Seasonal acoustic occurrence, diel-vocalizing patterns and bioduck call-type composition of Antarctic minke whales off the west coast of South Africa and the Maud Rise, Antarctica

FANNIE W. SHABANGU
Fisheries Management
Department of Environment, Forestry and Fisheries
Foreshore, Cape Town, South Africa
and
Mammal Research Institute Whale Unit
University of Pretoria, Private Bag X20, Hatfield, Pretoria 0028, South Africa

KEN FINDLAY
Cape Peninsula University of Technology
PO Box 652, Cape Town 8000, South Africa
and
Mammal Research Institute Whale Unit
University of Pretoria, Private Bag X20, Hatfield, Pretoria 0028, South Africa

KATHLEEN M. STAFFORD
Applied Physics Laboratory
University of Washington, Seattle, WA 98105, USA

Correspondence (e-mail: fannie.shabangu@yahoo.com).

ABSTRACT

Seasonal occurrence, diel-vocalizing patterns and call-types of Antarctic minke whales are described using bio-acoustic recordings from the west coast of South Africa and the Maud Rise, Antarctica. In Antarctica, minke whale bioduck calls were detected in seven of nine months of hydrophone deployment (peaking in May and September) while downsweeps were only detected in June. Bioduck calls were sporadically detected in South African waters with peak calling in September/October, and no bioducks were detected from March through August. Bioduck call occurrence were high during daytime in Antarctica but no diel-vocalizing pattern in South African waters. We split bioduck B call-type into two subtypes: B1 with 13±1 pulses (Dominello & Širović, 2016) and B2 with 9±1 pulses (this study). Bioduck B2 was detected both in Antarctic and South African waters, with harmonics up to 2 kHz. Similar bioduck call-types were detected in Antarctic and South African waters, with bioduck A2 being the most common. Month of the year was the most important predictor of bioduck occurrence both in Antarctic and South African waters. This is the first study to describe the seasonal occurrence, diel-vocalizing behavior and call-types of Antarctic minke whales off the South African west coast and eastern Weddell Sea.

KEYWORDS: MINKE WHALES, DIEL BEHAVIOR, OCCURRENCE, BIODUCK CALL-TYPES, ANTARCTICA, SOUTH AFRICA

1.INTRODUCTION

Antarctic minke whales (*Balaenoptera bonaerensis*) are one of the less studied small baleen whales in the southern African subregion due to low detectability during visual surveys, and lack of dedicated offshore research programs. Off the west coast of South Africa, Antarctic minke whales are rarely sighted as they tend to occupy the offshore waters during winter periods of poor weather compared to other baleen whales such as coastal southern right whales (*Eubalaena australis*) (Best, 2007). In Antarctica, minke whales have a circumpolar distribution where they tend to associate with the heavy pack ice, which can make it difficult and expensive to survey them using traditional methods (Matsuoka et al., 2003, Williams et al., 2014). Opportunely, Antarctic minke whales are vocally active and have been documented producing two kinds of sounds: bioduck calls and downsweeps (Schevill & Watkins, 1972; Matthews, Macleod, & McCauley, 2004; Risch et al., 2014; Dominello & Širović, 2016). The sources of bioduck calls were long unknown, but have recently been conclusively attributed to Antarctic minke whales by Risch et al. (2014). Bioduck calls range in frequency from 50 to 300 Hz, and may have harmonics up to 1 kHz (Matthews et al., 2004). These sounds seem to be used by Antarctic minke whales during foraging (Risch et al., 2014). Given Antarctic minke whales' close association with the sea ice pack and their low detectability during sighting surveys, passive acoustic monitoring is likely the most efficient means of detecting their presence. This method is independent of weather conditions, daylight, and can be cost effective relative to visual surveys (Mellinger & Barlow, 2003; Risch et al., 2014; Dominello & Širović, 2016). Even though passive acoustic monitoring only detects sounds of vocally active animals, it provides invaluable information that would not be obtained otherwise.

Antarctic minke whales are classified as 'Near Threatened' by International Union for the Conservation of Nature Red List of Threatened Species (Cooke, Zerbini, & Taylor, 2018). Modelling results suggest that the current abundance of Antarctic minke whales exceeds the pre-whaling population (Mori & Butterworth, 2004) whereas other research show that pre-whaling population size might be similar to or greater than current abundance (Rueagg et al. 2010). Current threats to the Antarctic minke population include climate change, marine pollution, ship strikes, underwater noise and fishing gear entanglement (Cooke et al. 2018; Risch et al., 2019). Until recently, Japan whaled Antarctic minke whales in the Southern Ocean under the IWC's Article VIII provision (Clapham, 2015) but now only commercially harvest common minke whales (*B. acutorostrata*) in their domestic coastal waters (Japan, 2019). Antarctic minke whales were regularly whaled in the Durban whaling ground, eastern South Africa, during the austral winter months from 1968 through 1975 (Best, 1982; Findlay & Best, 2016), where breeding and some feeding on krill were observed (Best, 1982). Commercial whaling for Antarctic minke whales did not occur on the west coast of South Africa due low whale numbers (Best, 1982, 2007). No abundance estimates of Antarctic minke whales are available for either coast of South Africa (Best, 2007). Connections between wintering and feeding ground are poorly known since migratory destinations remain to be determined; an extreme northward migration example includes the migration of a single Antarctic minke whale as far north as the Arctic - which is not a regular occurrence (Glover et al., 2010). Both the distribution and abundance of Antarctic minke whales have been found to coincide with favorable oceanographic conditions, sea ice concentration, and krill distribution (Mori & Butterworth, 2004; Friedlaender et al., 2011; Murase et al., 2013; Lee, Friedlaender, Oliver, & DeLiberty, 2017).

The west coast of South Africa is located within the Benguela Current Large Marine Ecosystem in the southeastern Atlantic Ocean (Fig.1) where upwelled cold, nutrient-rich water of the Benguela Current maintains high biological productivity on the west coast (Shannon, 2011). The Maud Rise is a seamount centered at 65°S, 2.5°E in the Weddell Sea of the Southern Ocean (Fig. 1). Bathymetric shoaling of the Maud Rise seamount disturbs the flow of the deep circumpolar waters resulting in upwelling of relatively warm, nutrient-rich deep waters to the sea surface which

