Identification of two potential whale calls in the southern Indian Ocean, and their geographic and seasonal occurrence

Emmanuelle C. Leroy
University of Brest and Centre National de la Recherche Scientifique, Laboratoire Géosciences Océan, Institut Universitaire Européen de la Mer, 29280 Plouzané, France

Flore Samaran and Julien Bonnel
Centre National de la Recherche Scientifique Unité Mixte de Recherche 6285 Lab-STICC, Ecole Nationale Supérieure de Techniques Avancées, Bretagne, 29806 Brest, France

Jean-Yves Royer[a)]
Centre National de la Recherche Scientifique and University of Brest, Laboratoire Géosciences Océan, Institut Universitaire Européen de la Mer, 29280 Plouzané, France

(Received 13 March 2017; revised 10 August 2017; accepted 17 August 2017; published online 15 September 2017)

Since passive acoustic monitoring is widely used, unidentified acoustic signals from marine mammals are commonly reported. The signal characteristics and emission patterns are the main clues to identify the possible sources. In this study, the authors describe two previously unidentified sounds, recorded at up to five widely-spaced sites (30 × 30 degree area) in the southern Indian Ocean, in 2007 and between 2010 and 2015. The first reported signal (M-call) consists of a single tonal unit near 22 Hz and lasting about 10 s, repeated with an interval longer than 2 min. This signal is only detected in 2007. The second signal (P-call) is also a tonal unit of 10 s, repeated every 160 s, but at a frequency near 27 Hz. Its yearly number increased greatly between 2007 and 2010, and moderately since then. Based on their characteristics and seasonal patterns, this study shows that both signals are clearly distinct from any known calls of blue whale subspecies and populations dwelling in the southern Indian Ocean. However, they display similarities with blue whale vocalizations. More particularly, the P-call can be mistaken for the first tonal unit of the Antarctic blue whale Z-call.
 [http://dx.doi.org/10.1121/1.5001056]

[JFL] Pages: 1413–1427

I. INTRODUCTION

Marine mammals are vocally active animals that produce a large and diverse range of sounds. The frequency, complexity, and variability of these sounds depend on the species, each of which has its own vocal repertoire.[1] This repertoire, described step by step through combined visual and acoustic surveys (e.g., Refs. 2 and 3), is the key for monitoring whales solely using passive acoustic methods, particularly in remote or inaccessible areas of the ocean.[4,5] Passive acoustics have, for instance, been commonly used in the Southern Ocean to monitor blue whale (*Balaenoptera musculus spp.*) distribution and migration.[6–8] Acoustic monitoring targeted at specific species often leads to the discovery of sounds from unknown sources.[9–13] Based on sound characteristics, such as the duration, spectral shape, frequency, overtones, or repetition patterns, it is generally possible to identify the nature of their source (biological, geological, or anthropogenic).[14] In the case of biological sounds, hypotheses can be made about the type of animal that produce them (e.g., shell fish, fish, mysticeti, odontoceti). For instance, Watkins *et al.*[10,11] concluded that the so called "52-Hz call" or "Watkins' whale call" is emitted by a baleen whale, which may correspond to a blue-fin hybrid whale, based on the call characteristics and its seasonal and geographic occurrences.[15] Similarly, Sousa and Harris[12] described two new acoustic signals recorded near Diego Garcia Island, in the northern Indian Ocean, which have similar characteristics to blue whale calls. Still, only a combination of visual and acoustic observations can confirm the source of new sounds. Such confirmation may take years, since it requires being in the right place at the right time, with the right tools. In other instances, previously unknown calls have been rapidly identified, extending our knowledge of the whale repertoire (e.g., Ref. 16).

In 2007, and then since 2010, the southern Indian Ocean has been continuously instrumented with networks of hydrophones covering a wide range of latitudes and longitudes (4° to 46° S, 53° to 81° E), to monitor the low-frequency acoustic signals produced by seismic and volcanic events, and by large baleen whales.[17,18] The resulting acoustic records hold a large collection of calls from known species and subspecies, such as fin whales (*Baleanoptera physalus*), minke whales (*B. bonaerensis*), Antarctic blue whales (*B. m. intermedia*), and three populations of pygmy blue whales (Australia, Madagascar, and Sri-Lanka types) (*B. m. brevicauda*).[7,8,18–20] This data base has been extensively investigated to monitor the geographic and seasonal distribution of Antarctic and pygmy blue whales.[7,8] In this analysis, we detected the presence of two unidentified acoustic signals. Both signals, hereinafter referred to as "M-calls" and "P-

[a)]Electronic mail: jean-yves.royer@univ-brest.fr

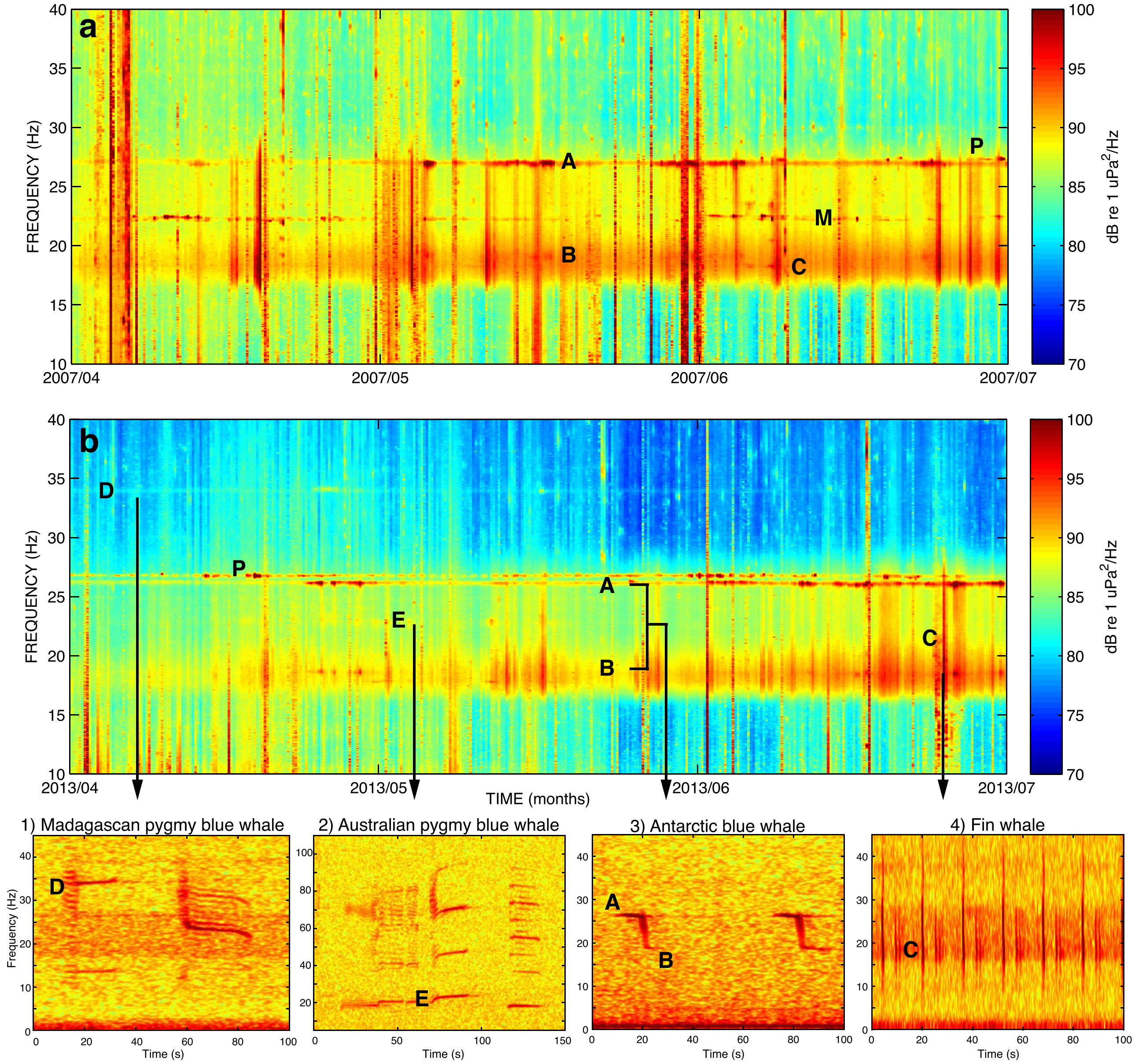

FIG. 1. (Color online) Long-term and close-up spectrograms of data recorded at the NEAMS site in 2007 (a) and in 2013 (b). The parallel horizontal frequency bands are made of Units A and B of Antarctic blue whale Z-calls (A and B), fin whale 20 Hz-pulses (C), pygmy blue whale calls of the Madagascar type (D), and Australia type (E), and unknown calls, reported as M- and P-calls in this paper. Spectrogram parameters: 6 h averaging window, 50% overlap, FFT window of 120 s.

calls," are clearly visible on long-term spectrograms, which offer a synthetic view of the main whale species present in acoustic records, thanks to energetic frequency bands formed by the presence of repeated and stereotyped calls. For example, in Fig. 1, high amplitudes between 18 and 26 Hz indicate the presence of Antarctic blue whale stereotyped Z-calls and fin whale 20 Hz-pulses. However, two other energetic bands stand out near 22 Hz [Fig. 1(a)] and 27 Hz [Fig. 1(b)]; both frequencies are different from typical Antarctic blue whale calls (A-B frequencies in Fig. 1). Although these frequencies are close to that of blue whale calls, they do not resemble other known vocalizations recorded in the area, namely, that of the Antarctic blue whale, the pygmy blue whale of the Madagascar and Australia types, and the fin whale. The call of the Antarctic blue whale, known as "Z" call, is made of a first tonal unit A at about 26 Hz, lasting about 10 s, followed by a 1 to 2 s-long downsweep from 26 to 18 Hz, and a second tonal unit B at about 18 Hz [Fig. 1(b.3)]. The Madagascar pygmy blue whale call has two long units emitted in patterned sequences every 90 to 100 s [Fig. 1(b.1)]. The first unit has a fundamental frequency of about 35 Hz and lasts about 11 s, followed by a 40 s-long gap, and then a frequency-modulated downsweep with a center frequency near 25 Hz and lasting about 10 s.[7] The Australian pygmy blue whale call is more complex [Fig. 1(b.2)]. It consists of three units with many overtones, repeated in sequences every 200 s. The first unit is a ~20 Hz tonal sound lasting 20 s, then shifting to 21 Hz for another 20 s. After a gap of a few seconds, it follows a frequency-modulated tone from 20 to 26 Hz lasting 23 s, and about 22 s later appears as a last and third unit near 18 Hz and lasting about 15 s.[7,21] Finally, the fin whale emits brief pulses from 15 to 30 Hz, repeated every 13 to 15 s, often along with an 99 Hz pulse[22] [Fig. 1(b.4)]. None of these complex multi-tonal vocalizations matches with the unidentified simple tonal units. A systematic examination of our extensive acoustic data set provides evidence—signal characteristics, patterns of emission, geographic distribution, and seasonality—that confirm the biological nature of their source, undoubtedly whale(s).[12,14] A comparison of this observation with other known whale calls in the area allows drawing hypotheses about their source(s).

