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Long-term acoustic monitoring of nonstereotyped blue whale calls in the southern Indian Ocean

Torterotot Maëlle [1,*], Samaran Flore [1], Royer Jean-Yves [2]

[1] Lab-STICC UMR 6285, ENSTA Bretagne, Brest, France
[2] Geo-Ocean UMR 6538, CNRS, Université de Brest, Brest, France

* Corresponding author : Maëlle Torterotot, email address : maelle.torterotot@ensta-bretagne.fr

Abstract :

Monitoring the presence of blue whale (Balaenoptera musculus ssp.) stereotyped calls has been a widely used method to assess the different populations' distribution worldwide. All blue whale populations also produce nonstereotyped vocalizations, or D-calls. Here, we monitored the presence of D-calls in long-term records from a large hydrophone array located in the open southern Indian Ocean, using an automated detection method and manual validation of the detections. D-calls were detected at all sites of the array, which extends from 24°S to 56°S, but the majority of them were detected at the two southernmost sites. We observed a latitudinal shift in their seasonal occurrence, with more D-calls in the north during austral autumn and winter and more in the south during austral spring. The geographical occurrence of D-calls compared to that of songs indicates that blue whale acoustic behavior switches from a song-intensive and sparse-D-call emission in the north to song-moderate and more intensive D-call emissions in the south. These findings support the hypothesis that both call types are used for different purposes, as D-calls are mainly detected around foraging grounds and songs in wintering grounds. Monitoring both call types might therefore be a relevant acoustic indicator of blue whale behavior.

Keywords : Antarctic blue whale, Balaenoptera musculus, D-calls, passive acoustic monitoring, pygmy blue whale, southern Indian Ocean

1. Introduction

Extensive commercial whaling greatly depleted blue whale (*Balaenoptera musculus ssp*) populations, especially in the Southern Hemisphere, including the southern Indian Ocean (Branch et al., 2007, Rocha et al., 1982,). Two blue whale subspecies occur in this region (Rice, 1998): the Antarctic blue whale (*B. m. intermedia*) and the pygmy blue whale (*B.m. brevicauda* (Ichihara, 1966). They differ morphologically (Ichihara, 1966), genetically (LeDuc et al., 2007), and acoustically (Ljungblad et al., 1998, McDonald et al., 2006). Blue whales produce long, loud, and low-frequency stereotyped phrases, repeated every few minutes to form songs (Cummings and Thompson, 1971). In the southern Indian Ocean, songs from Antarctic blue whales and two populations of pygmy blue whales - southeastern Indian Ocean (SEIO) and southwestern Indian Ocean (SWIO) types - have been recorded seasonally (Dréo et al., 2018, Leroy et al., 2016, Samaran et al., 2010, Samaran et al., 2013, Stafford et al., 2011, Torterotot et al., 2020). Songs have only been attributed to males, and are likely to have a reproductive function (Lewis et al., 2018, McDonald et al., 2001, Oleson et al., 2007b).

Blue whales also produce nonstereotyped calls, often referred to as Frequency-Modulated (FM) calls (Thompson, 1996), archsounds (Ljungblad et al., 1997), or D-calls (Thode et al., 1999). Their frequency is highly variable, decreasing from about 100 Hz to 30 Hz (Figure 1). Unlike songs, there is no obvious geographic variation in the D-call time-frequency shape. They have been recorded in association with blue whales in every ocean in which blue whale songs have been recorded (Barlow et al., 2021, Buchan et al., 2021, Ljungblad et al., 1997, McDonald et al., 2001, McDonald et al., 2006, Mellinger and Clark, 2003, Rankin et al., 2005, Samaran et al., 2010, Schall et al., 2019)

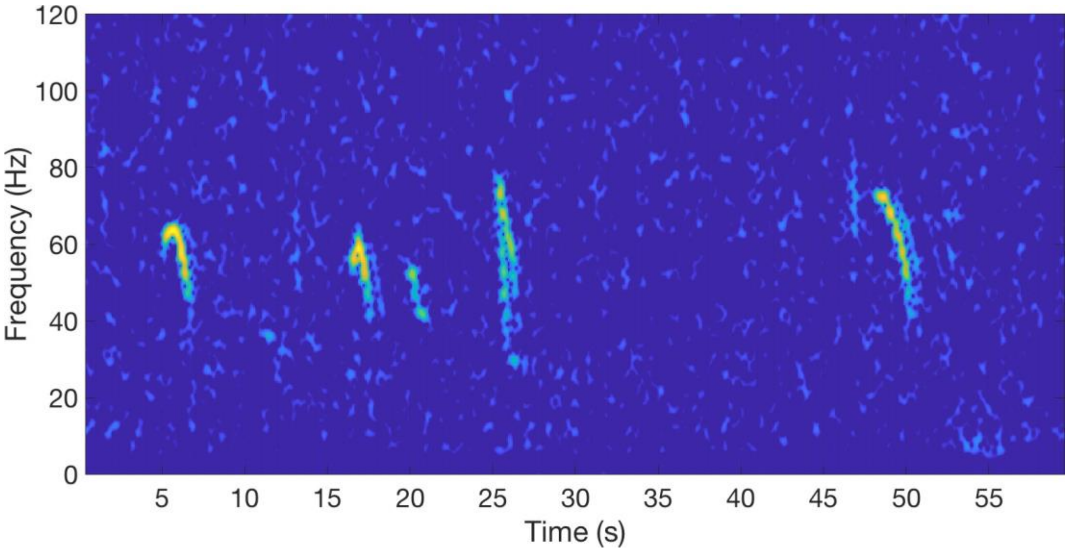

Figure 1: Spectrogram of a five D-calls series recorded in the southern Indian Ocean. (nfft= 1200, win size = 80 ms, overlap = 90 %)

D-calls are thought to be produced by both males and females (Lewis et al., 2018, Oleson et al., 2007b). Only a handful of studies, mainly from southern California feeding grounds, have investigated the behavioral context of their production. Some authors hypothesize that their use is related to social behaviors (Lewis and Širović, 2018, Oleson et al., 2007c, Szesciorka et al., 2020). For example, data collected with acoustic tags on whales in the northern Pacific Ocean found that D-calls were produced during shallow dives between deeper feeding dives, suggesting that they are used to attract conspecifics on productive feeding areas or to maintain communication between individuals (Lewis et al., 2018, Oleson et al., 2007b). In the St Lawrence estuary, Canada, and along the Chilean coast, D-calls would have the role of maintaining cohesion between male-female pairs of blue whales, particularly when joined by a third whale (Schall et al., 2019).

Automation of D-call detection remains a challenge, due to their highly variable time-frequency signature. Spectrogram correlation for Antarctic blue whale D-calls but resulted in highly variable detection rates (between 21% and 71% (Shabangu et al., 2017) and up to 87% (Shabangu et al., 2019), depending on the year from which the vocalization template was selected. These studies did not specify the false alarm rate (i.e., number of detections of a signal that is not a D-call). A detector based on a general power-law, primarily developed for the detection of humpback whale song units (Helble et al., 2012) was tuned to detect D-calls in data acquired off Antarctica (Thomisch, 2017). Detection rates varied from 75% in winter to

67% in summer, but about half of the automatic detections were incorrect. Given these difficulties, visual detection is still the most reliable and common method used for these vocalizations (Lewis and Širović, 2018, Oleson et al., 2007c, Romagosa et al., 2020, Samaran et al., 2010), despite its inconvenience for processing large data sets.

This study presents the first long-term acoustic monitoring of D-call presence in the southern Indian Ocean. Our analysis is based on 9 years (2010-2018) of low-frequency (sample rate: 240 Hz) continuous acoustic recordings at multiple sites. The monitored area spans historical whaling grounds where blue whales were intensively hunted during the 20th century (Branch et al., 2007). The hydrophone array extends from subtropical to subpolar latitudes, a productive area which includes oceanographic features such as the sub-Antarctic and polar fronts. D-calls were detected using a semiautomated technique whose performance was thoroughly evaluated. This study provides new insights into the blue whale occupation of the Indian Ocean, and complements data of Antarctic and pygmy blue whale (SWIO and SEIO) songs, that likely only illustrate male presence (Torterotot et al., 2020). If as hypothesized in previous studies, D-calls and songs are used in different behavioral contexts, monitoring seasonal and geographic occurrence of both calls could provide useful information about the blue whale habitat use of the Southern Indian Ocean.