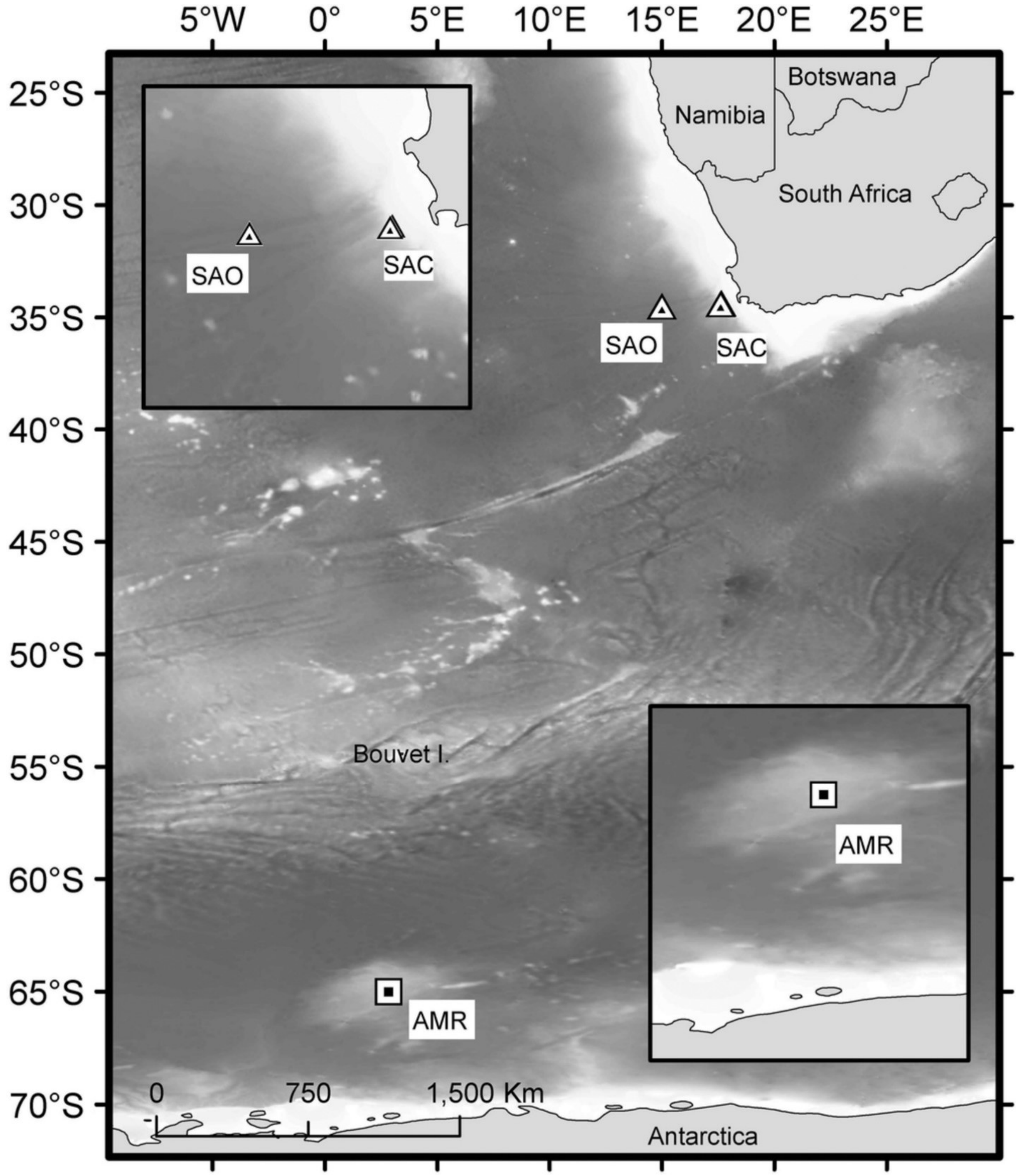

Figure 1. Map showing the positions of AAR deployments off the west coast of South Africa (SAC and SAO) and Maud Rise, Antarctica (AMR).

promotes phytoplankton growth (Comiso & Gordon, 1987; Hellmer, 2007). Furthermore, the newly upwelled waters disintegrate sea ice cover in winter, which leads to the formation of polynyas and initiates the sea ice melting in spring (Comiso & Gordon, 1987; Hellmer, 2007; Gordon, 2011). Large seasonal swarms of Antarctic krill (*Euphausia superba*) are prominent around Maud Rise due to both phytoplankton blooms and the presence of sea-ice algae which is grazed upon by krill (Everson, 2000).

While sighting surveys provide summer distribution patterns of minke whales in Antarctic waters (Matsuoka et al., 2003), these provide little information on seasonality due to vessel accessibility. To our best knowledge, the acoustic seasonal occurrence, diel-vocalizing patterns and bioduck call-type composition of Antarctic minke whales have not been previously described off the west coast of South Africa nor the eastern Weddell Sea. This study provides novel information on the seasonal occurrence, bioduck call-types, and diel-vocalizing patterns of Antarctic minke whales in Antarctic and South African waters.

2. METHODS

2.1. Collection of acoustic data

Acoustic data were collected over a period of four years at three different sites (five total deployments) off the west coast of South Africa, and for nine months off the Maud Rise, Antarctica (Fig. 1, Table 1). These acoustic data were collected as part of the South African Blue Whale Project (SABWP) to study acoustic occurrence and behavior of Antarctic blue whales (*B. musculus intermedia*) (Shabangu et al., 2019). Autonomous Acoustic Recorders (AARs) of Autonomous Underwater Recorder for Acoustic Listening (AURAL) Model 2 version 04.1.3 (Multi-Electronique Inc., Canada) were used to monitor the acoustic environment at passive acoustic monitoring stations (Table 1). The AARs were opportunistically deployed on oceanographic moorings in three South African Coastal (SAC) positions and one South African Offshore (SAO) position (Fig. 1, Table 1). AARs in the SAC area were designated SAC1, SAC2 and SAC3 (Table 1). One AAR was deployed on a dedicated mooring off the Maud Rise, Antarctica (AMR) in the eastern Weddell Sea (Fig. 1, Table 1). SAC1 was deployed approximately 70 km from the coast whereas SAC2 and SAC3 were deployed 75 km from the South African coast, giving a distance of ~ 5 km between SAC1 and SAC2 and SAC3. SAO was deployed approximately 240 km farther offshore from SAC1, SAC2 and SAC3 (Fig. 1). AMR was located approximately 667 km from the nearest landmark on the Antarctic continent (Fig. 1). Austral seasons of the year were used to parse and describe the data into seasons: summer (December to February), autumn (March to May), winter (June to August), and spring (September to November).

Table 1. Details of deployment and settings of the five AARs used in this study. AARs from the west coast of South Africa are numbered according to order of their chronological deployment and shoreline position. ID is for identification.

AAR ID	Latitude (S)	Longitude (E)	Water depth (m)	AAR depth (m)	Sample rate (Hz)	Duty cycle (hr)	Start recording date	Stop recording date
SAC1	34° 22.21’	17° 37.69’	855	200	4,096	0.5	24/07/2014	01/12/2014
SAC2	34° 23.64'	17° 35.66'	1,118	300	4,096	0.33	16/09/2014	01/12/2015
SAC3	34° 23.64'	17° 35.66’	1,118	300	8,192	0.42	04/12/2015	01/01/2017
SAO	34° 30.36’	14° 58.81’	4,481	200	8,192	0.42	04/12/2015	13/01/2017
AMR	65° 00.00’	02° 50.00’	1,267	250	2,048	0.42	12/01/2014	17/09/2014

2.2. Detection of bioduck and upsweep calls

Antarctic minke whale calls (Fig. 2) were visually detected (using spectrograms) and scrutinized aurally (when calls were visually identified) in Raven Pro (Bioacoustics Research Program, 2017). A nomenclature of Antarctic minke whale sounds from Dominello and Širović (2016) was used to classify the call-types detected in our acoustic records as it is the most recent and comprehensive description of Antarctic minke whale sounds. Examples of some of the Antarctic minke whale calls detected in our study are shown in Fig. 2. Measurements of parameters of randomly selected, non-overlapping series of bioduck B2 calls (Fig. 2a) were manually extracted from spectrograms using Raven Pro including start and end time (s), and start, end, and peak frequencies (Hz) for each pulse within a series. Peak frequency is defined here as the highest spectrum level of the bandwidth of the individual pulse within a call series. Furthermore, downswept pulse duration (s), number of pulses per series, inter-series interval (ISI) and inter-pulse interval (IPI) were also measured.

A "series" was defined as a cluster of downswept pulses separated by less than 1 s, and multiple series constitute a "call" (Dominello & Širović, 2016). We defined ISI as the time from the start of a downswept pulse in a series to the start of the first downswept pulse in the next series (Dominello & Širović, 2016). IPI was defined as the time difference between the start of one downswept pulse and the start of the next pulse within the series (Dominello and Širović (2016). Bio-duck B2 call deviations were determined by calculating the variability in frequency over the duration of the call, which indicated the rate of change in end and peak frequencies of the pulse. Mean± standard deviations of the different parameters were calculated in R (R Core Team, 2019) using built-in commands.