II. MATERIAL AND METHODS

A. Data acquisition

Two datasets were analyzed for this study. The first set was recorded by the DEFLOHYDRO[60] hydrophone network, deployed from October 2006 to April 2008 at three locations in the southern Indian Ocean. One instrument was located south of La Reunion Island in the Madagascar Basin (MAD), one mid-way between the Kerguelen and Amsterdam islands (SWAMS), and a third one northeast of the St Paul and Amsterdam volcanic plateau (NEAMS) (Fig. 2, stars with thick contours). Each mooring consisted of an anchor, an acoustic release, and a hydrophone moored in the axis of the sound fixing and ranging channel, at a depth of 1000 to 1300 m below sea-surface depending on the site. All hydrophones had a sensitivity of -153.7 dB re: 1 V/μPa and data were continuously sampled at 250 Hz (see Ref. 17 for a complete description of the recorder specifications). Only the data recorded in 2007 are analyzed here. The second set of data came from the OHASISBIO[61] hydroacoustic experiment, started in December 2009 in the same region and still on-

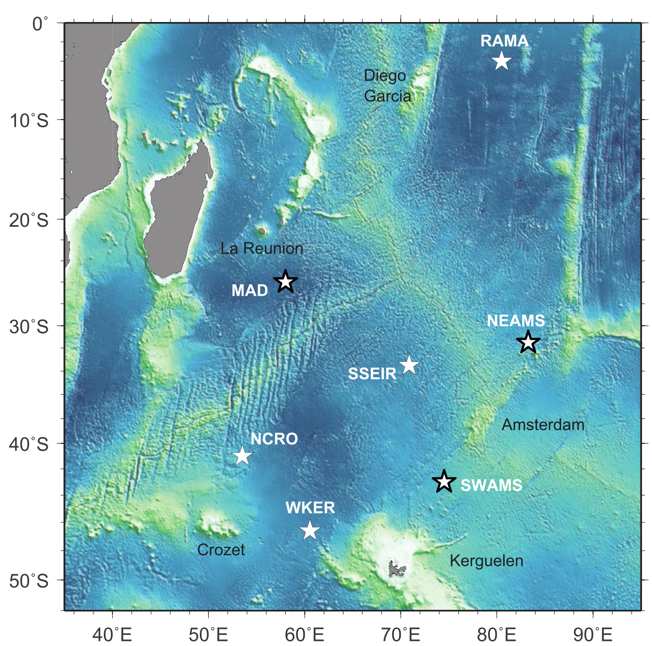

FIG. 2. (Color online) Hydrophone locations of the DEFLOHYDRO (stars with thick contours) and OHASISBIO networks (all stars) in the Indian Ocean.

going as of July 2017. In addition to the three sites instrumented during the DEFLOHYDRO experiment (MAD, NEAMS, and SWAMS), the OHASISBIO network comprised a site north of Crozet Islands (NCRO) and one between Crozet and Kerguelen islands (WKER). In 2012–2013, a temporary site was installed for 16 months in the central Indian Basin (RAMA) and in 2014 a new site was established in the northern Crozet Basin (SSEIR). Moorings were similar to those of the DEFLOHYDRO array. All hydrophones had a sensitivity of -163.5 dB re: 1 V/μPa and the data were continuously sampled at a rate of 240 Hz (see Ref. 23 for instrumental details). Data are collected every year during the annual voyages of the R/V Marion Dufresne to the French Southern and Antarctic Territories. The database is almost continuous for the past 6 years (2010–2015), except for some months or years depending on the site, due to battery failures or instrument losses. Deployment details are summarized in Fig. 3 and listed in Appendix A (Table III; see also Ref. 8). This study used the whole 6-yr-long data set, except from the NCRO site in 2010 and 2013, where the records were hindered by high noise levels likely due to the strumming of the mooring line.

B. Data analysis

1. Visual inspection

Acoustic data were first visually analyzed on long-term spectrograms such as Fig. 1, which provide an overview of all energetic frequency bands. Then, the newly identified signals were closely inspected and described using the Raven Pro software (v1.5, Cornell Lab of Ornithology). The first unknown signal, referred to as "M-call," is composed of one single tonal unit at about 22 Hz lasting about 10 s [Fig. 4(a)] and is regularly repeated in sequences of many calls. The Inter-Call Interval (ICI, defined as the gap between the beginning of a call and the beginning of the following one) is on the order of 2 min. Visual inspection of the data revealed that this signal is only present in the data recorded in 2007 and absent in the data recorded since 2010. Note that due to its limited occurrence, our study is less comprehensive than for the second unknown signal, referred to as P-calls. P-calls are also composed of a single tonal unit repeated in sequences of several calls 2 min apart, similar to M-calls, but at a higher frequency near 27 Hz [Fig. 4(b)]. Unlike M-calls, P-calls are present both in the 2007 data and every year since 2010. At first glance, the P-call can be mistaken for the unit A of an Antarctic blue whale Z-call [see Fig. 1(b.3)]. The unit A is indeed the most energetic part of a Z-call, and is sometimes the only visible part of low signal-to-noise ratio (SNR) Z-calls, which makes them highly similar to a P-call. However, it is clear from Fig. 1(b) that P-calls and Z-call's unit A occur in different frequency bands. In Sec. IV, we demonstrate that P-calls are not incomplete Z-calls.

2. Signal characteristics

The call duration and ICIs were measured manually on a selection of 611 M-calls and 2020 P-calls on spectrograms, using Raven Pro [Hanning window with 50% overlap and

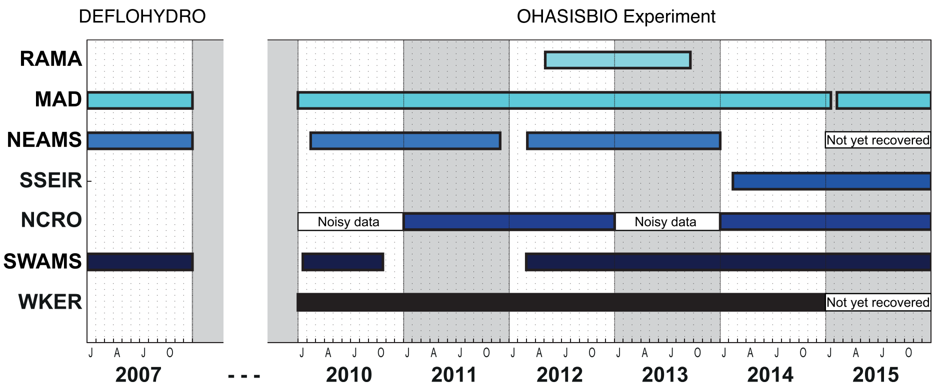

FIG. 3. (Color online) Periods of continuous acoustic recordings analyzed at each site. Details can be found in Table III of Appendix A.

256-point fast Fourier transform (FFT) for a good temporal resolution]. These calls were visually selected for their good quality, and were taken from different years and sites to enhance the number of samples. The call frequency was measured directly while running the automated detector (see Sec. II B 3), at the maximum of energy of each detected tonal unit (i.e., over more than 15 000 M-calls and 90 000 P-calls), with a precision of 0.035 Hz. Mean values associated with standard errors (s.e.) were calculated for the frequency and duration of each type of call. A median value was preferred to determine the ICI duration due to a high number of outliers.

3. Call detection

To detect P-calls in such a large acoustic dataset, we used an automated "*Z-detector*," an algorithm based on a subspace-projection method designed for detecting signals with a Z-shape in a time-frequency domain.[24] This algorithm models the Z-shaped signal with a logistical function and makes the assumption that the signal amplitude is piecewise constant, with four pieces of unknown amplitude that may be null. If the amplitudes of the third and fourth parts are null, the resulting signal is a tonal unit. In that way, the Z-detector is able to detect M- or P-calls with the same performances as for Z-calls.[24] To model the signal, the algorithm requires input parameters. The most important one for detecting tonal units such as P-calls is the search frequency band U, as for detecting the first tonal unit of a Z-shaped signal. The other parameters, pertinent to the other parts of Z-calls, were set to default values since they were not relevant here (see Refs. 8 and 24 for details). To allow for some flexibility, i.e., for frequency variations occurring between calls or throughout a year, the search frequency band U is bracketed in a $\pm$0.25 Hz interval. Since the *Z-detector* was originally designed for Antarctic blue whale Z-calls, which are ubiquitous in our data set,[8] we set the frequency parameter U so that the frequency interval $U \pm 0.25$ Hz does not overlap with the known frequencies of Z-call units A, investigated by Leroy *et al.*[8] In addition, long-term spectrograms and close-up inspections of some series of P-calls show that their frequency is decreasing over time, as also observed for Z-call units A.[25,26] In order to take this long-term decrease into account, the U frequency is adapted for each year of data (Table I).

The performance and reliability of the *Z-detector* were thoroughly investigated for Z-calls.[24] Notably, this detector has an adaptive detection threshold varying with the ambient noise level that ensures a maximum false-alarm probability of 3%, even in the presence of interfering signals (e.g., other whale calls, earthquakes, airgun shots; see Fig. 3 in Ref. 24). Since the detector is designed to detect unit A from complete and incomplete Z-calls with the same accuracy, and due to

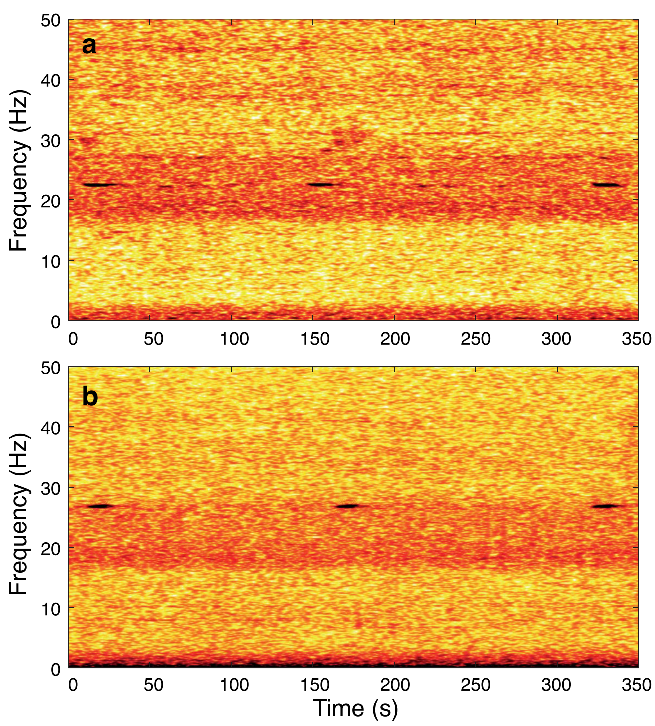

FIG. 4. (Color online) Spectrogram of three consecutive M-calls (a) and P-calls (b). Spectrogram parameters: Hamming window, 4096 point FFT length, 98% overlap.

TABLE I. Search frequency band U used for the automated detection of P-calls.

	U
2007	27.40 Hz $\pm$ 0.25 Hz
2010	27.05 Hz $\pm$ 0.25 Hz
2011	27.05 Hz $\pm$ 0.25 Hz
2012	26.95 Hz $\pm$ 0.25 Hz
2013	26.85 Hz $\pm$ 0.25 Hz
2014	26.60 Hz $\pm$ 0.25 Hz
2015	26.35 Hz $\pm$ 0.25 Hz

the similarity of P-calls to the Z-call units A (tonal units of the same duration and close frequency), there is no reason to believe that the performance in detecting P-calls would be different, except for the detections of unwanted Z-calls. Indeed, since the frequencies of a Z-call unit A and a P-call are close, the automated detector may not always be able to decipher them, despite the careful choice of the U parameter. For this reason, we post-processed the detections to check whether Z-calls were not mistakenly detected; as anticipated, there were many of them, but easily sorted out, since their frequency is significantly and consistently different, as shown in Fig. 6 (see also Fig. 11 in Appendix A).

