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Humpback Whales in the Western Indian Ocean

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Editorial Note

Humpback whales are well known especially for their very long migration routes and also because of the songs that males emit during the breeding season. In 1971, in their famous article published in the journal 'Science', Payne and McVay describe these songs as "a series of surprisingly beautiful sounds"! Since 1971, more acoustic data have been collected and more knowledge generated; we now know that the song 'leitmotiv' is different from one geographic area to another, and from one year to the next. We also now know how they produce these sounds from their respiratory system.

In the last two decades, different techniques have been deployed to observe humpback whales in all the oceans. Not only have passive acoustic monitoring techniques been used, but also visual observations, electronic devices, and genetics. The objectives of these studies have been to better understand whale activities, behaviors, and also the underwater environment in which they live, and the potential effects of anthropogenic activities on their societies. This has involved many different research teams, with their own skills, methods and programmes. Results have been published in the scientific literature and presented at different international conferences.

However, three things have recently become apparent: Firstly, the study of humpback whales is a wide subject requiring people with complementary skills. It was apparent that it was necessary to bring these people together to discuss this species of whale for several reasons: a) because it would highlight the major results obtained thus far; b) because it would be interesting to share experiences (especially on the data and methods used, but also on common challenges); c) to co-design future projects and identify priorities; and d) because it would provide an opportunity to start new collaborations.

Secondly, before 2015, no international scientific conference or workshop existed with regular annual sessions especially dedicated to this species of Mysticeti whales. In order to address this, we initiated the creation of the Humpback Whale World Congress (HWWC, http://www.hwwc.mg/). The first session was held in Madagascar in 2015 and the second in La Réunion Island in 2017. Our idea was to bring together researchers and technicians from universities, research institutes, government organizations, and industry, dealing with all aspects of the biology, ethology, genetics, ecology, acoustics, signal processing, pattern recognition, mathematics, and computer sciences applied to the study of the humpback whales and their environment, and the potential effects of anthropogenic activities on the species. The goal of the HWWC is to provide a forum for exchange of new results obtained from the latest advances in instrumentation and methods.

Thirdly, during the BaoBaB project I led from 2012 to 2014, it became apparent that the extensive movement of humpback whales, even during the breeding season (with more than 100 km being covered per day), resulted in the same individuals being observed from the east coast of Africa to the Mascarene Islands. Because of this remarkable characteristic of this baleen whale species, it was obvious that we needed to encourage collaboration at a regional level, and we envisaged a consortium of people who work collaboratively on the Southwestern Indian Ocean humpback whale population.

During the international HWWC we were very pleased by the quality of the work shared by different teams, and the strong motivation to exchange information and work together. For this reason, we requested some colleagues to describe their projects in full papers, to put them together, and publish this unique special issue.

I would like to thank all the authors and co-authors, all the persons who contributed to this special issue, and more strongly the Cetamada Team who currently does such amazing work on these humpback whales!

Enjoy reading!

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Medium-term stereophonic recording of humpback whales in Sainte Marie channel, Madagascar: daily variation in whale density

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Abstract

Humpback whales (*Megaptera novaeangliae*) are well known to be particularly active acoustically. In 2007 the research team started to investigate humpback whales in the breeding area in the Sainte Marie channel (Madagascar). An array of 2 synchronous hydrophones was deployed in 2012 as part of a feasibility study for the deployment of a permanent acoustic array in the channel for the research programme, BAOBAB. Eight continuous sets (mean duration: 27 h 15 min) were recorded between 3 August and 11 September. Stereophonic recording allows the discrimination of acoustic sources that are not spatially overlapping, as the bearing to the emitting whale can be estimated from the Time Difference Of Arrival between the sensors. Based on cross-correlation functions analyses, this paper proposes an assessment of the number of emitting whales in a given underwater soundscape, and changes in their numbers over the covered time period. The first results showed that this value changed between 0 and 10 singers over the survey period of more than a month, and a peak in density was observed in the third week of August. Daily trends indicated highest density at night and lowest density just before nightfall. The study attempts to link acoustic activity and spatial occupation to reveal interactions between the detected emitting whales.

Keywords: Humpback, Acoustics, Stereophonic, Density, Madagascar.

Introduction

Although 80 different cetacean species are known, knowledge about these animals is still disparate and marine mammal research remains of high interest, with multidisciplinary approaches being used to study classification, ecology, behaviour, acoustics and conservation. Many species were hunted over the past century and their stocks decreased drastically. Although some populations recovered, some species remain listed as endangered or vulnerable on the IUCN red list of threatened animals (IUCN, 1996). At the end of the 1990's interest began to develop about the effects of anthropogenic activities on marine mammals (Perry, 1998), including the impacts of activities on- and off-shore, fishing zone activities, emission of anthropogenic sounds, and chemical pollution. Considering past and new threats, it is of primary importance to evaluate the state of cetacean populations and introduce effective protection measures. In this context, abundance and population dynamics are key parameters that must be assessed and updated. The objective should be to estimate the number of individuals of one population in a defined area, and how this changes over time.