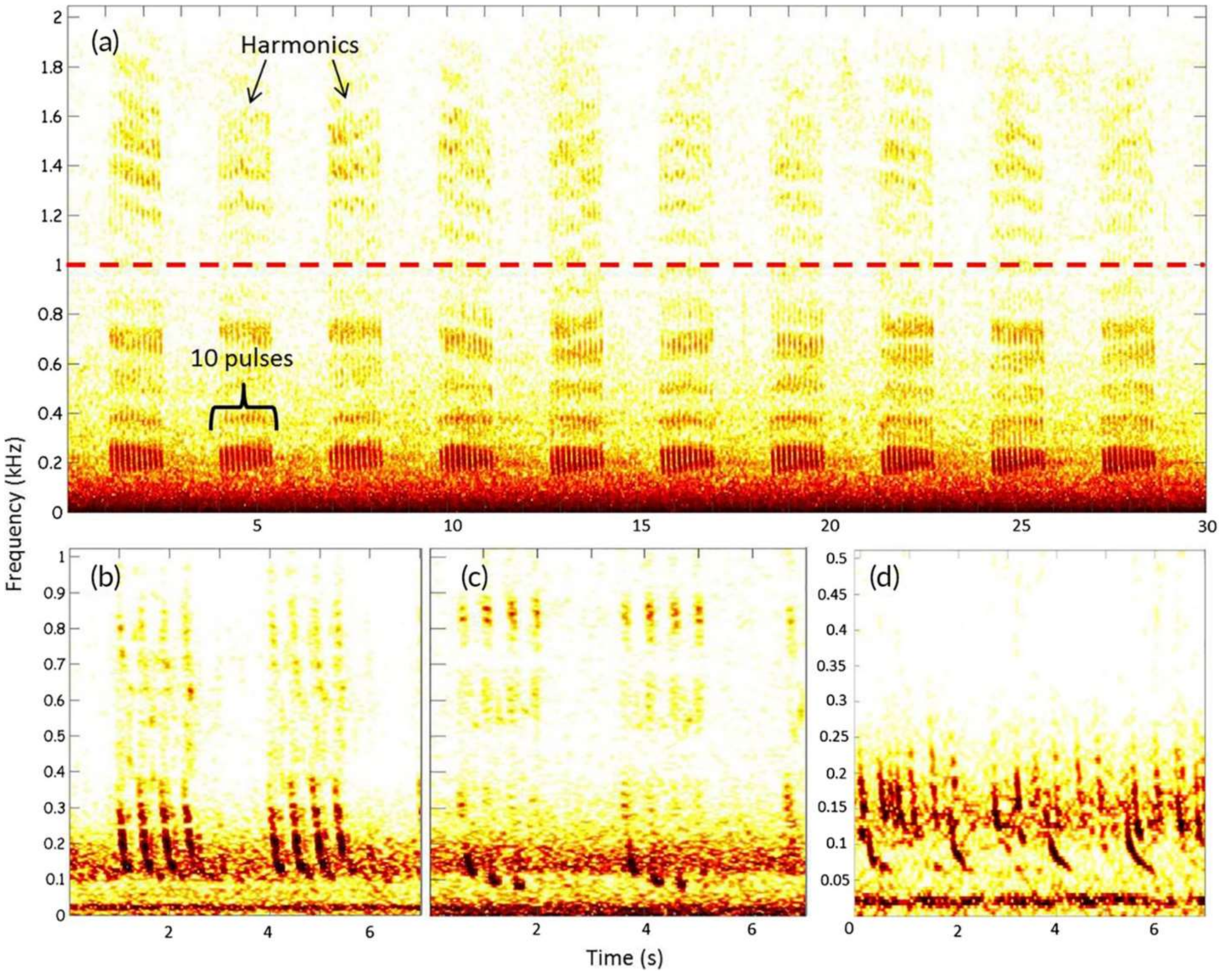

Figure 2. (a) Spectrograms of Antarctic minke whale bioduck B2 calls containing harmonics up to 2 kHz, (b) bioduck A1 calls, (c) bioduck C calls, and (d) downsweeps with bioduck A2 calls. Dashed horizontal red line in (a) represents the highest frequency (i.e., 1 kHz) reported for harmonics of minke whale sounds by Matthews et al. (2004). Note frequency scale difference for (b), (c), and (d). Spectrogram parameters: (a) frame size 0.125 s, 50% overlap, FFT size 512 points, Hanning window; (b) and (c) frame size 0.196 s, 25% overlap, FFT size 732 points, Hanning window; (d) frame size 0.098 s, 25% overlap, FFT size 475 points, Hanning window.

Acoustic presence of Antarctic minke whales was defined as the detection of any bioduck call-types (Fig. 2a-c) within a sampling interval (i.e., duty cycle). Acoustic absence refers to instances when no bioduck call-types were detected within a sampling interval. Acoustic presence and absence of different bioduck call-types were used to define the acoustic occurrence of Antarctic minke whales both in Antarctic and South African waters. Downsweeps (Fig. 2d) were not used to define the acoustic occurrence of Antarctic minke whales since they were detected on only a few occasions together with bioduck calls and only in Antarctica. The percentage of acoustic occurrence of Antarctic minke whales was calculated as the number of sampling intervals with call presences divided by the total number of sampling intervals recorded per month or hour for each AAR, and then multiplied by a hundred. The composition of Antarctic minke whale call-types recorded by each AAR were calculated as counts of each call-type occurrence divided by the total number of all call-type occurrence per AAR, and then multiplied by hundred. Bioduck B2 call rate (i.e. calls per hour) was calculated as the number of calls divided the sampling interval (i.e. duty cycles in Table 1) in an hour format.

2.3. Sea ice observations of the Maud Rise

Monthly distances of the AAR mooring position from the sea ice extent were used to determine the influence of sea ice on whale occurrence. Monthly sea ice extents were downloaded from the G02135 dataset housed at the National Snow and Ice Data Centre data repository (Fetterer et al., 2016). From the monthly sea ice extents, we measured the distance from the nearest sea ice edge to the AMR mooring position. Daily sea ice concentrations (%) were obtained for the Maud Rise using the satellite sea ice concentration product of the Advanced Microwave Scanning Radiometer-2 with a 3.125 km grid resolution (Spreen, Kaleschke, & Heygster, 2008; Beitsch, Kaleschke, & Kern, 2014).

2.4. Bioduck call occurrence modelling

We used random forest (RF) modelling (Ho, 1995; Breiman, 2001) to investigate the influences of predictor variables (month of the year, time of the day and distance to the sea ice edge) on the acoustic seasonal occurrence of Antarctic minke whale bioduck calls from our three AARs (SAC1, SAC2 and AMR). Data from SAC3 and SAO were not modelled due to very low occurrence of bioduck calls from those AARs. Based on generalized variance inflation factors (GVIFs; Fox & Monette, 1992), no multi-collinearity was found between predictor variables (month of the year, time of the day and distance to the sea ice edge) prior to fitting the RF model as the GVIF values were around one. The RF model was selected for use as it is an ensemble modelling approach that is used in a wide range of problems but mostly classification, regression, time series and survival data with non-parametric inferential properties (Breiman, 2001; Hastie, Tibshirani, & Friedman, 2009; Kane, Price, Scotch & Rabinowitz, 2014). As a machine learning method, RF modelling provides higher predictive capability and has considerable benefits over standard regression methods such as the simple linear regression or linear model model (GBM; Friedman, Hastie, & Tibshirani, 2000) and generalized linear model (GLM) owing to its non-parametric inferential properties and implicitly model interactive and non-linear effects (Elith, Leathwick, & Hastie, 2008; James, Witten, & Hastie, 2013). RF modelling uses a set of unpruned or unbootstrapped decision trees in the forest that are bootstrapped as they grow with sample training data, and rely on randomly chosen subsets of the predictor variables as candidate splitting tree nodes (Breiman, 2001; Hastie et al., 2009; James et al., 2013).

Candidate split-variable selection of RF model increases the probability of any single variable to be included in the final model output (Hastie et al., 2009; James et al., 2013). The RF model is generally built to avoid overfitting of growing trees in the training data (e.g., Hastie et al., 2009). The RF model is additionally known to be immune to autocorrelation from time series data and is also better at dealing with zero-inflated data from count data (Hastie et al., 2009; Mascaro et al., 2014). The relative importance of each of the variables in the model was determined by measuring the total decrease in node impurities from splitting on the variable, averaged over all trees (Liaw & Wiener, 2002). The node impurity was measured by the Gini index, measuring homogeneity from zero (homogeneous) to one (heterogeneous). The changes in Gini coefficients were summed for each variable and normalized at the end of the calculation. Variables that result in nodes with higher purity have a higher decrease in Gini coefficient.