On average, 63% of the initial detections were Z-calls, and thus removed. This high percentage is not surprising given the massive occurrence of Z-calls in the records (1 003 988 Z-calls vs 90 410 P-calls[8]). In one instance though, due to the vicinity of Z- and P-call frequencies at site NEAMS in 2007 [Fig. 1(a)], all the automatic detections were individually checked on spectrograms and false detections manually removed (about 33 000 out of 38 162 events). Except for this site and year, none of the other sets of data required such double-check. This classification based on the detection frequency also allowed a quick deletion of other potential false detections (i.e., with outlier frequencies). This post-process removal of false positives (Z-calls mostly) ensures that the resulting detections are within or better than the 3% false alarm expected probability.

In the same way, we adapted the *Z-detector* to automatically detect the M-calls. A visual exploration of the dataset using long-term spectrograms and close-up inspections showed that M-call frequency differs among the three DEFLOHYDRO sites. Thus, the parameter U was set to 21.50 ± 0.25 Hz for MAD, 22.45 ± 0.25 Hz for NEAMS, and 22.25 ± 0.25 Hz for SWAMS. As for the P-calls, checking the frequency of the detected events helped with removing false detections (about 40%).

4. Call occurrence

a. Variations between sites and years. To enable the comparison of the total number of detected calls among years and sites, and because some years of recording are incomplete, the number of detections is normalized by the number of recording days in a given year. This estimation is made with a Generalized Linear Mixed Model (GLMM) to avoid biases due to seasonal patterns of occurrence (and thus to non-constant numbers of calls per day). This GLMM here assumes a negative binomial distribution, which is suitable for overdispersed data count, using month and year as random effects.[27]

b. Seasonality. The numbers of M-calls detected in the DEFLOHYDRO dataset are summarized by month to provide information of their seasonal occurrence during 2007. Because of the 2-year gap between the DEFLOHYDRO and OHASISBIO experiment, the seasonality of P-calls is independently analyzed for the two datasets. For the DEFLOHYDRO database, the monthly number of detections is calculated for each site. For the six continuous years of recordings of OHASISBIO, to test whether seasonality varies from year to year at a given site, monthly distributions of detections are normalized by the total number of detected P-calls each year. This normalization makes the observation independent from variations in the absolute detection numbers among years and emphasizes their seasonality. The stability of this seasonality throughout consecutive years is then statistically tested, using Friedman comparison tests,[28] because of the non-normal distribution of the data. Where significant differences between distributions are found, additional Wilcoxon pairwise comparison tests with Bonferroni correction are used.[29,30] Statistical analyses were performed using R,[31] and GLMM was run using STAN called from R with the package RStanArm.[32]

III. RESULTS

A. Signal characteristics

All signal characteristics—duration, frequency, ICI—are summarized in Table II and Figs. 5 and 6. Duration parameters and their statistics are based on a subsample of calls of good quality (high SNR) and from different years and sites to have a meaningful sample size. Since M-call frequencies differ among sites, as observed on long-term spectrograms (see also Fig. 12 in Appendix A), mean values are estimated per site (Table II). However, since the frequency of P-calls do not vary among sites, as illustrated by long-term spectrograms for a given month or year [e.g., Fig. 1(b); see also Fig. 13 in Appendix A], the P-call frequency for a given time window is averaged over all sites.

B. Call occurrence

1. Variations between sites and years

In 2007, M-calls are found at the three sites of the DEFLOHYDRO array, but are totally absent in the data recorded since 2010 with the OHASISBIO array. NEAMS is the site with the largest number of detected M-calls, with 12 588 calls detected throughout the year (about 35.5 calls per day), whereas only 1610 M-calls are detected at SWAMS (about 4.4 calls per day), and twice less, 809 M-calls at MAD site (about 2.2 calls per day).

In 2007, only a few P-calls are detected at NEAMS, and none at the two other sites (MAD and SWAMS). Since 2010, P-calls are recorded at every site of the OHASISBIO array, except at RAMA and WKER, and every available year of data. In total, 11 213 P-calls are detected over the 7 yrs of recordings at MAD (2007, 2010 to 2015), 49 300 P-calls are detected across 5 yrs at NEAMS (2007, 2010 to 2013), 11 491 P-calls over 6 yrs at SWAMS (2007, 2010, 2012 to 2015), 15 786 P-calls across 4 yrs at NCRO (2011, 2012, 2014, and 2015), and 2621 in 2014 at SSEIR. Figure 7 shows the distribution of the estimated number of P-calls per days for each available year of data at each site. This metric allows comparisons among years and sites when some years of data are incomplete. Every year, the greatest number of P-calls is detected at NEAMS. The number of P-calls increases drastically between 2007 and 2010 (more than a 400% increase at NEAMS), but moderately since then, except in 2011 (increase of 11% at NEAMS between 2010 and 2015). NCRO displays

TABLE II. Call characteristics. Duration parameters are manually measured on "good quality" calls from different years and sites (N = number of measured calls and ICI). Frequency is automatically measured at the peak amplitude of all detected calls.

	M-call	P-call
Call duration (mean ± s.e.)	10.56 ± 0.09 s $N = 611$	10.8 ± 0.06 s $N = 2020$
ICI duration (median, [range])	149 s, [64–500 s] [Fig. 5(a)] $N = 576$	159 s, [100–500 s] [Fig. 5(b)] $N = 1905$
Call frequency (mean ± s.e.)	21.74 ± 0.003 Hz at MAD 22.15 ± 0.005 Hz at SWAMS 22.36 ± 0.002 Hz at NEAMS	Long-term decrease of 1 Hz over 8 years, from 27.30 Hz in 2007 to 26.25 Hz in 2015 (Fig. 6)

numerous P-calls with a regular increase over time, except in 2012 where the number decreases abruptly. MAD, SSEIR, and SWAMS have the lowest rates of P-calls, with less than 25 P-calls per day. These numbers slightly increase over the years at MAD and SSEIR, but slightly decrease at SWAMS.

2. Seasonal pattern

M-calls are present year-round at all DEFLOHYDRO sites [Fig. 8(a)]. At NEAMS, where they are the most numerous, they occur mainly in autumn, with a high peak in April and a weaker peak in June. At SWAMS they mainly occur during summer and autumn, and are almost absent from June to December. At MAD, where they are the least numerous, the majority of detections occurs in August, with relatively few calls during the other months.

Detected only at the NEAMS site in 2007, P-calls are present from June to December, with a peak in June [Fig. 8(b)]. However, this June detection peak is very small (about 1700 calls) relative to P-call peaks occurring post-2010, consistently higher than 4000 calls. The results for each year and each OHASISBIO site are presented in Appendix B (Fig. 14).

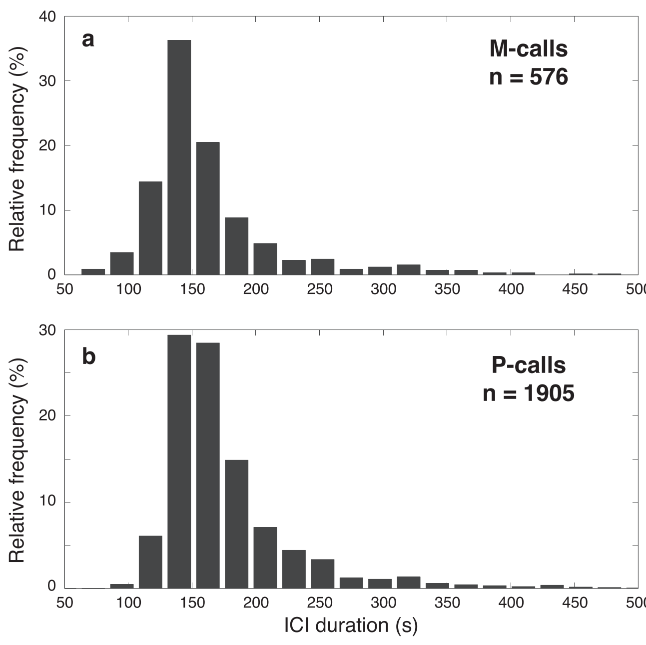

FIG. 5. Relative frequency of ICI duration for M-calls (a) and P-calls (b), n is the number of sampled ICI. (Bin size = 22.5 s.)

Statistical comparisons show no significant difference among the normalized monthly distributions of P-calls between years for MAD, NEAMS, NCRO, and SWAMS sites (Friedman tests, respectively, for MAD, NEAMS, NCRO, and SWAMS, *Friedman chi-squared* = 2.9; 0.2; 7; 0.4; all *p-values* >0.05). For SSEIR site, a Wilcoxon test for paired data (V) shows no significant difference between the 2 years of data (Wilcoxon paired test, $V = 31$, $p = 0.89$). This implies that the observed seasonality is stable among years and can be derived by averaging the normalized monthly distributions over the available years for these sites (Fig. 9). At sites where P-calls are detected, they are present throughout the year, but with marked seasonal patterns that differ between sites. For the westernmost sites, MAD and NCRO, P-calls are mainly present from the beginning of austral winter to the end of spring (from June to November). At the easternmost sites, NEAMS and SWAMS, P-calls are mainly present from the middle of austral summer to the end of autumn (from February to July for NEAMS and from January to May for NCRO). Call numbers drop during winter, and increase in spring, although the levels are lower in spring than in autumn. At SSEIR, in the middle of the network, there is no obvious seasonal pattern, but only 2 years of data are available for this site. The P-call seasonal patterns appear to vary with longitude.

IV. DISCUSSION

The new acoustic signals described in this study meet the criteria given by Stafford *et al.*[14] and Sousa and Harris[12] to identify potential biological sounds: they are produced in non-random patterns, show clear seasonal patterns of emission, are non-continuous and narrowband, contain modulation in amplitude, and have frequencies higher than 10 Hz. This combined evidence provides confidence about the biological origin of M- and P-calls. Furthermore, they are similar to baleen whale vocalizations, and, given their low frequency range, are very likely produced by large whales.

A. P-calls are not incomplete Z-calls

P-calls tonal units, with a frequency of about 26–27 Hz and a duration of about 10 s, closely resemble to units A of Z-calls, and thus can be easily mistaken for incomplete Antarctic blue whale Z-calls. However, our analysis shows that P-call characteristics are clearly different from those of Z-call units A (Fig. 10). The first evidence is their higher frequency (Figs. 1 and 6). Long-term spectrograms clearly

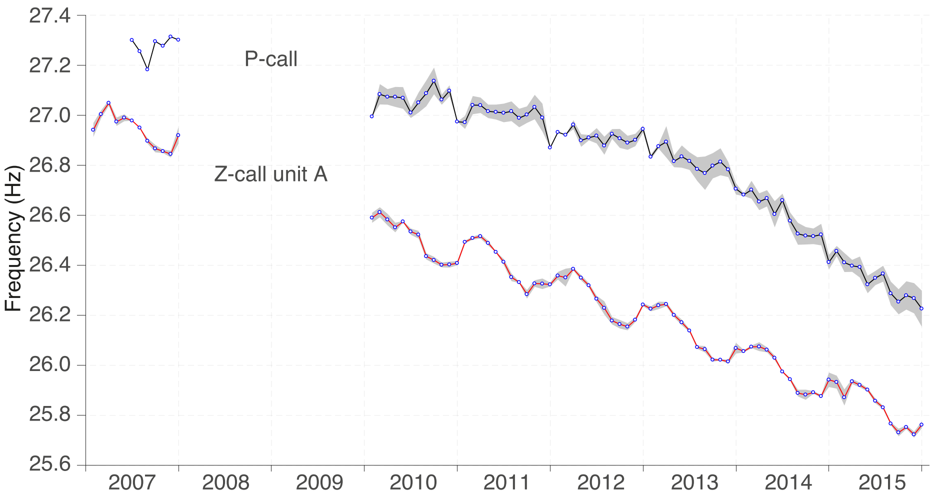

FIG. 6. (Color online) Top curve shows the P-call frequency averaged per month for each year of data. Bottom curve shows the frequency of Z-call units A found in the same data set [based on Leroy *et al.* (Ref. 8)]. Gray areas are s.e.

show two closely-spaced but distinct high-energy frequency bands near 26–27 Hz, the upper one corresponding to P-calls, and the lower one to units A of Z-calls (Fig. 1). On average, the P-call frequency is 0.6 ± 0.02 Hz (mean $\pm$ s.e.) higher than the Z-call units A (Fig. 6). This difference is meaningful despite all the intra- and inter-annual variations observed for the P-calls and Z-call units A. The latter have been analyzed in the same way and in the same data set as the P-calls (unpublished data based in Ref. 8). Furthermore, these intra- and inter-annual variations differ significantly between the two types of calls, suggesting that they are produced by distinct whale species. Although the reason for this long-term frequency decrease is still uncertain,[25,26,33] P- and Z-call unit A frequencies follow different trends, with a steeper slope (i.e., faster decrease) since 2013 for P-calls.