Simmonds and Eliott (2009) suggested that global changes could be estimated from observations of cetaceans, and also that the effects of these changes on cetaceans should be measured. Two main areas of study were proposed: 1) for migratory cetaceans, observations should focus on the short-term variation of periods spent in breeding and feeding areas; and 2) for resident cetaceans, observations should focus on the 3 primary activities of feeding, reproduction, and resting.

Observations of cetaceans can be made by using 4 different methods: visual observations; the use of electronic sensors; genetics; and passive acoustics. All of these methods have benefits and drawbacks (Swartz, 2001; Gandilhon, 2010). They can be used as complementary methods depending on the goals of the study. The usual density and abundance estimation methods applied to terrestrial and marine species have consisted of extrapolating observations made in a limited area, to the whole area of interest. Distance sampling is a statistical approach initially used for visual observation (Buckland, 2001). Marine mammal case studies allow an interesting observation method to be used, as they are very active acoustically. Visual methods have contributed to the bioacoustics field by: 1) associating visual observations and acoustic monitoring; and 2) adapting the previous estimators used to acoustic detections (Marques, 2013). Past studies have provided useful results for both odontocetes (Lewis, 2007; Marques, 2009; Küsel, 2011) and mysticetes (McDonald, 1999; Mellinger, 2007; Marques, 2010).

The humpback whale, *Megaptera novaeangliae*, is one of the most studied cetacean species, for many reasons, including because male individuals emit songs during the breeding season (Payne 1971), and because they come close to the shore during this season, facilitating approach and observation. The roles of these songs have been much studied and multiple hypotheses have been proposed, including male/female interactions (Winn, 1978; Herman, 1980; Tyack, 1981; Medrano, 1994; Adam, 2013) and/or territorial behaviour (Darling, 2001; Cholewiak, 2008). Some songs have been recorded on migration routes and are thought to be used to guide other individuals (Clapham, 1990). Humpback whale populations are present in all the oceans, migrating to high latitude areas during the spring-summer months for feeding, and to low latitude areas during the autumn-winter months for breeding. However, knowledge on humpbacks is disparate and some areas are poorly studied due to access difficulties or security concerns, as is the case for some breeding sites in the southwestern Indian Ocean. Most past studies have chosen to conduct counts of individuals using passive acoustics localization, Frankel et al. (1995) used an array of 3 hydrophones off Hawaii to detect calls and the position of whales was estimated by intersection of hyperbolic bearing lines. Improvements to these acoustic techniques have been made by the use of adequate underwater sound propagation models taking into account non constant wave speed (Tiemann, 2004). In the southern Caribbean Sea, Swartz *et al*. (2001; 2003) used Directional Frequency Analysis and Recording (DIFAR) to estimate the location of calling whales. This method uses the difference in phase and magnitude between acoustic vector sensors and an omnidirectional hydrophone. Later, various software able to process DIFAR data were designed. The major limitation though, is the availability of this expensive material and software, and the inability to work "in real time". Recently, an open-source software (PAMguard) has been developed to overcome these aspects (Miller, 2016).

In 2012, based on the previously mentioned multi-disciplinary approach, the BAOBAB (Balises et Acoustique pour l'Observation des Baleines A Bosse) project was initiated in the Sainte Marie channel of Madagascar. Despite this area being considered a major humpback whale site, there was no scientific study on estimating animal density or seasonal fluctuation. Evaluating the density of whales in this defined area in a quantitative manner is useful to establish conservation approaches, actions and rules. The project followed on from the work carried out in the region since 2007 by members of the team in collaboration with Cetamada, a Malagasy NGO dedicated to the protection of cetaceans in this austral winter breeding area for humpback whales. The first step, between 2007 and 2011, was to evaluate methods based on signal processing and pattern recognition algorithms of real songs instantaneously recorded with one hydrophone deployed from a motor-boat (Pace, 2010; Doh, 2013; Doh, 2014). The second step was to design an original array dedicated to provide continuous recordings from the Sainte Marie channel. The aim of collecting and analysing acoustic data in the medium or long term was to produce assessments on whale distribution and changes over time. Moreover, a large amount of data ensured validity, and could reveal seasonal aspects. During the austral winter of 2012, a first version of the device made up of only 2 hydrophones was deployed for testing and adjustment, and it provided the first dataset.

The width of the channel between the Madagascar mainland and the island of Sainte Marie is about 30 km. The study area was at the southern end of the channel, which is characterized by low bathymetry (<60 m) and coral reefs along the coast, and is an important concentration area for humpback whales. As acoustics need sound production, it was necessary to answer the question as to whether the number of emitting humpback whales could be estimated from the stereophonic data. In order to answer this question, it was necessary to consider aspects such as multiple emitting animals, time/frequency overlapping of the sound emissions, variations in Sound Pressure Level (SPL), spatial overlapping of the animals, and anthropogenic and environmental noises.