2. Material and methods

1. Data acquisition

All acoustic data were recorded by the Observatoire Hydro-Acoustique de la SISmicité et de la Biodiversité (OHASISBIO) hydrophone network (Royer, 2009), located in the southern Indian Ocean (Figure 2). This network was first deployed in December 2009 and is still recording as of the date of publication (Table 1). From 2009 to 2016, 5 permanent mooring sites were deployed, located south of La Réunion Island (MAD), north of Crozet archipelago (NCRO), west of Kerguelen Island (WKER), and southwest and northeast of St Paul and Amsterdam islands (SWAMS and NEAMS). In 2012-2013, a mooring (RAMA) was temporarily deployed near the Equator, in the Central Indian Basin, east of Diego Garcia archipelago. Since 2014, a new site was instrumented, south of the southeast Indian Ridge (SSEIR). In 2017, the coverage of the northern area was improved to refine the location of blue-whale wintering grounds. The network geometry was slightly modified, with three new sites RTJ, MAD-W and MAD-E, the latter two respectively located southwest and northeast of the initial MAD site, which was removed. A new site (SSWIR) was installed 273 km north of the initial NCRO site to replace it, as recordings were often corrupted by flow noise due to strong currents in this region. Finally, an additional mooring (ELAN) was installed at 56° S, south of Kerguelen plateau, to expand the spatial coverage southward. Most of the sites are equipped with a single hydrophone mooring, but triads of hydrophones were temporarily deployed at some locations. In 2010 and 2011, 30 km spaced triads were installed at NCRO and WKER. In 2012, the NCRO triad was removed and in 2014, the WKER triad was moved to SWAMS with a 10 km spacing between moorings, and deployed until the end of 2015.

The hydrophones are moored between 1,000 m and 1,300 m depth, in the local sound fixing and ranging (SOFAR) channel axis. This channel acts as a waveguide, where low-frequency sounds can propagate over very long distances (Lurton, 2002). The continuous recordings are sampled at 240 Hz using a 24-bit analog-to-digital conversion (d’Eu et al., 2012) and stored on hard drives in the instrument. Figure 3 summarizes the site coordinates and the recording periods of the

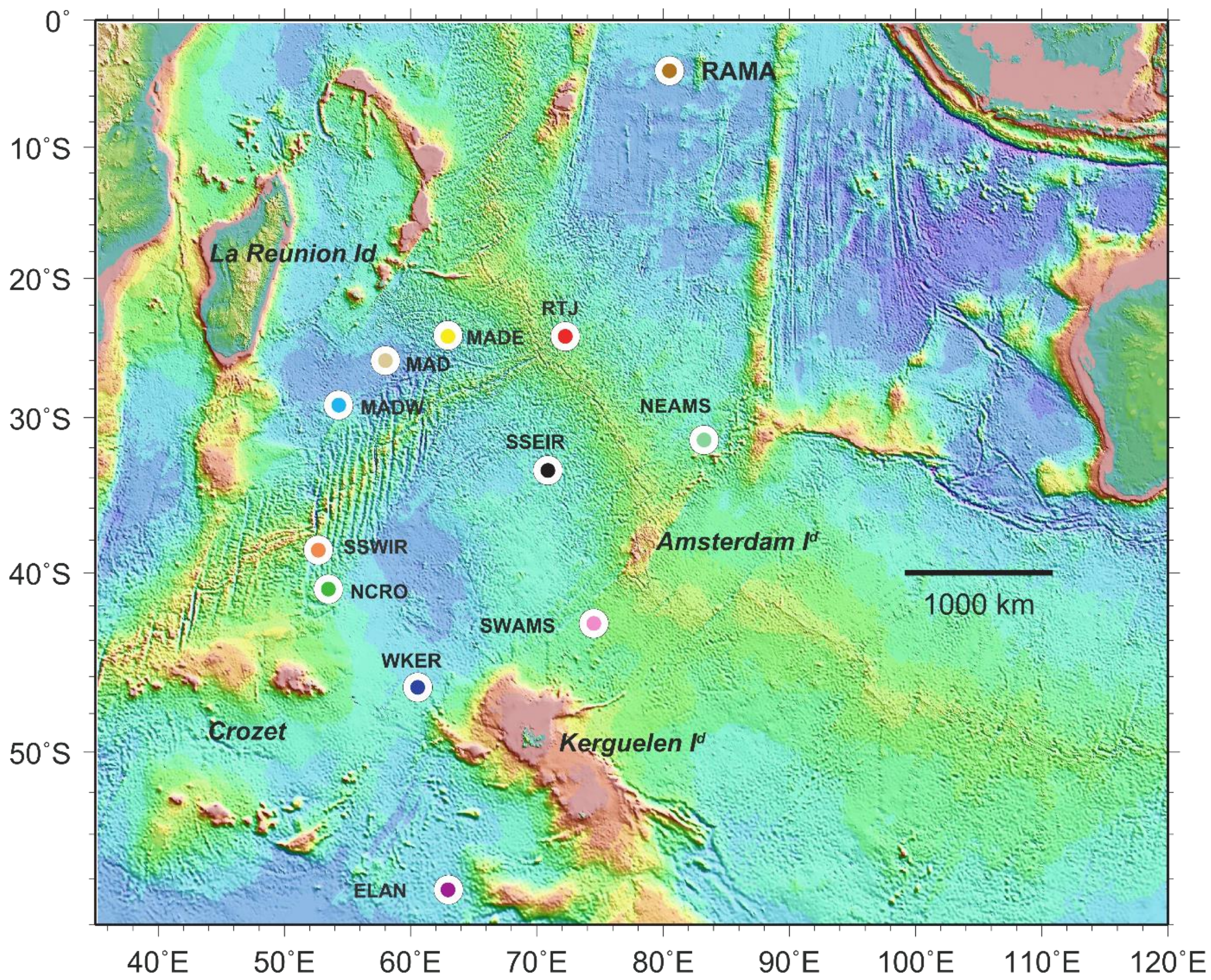

Figure 2: The OHASISBIO hydrophone network in the southern Indian Ocean. Colored dots represent mooring sites.

data used in this study. Only one hydrophone of the triad was used for analysis at SWAMS and NCRO, but some results from the three hydrophones at WKER in 2012 are presented in Figure 5. In the other figures, only the data of the mooring at WKER1 are used from 2010 until 2013.

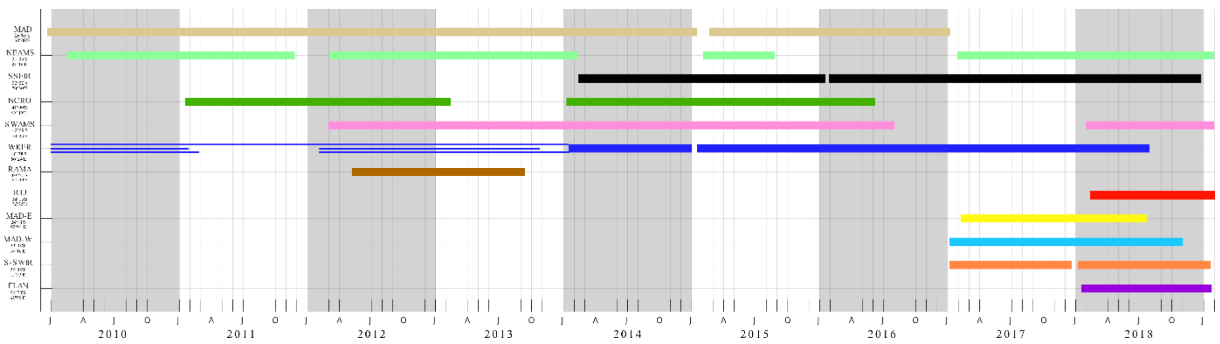

Figure 3: Analyzed periods of the different recorders of the OHASISBIO hydrophone network. The horizontal bars represent the time ranges of the acoustic recordings analyzed in this paper for all the sites, from 2010 to early 2019. The three bars at WKER are for the hydrophones of the triads (from top

to bottom WKER1, WKER2 and WKER3). The colors match the position of the instruments represented on the map in Figure 2.