A second evidence of the difference between P-calls and incomplete Z-calls is the longer ICI between P-calls (Fig. 10). The P-call ICI is of about 160 s, more than twice the duration of the Z-call ICI, lasting between 50 and 60 s.[6,34,35]

Finally, the third evidence, although indirect, is the differences in the geographic and seasonal patterns of P- and Z-calls (see Fig. 6 in Ref. 8). No P-calls are detected at WKER, but they are detected at all the other sites, from late summer to late autumn at the easternmost sites (NEAMS and SWAMS), and during winter and spring at the westernmost sites (MAD and NCRO). Since the noise level over the years and sites is fairly constant,[8] these observations are likely not an artifact of the ambient noise level, which can impact the call detection range.[36] This distribution pattern would thus point to a yearly east–west migration of the source of P-calls, in contrast with

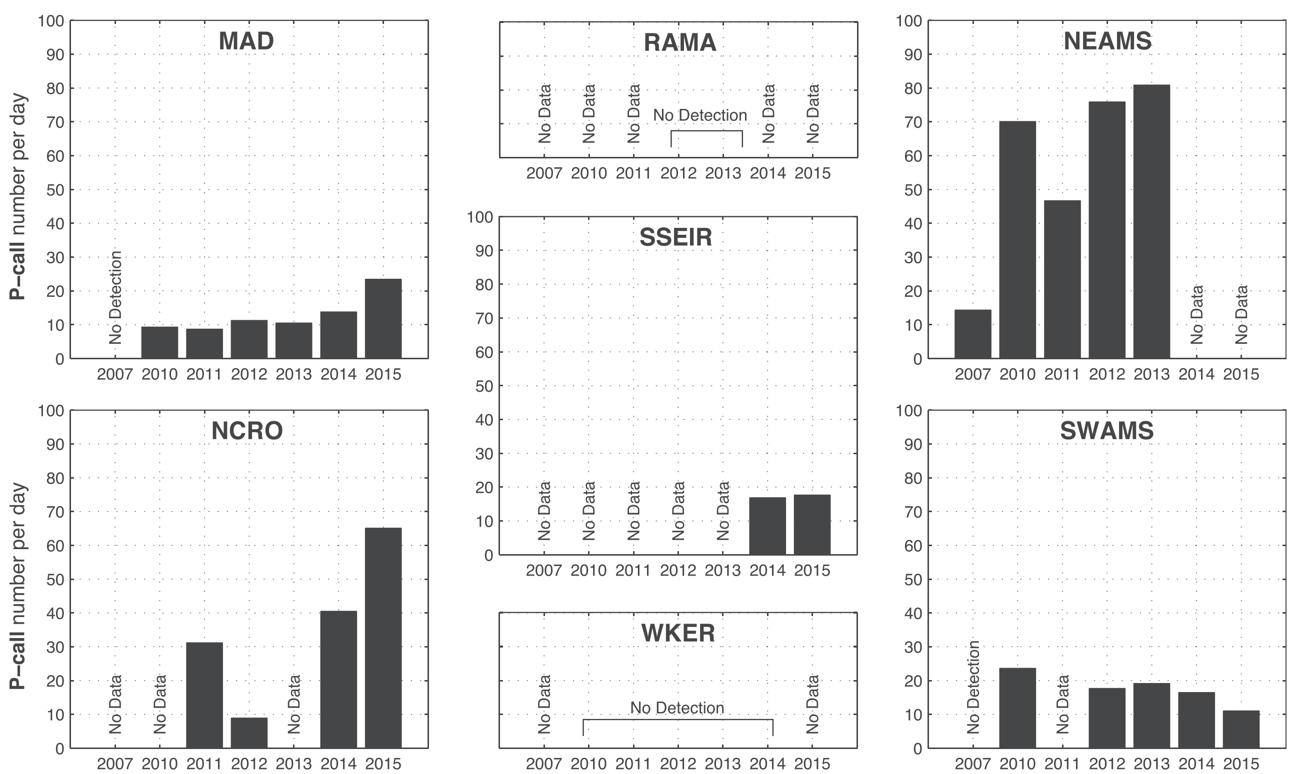

FIG. 7. Averaged and normalized number of P-calls per day for each year at each site as estimated by a GLMM.

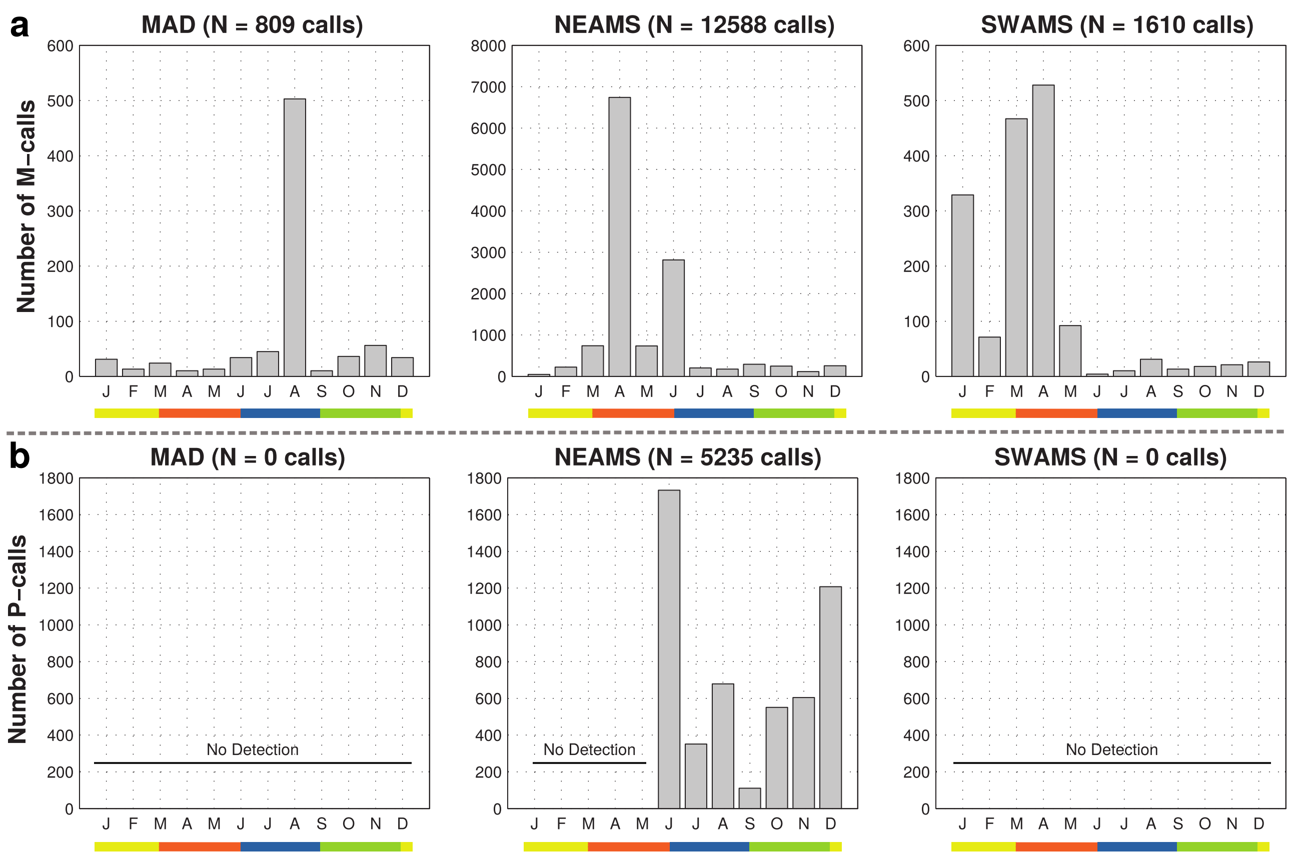

FIG. 8. (Color online) Number of M-calls (a) and P-calls (b) per month at each DEFLOHYDRO site in 2007. Note that the vertical scale differs among sites. Horizontal bars outline the seasons (from left to right: summer, autumn, winter, spring, summer).

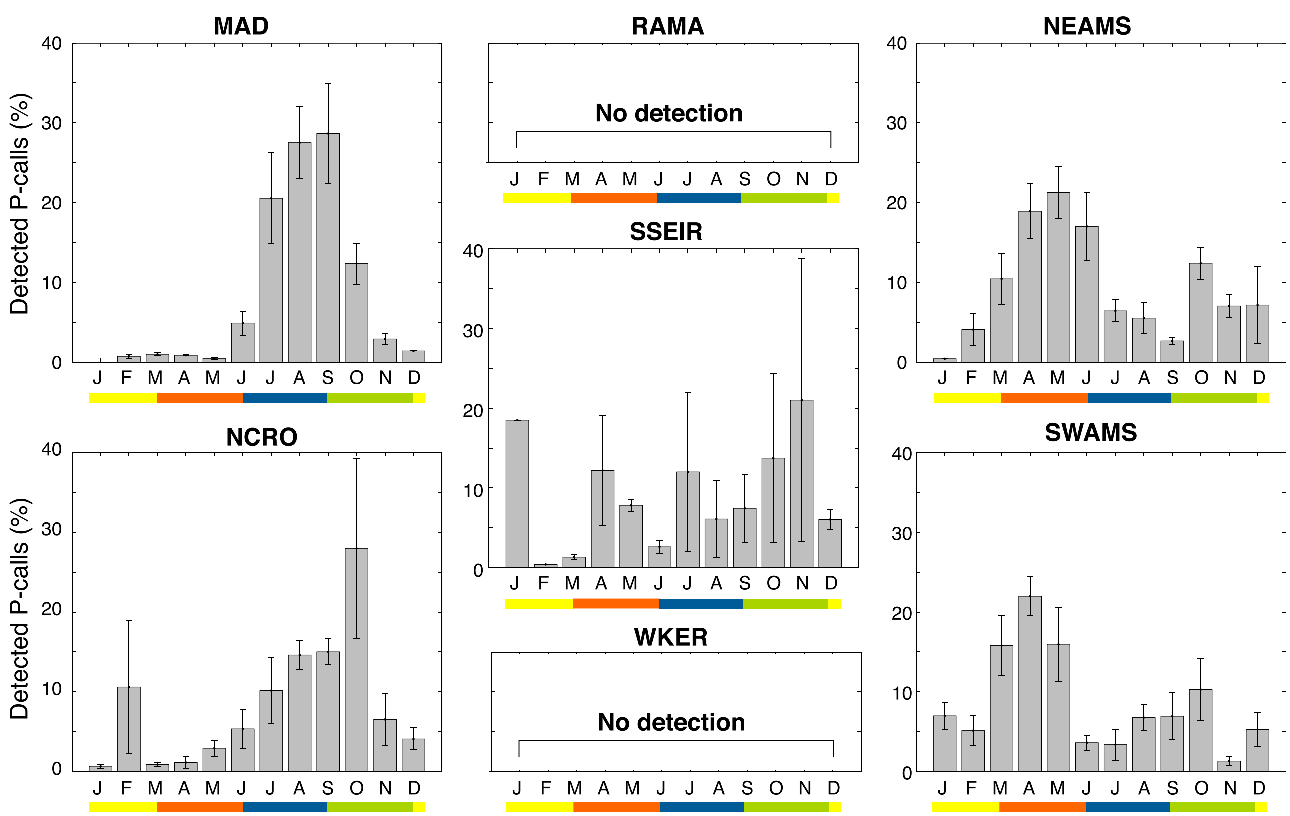

FIG. 9. (Color online) Normalized number of P-calls detected per month averaged over the available years of data for each site. Horizontal bars outline the seasons (from left to right: summer, autumn, winter, spring, summer).

the north–south migration observed for Antarctic blue whales.[7,8,37] To explain these differences, it can be argued that the P-call is another vocalization of Antarctic blue whales, with a different purpose at different periods of the year. The observed mismatches between the periods and places of occurrence of P- and Z-calls, and the absence of P-calls at the WKER site tend, on the contrary, to suggest that P- and Z-calls are not emitted by the same whale species.