The soundscape of the large diversity of humpback sound production seems to be dominated by persistent "songs". Humpback whale songs are based on successive patterned sound units (a sound unit is an emitted sound between two silences). Some of these sound units are repetitively organized in successive sequences, phrases and themes (Payne, 1971). Pace *et al.* (2009) defined the concept of sub-units as the elementary basis for forming sound units by combination. Males share these sound units in the same area at the same period of time (Payne, 1983; Helweg, 1990; Cerchio, 2001). This means that these emitted sounds can be used to differentiate one population from another in different areas, and to discern a specific year. Basic features of these sound units are low fundamental frequency (<100Hz), powerful sound (165-175dB re 1µPa at 1m), and a short time duration (< 5sec), with or without harmonics (Au, 2006). These sound units could roughly be classified into two types; tonal and pulsed (Cazau, 2013). Nevertheless, variations in the intrinsic features of these sound units are significant even for the same individual and, of course, from one individual to another. Therefore, automatic detection and classification of sound units is still a challenge, especially in areas where more than one singer is present, because they produce songs simultaneously.

Figure 1. Location of the prototype array in front of the former CETAMADA Research Center (Vohilava), south of Sainte Marie Island.

Despite the fact that precise trajectography or positioning could not be performed from this prototype device, the current study had the objective to exploit the data by taking advantage of stereophony. This paper aims to present the methods developed and the first results about the number of emitting humpback whales in the Sainte Marie channel based on the extraction of acoustic indicators.

Method and materials

Preliminary and new designs

From 2007 to 2011, humpback whale singers were recorded during the breeding seasons off Sainte Marie Island on the northeast coast of Madagascar, using a single hydrophone (ColmarItalia GP0280) digitized by a Tascam HD-P2 recorder. This approach was appropriate to provide recordings from isolated singers, but required a boat to search for singers at sea. This is always a challenge because when males sing, they spend very little time at the sea surface (Adam, 2013), so they are very difficult to observe. The major limitations of this approach are: 1) it provides short-term recordings (30 min recording), thus collecting a large amount of data requires much time and energy; 2) as the singer is acoustically isolated, songs are studied out of interaction context of other singers; and 3) the state of the sea can be rough during the austral winter which does not allow the boat engines to be turned off for recordings.

The BAOBAB project was launched in 2012 and started off with a general test of the feasibility of hydrophone array deployment in the channel (Doh, 2014). It took 2 h on 3 August to deploy the prototype version of the array (Fig. 1) designed and provided by CeSigma Signals & Systems. It was made up of 2 omni-directional hydrophones spaced by 300 m and linked to an immersed autonomous central device supplying energy and allowing the stereophonic data acquisition at a 44.1 kHz sample rate. The whole device was located at 500 m from the shore outside the coral reef, and anchored at 25 m depth. It was necessary to regularly change the battery (every 2 or 3 days) and recover the data with scuba from a surface boat.

Dependent on weather conditions and logistic factors, 8 recording sessions of continuous recordings (duration between 22 and 42 h) were conducted from 3 August to 11 September. This period corresponds to the second half of the breeding season. The diagram in Fig. 2 gives basic information on the sampling method and includes the date, recording duration, and hour of starting. The variation in session duration is explained by fluctuations in the battery charging process which was dependant on erratic local power supply. The longest duration (42 h) occurred after the replacement of a new battery. In total, 218 h of stereophonic data were recorded.

Methods

Given the configuration of the device (only 2 hydrophones), obtaining the precise location of sound sources is not possible. However, counting the acoustic sources is possible if they can be discriminated. This method is based on the hypothesis that different emitting whales have a high probability of obtaining a distinctive position in space, allowing a distinctive bearing to the recording hydrophone(s) to be obtained. Geometric relationships involving the Time Difference Of Arrival (TDOA) between hydrophones, and the angle of arrival, are included in a set of geometric solutions formed by a hyperbola branch (Gebbie, 2015; Medwin, 2005). Thus, analysis of the TDOAs allows the extrapolation of the bearing of the acoustic source.

The signal received at the hydrophone (i) is a time-translated version of the signal at the source, and is represented as:

$$x_i(t) = x(t - t_i) + N_i(t),$$

Where t_i is the time of arrival at the hydrophone, and i and N is a noise factor (external and numerical). The geometric and frequency attenuation is not formalized in this equation. Therefore, $\tau_{ij} = t_j - t_i$, and is considered to be the TDOA between hydrophones i and j. In this study, the value of the time delay has been estimated by an analysis of the normalized correlation function R_{ij} . Computing of this function is