2. Automated call detection

Altogether, the OHASISBIO data set amounts to more than 50 years of recordings. Each audio file lasts 6.48 hr, therefore a whole year of data comprises about 1,300 files. Although visual examination of the data proved to be the most reliable technique to detect D-calls, we had to resort to a semiautomated detection method to process such a large amount of data. We selected an automated detection algorithm based on dictionary learning and sparse representation (Socheleau et al., 2018) and combined it with a postprocessing algorithm to reject false positives (Torterotot et al., 2019).

The Sparse Representation based Detector, or SRD (Socheleau et al., 2018) is particularly well adapted for the detection of D-calls, using dictionaries that take D-calls' time-frequency variability into account. Dictionaries are matrices composed of **M** waveforms designed by using the K-SVD algorithm (Aharon et al., 2006) on **L** manually annotated D-calls constituting the training data set. The algorithm then tries to reconstitute the observed signal (i.e. the signal in which we search for D-calls) with sparse combinations of the waveforms stored in the dictionaries. If the signal is well reconstructed by the linear combination of **K** elements among the dictionary's waveforms, then the resemblance metric is higher than the threshold measured empirically in Torterotot et al., (2019), meaning that it is likely that a D-call lays in the observed signal (Guilment et al., 2018, Socheleau et al., 2018). Before applying the SRD to detect D-calls on the whole data set, its performance was investigated on manually annotated data subsets containing 240.5 hr of recordings from different years and locations of the OHASISBIO data set (NEAMS 2015, SSWIR 2017, WKER 2015, and WKER 2012) with a total of 3,467 D-call annotations, to encompass potential temporal and geographical variation of the calls. These annotations were split into a training set, used to build the dictionary and a test set used to evaluate the performance. The first step was to determine the optimum parameters of the dictionary **L** = 200, **K** = 3, and **M** = 45. Then, to further test the robustness of the algorithm, the performance was computed multiple times with dictionaries built with different calls each time by using the k-fold cross validation method. Performance was computed as detection rate (or recall) as a function of the average number of false detections per hour for different thresholds (Figure 3 in Torterotot et al. (2019)). To limit the number of false alarms, the threshold that was used for the detection on the whole data set was set so that the average number of false alarms per hour is equal to one. The matching detection rate reached between 80% and 90% for positive Signal to Noise Ratio (SNR) calls (Torterotot et al. 2019). As the composition of the dictionary did not influence the detection performance, a single dictionary composed of 200 randomly selected D-calls from this data subset was used for the detection in the whole data set. The detector was then applied on a complete year of data (2015) at WKER and every detection was visually double checked. This site and year were chosen based on manual inspection and previous analysis of the data establishing the presence of D-calls as well as other blue whale stereotyped songs that were investigated for other research purposes (Torterotot et al., 2019, 2020). We found that most of the false detections were due to two specific sound types: seismic airgun blasts and fin whale 40 Hz pulses (see spectrogram on Figure 4). A postprocessing strategy was thus developed to eliminate most of these predictable interferences and to minimize the tedious visual verification task. The call detection principles are detailed in Socheleau & Samaran, (2018). The performance evaluation of the detector on our data set and the postprocessing algorithm to avoid false detections are thoroughly described in Torterotot et al., (2019).

Two separate postprocessing algorithms were used (see Torterotot et al., (2019) for a complete description). The first one differentiates D-calls from fin-whale 40 Hz pulses. This second call type is much shorter and more impulsive (Širović et al., 2013, Watkins, 1981) than D-calls and thus, the classification method is based on those criteria. Each detection's waveform was analyzed separately and a metric (Call to Noise Ratio or CNR) was defined by comparing the peak energy with the noise energy of the signal. Using labeled D-calls and fin whale 40-Hz calls, we were able to set a CNR threshold that discriminated both call types (see Figure 8 and Discussion in Torterotot et al., (2019)). All detections classified as fin whale 40-Hz calls were automatically discarded from the analysis. The second postprocessing algorithm recognizes the presence of airgun shots in the recordings, based on their energy

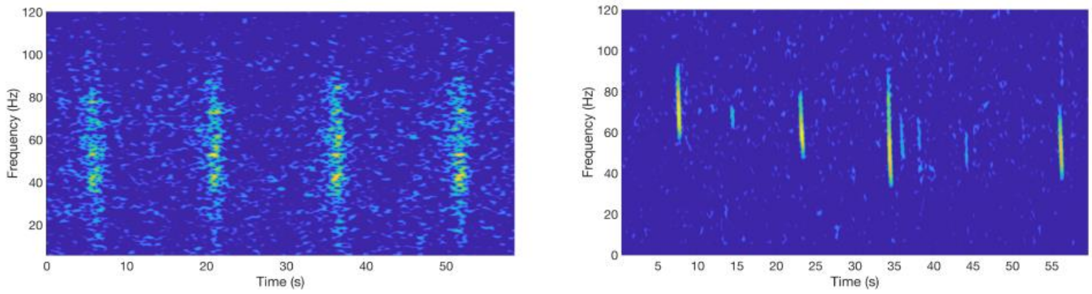

Figure 4: Spectrograms of the two sound types that wrongly trigger the automated D-calls detector, airgun shots (left) and fin whale 40 Hz pulses (right). (nfft= 1,200, win size = 80 ms, overlap = 90%)

and periodicity (Mellinger, 2004, Nieukirk et al., 2012), since they are shot at a constant rate (from 8 s up to 1 min) within each seismic survey (e.g., (Fitzgibbon et al., 2017, Nieukirk et al., 2012)). Every file containing airgun sounds (i.e., files in which a signal was periodically repeated every 8 to 12 s – the most common periodicity found in the OHASISBIO data set - was measured, (see Torterotot et al., 2019)) was then discarded in all subsequent analyses, without any visual inspection when routinely applied. Since airgun shots are ubiquitous in the OHASISBIO recordings (see Appendix 1), eliminating the false alarms they generated in our detections largely overcomes the loss of the few true discernable D-calls in the discarded files (6.48 h long). Both postprocessing methods were tested on recordings from 2015 at WKER site and the results showed that almost 95% of false alarms due to fin whale 40 Hz pulses and airguns were removed, while more than 75% of the D-calls initially detected remained (Torterotot et al., 2019). All the SRD detections were thus postprocessed as described.

Table 1 illustrate the seasonal and geographical loss of data induced by this post-processing step. Finally, all remaining detections were double-checked by an experienced human operator by visual inspection of 10 minute-bin spectrograms (Hanning window, nfft = 512, time window = 256 samples, overlap of 90%), to make sure they were all D-calls. If not, they were classified as false alarms and removed from the analysis. Many species of baleen whales produce downswept calls similar to blue whale D-calls (e.g., fin whales (Širović et al., 2013; Watkins, 1981), right whales (Webster et al., 2016), sei whales (Baumgartner et al., 2008; McDonald et al., 2005), Bryde's whales (Širović et al., 2014), and minke whales (Dominello & Širović, 2016)) and so the annotator carefully referred to the example spectrograms presented in the literature when in doubt. For example, sei whale downswept calls are often emitted in doublet or triplet, and they have a convex time frequency downswept shape (Tremblay et al., 2019), whereas D-calls generally have a concave frequency shape. Similarly, minke whale downswept calls have a convex time frequency downswept shape and their frequency range is higher than D-call's (55 – 1296 Hz) (Dominello & Širović, 2016). To increase the accuracy of the double-check phase and limit the ambiguity with other baleen whale downswept call types, the expert did not label above 100 Hz, pulsed, or upswept detections as D-calls. A total of 189 730 false alarms were removed manually, which matches the theoretical false alarm rate of one per hour in average, computed in Torterotot et al. (2019).

Table 1: Annual proportion of files without airguns, kept in the study for each site. Colors indicate the proportion of data retained for analysis from green (low) to red (high). In WKER 2015, all data were double checked manually, therefore 100% of the data were kept for analysis this year at this site. For all other years and sites, the percentage of kept data corresponds to the percentage of "airgun-free" data.