Due to their apparent similarity, P-calls may have been misinterpreted as incomplete Z-calls in previous studies. For instance, Tripovich *et al.*[38] explain that "single-part calls from Antarctic blue whale" are predominantly present in their recordings, which they illustrate (Fig. 1 of Ref. 38) by a series of single tonal units with a long ICI (about 150 s), more typical of P-calls than of Z-calls. The different seasonality between P- and Z-calls may then introduce an important bias if P- and Z-calls are mixed up.

B. M- and P-calls could be blue whale calls

Following the reasoning of Sousa and Harris,[12] among the six baleen whale species known to dwell in the Indian Ocean [i.e., Bryde's whales (*Balaenoptera edeni*), humpback whales (*Megaptera novaeangliae*), minke whales, sei whales (*B. borealis*), fin whales and blue whales], our new calls are closer to blue whale vocalizations. Indeed, M- and P-calls are too long in duration and/or too low in frequency to be either minke, sei, or Bryde's whale vocalizations.[12,39–41] Humpback whales are known for their complex songs, composed of several different units with frequencies often greater than 500 Hz.[42] This species also emit non-song vocalizations, described as social sounds, but these sounds are generally higher in frequency and shorter in duration (less than 1 s).[43,44] The simple tonal unit of M- and P-calls is far from such complexity. Finally fin whales mainly emit low-frequency stereotyped vocalizations, near 20 Hz, known as the "20 Hz-pulses" due to their very short duration (less than 1.5 s[22,45]), while M- and P-calls last about 10 s, which makes them more similar to the highly stereotyped, long duration and low frequency blue whale calls.[46] In addition, the reasons for the frequency decline observed worldwide

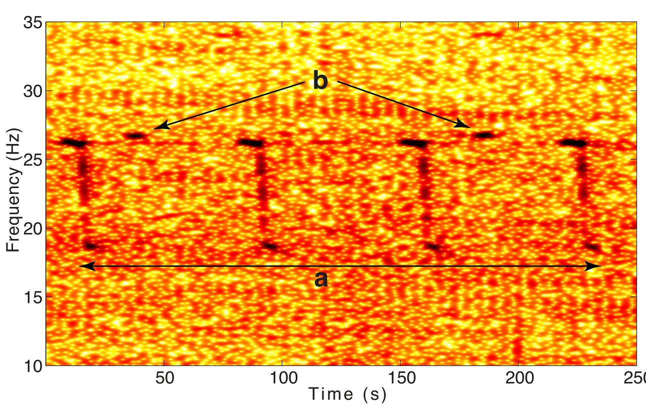

FIG. 10. (Color online) Spectrogram of four consecutive Z-calls (a) and two consecutive P-calls (b) recorded at NEAMS in April 2013. Spectrogram parameters: Hamming window, 4096 point FFT length, 98% overlap.

for blue whale calls, although uncertain,[25,26,33,47] are also impacting the P-call source (Fig. 6).

Two subspecies of blue whales are found in the southern Indian Ocean, the Antarctic, and pygmy blue whales.[7,19,20] We already presumed that P-calls and also probably M-calls are most likely not produced by Antarctic blue whales. The M- and P-calls mainly occur in subtropical waters, based on the absence of P-calls at RAMA (4° S) and at WKER (46° S), at least since 2010 (neither site was instrumented in 2007). The sources of these vocalizations seem thus to occur from 26° S (MAD) to 42° S (SWAMS) in latitude, and at least from 58° E (MAD) to 83° E (NEAMS) in longitude for M-calls (no recordings are available at NCRO in 2007) and from 53° E (NCRO) to 83° E (NEAMS) for P-calls. Moreover, as hinted in Sec. IV A, P-calls seem to have been recorded off Portland, Australia,[38] which would extend their occurrence to the eastern Indian Ocean (141° E).

The subtropical distribution of M- and P-calls, and particularly their absence south of 43° S, is similar to that of pygmy blue whales. The latter are generally found in northerly waters of the Indian Ocean (north of 55° S), and do not migrate to higher latitudes.[7,19,48–50] Three acoustically-distinct populations of pygmy blue whales are known in our study area: the northern Indian Ocean population, referred to as the Sri Lanka type and sometimes considered as a separate subspecies, *B. m.* indica;[50,51] the sub-Antarctic and south-western Indian Ocean population, referred to as the Madagascar type; and the population in the Indonesian and Australian regions, known as the Australia type.[7,19,20] However, the seasonal patterns of M- and P-calls differ from that known for these pygmy blue whale populations. As previously mentioned, P-calls seems to follow a yearly east–west migration. The same hypothesis can be proposed for M-calls, which are mainly detected in late summer to late autumn at NEAMS and SWAMS (located west of the network), and during winter further east, at MAD. Samaran *et al.*[7] reported Sri Lankan pygmy blue whales mainly at NEAMS, during summer. None were recorded at MAD, or near Crozet Islands. Madagascar-type calls are recorded mostly near Crozet Islands during summer and early autumn. None are detected at NEAMS. Finally, Australian pygmy blue whale calls are recorded mostly at SWAMS during summer and early autumn, and during winter at NEAMS. None are found at MAD or near Crozet Islands. None of these pygmy blue whale geographic and seasonal distributions matches the M- and P-call distributions, which are thus probably unrelated to these populations. Still they share the same mid-latitude area as the two blue whale subspecies,[19] but follow different migration patterns.

C. Do M- and P-calls originate from the same source?

A surprising observation about the new calls is the absence of detectable M-calls since 2010, as if its source had vanished between 2008 and 2010. Meanwhile, the presence of P-calls increases between 2007 and 2010: only present at NEAMS site in 2007 and in small numbers (less than 14 calls per day), since 2010 they have spread to 5 of the 7 instrumented sites, with a fivefold increase in detection numbers (more than 72 calls per day at NEAMS).

A first possibility is that M- and P-calls are emitted by two distinct sources. M-call sources would have been present in the area covered by the DEFLOHYDRO array, and, under the basic assumption that call numbers are a proxy for the number of individuals,[7] preferentially near NEAMS where the largest number of M-calls are detected. Then between 2008 and 2010, M-call sources would have moved away from this area, perhaps in response to some environmental changes. In favor of such a scenario, we note that signals similar to M-calls have been recorded between 2012 and 2013 off Namibia (21°S, 6°E).[52] At the same time, P-call sources, which were only present near NEAMS, and in small number given the small quantity of detections, would have increased in number and spread more widely.

An alternative hypothesis is that M- and P-calls are emitted by the same whale species, and that their call evolved between 2007 and 2010, with a shift in frequency from 22 to 27 Hz. The similarities in their characteristics argue in favor of such hypothesis. Both last about 10 s and have ICIs centered on 150–160 s. The reason for such frequency shift could be a level increase of the chorus where M-calls occur. The 22 Hz tonal call falls in the 18 to 28 Hz frequency-band dominated by Antarctic blue whale Z-calls and fin whale 20 Hz-pulses. A loud and continuous chorus will diminish the detection range of any signal emitted in this bandwidth, and thus the range over which individuals can communicate.[36,53] Despite large uncertainties, populations of Antarctic blue and fin whales seem to be increasing since the end of whaling, at a rate of 8.3% per year for Antarctic blue whales.[49] Population recovery, even if slow, may increase the number of calling individuals, and thus the chorus power. Switching frequency could then be an appropriate strategy to stand out from this increasingly noisy frequency band, as it has been suggested for right whales (*Eubalaena glacialis*),[53] belugas (*Delphinapterus leucas*),[54] and common dolphins (*Delphinus delphis*).[55] To test this idea, we measured the chorus power in the 18–28 Hz frequency band for 2007 and 2010 and for MAD, NEAMS, and SWAMS, which are common to both networks. The chorus power increases between 2007 and 2010 for SWAMS (88.4 ± 0.14 dB/Hz in 2007 vs 90.7 ± 0.19 dB/Hz in 2010), but decreases at MAD (87.00 ± 0.16 dB/Hz in 2007 vs 85.5 ± 0.15 dB/Hz in 2010) and NEAMS (87.6 ± 0.12 dB/Hz in 2007 vs 86.19 ± 0.16 dB/Hz in 2010). So the power evolution of the Antarctic blue whale chorus is neither uniform nor significant between 2007 and 2010. Unless the increase occurred earlier than 2007, and the change in frequencies appeared progressively.

V. CONCLUSION

This paper describes two signals, M- and P-calls, not reported or fully documented elsewhere in the literature, based on the analysis of a comprehensive data set, spanning 7 yrs and 7 sites spread over a 9 000 000 km^2 area in the southern Indian Ocean. More than 15 000 M-calls and 90 000 P-calls have been extracted from this data set.

Both M- and P-calls have general characteristics of biologic sounds, which are furthermore close to but different from other blue whale calls. These low frequency tonal units (~22 and ~27 Hz, respectively) lasting 10 s with ICIs longer than 2 min provide clues for identifying their source(s) as large baleen whales, possibly blue whale species. The geographic and seasonal distributions of M- and P-calls are similar, but neither of them matches those of the other known blue whale species dwelling in the southern Indian Ocean.

The described P-call is clearly distinct from an incomplete Z-call (unit A) produced by Antarctic blue whales. Although they are both tonal units with 10 s duration, their frequency is different, with an average difference of 0.6 Hz, and their ICI is different (160 s 60 s, respectively). In addition, at least in the southern Indian Ocean, they display different spatial and seasonal distributions. Mistaking them may thus introduce significant biases if used to infer the seasonal presence of their sources.

The disappearance of M-calls from the data recorded since 2010 and the drastic increase in the number of P-calls between 2007 and 2010 is a puzzling coincidence. The probable M-call presence off Namibia in 2012–2013 argues for a possible migration of its source from the Indian to the Atlantic Ocean. Further analyses of acoustic data from 2007 to 2010 may help understanding this observation. Additional data from other locations would also be helpful to better assess the distribution of the M- and P-call sources.