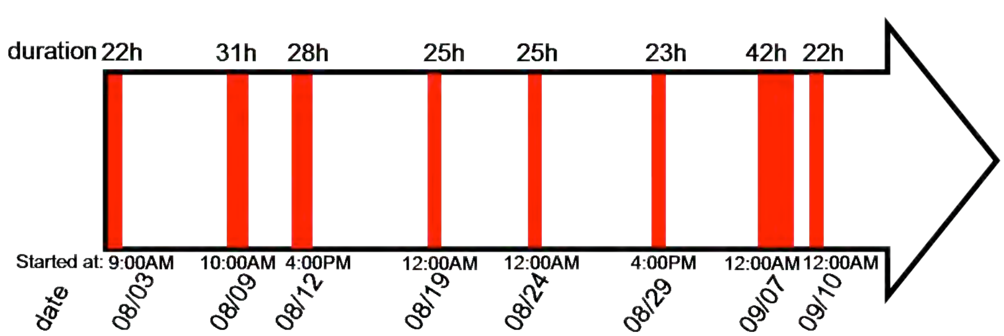

Figure 2. Acoustic temporal cover and duration, and starting hour of each recording session (date/month/day).

based on the spectrum correlation for reasons of time computing efficiency, as follows:

$$R_{ij} = \frac{1}{\sqrt{E_i E_j}} TF^{-1}\left\{TF\left\{x_i(t)\right\} \times TF\left\{x_j(t)\right\}^*\right\},$$

Where E_i and E_j are the respective received energies on hydrophones *i* and *j*. The peak of R_{ij} appears at the value corresponding to the TDOA between both channels. Thus, the TDOA τ_{ij} is expressed by:

$$\tau_{ij} = Arg\ \max\left\{R_{ij}\right\}.$$

Several peaks can be found in the framework of multiple acoustic sources. Although the sources are emitted simultaneously with possible frequency overlap, the cross-correlation gives a multimodal representation discriminating each source by its specific TDOA. The number of peaks is directly linked to the number of acoustic sources. As one source cannot emit from different positions at the same time, this approach is consistent if the whales are not spatially overlapping. The major limitation of this method is the case of animals emitting close together, or when physically in contact. Depending on the ability of the array to discriminate respective bearings, one peak may be produced, leading to poor estimation of the true number of sources.

Tool box dedicated to data processing

A customized tool box was developed (using Matlab) in order to analyze 218 hours of data, processing each recording file (10 min duration) as described in Fig. 3. The toolbox includes: Step 1 - cross correlation functions between both channels are computed over a 73 ms sliding window. Each channel spectrum is computed by standard Fast Fourier Transform (FFT). The choice of the window duration is a compromise between a reasonable time of computing and the time needed for resolution in order to discriminate sources and time-overlapping sound emissions. The output is a matrix [time x time delay] describing the different TDOAs as a function of the running time. The spacing between both hydrophones determines the maximum time delay which is 200 ms given the current dimensions. This stage is the most time consuming as it requires about 10 min to process a 10 min recording. Step 2- the cross correlation matrix is preconditioned by a binarization of its magnitude. Either 1 if the value is over an arbitrary energy threshold criterion, or 0. This operation allows only the most powerful sources to be taken into account, to make the next manipulation easier and to also fix the acoustic volume of reference for further source number estimation. Step 3 - a one dimensional reduction is conducted on the binary matrix by an average along the time duration of the file. This contains the different time delays appearing over