Site	2010	2011	2012	2013	2014	2015	2016	2017	2018
MAD	0,72	0,74	0,68	0,79	0,73	0,64	0,66	NaN	NaN
MADW	NaN	NaN	NaN	NaN	NaN	NaN	NaN	0,77	0,86
NEAMS	0,56	0,64	0,65	0,67	0,57	0,72	NaN	0,70	0,86
SSEIR	NaN	NaN	NaN	NaN	0,82	0,55	0,64	0,76	0,90
SSWIR	NaN	NaN	NaN	NaN	NaN	NaN	NaN	0,91	0,82
NCRO	NaN	0,87	0,91	0,83	0,83	0,70	0,57	NaN	NaN
SWAMS	NaN	NaN	0,90	0,79	0,88	0,61	0,53	NaN	0,91
WKER	0,58	0,76	0,88	0,82	0,88	1,00	0,82	0,90	0,85
ELAN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	0,95

To further validate the reliability of the detection method (SRD followed by the post-processing algorithms to automatically remove airguns and fin whale 40 Hz-calls), we manually double checked the remaining detections from the three recordings of the WKER hydrophone triad (30 km spacing) in 2012. Given that D-calls likely propagate over tens of kilometers (Oleson et al., 2007a), we hypothesized that if the detector performed well, then the detection patterns would be highly similar for the three recordings of the triad. A Pearson correlation test was used to compare the three time-series.

3. D-call metrics

At each site, the annual number of D-calls as well as the annual number of days of recording (corrected by the number of days removed because of airgun presence in the data) were computed. The weekly number of D-calls detected, normalized by the corrected week duration was also computed. Each week duration was corrected by removing duration corresponding to the number of files in which airguns were detected. The weekly proportion of files with airgun signals is represented in Appendix 1.

The number of D-calls recorded during each season was also computed for the whole recording period and rectified by the corrected duration of the season, if shortened by the removal of files with airgun shots.

Austral seasons are defined as in Samaran et al., (2010, 2013): summer (December, January, February), autumn (March, April, May), winter (June, July, August), and spring (September, October, November).

Unlike songs, D-calls cannot be attributed to a specific blue whale population based on their time-frequency signature. Therefore, to associate D-calls presence with the presence of a specific blue whale population, we measured the co-occurrence of D-calls and stereotyped songs as the monthly number of hours within which both were detected, over the total number of hours in which D-calls were detected. We only measured this metric at WKER and ELAN as they are the two sites with the most D-call detections. The song presence metrics are based on the detections presented in Torterotot et al., (2020).

3. Results

THE WEEKLY D-CALL DETECTION PATTERNS FROM THE HYDROPHONE TRIAD DEPLOYED AT WKER SITE IN 2012 WERE HIGHLY SIMILAR, INCLUDING A DETECTION PEAK IN APRIL AND FEWER DETECTIONS DURING THE REST OF THE YEAR (PEARSON'S CORRELATION *P* > 97%, P <0.001; FIGURE 5). HOWEVER, THE TOTAL NUMBER OF WEEKLY DETECTIONS VARIES DEPENDING ON THE SITE, ESPECIALLY IN APRIL, WITH ABOUT 800 DETECTIONS AT WKER1 AND WKER3 AND ALMOST 1,000 DETECTIONS AT WKER2 DURING THE FIRST WEEK OF APRIL. D-CALLS WERE DETECTED EVERY YEAR AT ALL THE OHASISBIO RECORDING SITES, EXCEPT RAMA (FIGURE 6). ONLY 10 D-CALLS WERE DETECTED AT RTJ DURING THE ONLY AVAILABLE YEAR OF RECORDING (2018), AND ONLY 36 D-CALLS AT MADE IN ITS 2-YEAR DATA SET (2017-2018); THEREFORE, THESE SITES ARE NOT INCLUDED IN THE FOLLOWING FIGURES. THE HIGHEST NUMBER OF DETECTIONS OCCURRED AT WKER IN 2015 (N = 6,760) AND AT ELAN IN 2018 (N = 6,594). OVERALL, MORE D-CALLS WERE DETECTED AT THE SOUTHERN SITES - ELAN AND WKER - THAN AT THE NORTHERN

SITES - SSEIR, MADE, MADW, NEAMS, RTJ - (N < 1,346) (FIGURE 6). HOWEVER, MORE SEISMIC SHOTS WERE DETECTED AT THE NORTHERN SITES, LEADING TO REDUCED DATA SETS (

Table 1 and Appendix 1). During the recording period (2010 to 2018), there is no trend showing an increase or decrease in the number of D-calls at any site (Figure 6).

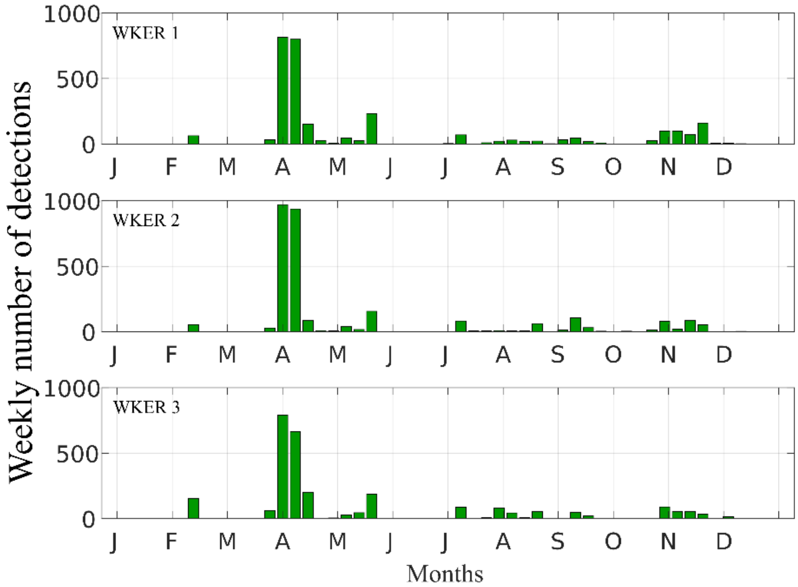

Figure 5: Number of blue whale D-calls detected per week for each hydrophone of the WKER triad (from top to bottom: WKER 1, WKER 2, and WKER 3) in 2012; all detections were visually checked by an expert operator

The seasonal pattern of D-call presence is shown in Figure 7. Almost no D-calls were detected in summer (December to February) at the northern MAD, MADW, NEAMS, and SSEIR sites (<3%). At all these sites, most of the D-calls were detected during winter (MADW: 70%, NEAMS: 49%, SSEIR: 73%) or during autumn (MAD: 50%). At the other sites, D-calls were detected in all four seasons, but mostly in winter at SSWIR, NCRO, SWAMS, and WKER (respectively 45%, 31%, 38%, and 49%) and in spring at ELAN (50%). The weekly distribution of D-calls is detailed in Appendix 2.

To synthesize both song and D-call data, we used annual song detection data from 2010 to 2018 from Torterotot et al., (2020) and compared that to D-call detections for the same sites and time frames (Figure 8). While songs from both Antarctic and pygmy blue whales were recorded throughout the array, with geographic variation arising mainly from the recorded song types, D-calls were infrequently recorded by the northern instruments and their occurrence increasing with latitude.