The 'randomForest' library (Liaw & Wiener, 2002) was used to perform the RF modelling in R (R Core Team, 2019). Values of optimal parameter configuration for RF models were determined using the 'ranger' library as a computational-time-saving method for the implementing RF models (Wright & Ziegler, 2017). The area under the receiver operating characteristic curve (AUC) was used to measure the predictive accuracy of each model with different parameter configurations. RF models with optimal parameter configurations had the highest AUC values. Optimal parameter configurations for each RF model used to investigate the effect and importance of predictors on bioduck call occurrence were: SAC1 (number of trees: 1500), SAC2 (number of trees: 2500) and AMR (number of trees: 1000). Default number of variables randomly selected at each tree node were used, and the splitting minimum size of terminal nodes of trees of one were applied to all RF models.

Table 2. Seasonal number and percentage of hours and days containing Antarctic minke whale bioduck calls off the west coast of South Africa and the Maud Rise, Antarctica.

AAR ID	Season	Hours recorded	Hours with bioduck calls	% of hours with bioduck calls	Days recorded	No. of days with bioduck calls
SAC1	Summer	10	0	0	1	0
	Autumn	-	-	-	-	-
	Winter	465	23	1.44	39	8
	Spring	1,092	103	6.54	91	28
SAC2	Summer	715	124	3.55	91	34
	Autumn	729	0	0	92	0
	Winter	729	6	0.17	92	3
	Spring	1,317	287	8.23	167	72
SAC3	Summer	1,210	0	0	120	0
	Autumn	927	0	0	92	0
	Winter	927	0	0	92	0
	Spring	917	1.26	0.03	91	1
SAO	Summer	1,324	1.26	0.03	132	1
	Autumn	927	0	0	92	0
	Winter	927	0	0	92	0
	Spring	917	0	0	91	0
AMR	Summer	481	0.42	0.02	48	1
	Autumn	927	309	12.45	92	36
	Winter	927	648	26.12	92	89
	Spring	164	163	6.57	17	17

3. RESULTS

3.1. Seasonal occurrence and diel calling

A total of 2,499 hours of acoustic data were recorded from AMR, of which 1,120 hours (45%) contained Antarctic minke whale bioduck calls (Table 2). A total of 13,135 hours were recorded from all AARs deployed off the west coast of South Africa, with the seasonal number of hours recorded by each AAR given in Table 2. SAC2 produced the highest number (416) and percentage (12%) of hours with bioduck calls in the South African waters, and SAC1 produced the second highest number (125) and percentage (8%) of hours (Table 2). Highest number and percentage of hours with bioduck calls occurred in spring for SAC1 and SAC2, and in winter for AMR (Table 2). Overall, the AMR recorded the highest number and percentage of hours and days with bioduck calls. No acoustic data were recorded in autumn from SAC1 (Table 2). SAC3 and SAO recorded very few bioduck calls (0.03% for both AARs) and were therefore excluded from further analyses (Table 2).

The percentage of bioduck call occurrence from AMR had bimodal peaks, with the first peak of 91.40% in May and the second peak of 99.48% in September (Fig. 3). For SAC1, percentage of bioduck call occurrence peaked in October, whereas for SAC2, peaks in call occurrence were in September and in October (Fig. 3). In Antarctica, few bioduck calls were detected in summer whilst bioduck call occurrence drastically increased above 50% from mid-autumn until early spring (Fig. 3). Bioduck calls were sporadically detected in spring through summer in South African waters, and no bioduck calls were detected from autumn until mid-winter (Fig. 3). Simultaneously high percentages of bioduck call occurrence were observed on both AMR and SAC2 in September 2014 (Fig. 3). Bioduck calls were simultaneously detected by AMR and SAC1 in August and September 2014 (Fig. 3). There was strong inter-annual variability in bioduck call detections off the west coast of South Africa (Fig. 3).

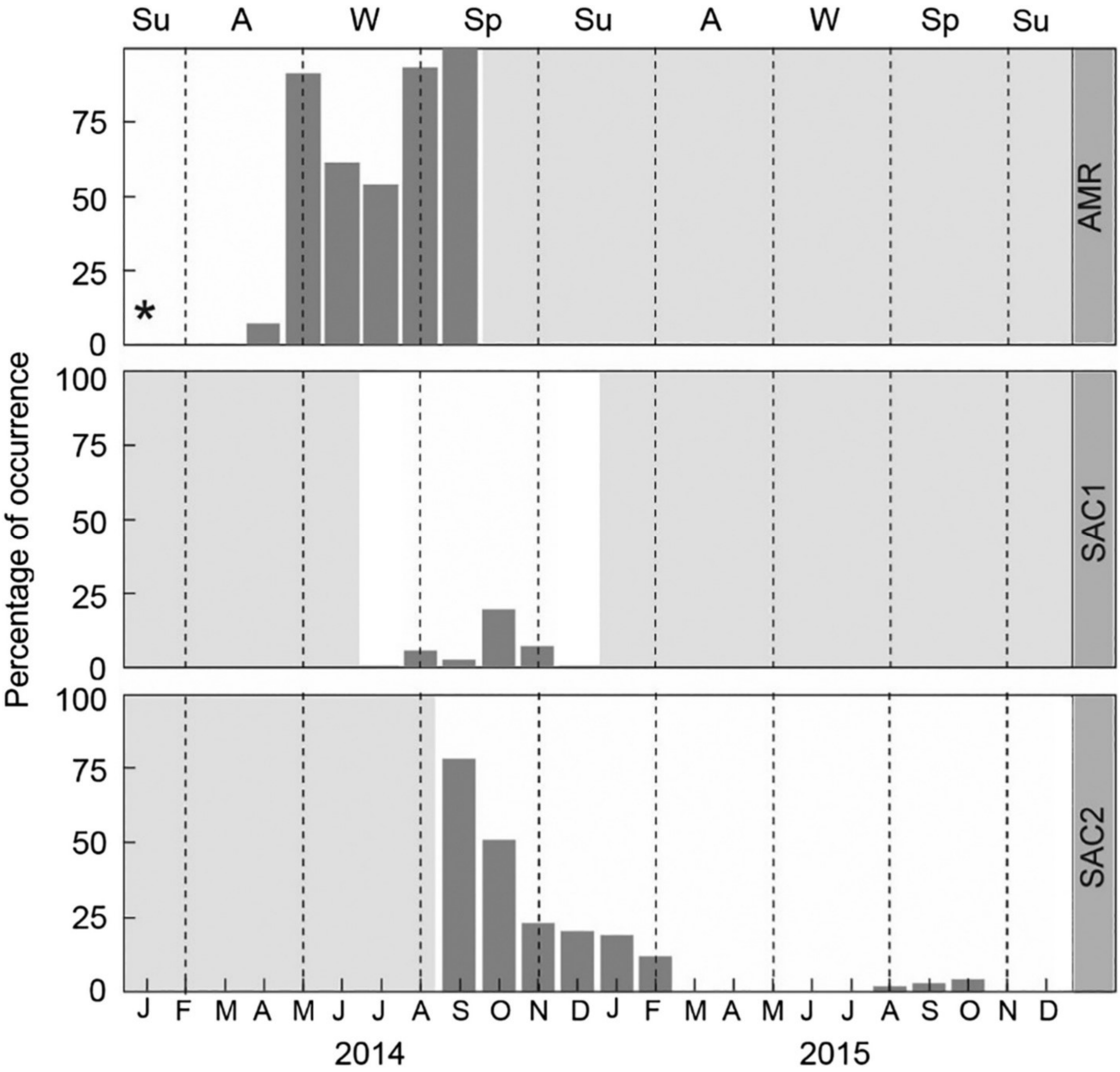

Figure 3. Monthly percentages of Antarctic minke whale bioduck call occurrence for AARs from the west coast of South Africa (SAC1 and SAC2) and Maud Rise, Antarctica (AMR). Asterisk represents a case when the monthly percentage of call occurrence was less than 0.2% but at least one call was recorded. Gray shaded areas indicate periods without passive acoustic monitoring effort. Seasons (Su: summer, A: Autumn, W: winter, and Sp: spring) are shown on the top axis and outlined by dashed lines, and years are stated on the bottom axis.