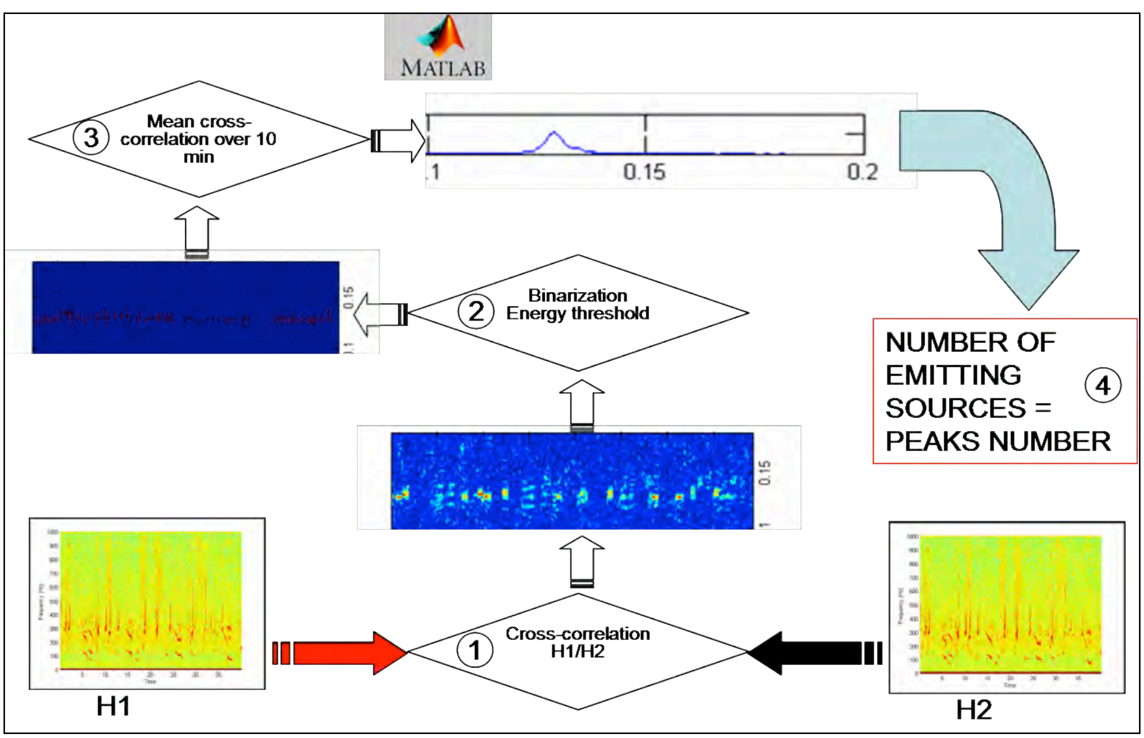

Figure 3. Block diagram showing the estimation of the number of sources using the customized Matlab Toolbox.

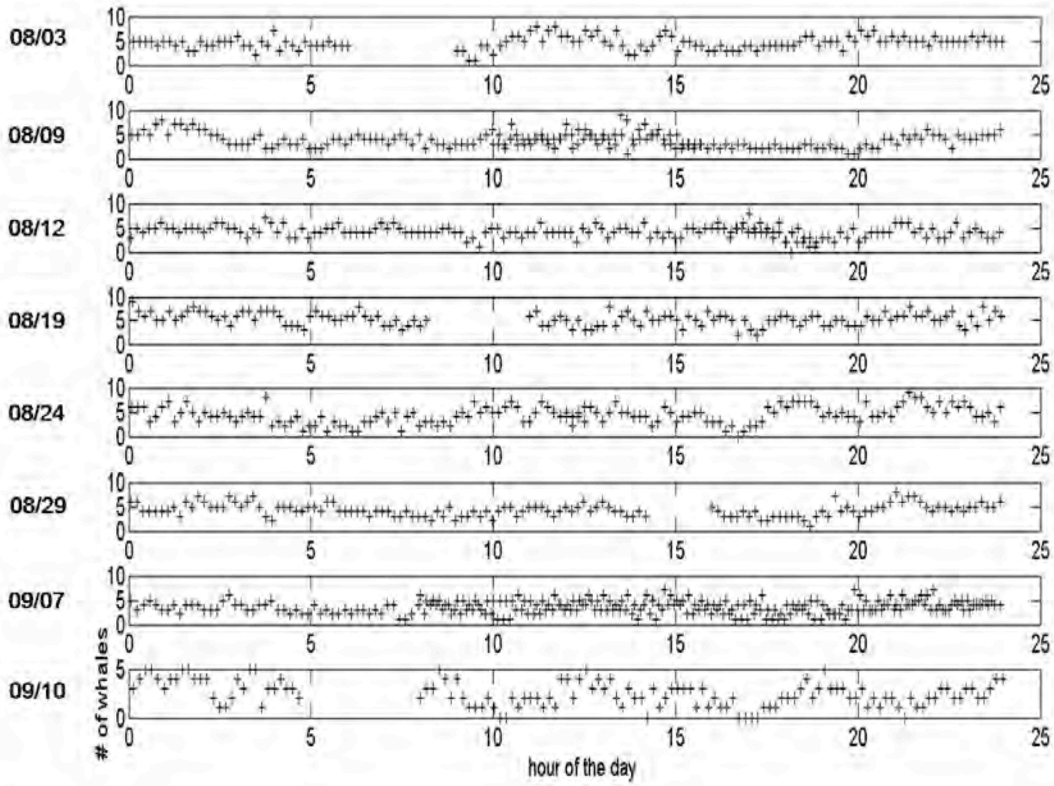

Figure 4. Raw estimations of the number of emitting humpback whales. Each line encompasses the results of one recording session and the hour of the day (date/month/day). Overlapping points mean the session lasted more than 24 h.

the 10 min period. The magnitude of the peaks is high and narrow if the source is static and active. The peak is wider if the source is moving. Step 4 - assuming the peaks correspond to distinctive emitting sources, the estimation of the number of emitting whales is given by the number of peaks included in the last representation. The peak magnitude threshold ensures that only sources likely to vocalize frequently are captured. In this way, occasional and continuous emitting sources, such as episodic vocalizations and boats, are not taken into account. Peaks appearing for $\tau_{ij} \approx 0$ should be viewed with caution as it could result from parasite noises caused by the acquisition device, or generated by independent random processes. Fluctuations in magnitude were observed throughout the analyses, suggesting there was no constant noise pollution.

Results

Number of emitting whales

A total of 218 hours were analyzed using the above mentioned processing methods. In order to compare each session, it is important to note that the thresholds (energy and mean cross-correlation) stayed the same, regardless of the sessions analyzed. Fig. 4 summarizes the raw estimation of the number of emitting whales resulting from each 10 min file. The values have been represented as a function of the hour of the day (not *vs.* recording time). Over a period of almost 5 weeks, the estimations vary between night and day from 0 to 10 detected individuals, with few values under 2 individuals. Short time variations are due to any new individual arriving or leaving the detection area. Some consecutive estimations are constant over 10 files (1 hour). A significant decrease in this number is observed toward the beginning of September, with 5 individuals being the maximum detected. These results also confirm the continuous presence of emitting whales, or singers, in the Sainte Marie channel.