Figure 9 shows the proportion of hours containing detections of D-calls as well as non-exclusive detections of Antarctic or SWIO pygmy blue whale calls (i.e., both Antarctic and SWIO pygmy blue whale calls could be detected within the hour) for the two sites with the highest number of detected D-calls (WKER and ELAN). At WKER, D-calls mainly co-occurred with Antarctic blue whale calls

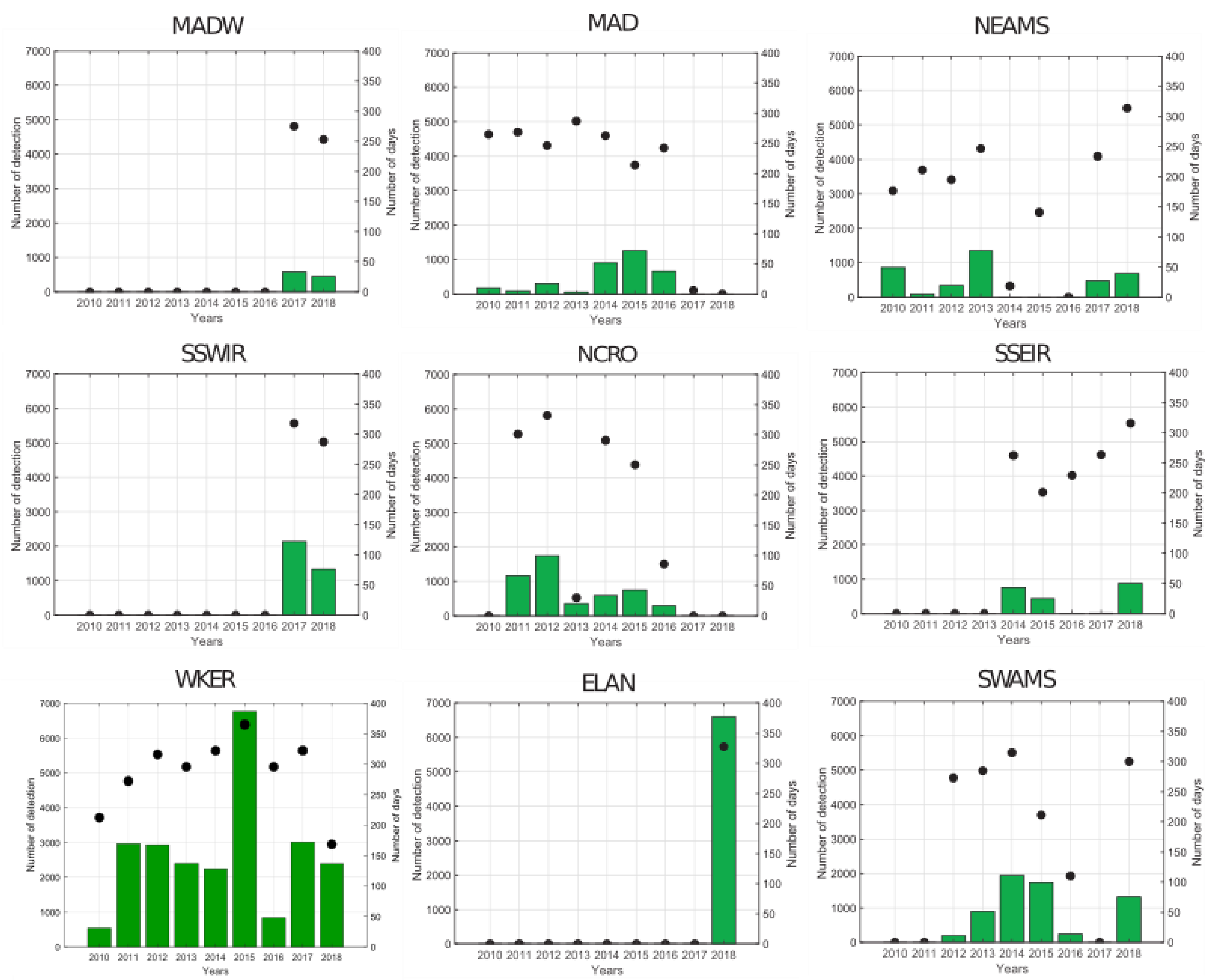

Figure 6: Number of detected D-calls per year at sites of the OHASISBIO network. Black dots represent the number of days of recording for each year, corrected for the number of days when seismic shots were detected (files containing airgun sounds were removed from the analysis).

from July to December. During the rest of the year, D-calls were detected together with both Antarctic and SWIO pygmy blue whale songs. At ELAN, D-calls are associated with Antarctic blue whale calls from August to December and to SWIO pygmy blue whale calls in November.

4. Discussion

Oleson et al. (2007a) found that, in the California bight, the number of D-calls was related to the number of visually observed animals. Therefore, they suggested that monitoring D-calls might better indicate blue whale presence than monitoring songs, emitted only by males and whose production rate exhibits spatial and temporal variability due to their reproductive function. However, in our data set, the proportion of D-calls relative to song is always small, especially at subtropical latitudes (MAD, MADW, NEAMS, SWAMS) (Torterotot et al., 2020). Furthermore, we observe an opposite pattern between D-call and song counts, where more D-calls are detected at the southern sites (WKER and ELAN) than at the northern sites (MADE, RTJ, MADW, NEAMS) whereas more songs are detected at the northern sites (MAD, MADW, NEAMS) than at the southern sites (WKER, ELAN) (Torterotot et al., 2020). This reversed pattern suggests that the temporal emission pattern of both D-calls and songs is dependent on the geographical location, and thus probably of the behavioral context, in a decorrelated manner and thus that the number of D-calls or songs detected at a given site is not an appropriate proxy for assessing the relative abundance of whales within the vicinity of a hydrophone.