From 12 January to 20 April 2014, the sea ice concentration was 0% around the Maud Rise but increased to 50% by the end of April. The AMR mooring position was under sea ice from the beginning of May through mid-September, with sea ice concentrations around 80% at beginning of May and 100% by mid-May through mid-September. Occurrence of Antarctic minke whale bioduck calls were positively affected by the increase in the distance of the sea ice edge from AMR position, May through September and daytime (09h00, 11h00-14h00 Coordinated Universal Time) hours (Fig. 4a-c). Month of the year was the most important predictor, followed by the distance to the sea ice edge as moderate important and time of the day was the least important predictor of minke whale bioduck occurrence in Antarctica (Fig. 4d). Given the high absence of bioduck call in these months from SAC1, July through September and November and December had the highest effect on acoustic occurrence whereas October had the lowest effect on bioduck call occurrence (Fig. 5a). No clear effect of time of the day on bioduck call occurrence was evident for SAC1 (Fig. 5b). For SAC2, due to high absence of bioduck calls in those months, February through August and November had the highest effect on acoustic occurrence whereas January, September, October and December had the lowest effect on bioduck call occurrence (Fig. 5c). Hours between 07h00 and 12h00 had the lowest effect on bioduck call occurrence for SAC2 (Fig. 5d). Month of the year was the most important predictor of bioduck call occurrence for both SAC1 and SAC2, and time of the day was the least important predictor of bioduck call occurrence (Fig. 5 e-f).

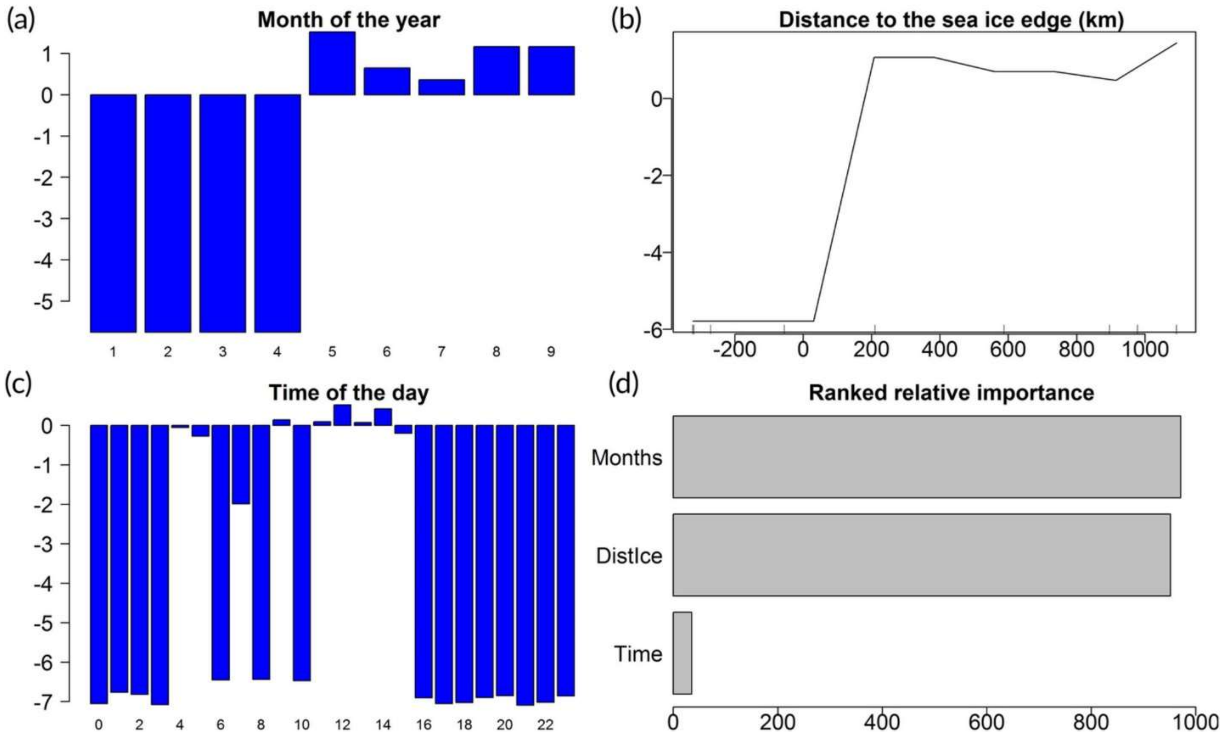

Figure 4. Effect and relative importance of predictor variables on Antarctic minke whale occurrence from AMR according to the RF model. Negative values of distance to the sea ice edge represent instances when the AAR deployment position was not submerged under ice, and positive values of distance to the sea ice edge represent instances when the AAR deployment position was submerged under sea ice. Y-axes (a - c) are the effects of each predictor variable on acoustic occurrence.

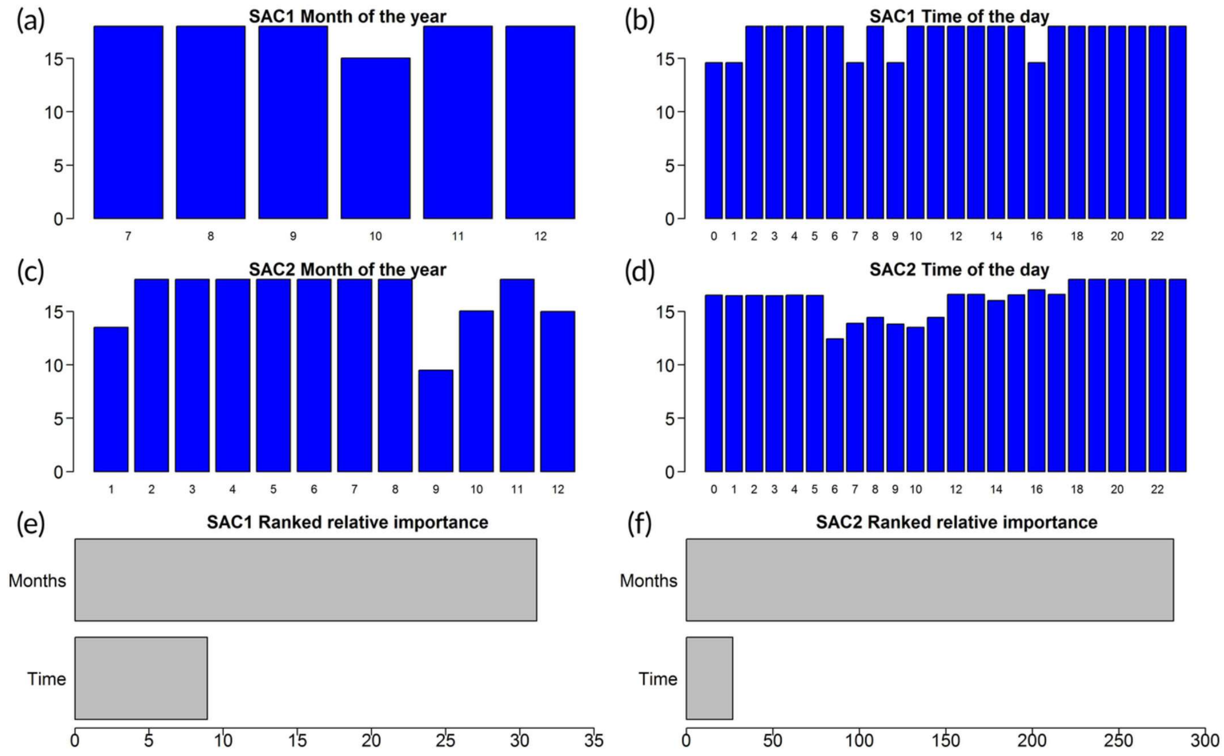

Figure 5. Effect and relative importance of predictor variables on Antarctic minke whale occurrence from SAC1 and SAC2 as determined by RF models. Y-axes (a - d) are the effects of each predictor variable on acoustic occurrence.