Weekly variation in the number of emitting whales

Basic statistical processing was applied to the raw estimations. Fig. 5 (top) shows the normalized distribution of the estimations for each session. It shows similar shapes with one observed mode, but a progressive displacement of the maximum probability in time. The mean estimated number is continued in Fig. 5 (bottom). The estimations of the first session on 3 August seem to reflect a decreasing dynamic initiated in July. On 9 August, the number reaches a minimum of 4 individuals, then tends to increase until 5.5 whales on 19 August, which is the maximum estimated mean value. Then, it significantly decreases to around 2.5 individuals on 10 September (minimum value). The standard deviation (SD) is relatively steady over the time period, between 1.2 and 1.8, and does not seem to be correlated with the estimated number. However, a significant spreading of the estimation is found at 08/24, as the SD reaches the highest value. No weekly cyclic behavior was observed for the duration of the present study.

The mean normalized strength received from the raw recordings (red curve) has been added to the last representation after scale modifications. Both curves are highly correlated, probably due to the cumulative impact of the numerous singers, or because the song level was intentionally increased. An exception is found for the last session, as aural analysis reveals that one singer was very close to the hydrophones. It significantly increased the level received compared the previous sessions.

Daily distribution

The variation of the estimated individual number over 24 h has been investigated by pooling all the estimations. A two dimensional normalized histogram (bi-distribution) resulted, as shown on Fig. 6 (top). The observed probability of a couple (whales number, hour of the day) is not flat or uniform, and modulations are perceptible. Fig. 6 (bottom) represents the value of the estimated number resulting from the maximum probability for a given hour of the day. A general stepwise pattern seems to be apparent. The duration of the steps are about 4-5 h suggesting that regular changes in the spatial configuration of the animals may occur over a 24 h period. The number is higher during the night (from 8 pm to 5 am) and constant at around 4-5 individuals. During the day, estimations vary much more, from 2-5 individuals. The lowest number appears at the end of the day (from 3 to 8 pm).

Discussion

A. Estimation of the number of emitting whales

Few studies exist on whale distribution or density in the waters of Madagascar, and none by passive acoustics, which is restrictive for comparative purposes. A paper based on visual observation and historic