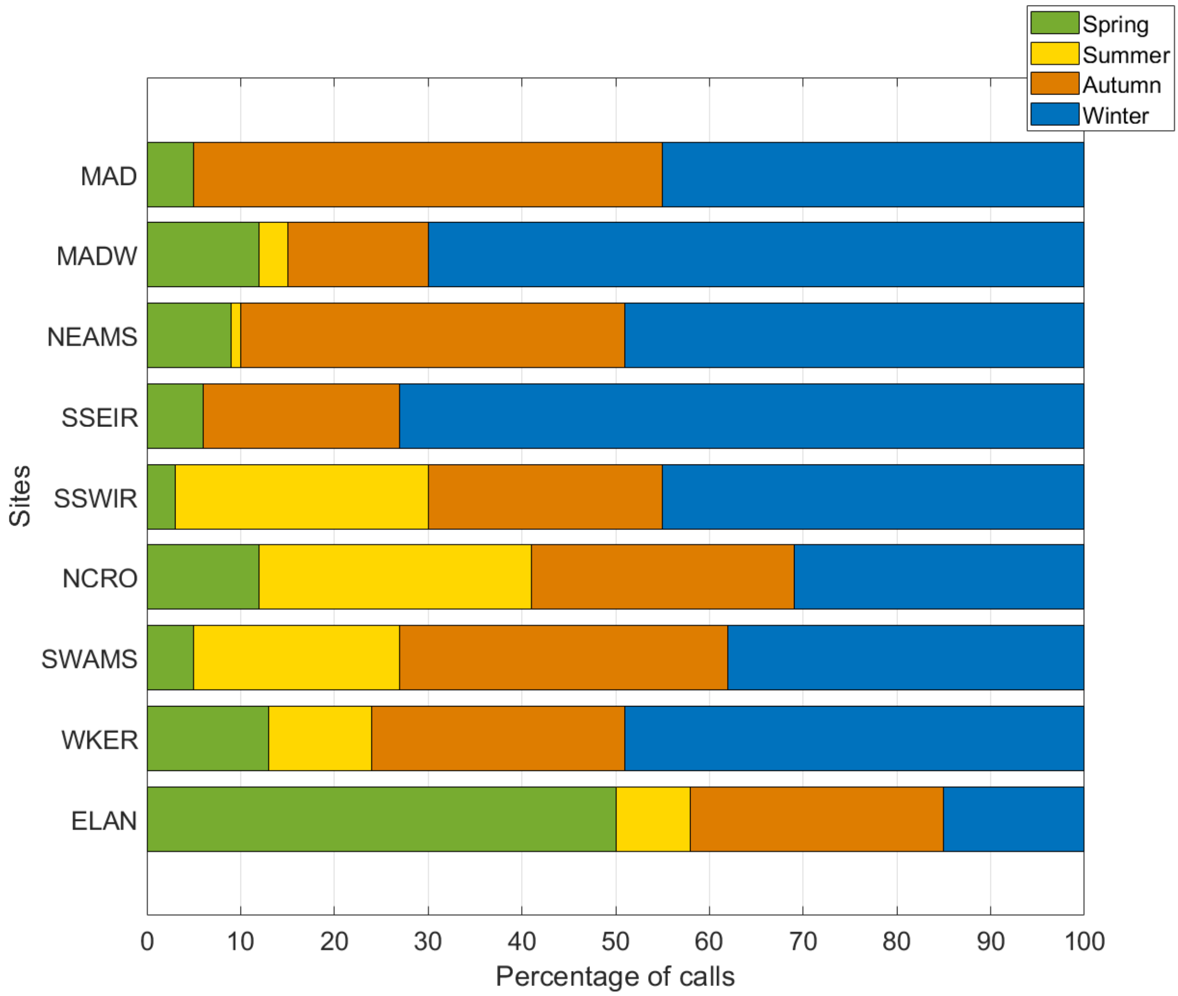

Figure 7: Percentage of hours containing D-calls each season

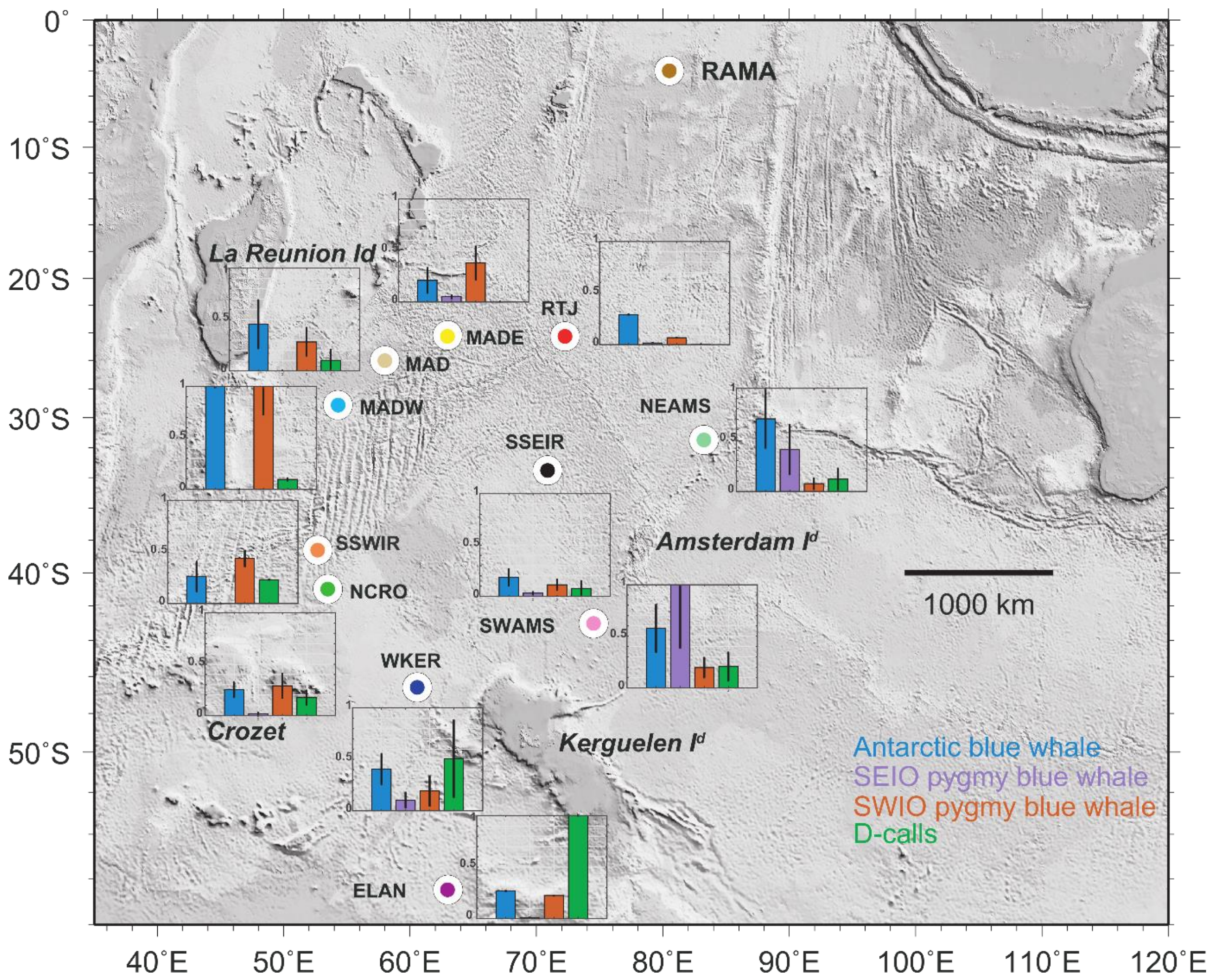

Figure 8: Mean and standard deviation of the number of Antarctic blue whale calls (blue), SEIO pygmy blue whale calls (purple), SWIO pygmy blue whale calls (orange) and D-calls (green) detected per year normalized by the number of days of recording per year. The results were then normalized by the maximum averaged number of detections for each call type.

Thomisch, (2017) used D-calls to describe Antarctic blue whale movement in the Southern Ocean and found persistent D-call presence at 59°S, implying that part of the population remains close to the sea ice edge during winter months. In New Zealand, this call type was monitored and its seasonal presence was compared with environmental parameters to better understand the relationships between physical drivers and biological responses and improve forecasting of species distribution patterns (Barlow et al., 2021). As songs are likely emitted seasonally, and only by half the population, D-calls are better proxies for this kind of study. D-call presence was also used as a proxy to describe blue whale arrival at the Southern California feeding ground, while the stereotyped B-calls were used as a proxy for blue whale departure (Szesciorka et al., 2020). In this case, monitoring both call types bring complementary information about blue whale occupancy of the area. In the north of the OHASISBIO array, D-calls were mainly recorded during the end of autumn and the start of winter, a time span when all three acoustic population of blue whales are also detected (Torterotot et al., 2020). Monitoring the seasonal presence of D-calls at these locations might therefore allow assessing the peak period when the three population are sympatric. South of the array, D-call seasonality is less pronounced, but about half of the detections occur in spring, the peak period for Antarctic blue whale acoustic presence (Torterotot et al., 2020), whereas the peak period of SWIO pygmy blue whale acoustic presence occur in austral autumn, suggesting different acoustic behavior among population at this location. As shown here, unlike the Californian feeding ground or New-Zealand waters where a unique blue whale population is found, the simultaneous presence of multiple blue whale populations in the Indian Ocean makes it more challenging to monitor their movements only from D-calls. Indeed, unlike songs, it has never been shown that D-calls' time-frequency signatures were geographically distinct or specific to populations. The comparison of the presence of D-calls with that of other stereotyped calls (Figure 9) was unable to univocally associate D-calls with any of the different acoustic populations present (e.g., both Antarctic and SWIO pygmy blue whales were detected from January to June at WKER and in November at ELAN, Figure 8). Thus, this data set could not be used to measure D-call acoustic parameters (frequency, duration, etc) or try to associate specific acoustic features with the different populations. Therefore, monitoring only D-calls could not serve to distinguish the distribution and seasonal presence of different acoustic populations of blue whales in this region. However, this call type brings new insight on blue whale behavior and how they use the Indian Ocean as a habitat.

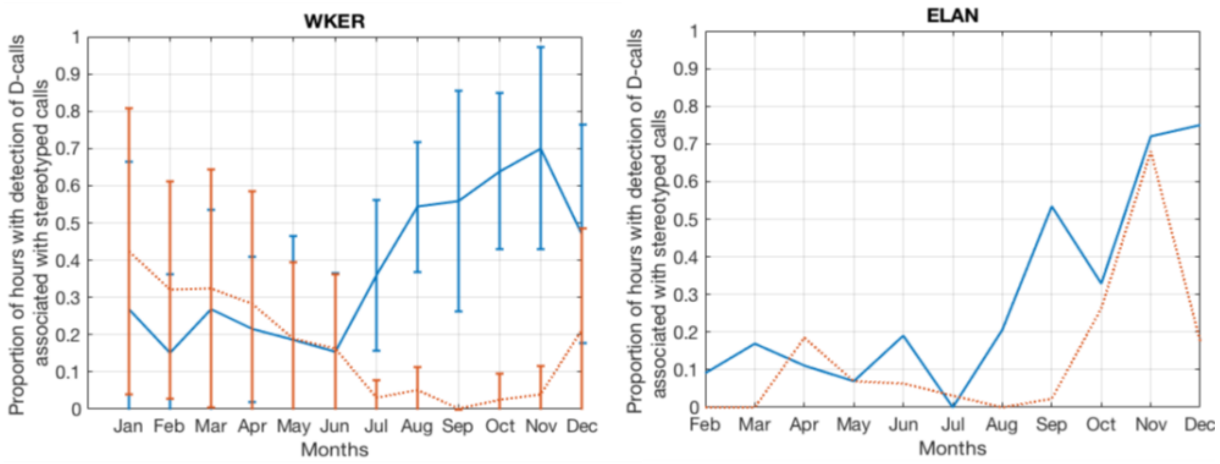

Figure 9: Monthly proportion of hours with d-calls associated with Antarctic blue whale calls (blue) and SWIO pygmy blue whale (orange dotted line) over the total number of hours with D-call detections at (left) WKER from 2010 to 2018 and (right) ELAN in 2018. Hours could be associated with both subspecies if both their songs were present within the hour. Vertical bars are standard deviations values. They do not appear in the panel on the right because only 1 year of data was analyzed.