3.2. Bioduck B subtypes

We categorized bioduck B call-type into two subtypes: bioduck B1 and B2. Parameters and characteristics of bioduck B1 were described by Dominello and Širović (2016) and characteristics of bioduck B2 (Fig. 2) are described in this study (Table 4). Comparison of the start, peak and end frequencies; peak and end frequency change rates; number of pulses per series; IPIs; and ISIs between the two subtypes indicates that they are distinctly different from each other (Table 4). Bioduck B2 calls were recorded in both Antarctic and South African waters. In Antarctic waters the bioduck B2 consisted of an average of 9 pulses while the one in South African waters had an average of 10 pulses. The pulses within a call decreased or increased in frequency (not repetition rate) depending on the bioduck call-type (Table 3). The peak frequency of bioduck B2 pulses increased from the beginning to the end of the calls whereas for bioduck B1 the peak frequency of each pulse decreased over the duration of the call (Table 4). The ISI and IPI metrics of bioduck B2 are shorter than those of bioduck B1 (Table 4). Harmonics of bioduck B2 call extended as high as 2 kHz (Fig. 2).

Table 3. Comparison of measured parameters of Antarctic minke whale bioduck B1 call (Dominello & Širović, 2016) to bioduck B2 call (this study). Shown according to Dominello and Širović (2016) are total number of samples (N), mean value ±standard deviation of call start and end frequency, pulse duration, peak frequency, rate of change in peak and end frequency, ISI and IPI. Rate of change in peak frequency and ending frequency are computed as (end value-start value)/number of pulses, values for calculating peak and end frequency change rates are not provided in the below table.

Call-types	N (events)	No. of pulses per series	Start frequency (Hz)	Peak frequency (Hz)	End frequency (Hz)	Pulse duration (s)	Peak frequency change rate (Hz/pulse)	End frequency change rate (Hz/pulse)	ISI (s)	IPI (s)
Bio-duck B1*	3	13±1	244±7	216±14	177±12	0.1±0.1	-0.3	+0.5	5.1±0.8	0.3±0.0
Bio-duck B2	20	09±1	297±14	201±35	138±15	0.1±0.0	+1.2	+3.3	2.8±0.0	0.2±0.0

*The start frequency is not necessarily the call's true start as it is close to the recording Nyquist frequency (Dominello & Širović, 2016).

3.3. Call-types composition

The following bioduck call-types were recorded from our acoustic data: A1, A2, B2, C, and D (Fig. 6). Bioduck A2 call was the most commonly detected call-type in all recordings (Figs. 6), where it represented 91% of the total call composition for AMR, 59% for SAC1 and 81% for SAC2 (Fig. 7). The seasonality of bioduck A2 was complementary between AMR and SAC2 (Fig. 6). Antarctic minke whale downsweeps were only detected from AMR in June 2014 on 14 occasions and contributed 2% and 1% towards the monthly percentage of call occurrence and call-types composition respectively (Figs. 6, 7). Percentage of call-type occurrence changed inter-annually for SAC2 (Fig. 6). Bioduck B2 was recorded in spring (i.e., September and October) by both SAC1 and SAC2 off the west coast of South Africa and contributed around 1% towards the final call composition of each AAR (Figs. 6, 7). Bioduck B2 was detected in May and June from AMR (Fig. 6), but contributed less than 1% towards the call composition of AMR (Fig. 7). No bioduck B1 call-types were detected from our stations off the west coast of South Africa or the Maud Rise, Antarctica (Figs. 6 and 7). There were no calls detected for most of the months by SAC3 and SAO except for a very few detections of a combination of bioduck C and D calls in October 2016 for SAC3 and in December 2015 for SAO. High call rates of bioduck B2 were observed during the night at SAC2, and 676 calls per hour was highest call rate for SAC2 (Fig. 8). For SAC1, the highest call rate of 186 calls per hour was observed during the day (Fig. 8). Call rates of 624 and 33 calls per hour were detected in May and June respectively from AMR.

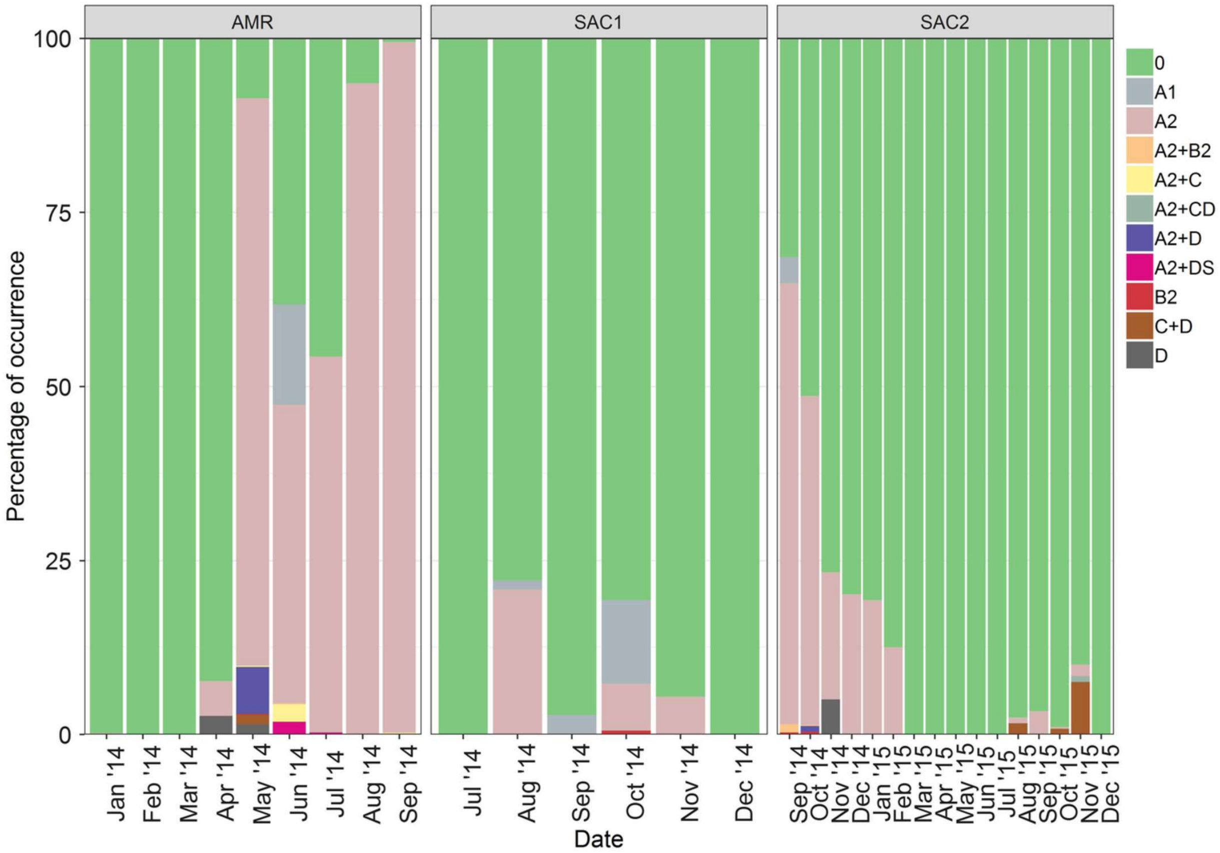

Figure 6. Monthly percentage of Antarctic minke whale call occurrence of each call-types per AAR off the west coast of South Africa (SAC1 and SAC2), and Maud Rise, Antarctica (AMR). Bar color shading represents: 0 is instances where no calls were detected; A1 is bioduck A1; A2 is bioduck A2; A2+B2 is bioduck A2 together with bioduck B in the same sampling interval; A2+C is bioduck A2 together with bioduck C in the same sampling interval; A2+CD is bioduck A2 together with bioducks C and D in the same sampling interval; A2+D is bioduck A2 together with bioduck D in the same sampling interval; A2+DS is bioduck A2 together with downsweeps (DS) in the same sampling interval; B2 is bioduck B2; C+D is bioduck C together with bioduck D in the same sampling interval; and D is bioduck D.