Finally, this paper provides the basis (what to search for, where, and when) to organize an expedition combining visual and acoustic observations to fully identify the whales that produce these vocalizations.

ACKNOWLEDGMENTS

The authors wish to thank the Captains and crew of RV Marion Dufresne for the successful deployments and recoveries of the hydrophones of the OHASISBIO[61] and DEFLOHYDRO[60] experiments. French cruises were funded by the French Polar Institute (IPEV), with additional support from INSU-CNRS. NOAA/PMEL also contributed to the DEFLOHYDRO project. E.C.L. was supported by a Ph.D. fellowship from the University of Brest and from the Regional Council of Brittany (Conseil Régional de Bretagne). The contribution of Mickael Beauverger at LGO to the logistics and deployment cruises is greatly appreciated. We thank Kate M. Stafford for her careful reading and encouraging comments.

APPENDIX A: METHODS

1. Site location and data availability for the DEFLOHYDRO and OHASISBIO networks

See Table III.

2. Data analysis

After the automatic detection of P-calls, using the *Z-detector*, we post-processed the detections to check for false positives (i.e., unwanted Z-calls). These false

TABLE III. Site location and data availability for the DEFLOHYDRO and OHASISBIO autonomous hydrophone networks. The character "-" indicates continuous records without intermediate data recovery, "x" indicates a lack of recordings.

Site	Geographic coordinates	DEFLOHYDRO 2007		<- - - - OHASISBIO - - - -> 2010		2011		2012		2013		2014		2015	
		Start	End	Start	End	Start	End	Start	End	Start	End	Start	End	Start	End
RAMA	03° 50′ S, 080° 30′ E	x	x	x	x	x	x	05/05/12	-	-	09/19/13	x	x	x	x
MAD	26° 05′ S, 058° 08′ E	10/30/06	01/05/08	12/20/09	02/19/11	02/19/11	03/09/12	03/10/12	03/09/13	03/09/13	02/16/14	02/16/14	01/18/15	02/08/15	01/28/16
NEAMS	31° 35′ S, 083° 14′ E	10/10/06	04/26/08	02/13/10	–	–	11/25/11	03/04/12	03/04/13	03/04/13	02/10/14	x	x	To be recovered	
SWAMS	42° 59′ S, 074° 35′ E	10/11/06	01/13/08	01/17/10	11/21/10	x	x	02/29/12	02/27/13	02/28/13	02/07/14	02/07/14	01/27/15	01/27/15	01/20/16
NCRO	41° 14′ S, 052° 59′ E	x	x	12/25/09	01/20/11	01/20/11	01/31/12	01/29/12	02/10/13	02/12/13	01/10/14	01/11/14	01/11/15	01/11/15	01/08/16
WKER	46° 38′ S, 060° 07′ E	x	x	12/28/09	01/24/11	01/25/11	02/03/12	02/04/12	02/14/13	02/15/13	01/15/14	01/15/14	01/01/15	To be recovered	
SSEIR	33° 30′ S, 070° 52′ E	x	x	x	x	x	x	x	x	x	x	02/13/14	02/04/15	02/05/15	01/18/16

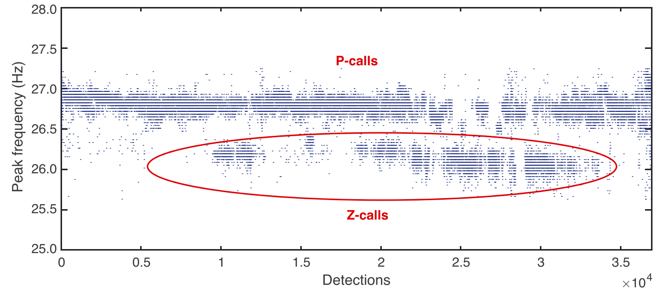

FIG. 11. (Color online) Peak frequency of each event detected at NEAMS site in 2013. The frequency gap between P-calls and Z-call units A is clearly visible.

positives were easily sorted out and removed, since their frequency is significantly and consistently different, as shown in Fig. 11.

The characteristic frequencies of the M- and P-calls are based on automatic measurements on each detected call (frequency of the peak amplitude). As shown in Fig. 12, M-call frequencies differ over 1 Hz among sites, thus, mean values are estimated per site (Table II). However, as shown in Fig. 13, the frequency of P-calls does not vary among sites within 0.5 Hz, thus the P-call frequency for a given time window is averaged over all sites. The P-call frequencies display a regular decline of about 1 Hz from 2007 to 2015 (Fig. 6; Table II).

APPENDIX B: COMPLEMENTARY RESULTS ON P-CALL OCCURRENCE PER SITE

See Fig. 14.

APPENDIX C: DIEL PATTERN

A. Methods

To analyze the diel pattern of both M- and P-calls, detections were sorted into four light regimes based on the altitude of the Sun: dawn, light, dusk, and night. Dawn hours start when the Sun is 12° below the horizon (i.e., morning nautical twilight) and end at sunrise; light hours are between sunrise and sunset; dusk is between sunset and the evening nautical twilight; and night hours are between dusk and dawn, when the altitude of the Sun is less than −12°. Daily hours of sunset, sunrise, and nautical twilights were obtained from the United States Naval Observatory Astronomical Applications Department Website (http://aa.usno.navy.mil[59])

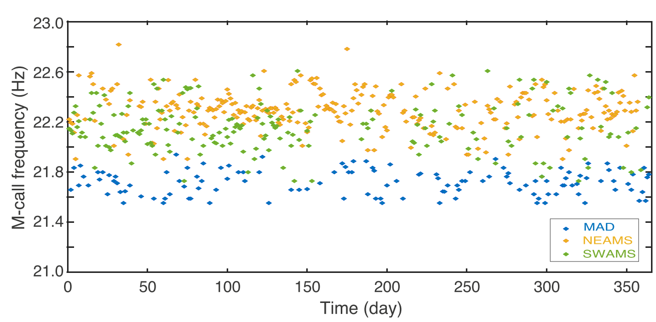

FIG. 12. (Color online) Daily average frequency of M-calls recorded in 2007 for each site.

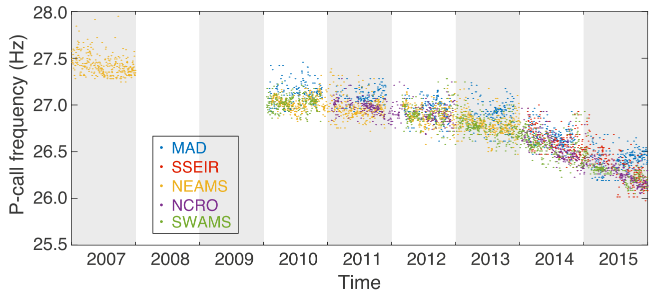

FIG. 13. (Color online) Daily average frequency of P-calls recorded from 2007 to 2015 for each site.

for each year and each site location. The daily number of calls in each light regime was calculated, and divided by the duration of the corresponding light period for a given day, to account for the differences of duration among the four light regimes and their seasonality. The resulting normalized detection rates (in detections/h), for each light regime and each day, were then adjusted by subtracting the mean number of detections per hour of the corresponding day.[56,57] These adjusted means of calls per light period were finally averaged over the seasons of call presence depending on the site location, when these seasons displayed the same trend of variation per light regime. Seasons are defined by the dates of the solstices and equinoxes for each year. Because of the non-normal distribution of the adjusted means, Kruskal-Wallis (KW) tests[58] were applied to compare the light regimes for each site. In case of significant differences, Wilcoxon pairwise comparison tests Bonferroni corrections were used.

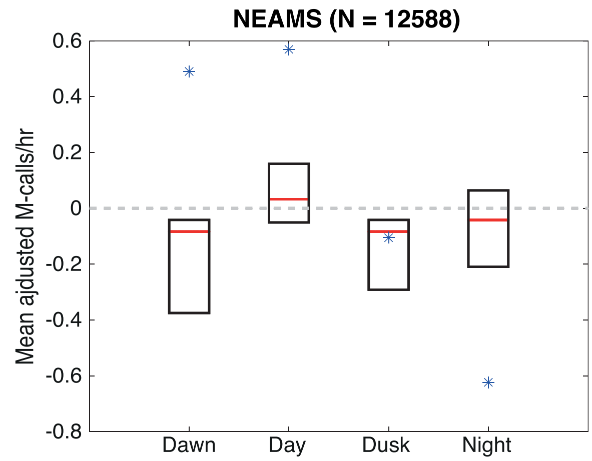

FIG. 15. (Color online) Boxplot of mean-adjusted number of M-calls per hour during four light regimes, averaged over the entire 2007 year at NEAMS. Lower and upper bounds of boxes represent lower and upper quartiles, respectively. Horizontal lines are median values and asterisks are mean values. Note that means (asterisks) differ from median due to outliers, not shown in the graphic for readability. N is the total number of detections during the seasons of presence.

B. Results

1. M-calls

Due to the low numbers of M-calls at MAD and SWAMS, the diel distribution is only meaningful for NEAMS. At this site, KW analysis of variance (ANOVA) rejects the null hypothesis that the call rate is the same for the four light regimes (KW $= 87.5$; $p < 0.001$). Wilcoxon pairwise comparison tests (W) indicate that significantly more M-calls are emitted during

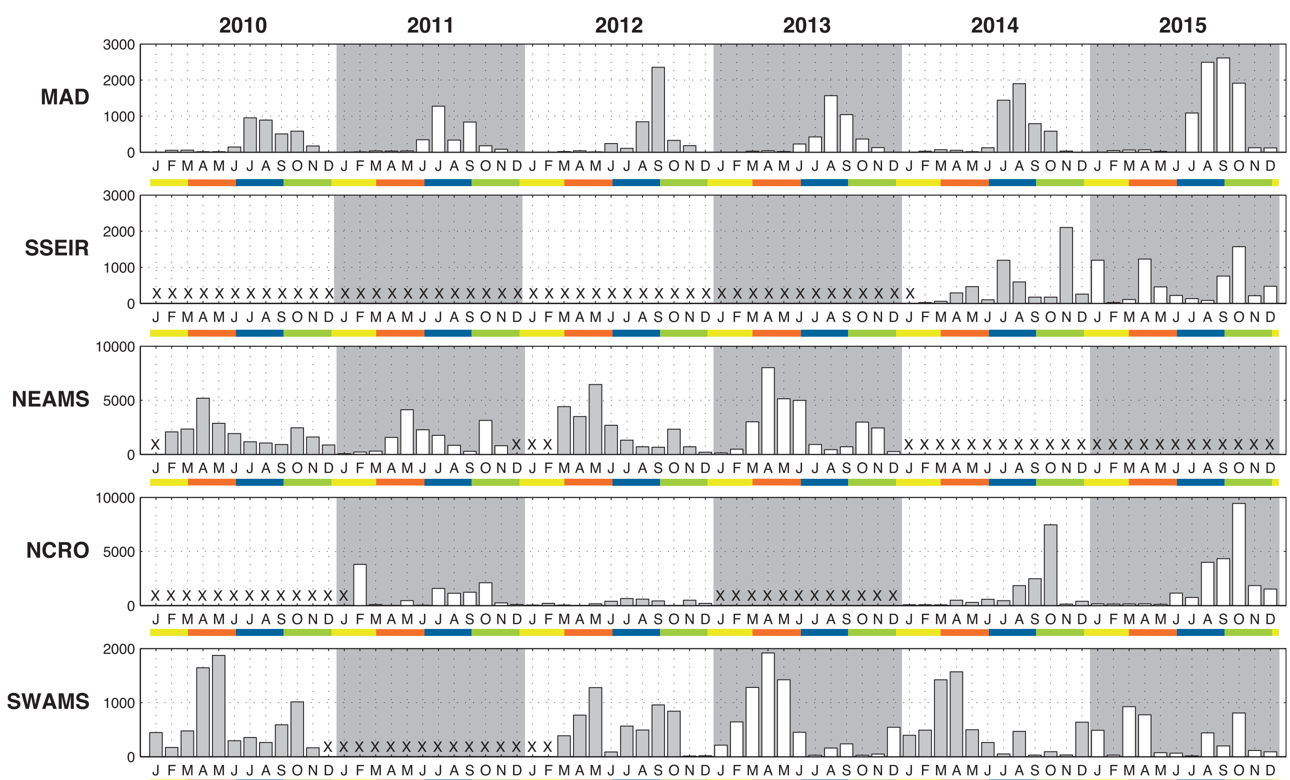

FIG. 14. (Color online) Number of P-calls per month at each OHASISBIO site from 2010 to 2015 (none are detected at site WKER). Note that the vertical scale differs depending on the site. "x" indicates that there is no available data. Horizontal bars outline the seasons (from left to right: summer, autumn, winter, spring, summer).