In the southern Indian Ocean, more D-calls were detected in highly productive latitudes (WKER and ELAN), a preferential blue whale foraging ground (Branch et al., 2007, Samaran et al., 2010). The majority of the detections at 56° S occured in spring, a productive season due to the melting of the ice cap, which induces phyto-planktonic blooms (Pakhomov and McQuaid, 1996). This observation supports the hypothesis that D-calls are produced during or between foraging behavior as observed offshore California (Oleson et al., 2007b). The large number of D-calls recorded in Antarctic feeding grounds during the ENRICH survey in 2019 also corroborate this observation (Miller et al., 2019). The few winter D-call detections at the northern sites of the array therefore suggests that blue whale also feed in their wintering grounds. Such behavior has previously been observed for humpback whales off Brazil (19°35’ S) (Pinto de sa Alves et al., 2009), Mexico (24° N) (Gendron, 1993) and Dominican Republic (19° N) (Baraff et al., 1991). Detections of D-calls at sub-Antarctic locations (NCRO, SSWIR, SWAMS) could indicate that blue whales are feeding during migration, maybe taking advantage of productive seamounts. Such isolated areas have been recognized as highly important for biodiversity as they support rich underwater ecosystems (Pitcher et al., 2007).

In the Pacific Ocean, D-calls production rates have been found to be significantly higher during shallow nonlunging dives and periods of surface nonfeeding related behavior (Lewis et al., 2018). D-calls were also detected during dynamic behaviors associated with mating (Schall et al., 2019). These observations, although reported at feeding areas, favor the hypothesis of a multi-purpose social call. D-call would therefore be expected to be detected on wintering grounds, where potential mating and calving would induce the need of social communication. This does not appear to be the case in the Indian Ocean, where only a few D-calls were recorded in low latitudes (Figure 6). Wintering grounds may be geographically more extended than feeding grounds, resulting in a widely distributed blue whale presence and thus fewer social acoustic interactions in the low latitudes. In this case, the low number of D-calls detected at MADW (relatively to the average number of D-calls detected at the other sites), the site with the greatest number of Antarctic and SWIO pygmy blue whale stereotyped calls (Figure 8) is therefore puzzling, as the context would suggest high levels of social interactions. These observations support the hypothesis that D-calls are mainly produced in feeding contexts and can therefore be a relevant acoustic indicator of blue whale feeding behavior.

The actual number of D-calls in the data is likely underestimated. Indeed, the final detection results rely on a detector with a recall between 60% and 80% depending on the calls' SNR and on a postprocessing phase that removed files containing airgun sounds from the analysis (Torterotot et al., 2019).

Table 1 shows that the northern sites MAD and NEAMS are more affected by the removal of files due to airgun sounds. However, Figure 6 shows that the number of D-calls detection is not correlated with the number of days kept for the analysis (*e.g.* 52 D-call detections for 287 days at site MAD in 2013 VS 1251 D-call detections for 214 days at site MAD in 2015). Appendix 1 gives a finer seasonal overview of the subsampling caused by this post-processing with a figure showing the weekly proportion of files with seismic shots. This subsampling appears to be random and therefore would not mask any seasonal D-call presence pattern. Still, the great presence of airgun signals in summer 2015 (from January to February), spring 2015, and summer 2016 (from September 2015 to April 2016) and in summer and autumn 2017 (from February to April) might have had an influence on the resulting seasonal D-call pattern (see Appendix 1). However, from the other years with data it appears that only a few D-calls are detected in spring of these years, especially at the northern sites, suggesting that only a little number of D-calls might have been discarded by these huge noisy events. The source localization of these events is beyond the scope of this paper, but the simultaneous detection of few-month long seismic events on sites located several hundreds of kilometers away suggests that airgun sounds might propagate at a whole ocean basin scale as described in the Atlantic (Nieukirk et al., 2012). The high number of D-calls detected at WKER in 2015 was first noticed during visual inspection of the data, hence the selection of this dataset to validate the detector performance. The automated detection further confirmed this initial observation. As the templates for D-call detection was generated from multiple sites and years, it is unlikely that the high detection number at WKER in 2015 is due to a bias in the detector learning process. Interannual variability in the number of detected D-calls could result from changes in local ecological parameters, leading to the attraction or the repulsion of the whales (Pérez-Jorge et al., 2020; Shabangu et al., 2019). The high correlation between the detection patterns measured at the WKER hydrophone triads (Figure 5) further corroborate the reliability of the detection method. Indeed, as D-calls likely propagate over tens of kilometers, we hypothesized that if the detector was performing well, the three detection patterns would be similar. It is, however, worth noting that the actual number of detections may vary from one hydrophone of the triad to the other, depending on the week. To date, there are very few estimates of the source level of D-calls (Berchok et al., 2006) or songs (Bouffaut et al., 2021; Gavrilov et al., 2011; Samaran et al., 2010; Širović et al., 2007; Thode et al., 2000), but it is generally agreed that D-call' source level is likely lower than that of stereotyped calls implying that their detection range is likely smaller (Oleson et al., 2007a). The variable weekly number of D-calls detections on the triad hydrophone recordings might therefore be due to a lesser propagation range of D-calls, which, depending on the whale location, might not be recorded by all three sensors. It suggests that in this configuration (*i.e.* hydrophones located in the SOFAR channel in the open Indian Ocean), D-call detection range might be just a little more than 30 km (the distance between two hydrophones of the triad) and certainly don't reach 100 to 200 km as suggested for blue whale songs (Širović et al., 2007; Thomisch et al., 2016). It is also possible that this variability is due to some propagation effects on the calls, causing the masking of certain calls on one or two of the hydrophones. The detection or double check process might also not be fully reproducible, even if performed by the same operator, a bias highlighted in Leroy et al., 2018 b. Finally, as stated in the Method section, many baleen whale species likely present in the Indian Ocean produce similar downswept calls (Dominello & Širović, 2016; McDonald et al., 2005; Širović et al., 2013, 2014; Webster et al., 2016). Even if the annotator carefully double checked all D-call detections, by comparing the spectrograms with those found in the literature, some calls produced by other baleen whales might have been kept in the data set. More simultaneous visual and acoustic observations will be needed to fully differentiate these downswept call types from different species.

5. Conclusion

This paper is the first broad-scale study describing the seasonal and geographical presence of blue whale D-calls in the southern Indian Ocean. While monitoring songs proved to be an efficient way to infer their distribution in this region (Leroy et al., 2018, Torterotot et al., 2020), monitoring D-calls adds useful information on how this species uses its habitat. We show a behavioral switch, from song-intensive and sparse-D-call emissions in the north to song-moderate and more intensive D-call emissions in the south (Figure 8), suggesting a latitudinal partition of blue whale habitat use. The highest number of D-calls was detected at ELAN (56°S) during spring, a highly productive season, whereas only a small number of D-calls was detected in low latitudes, where stereotyped calls are highly detected. This supports the hypothesis that this call type is used mainly on foraging grounds and might therefore be a relevant indicator of blue whale feeding behavior.

To better interpret D-call occurrence, joint visual and acoustic observations along with biopsies, would be appropriate to determine where, when and in which context each subspecies and acoustic population produce D-calls. This would help decifer whether D-calls are associated to a specific behavior and/or to a specific subspecies. Additionnaly, comparing D-call occurrence with environmental data (e.g., sea surface temperature, chlorophyll A) could provide insights on blue whale habitat preferences and whether they evolve in response to the rapid ocean and climate changes.