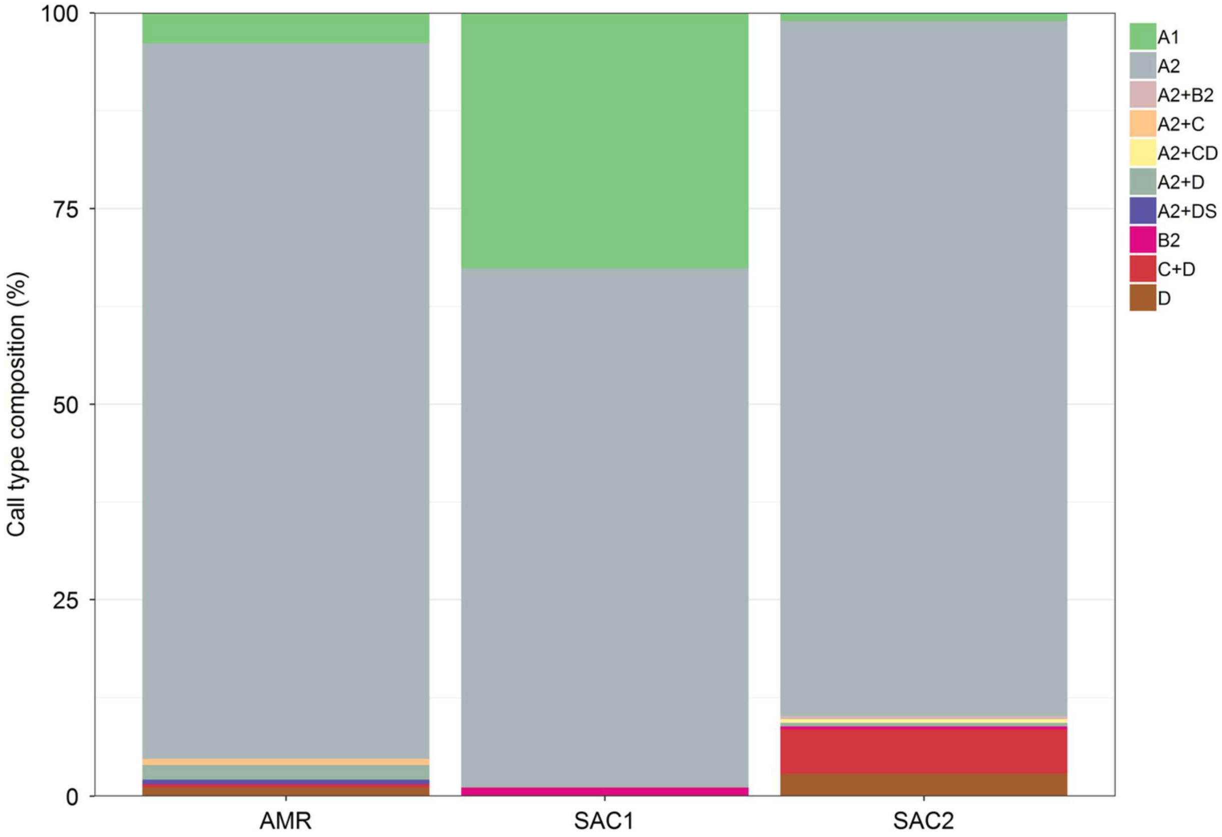

Figure 7. Overall percentages of composition of each Antarctic minke whale call-types per AAR.

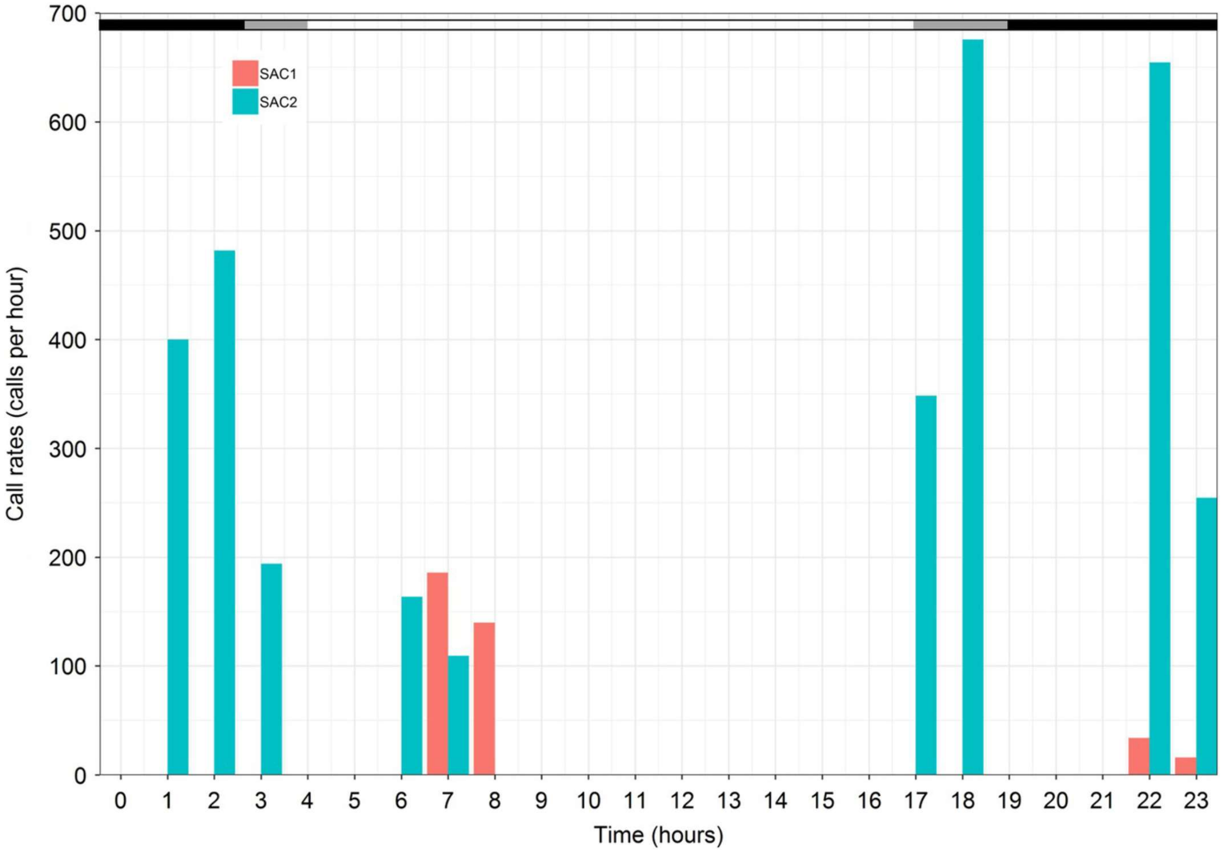

Figure 8. Diel call rates of Antarctic minke whale bioduck B2 from SAC1 and SAC2 in spring off the west coast of South Africa. Horizontal diel bar shading: black represents average nighttime hours, grey represents average twilight hours and white represents average daytime hours.