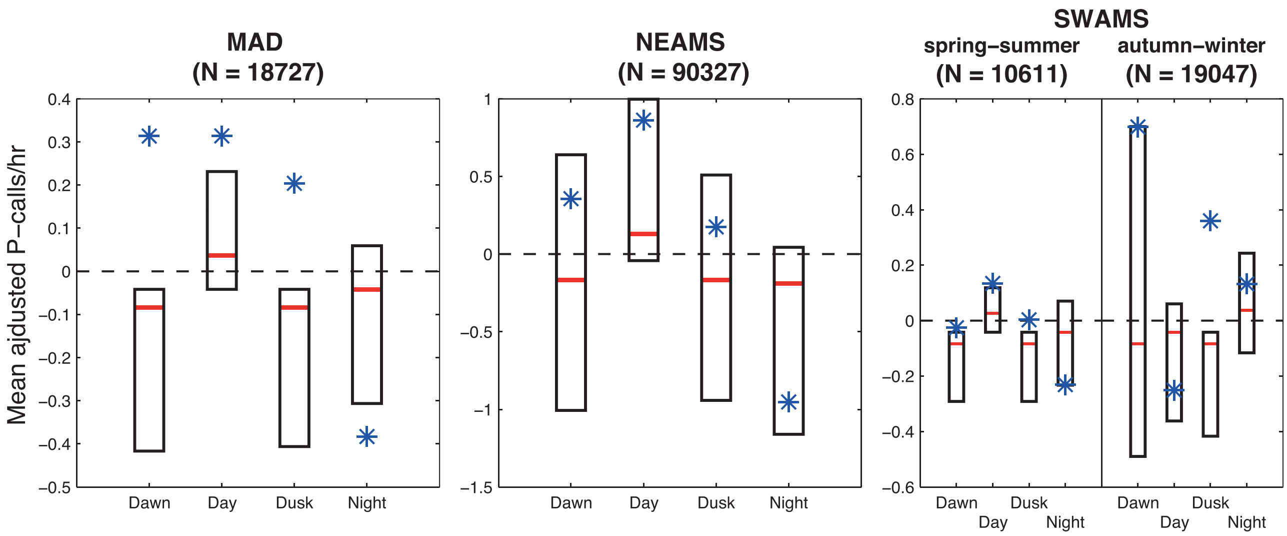

FIG. 16. (Color online) Boxplot of mean-adjusted number of P-calls per hour during four light regimes, averaged over the available years of the OHASISBIO-data, over winter and spring for MAD and the entire year for NEAMS. For SWAMS, the diel pattern is averaged over spring-summer on the left and over autumn-winter on the right. Lower and upper bounds of boxes represent lower and upper quartiles, respectively. Horizontal lines are median values and asterisks are mean values. Note that means (asterisks) differ from median due to outliers, not shown in the graphs for readability. N is the total number of detections during the seasons of presence.

daytime than during nighttime, and during dusk and dawn (Wilcoxon comparison test between day and, respectively, night, dusk, and dawn: $W = 23\,826$; 8.369; 20 661, all $p < 0.00017$). Dawn and dusk are not significantly different ($W = 3176$; $p > 0.0083$), and none of them differs significantly from night (respectively, for dawn/night and dusk/night comparison: $W = 9072$ and 9351; $p > 0.0083$) (Fig. 15).

2. P-calls

Due to the limited number of P-calls in 2007, we excluded this year from our analysis. From 2010 onwards, the diel distribution is examined over the entire year for SSEIR, NEAMS, and SWAMS, and over winter and spring at MAD and NCRO, which are the two seasons of highest P-call presence. At MAD and NEAMS sites (Fig. 16),

TABLE IV. Wilcoxon pairwise comparison test results for diel patterns of P-calls detected at MAD, NEAMS, and SWAMS in the data from 2010 to 2015. W is the value of the test, p the probability to wrongly reject the null hypothesis. The test significance is indicated by *** if $p < 0.0002$, ** if $p < 0.0017$, * $p < 0.0083$, and NS if the test is non-significant, i.e. if $p > 0.0083$.

	Wilcoxon pairwise comparison test between	W	p	Significance
MAD	Dawn/Day	56 280	2.9×10^{-13}	***
	Dawn/Dusk	20 786	0.2505	NS
	Dawn/Night	66 920	0.5928	NS
	Day/Dusk	119 460	3.3×10^{-16}	***
	Day/Night	163 520	8.1×10^{-14}	***
	Dusk/Night	59 799	0.0297	NS
NEAMS	Dawn/Day	216 310	$<2.2 \times 10^{-16}$	***
	Dawn/Dusk	135 340	0.2318	NS
	Dawn/Night	279 950	0.0055	*
	Day/Dusk	406 570	$<2.2 \times 10^{-16}$	***
	Day/Night	532 870	$<2.2 \times 10^{-16}$	***
	Dusk/Night	285 730	0.0002	***
SWAMS Spring-Summer	Dawn/Day	33 095	2.895×10^{-12}	***
	Dawn/Dusk	9231	0.9349	NS
	Dawn/Night	27 765	0.9067	NS
	Day/Dusk	72 712	2.2×10^{-14}	***
	Day/Night	87 457	8.7×10^{-9}	***
	Dusk/Night	23 320	0.0906	NS
SWAMS Autumn-Winter	Dawn/Day	53 509	0.0122	NS
	Dawn/Dusk	23 146	0.0778	NS
	Dawn/Night	55 439	0.0853	NS
	Day/Dusk	47 786	0.5162	NS
	Day/Night	56 436	1.1×10^{-6}	***
	Dusk/Night	42 698	3.9×10^{-6}	***

the detection rates per light regime vary similarly for the different seasons; they are thus averaged over these seasons. The null hypothesis that the call rate is the same for the four light regimes was rejected by KW ANOVAs (respectively, for MAD and NEAMS, $KW = 224.3$ and 462.3; both with $p < 0.001$). Wilcoxon pairwise comparison tests (W) show that day and night periods are significantly different from one another, with more P-calls emitted in daytime than in nighttime (Wilcoxon test results are presented in Table IV). Dusk and dawn are not significantly different from each other, or from night, but significantly differ from day, with higher call rates during the day (Fig. 16).

At SWAMS site, call rates vary with the season, but are similar in spring and summer, and in autumn and winter. Call rates per light regimes are thus averaged over each pair of seasons. KW ANOVA rejects the null hypothesis that the call rate is the same for the four light regimes for both groups of seasons (respectively, for spring-summer and autumn-winter, $KW = 182.6$ and 73.1; $p < 0.001$). Wilcoxon pairwise comparison tests show that in spring and summer, day and night call rates differ significantly, with more calls emitted during daytime. Conversely, during autumn and winter, significantly more calls are emitted during nighttime. Dawn and dusk are not significantly different from each other for either cases, and there is no general trend between these regimes and night or day. All statistical tests are presented in Table IV.

For SSEIR and NCRO, no general trend is found in the diel pattern. Variations occur between years and/or between seasons, which prevents any averaging. For conciseness, the statistical results are not presented here.

[1]W. W. L. Au and M. C. Hastings, *Principles of Marine Bioacoustics* (Springer, New York, 2008), pp. 439–442.

[2]W. C. Cummings and P. O. Thompson, "Underwater sounds from the blue whale, *Balaenoptera musculus*," J. Acoust. Soc. Am. **50**, 1193–1198 (1971).

[3]D. K. Ljungblad, C. W. Clark, and H. Shimada, "Sc/49/sh17 a comparison of sounds attributed to pygmy blue whales (*Balaenoptera musculus brevicauda*) recorded south of the Madagascar Plateau and those attributed to 'true' blue whales (*Balaenoptera musculus*) recorded off Antarctica," Rep. Int. Whaling Comm. **48**, 439–442 (1998).

[4]D. K. Mellinger, K. M. Stafford, S. Moore, R. P. Dziak, and H. Matsumoto, "Fixed passive acoustic observation methods for cetaceans," Oceanography **20**, 36–45 (2007).

[5]F. Samaran, O. Adam, and C. Guinet, "Discovery of a mid-latitude sympatric area for two Southern Hemisphere blue whale subspecies," Endanger. Species Res. **12**, 157–165 (2010).

[6]K. M. Stafford, D. R. Bohnenstiehl, M. Tolstoy, E. Chapp, D. K. Mellinger, and S. E. Moore, "Antarctic-type blue whale calls recorded at low latitudes in the Indian and eastern Pacific Oceans," Deep Sea Res. Part I **51**, 1337–1346 (2004).

[7]F. Samaran, K. M. Stafford, T. A. Branch, J. Gedamke, J.-Y. Royer, R. P. Dziak, and C. Guinet, "Seasonal and geographic variation of southern blue whale subspecies in the Indian Ocean," PLoS One **8**, e71561 (2013).

[8]E. C. Leroy, F. Samaran, J. Bonnel, and J.-Y. Royer, "Seasonal and diel vocalization patterns of Antarctic blue whale (*Balaenoptera musculus intermedia*) in the Southern Indian Ocean: A multi-year and multi-site study," PLoS One **11**, e0163587 (2016).

[9]G. M. Wenz, "Curious noises and the sonic environment in the ocean," Mar. Bioacoust. **1**, 101–119 (1964).

[10]W. A. Watkins, J. E. George, M. A. Daher, K. Mullin, D. L. Martin, S. H. Haga, and N. A. DiMarzio, "Whale call data for the North Pacific: November 1995 through July 1999 occurrence of calling whales and source locations from SOSUS and other acoustic systems," Tech. Rep. (Woods Hole Oceanographic Institution, 2000).

[11]W. A. Watkins, M. A. Daher, J. E. George, and D. Rodriguez, "Twelve years of tracking 52-Hz whale calls from a unique source in the North Pacific," Deep Sea Res. Part I **51**, 1889–1901 (2004).

[12]A. G. Sousa and D. Harris, "Description and seasonal detection of two potential whale calls recorded in the Indian Ocean," J. Acoust. Soc. Am. **138**, 1379–1388 (2015).

[13]D. C. Brodie and R. A. Dunn, "Low frequency baleen whale calls detected on ocean-bottom seismometers in the Lau basin, southwest Pacific Ocean," J. Acoust. Soc. Am. **137**, 53–62 (2015).

[14]K. M. Stafford, S. L. Nieukirk, and C. G. Fox, "Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical Pacific," J. Acoust. Soc. Am. **106**, 3687–3698 (1999).

