (40% vs. 35%) of orcas.

This result follows the conclusion of [20], [21] about the influence of the tide in a semi-enclosed environment.

Moreover, we demonstrate that acoustic activity as well as the proportion of movements changed between day and night (13% vs. 9% and 42% vs. 34%, respectively). The phenomenon was previously revealed for other odontocetes (variation of Guiana dolphin emissions according to day/night period [22]).

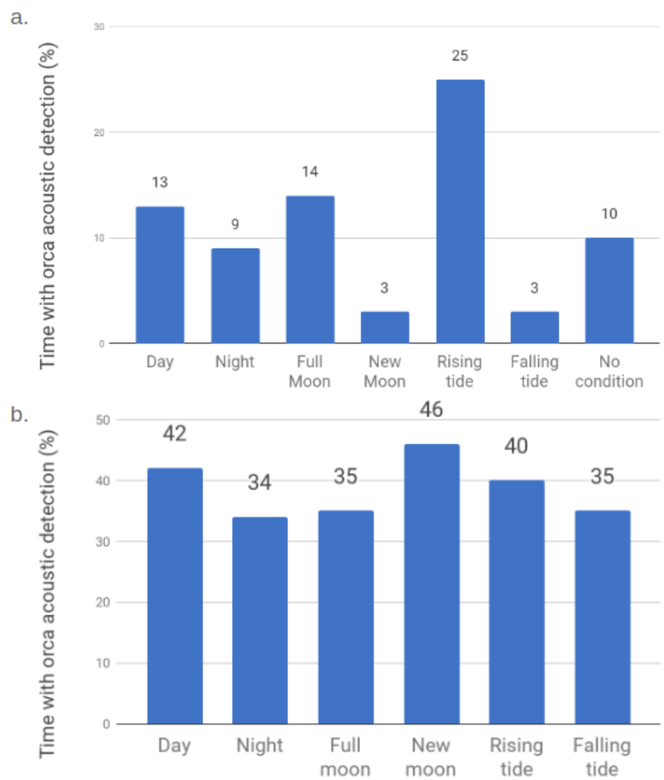

Figure 10. Global statistics of the detector. (a) Percentage of recordings with acoustic orca detections depending on time conditions. (b) Proportions of state changes, estimating the amount of movements done by the orcas.

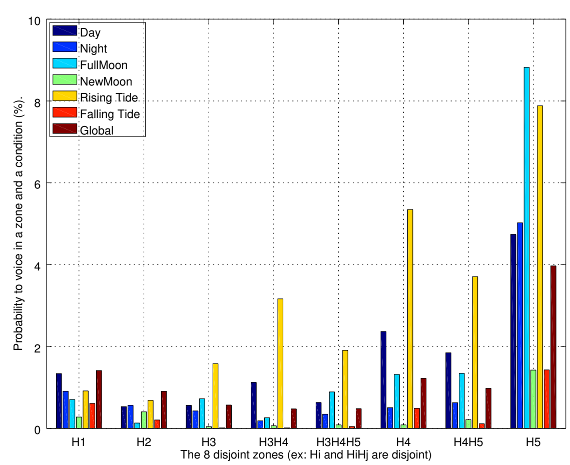

Figure 11. Probability of voicing of orca in a zone during a given condition. 'Global' refers to no specific condition. This probability is defined as the amount of recordings with orcas calls in a zone Zi during a condition Cj, divided by the total amount of recordings in Zi during Cj.

VI. Conclusion and Perspectives

This preliminary work lays the basis for later high-level and large-scale analysis. The collected data, which is continuous over large time scales, allows us to understand more of the orcas' behaviour in relation to several factors.

A. Towards a spatio-temporal orca call and anthropophonic massive database

The previous Orchive [11] database, composed of selected segmented orca calls, has an important value to scientists working on understanding the orcas' voicing. Likewise, collecting and structuring continuous recordings could increase the scientists' materials to work on, and hopefully help elevate our knowledge of this cetacean, by correlating the voicings with other acoustic features. We show in this paper first results computed from the OrcalabToulon dataset. Current work is being done to measure potential correlations between orcas' acoustic activities and decibel levels in selected frequency bands, anthropophonic content, acoustic events or complexity of the soundscape [23].

B. Trajectography improvements

Some limited localization of the orcas is now possible by deducing from the hydrophones' activation as described in Section IV, but localization techniques presented here are quite inaccurate. We will investigate using the time difference of arrival (TDoA) between hydrophones to increase location accuracy [24], [25], and draw precise trajectories following specific pods. Large scale statistics on the orcas' travels, speed, and general presence will be computed from those improved localization techniques, helping to better understand orcas behaviour, or supporting existing hypotheses on larger scales. Indeed, the evolution of behaviour and acoustic activity on a large time scale could help us understand more about the long-term impact of human activity on orcas. In the near future, it will be possible to carry out an "ethoacoustic study" [26] and use the 48 dimensions (6 zones in 8 conditions) that can be reduced (e.g., using t-SNE [27]) in order to highlight the clusters that would be associated with the zones or time periods. A precise localization study could be set up for the orcas tracking with an antenna of 40cm of size at 2km away (to not interfere with animals) [28].

C. Call classification

We intend to extend our current detection model to a call type classifier. We will either investigate supervised methods using expert annotations (e.g., from Orcalab) and unsupervised techniques. The latter can be used to outline call characteristics of cetaceans in specific situations, for instance when changing direction or with approaching boat. We also assume that the orca voicing patterns change according to tides, moon phase, and time of the day. Our research program 'OrcalabToulon' also allows variations of orca voicing patterns during approaches and meetings of matrilines in various hydrophones zones including acoustic classification of matrilines.

D. Behavioural response to vessel traffic

Numerous studies [29]–[31] have focused on orcas' behavioural response to anthropogenic noise, using manually collected data in relatively small scales. They have shown that vessel traffic causes fleeing, decreased foraging time, or higher swim speed [32], thus being noxious to the animals. Moreover, "acoustic harassment devices" used by salmon farms have been shown to induce Killer Whale displacement [33]. Correlating the orcas' activity (position, speed, density of calls) with the anthropogenic noises in a larger scale could strongly support the current knowledge and might support the creation of local measures to mitigate the impact of human activity on the animals.

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