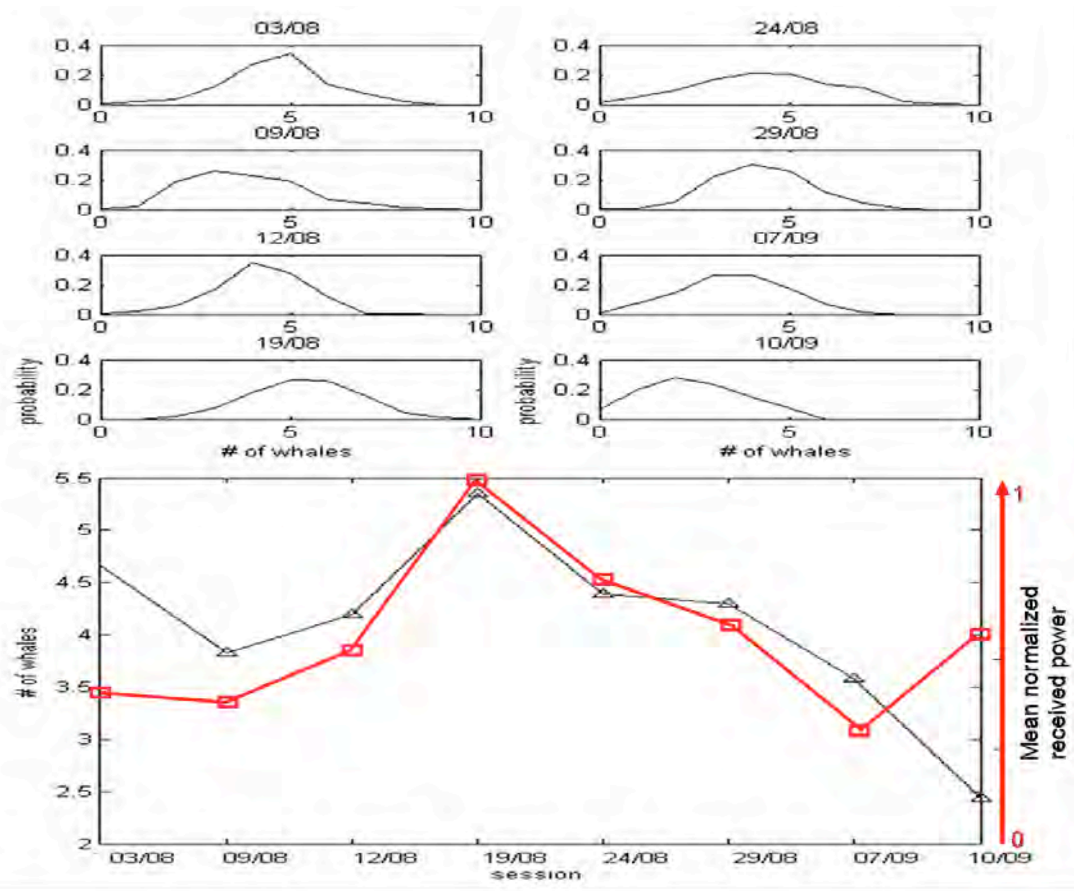

Figure 5. Top - Normalized distribution of estimated emitting whale number for each session (date/day/month). Bottom - mean estimated number of emitting humpback whales by session in comparison with the mean normalized acoustic strength received.

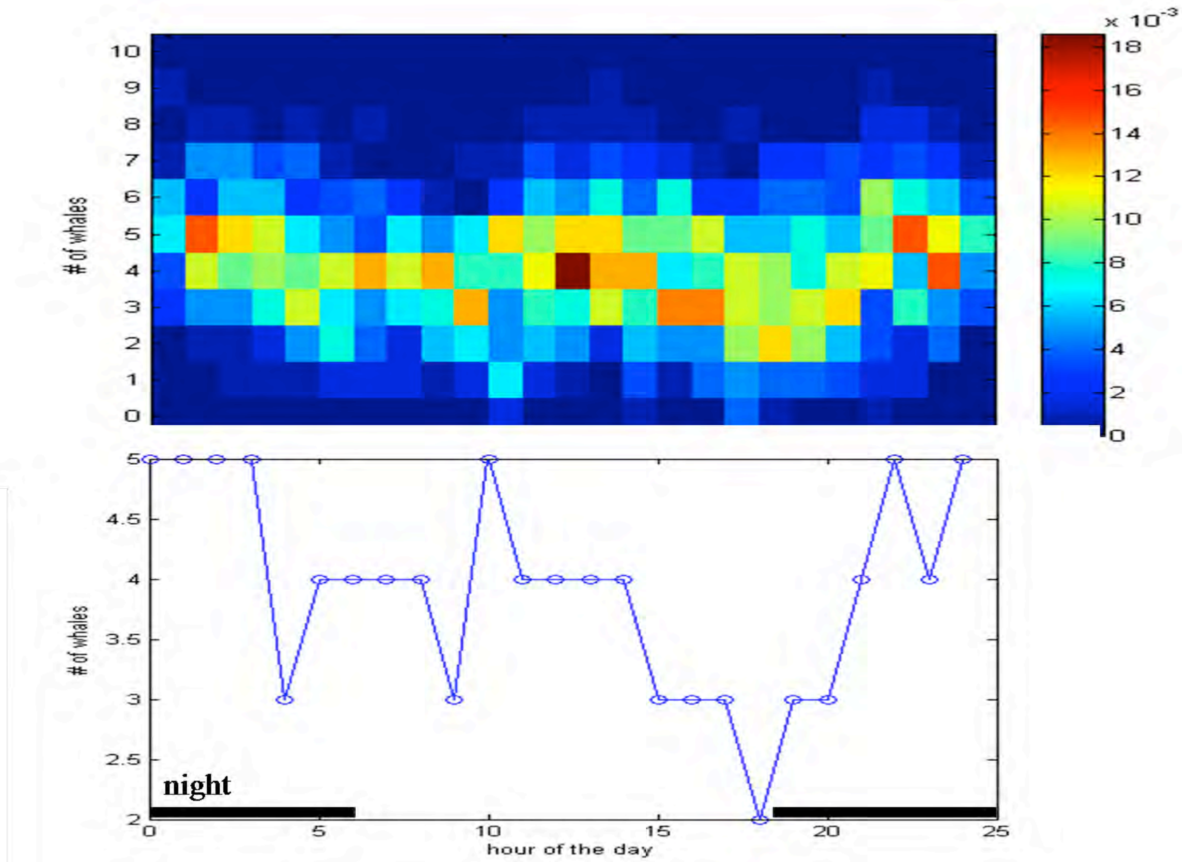

Figure 6. (Top) - Bi-distribution of the number of emitting whales vs the hour of the day. All data are pooled. (Bottom) - maximum probability of the previous bi-distribution.

catch data along the south and southeastern coast of Madagascar (Best, 1998), reports a bimodal seasonal distribution of humpback catches, which reflects seasonal abundance. One peak occurs in the third week of August and one wider peak, in July. This bi-modality would suggest that the population follows two waves of migration. The monthly distribution from the present study is very similar in the respective periods, with a peak occurring at the end of the second week of August. The estimated values at the beginning of August and in the middle of September remain almost equivalent. Despite the fact that the data seems to indicate fewer whales present before August 03, the second expected peak was not significantly apparent during the observation period in the present study.