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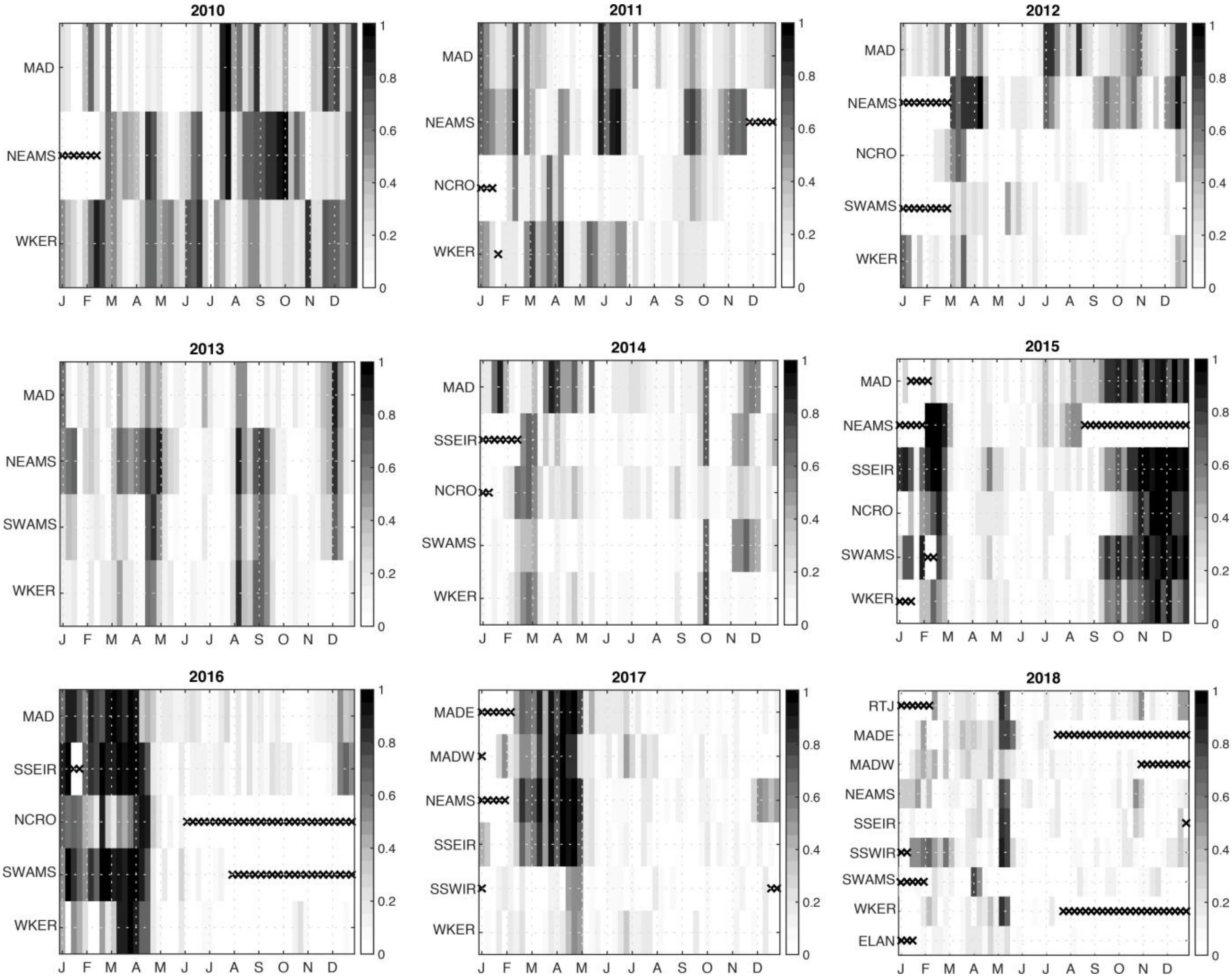
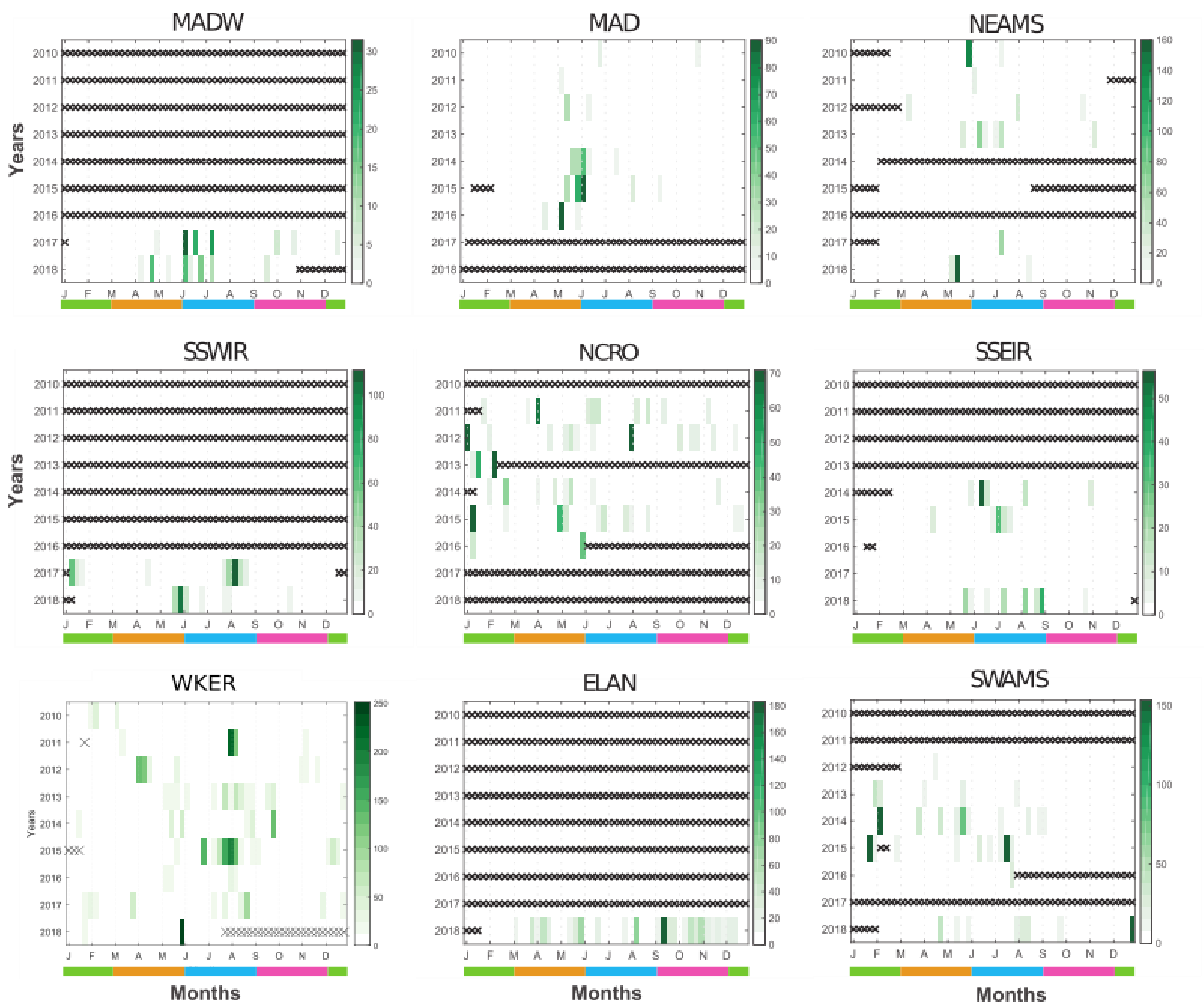
8. Appendix



Appendix 1: Weekly proportion of files with airgun signals for every year of recording. Black crosses indicate weeks with no available recordings



APPENDIX 2: WEEKLY NUMBER OF D-CALLS DETECTED, NORMALIZED BY THE CORRECTED WEEK DURATION. BLACK CROSSES INDICATE WEEKS WITH NO AVAILABLE RECORDINGS. SEASON ARE COLOR CODED AS FOLLOW: SUMMER: GREEN; AUTUMN: ORANGE; WINTER: BLUE AND SPRING: PINK