[15]K. M. Stafford, D. K. Mellinger, S. E. Moore, and C. G. Fox, "Seasonal variability and detection range modeling of baleen whale calls in the Gulf of Alaska, 1999–2002," J. Acoust. Soc. Am. **122**, 3378–3390 (2007).

[16]S. Rankin and J. Barlow, "Source of the North Pacific 'boing' sound attributed to minke whales," J. Acoust. Soc. Am. **118**, 3346–3351 (2005).

[17]J.-Y. Royer, R. Chateau, R. P. Dziak, and D. R. Bohnenstiehl, "Seafloor seismicity, Antarctic ice-sounds, cetacean vocalizations and long-term ambient sound in the Indian Ocean basin," Geophys. J. Int. **202**, 748–762 (2015).

[18]E. Tsang-Hin-Sun, J.-Y. Royer, and E. C. Leroy, "Low-frequency sound level in the southern Indian Ocean," J. Acoust. Soc. Am. **138**, 3439–3446 (2015).

[19]F. Samaran, C. Guinet, O. Adam, J.-F. Motsch, and Y. Cansi, "Source level estimation of two blue whale subspecies in southwestern Indian Ocean," J. Acoust. Soc. Am. **127**, 3800–3808 (2010).

[20]K. M. Stafford, E. Chapp, D. R. Bohnenstiel, and M. Tolstoy, "Seasonal detection of three types of 'pygmy' blue whale calls in the Indian Ocean," Mar. Mammal Sci. **27**, 828–840 (2011).

[21]A. N. Gavrilov and R. D. McCauley, "Acoustic detection and long-term monitoring of pygmy blue whales over the continental slope in southwest Australia," J. Acoust. Soc. Am. **134**, 2505–2513 (2013).

[22]A. Širović, J. A. Hildebrand, S. M. Wiggins, and D. Thiele, "Blue and fin whale acoustic presence around Antarctica during 2003 and 2004," Mar. Mammal Sci. **25**, 125–136 (2009).

[23]J.-F. D'Eu, J.-Y. Royer, and J. Perrot, "Long-term autonomous hydrophones for large-scale hydroacoustic monitoring of the oceans," in *OCEANS, 2012-Yeosu* (IEEE, New York, 2012), pp. 1–6.

[24]F.-X. Socheleau, E. C. Leroy, A. C. Pecci, F. Samaran, J. Bonnel, and J.-Y. Royer, "Automated detection of Antarctic blue whale calls," J. Acoust. Soc. Am. **138**, 3105–3117 (2015).

[25]A. N. Gavrilov, R. D. McCauley, and J. Gedamke, "Steady inter and intra-annual decrease in the vocalization frequency of Antarctic blue whales," J. Acoust. Soc. Am. **131**, 4476–4480 (2012).

[26]B. S. Miller, R. Leaper, S. Calderan, and J. Gedamke, "Red shift, blue shift: Investigating Doppler shifts, blubber thickness, and migration as explanations of seasonal variation in the tonality of Antarctic blue whale song," PLoS One **9**, e107740 (2014).

[27]B. M. Bolker, M. E. Brooks, C. J. Clark, S. W. Geange, J. R. Poulsen, M. H. H. Stevens, and J.-S. S. White, "Generalized linear mixed models: A practical guide for ecology and evolution," Trends Ecol. Evol. **24**, 127–135 (2009).

[28]M. Friedman, "The use of ranks to avoid the assumption of normality implicit in the analysis of variance," J. Am. Stat. Assoc. **32**, 675–701 (1937).

[29]F. Wilcoxon, "Individual comparisons by ranking methods," Biometrics Bull. **1**, 80–83 (1945).

[30]C. E. Bonferroni, *Il calcolo delle assicurazioni su gruppi di teste* (*Calculation of Insurance on Groups of Heads*) (Tipografia del Senato, 1935).

[31]R Core Team, R: A Language and Environment for Statistical Computing (www.R-project.org), R Foundation for Statistical Computing, Vienna, Austria (2016).

[32]Stan Development Team, RStanArm: Bayesian applied regression modeling via Stan (http://mc-stan.org) (2016).

[33]M. A. McDonald, J. A. Hildebrand, and S. Mesnick, "Worldwide decline in tonal frequencies of blue whale songs," Endanger. Species Res. **9**, 13–21 (2009).

[34]S. Rankin, D. Ljungblad, C. Clark, and H. Kato, "Vocalisations of Antarctic blue whales, *Balaenoptera musculus intermedia*, recorded during the 2001/2002 and 2002/2003 iwc/sower circumpolar cruises, Area v, Antarctica," J. Cetacean Res. Manage. **7**, 13–20 (2005).

[35]A. Širović, J. A. Hildebrand, S. M. Wiggins, M. A. McDonald, S. E. Moore, and D. Thiele, "Seasonality of blue and fin whale calls and the influence of sea ice in the western Antarctic Peninsula," Deep Sea Res. Part II **51**, 2327–2344 (2004).
[36]J. L. Miksis-Olds, J. A. Vernon, and K. D. Heaney, "The impact of ocean sound dynamics on estimates of signal detection range," Aquatic Mammals **41**, 444–454 (2015).
[37]N. A. Mackintosh, "The distribution of southern blue and fin whales," in *Whales, Dolphins, and Porpoises*, edited by K. S. Norris (University of California Press, Berkeley, 1966), pp. 125–144.
[38]J. S. Tripovich, H. Klinck, S. L. Nieukirk, T. Adams, D. K. Mellinger, N. E. Balcazar, K. Klinck, E. J. S. Hall, and T. L. Rogers, "Temporal segregation of the Australian and Antarctic blue whale call types (*Balaenoptera musculus spp.*)," J. Mammalogy **96**, 603–610 (2015).
[39]E. M. Oleson, J. Barlow, J. Gordon, S. Rankin, and J. A. Hildebrand, "Low frequency calls of Bryde's whales," Mar. Mammal Sci. **19**, 407–419 (2003).
[40]M. F. Baumgartner, S. M. Van Parijs, F. W. Wenzel, C. J. Tremblay, H. C. Esch, and A. M. Warde, "Low frequency vocalizations attributed to sei whales (*Balaenoptera borealis*)," J. Acoust. Soc. Am. **124**, 1339–1349 (2008).
[41]S. Rankin, T. F. Norris, M. A. Smultea, C. Oedekoven, A. M. Zoidis, E. Silva, and J. Rivers, "A visual sighting and acoustic detections of minke whales, *Balaenoptera acutorostrata (cetacea: Balaenopteridae)*, in nearshore Hawaiian waters," Pacific Sci. **61**, 395–398 (2007).
[42]R. S. Payne and S. McVay, "Songs of humpback whales," Science **173**, 585–597 (1971).
[43]R. A. Dunlop, D. H. Cato, and M. J. Noad, "Non-song acoustic communication in migrating humpback whales (*Megaptera novaeangliae*)," Mar. Mammal Sci. **24**, 613–629 (2008).
[44]A. K. Stimpert, W. W. L. Au, S. E. Parks, T. Hurst, and D. N. Wiley, "Common humpback whale (*Megaptera novaeangliae*) sound types for passive acoustic monitoring," J. Acoust. Soc. Am. **129**, 476–482 (2011).
[45]W. A. Watkins, P. Tyack, K. E. Moore, and J. E. Bird, "The 20-Hz signals of finback whales (*Balaenoptera physalus*)," J. Acoust. Soc. Am. **82**, 1901–1912 (1987).
[46]M. A. McDonald, S. L. Mesnick, and J. A. Hildebrand, "Biogeographic characterization of blue whale song worldwide: Using song to identify populations," J. Cetacean Res. Manage. **8**, 55–65 (2006).
[47]A. N. Gavrilov, R. D. McCauley, C. Salgado-Kent, J. S. Tripovich, and C. Burton, "Vocal characteristics of pygmy blue whales and their change over time," J. Acoust. Soc. Am. **130**, 3651–3660 (2011).
[48]H. Kato, T. Miyashita, and H. Shimada, "Segregation of the two subspecies of the blue whale in the southern hemisphere," Rep. Int. Whaling Comm. **45**, 273–283 (1995).
[49]T. A. Branch, "Abundance of Antarctic blue whales south of 60 S from three complete circumpolar sets of surveys," J. Cetacean Res. Manage. **9**, 253–262 (2007).
[50]T. A. Branch, K. M. Stafford, D. M. Palacios, C. Allison, J. L. Bannister, C. L. K. Burton, E. Cabrera, C. A. Carlson, B. Galletti Vernazzani, P. C. Gill, R. Hucke-Gaete, K. C. S. Jenner, M.-N. M. Jenner, K. Matsuoka, Y. A. Mikhalev, T. Miyashita, M. G. Morrice, S. Nishiwaki, V. J. Sturrock, D. Tormosov, R. C. Anderson, A. N. Bakeer, P. B. Best, P. Borsa, R. L. Brownell, Jr., S. Childerhouse, K. P. Findlay, T. Gerrodette, A. D. Ilangakoon, M. Joergensen, B. Kahn, D. K. Ljundblad, B. Maughan, R. D. McCauley, S. McKay, T. F. Norris, Oman Whale and Dolphin Research Group, S. Rankin, F. Samaran, D. Thiele, K. Van Waerebeek, and R. M. Warneke, "Past and present distribution, densities and movements of blue whales *Balaenoptera musculus* in the Southern Hemisphere and northern Indian Ocean," Mammal Rev. **37**, 116–175 (2007).
[51]E. Blyth, "On the great rorqual of the Indian Ocean, with notices of other cetals, and of the Syrenia or marine pachyderms," J. Asiatic Soc. Bengal **28**, 481–498 (1859).
[52]K. Thomisch, "Distribution patterns and migratory behavior of Antarctic blue whales," Berichte zur Polar-und Meeresforschung= Rep. Polar Mar. Res. **707**, 149–160 (2017).
[53]S. E. Parks, C. W. Clark, and P. L. Tyack, "Short- and long-term changes in right whale calling behavior: The potential effects of noise on acoustic communication," J. Acoust. Soc. Am. **122**, 3725–3731 (2007).
[54]V. Lesage, C. Barrette, M. Kingsley, and B. Sjare, "The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada," Mar. Mammal Sci. **15**, 65–84 (1999).
[55]I. C. Ansmann, J. C. Goold, P. G. H. Evans, M. Simmonds, and S. G. Keith, "Variation in the whistle characteristics of short-beaked common dolphins, *Delphinus delphis*, at two locations around the British Isles," J. Mar. Biological Assoc. U. K. **87**, 19–26 (2007).
[56]K. M. Stafford, S. E. Moore, and C. G. Fox, "Diel variation in blue whale calls recorded in the eastern tropical Pacific," Animal Behaviour **69**, 951–958 (2005).
[57]S. M. Wiggins, E. M. Oleson, M. A. McDonald, and J. A. Hildebrand, "Blue whale (*Balaenoptera musculus*) diel call patterns offshore of Southern California," Aquatic Mammals **31**, 161–168 (2005).
[58]W. H. Kruskal and W. A. Wallis, "Use of ranks in one-criterion variance analysis," J. Am. Stat. Assoc. **47**, 583–621 (1952).
[59]"Tables of sunrise/sunset and twilights," U.S. Naval Observatory, Astronomical Applications Dept., Washington, DC. Available at: http://aa.usno.navy.mil/data/ (Last viewed 16 December 2015).
[60]DEFLO-HYDRO cruises: Observation of the intraplate deformation of the oceanic lithosphere with hydrophones (2006-2008).
[61]OHASISBIO cruises: Hydroacoustic observation of the seismicity and biodiversity in the Indian Ocean (2009-2015).