The significant decrease in September could be explained by changes in the proportion of singers in the total population during the breeding season. As the end of the breeding season is approaching, more and more males achieve their mating goal, and these could then become less active as singers, or they could have left the area. Another study (Trudelle *et al*., 2018) describes how the composition of the channel humpback population varies based on visual observations, and pointed to a 35% decrease in observed cases of singing among single individuals, couples, and competitive groups, between the middle of August and the middle of September. The current standard deviation anomaly detected in the distribution on August 24 corresponds to the first measurement after the maximum peak. This could be a consequence of a reorganization of the population, with more displaced individuals or individuals in transit in the study area.

Even though the raw acoustic strength received can be highly impacted by motor boats, bad weather, or whales singing close to the hydrophone, it is interesting to observe that the acoustic level measurement is consistent for qualitatively evaluating the density of emitting whales. Seger (2016) agrees that most of the ambient noise in generated by whale vocal activity.

An indisputable contribution of acoustic monitoring is highlighted when the objective is to detect diurnal/nocturnal effects, or fine temporal scale variations. Many previous studies can be found (often based on acoustic strength measured) concluding that there is more acoustic activity at night (e.g. Au, 2000), but none show clear trends during a complete 24 h period based on a significant amount of data. The current study provides the typical hour by hour pattern of the number of singers present. The reason for lower acoustic activity during the day could be a result of a relatively higher number of males involved in active surface groups during daylight hours. However, there are no studies suggesting a significant reduction of activity just before nightfall.

Consistency of the estimations

The toolbox developed uses an algorithm based on the spatial consistency of the acoustic sources. This method is efficient to filter out environmental noises such as rain, random clicks generated by coral reef organisms, and anthropogenic sources, as these are either occasional (short time duration) or of rapid motion. The estimations are also robust regarding time and frequency overlaps, and the changing SPL of the sound productions, once the sources are recognized as spatially distinctive. The known major limitations are if whales emit close together, or get into a different position but with the same bearing to the hydrophone. The consequence of this is an underestimation of the true number of whales. The results given in this study can be considered as minimally effected by these limitations. However, the precision of results could be increased by implementing a range estimation model.

Despite the fact that the detection function could not be evaluated, the detection threshold, materials and methods stayed unchanged, maintaining the same acoustic volume/area of coverage for all the sessions. Thus, the estimated number is likely to be proportional to the density of animals in the study area. The present results may be particularly reliable to describe the local fluctuation of the humpback population. A previous study (Helble, 2013) established the probability of detection using their own sound recording device. The resulting probability function was equal to 1 to 3 km for humpback whales. By taking into account this maximum distance, any emitting humpback whales should be detected within a surface area $S_{max} = 14\ km^2$. As an indicative overview, the ratio of the estimated number using this area gives a density ranging between 0.07 and 0.7 whale/km^2. Frankel *et al.* (1995) mentioned a comparable result of 0.62 whales/km^2 for an acoustic survey in the shallow waters of Hawaii.

Conclusions and further work

When and for how long does the whale emit sound? During the present study, actual investigations were conducted over a short time scale. Cross-correlations provided information on the position of the source and also on the duration that the source has been active. The toolbox developed here can be harnessed to extract basic features, such as the starting time of a continuous sound, its duration, and rhythm. Such an automatic analysis may be a significant contribution to this research topic as different levels of study might be available; from the scale of the song unit to the scale of a complete song. Although, several studies on song duration have been done in the past (Thompson, 1981; Payne, 1983; Fristrup, 2003), few have focused on the rhythm and silence duration. Additionally, previous work has been limited by the amount of continuous data and the fact they did not use automatic analysis. A complete song can last more than 22 h (Winn and Winn, 1978). The current dataset and further implementation of the toolbox provides the opportunity to shed some light on these questions, with the longest session duration available in the current dataset being 42 h.

As distinctive singing whales (not overlapping) are well separated by the cross-correlation, this method would offer perspectives to study soundscapes including multiple emitting humpback whales. Thus, it will be possible to consider the songs within a social context and to reveal important clues on acoustic interactions among the individuals. Although some research has highlighted such interactions associated with humpback social calls (Silber, 1986), or between singers and surface activity (Tyack, 1981), most previous works on songs are based on single singer sequences, and have not been able assess any element of communication between singing individuals present in a given area. Is there any accordance among the individuals on the song duration or rhythm? Do they overlap their sound production? Is it possible to observe a pattern as "emitter- receiver"? Such questions could be firstly investigated by the extraction of the previously mentioned parameters without any investigation into the frequency-temporal structure of the songs. Similarly to the detection of short term displacement of the sources, sound production and motion could also linked.

More acoustic surveys may be needed over a complete season (ie. from June to October) to observe cyclical behaviour or multi-modal distribution, while yearly measurements are needed to compare inter-annual variations and distribution, perhaps with the use of more acoustic stations along the Sainte Marie channel, in order to refine the current findings.

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