4. DISCUSSION

The almost continuous acoustic detection (January through September) of Antarctic minke whale bioduck calls off the Maud Rise, eastern Weddell Sea, Antarctica, suggests that minke whales use this area year-round. Although our acoustic data did not cover October-December, Van Opzeeland (2010) detected Antarctic minke whale bioduck calls from April through October and sometimes through December in the western Weddell Sea. It is known that Antarctic minke whales are well adapted to live in heavy sea ice-covered areas (e.g., Friedlaender et al., 2014; Lee et al., 2017); the RF model medium ranking of the AMR distance to the sea ice edge to predicting bioduck call occurrence supports those conclusions. Antarctic minke whales use polynyas (Ribic, Ainley, & Fraser, 1991) and create breathing holes in ice-covered areas in order to maintain their winter distribution in the region (Schevill & Watkins, 1972; Plötz, Weidel, & Bersch, 1991; Scheidat et al., 2008). Large, recurring polynyas off the Maud Rise (known as the Weddell Polynyas) are common in the region during winter (Comiso & Gordon, 1987; Hellmer, 2007), and these provide suitable winter habitats for Antarctic minke whales (Plötz, Weidel, & Bersch, 1991). RF model classified months from late autumn through early spring (i.e. May through September) as the most influential months of the year for bioduck call occurrence in Antarctica, further demonstrating the importance of sea ice on these whales' ecology as the AMR position was submerged under ice during those months. The few or complete lack of call detections during summer (January and February) in Antarctica could be because most of the Antarctic minke whales are in offshore areas in summer when sea ice is fully retracted and return to Antarctic waters in mid-autumn when the sea ice starts to form (van Opzeeland 2010). Additionally, a proportion of the population could be in the low latitudes during that time of the year (Best, 1982, 2007). For example, acoustic studies off Namibian (Thomisch et al. 2019) and South African (this study) waters detected Antarctic minke whale calls from late winter through summer.

Tagged Antarctic minke whales performed shallower lunge feeding dives under sea ice during nighttime and deep dives during daytime to feed on Antarctic krill off the western Antarctic Peninsula (Friedlaender et al., 2014; Risch et al., 2014). Such shallow feeding at night coincides with the diurnal vertical migration of their prey, Antarctic krill, where krill is in the deep waters during the day but migrate to shallower waters at nighttime (Demer & Hewitt, 1995; Gaten et al., 2008). Risch et al. (2014) observed that Antarctic minke whales produced bioduck calls before lunge feeding, but not during lunges. In eastern Weddell Sea, we observed a higher effect of daytime on bioduck call occurrence from the RF model output, which might indicate that feeding occurs more during daytime in Antarctica. Although RF models indicated that time of the day was the least important variable to predict bioduck call occurrence in South African waters, high call rates of bioduck B2 were detected from SAC2 during nighttime in spring. Such high bioduck B2 call rates at night from SAC2 might be indicative of whales feeding on krill in the shallow waters at nighttime (assuming that bioduck B2 is used for a similar function as bioduck B1). Furthermore, the low classification of time of the day by our RF models show the lack of diel-vocalizing patterns by Antarctic minke whales off the west coast of South Africa.

Antarctic minke whale downsweeps were very rare from our acoustic dataset as they were only detected in 14 occasions in June 2014 from AMR; this was unexpected as previous studies have commonly detected these call-types in the western Antarctic Peninsula (e.g., Risch et al., 2014; Dominello & Širović, 2016). This regional difference in percentage of occurrence of downsweeps reflect some region-specific usage of this call-type or differences due to acoustic sampling efforts and/or whale temporal variations in relation to environmental conditions and food availability. Antarctic minke whale downsweeps were not confused with those produced by Antarctic blue whales (*B. musculus intermedia*) and fin whales (*B. physalus*) as those downsweeps have been previously identified in our acoustic dataset by Shabangu (2018) and Shabangu et al. (2019). Downsweeps of humpback whale (*Megaptera novaeangliae*) have also been detected in our acoustic dataset (Shabangu, unpublished data), and these were observed in the absence of minke whale bioduck calls.

Bioduck calls were mainly detected in late winter, spring and summer off the west coast of South Africa, suggesting that the west coast of South Africa might be used as a seasonal feeding and breeding ground as observed off Durban, on the east coast of South Africa (Best, 1982). RF model outputs indicated that month of the year was the most important predictor of bioduck call occurrence off the west coast of South Africa due to strong inter-annual variability of call occurrence. Detections of bioduck calls in this study suggest the possibility of feeding by this species on the west coast of South Africa, Antarctic blue whales were also observed to produce their feeding associated call, D-call, on the west coast of South Africa (Shabangu et al., 2019). Alternatively, these whales may use the west coast of South Africa as a migratory corridor to southern Angola (Best, 2007; Weir, 2010). The year 2016 was anomalous in terms of acoustic occurrence of Antarctic minke whales off the west coast of South Africa as very few bioduck calls were detected from SAC3, which was a replacement of SAC2 on the same oceanographic mooring and location, and SAC2 recorded much higher numbers of bioduck calls in the previous year. This strong inter-annual variability highlights the need for long-term passive acoustic monitoring to better understand Antarctic minke whale habitat usage off South African coasts.

Additionally, the annual variation in the acoustic detections of bioduck calls off the west coast of South Africa may suggest that these whales might travel to different locations each year, implying that there might be limited site fidelity by this species. The lack of bioduck call detection between March and July (i.e., autumn through midwinter) for all recording years off the west coast of South Africa could be due to low numbers of whales in the area that led to little or no vocalizations. Thomisch et al. (2019) seasonally detected Antarctic minke whale bioduck calls off Namibia between November and January and from June to August, suggesting some common arrival of whales in the southern African subregion in the two datasets. Antarctic minke whales are, however, seldom sighted during sighting surveys in autumn and winter (i.e. a period without bioduck detections) off the west coast of South Africa (e.g., Cape Town Pelagics, 2012; Shabangu et al., 2019; Shabangu, unpublished data). It is possible that this species could be using the South African west coast year-round (as found on the east coast by Best (1982)) but may be seasonally vocal as whales are sighted during periods of no acoustic detections. Whale catch statistics off the Durban whaling ground indicated that Antarctic minke whales were present in low numbers in winter but more abundant in late winter through spring (Best, 1982; Findlay & Best, 2016).

The simultaneous detections of Antarctic minke whale bioduck calls in the Antarctic and South African waters between August and September might be indicative of both dynamic and asynchronous migration where a certain portion of the population migrates to the low latitudes whilst some portion of the population remains in Antarctica. Additionally, the above observation could imply residence by a certain portion of the population in either location, thus creating an important link between a potential wintering ground and a feeding ground. The complementary seasonality of bioduck A2 between AMR and SAC2 also supports the possibility of whale migration between Antarctic and South African waters. Call-type composition from our AARs deployed off the west coast of South Africa are comparable to those from AMR, and those reported for Antarctic minke whales by other studies in the western Antarctic Peninsula (Risch et al., 2014; Dominello & Širović, 2016) and western Weddell Sea (van Opzeeland, 2010). The comparable bioduck call-type composition indicates that these calls are indeed produced by Antarctic minke whales and not by common or dwarf minke whales that are sometimes sympatric with Antarctic minke whales (Best, 2007; Jefferson, Webber, & Pitman, 2015).

Given the difference in the start, peak and end frequencies; peak and end frequency change rates; number of pulses per series; ISIs; and IPIs between bioduck B1 reported in Dominello and Širović (2016) and bioduck B2 from this study, we maintain that Antarctic minke whale bioduck B call should be split into two subtypes. Our study reports the full frequency range of bioduck B2 subtype call; whereas the exact start frequency of bioduck B1 is uncertain due to recording Nyquist frequency limitation of the Dominello & Širović (2016) study. The detection of bioduck B2 in both the west coast of South Africa and Antarctica suggests that this call subtype is broadly produced by Antarctic minke whales. We classified the 9 pulse bioduck call from Antarctica and the 10 pulse bioduck call from the west coast of South Africa as bioduck B2 because they both have similar start, peak, and end frequencies; pulse durations; peak and end frequency change rates; ISIs and IPIs.

Harmonics of Antarctic minke whales bioduck B2 were observed to exceed the maximum frequency of 1 kHz previously reported by Matthews et al. (2004) and Risch et al. (2014). Bioduck B2 harmonics are likely to exceed the maximum 2 kHz found in this study as these harmonics appeared to have strong energy at 2 kHz; however, this cannot be determined from our data since the AAR that recorded those sounds had recording Nyquist frequency of 2 kHz. The recording of these relatively high frequency harmonics might indicate that vocalizing whales were very close to the AAR as echo strength decreases with distance from the sound source due to sound spreading and attenuation (e.g., Urick, 1983; Lurton, 2002). Such decrease of harmonic echo strength with distance has been observed in terrestrial mammals such as big brown bats (*Eptesicus fuscus*) (e.g., Bates, Simmons, & Zorikov, 2011).

Although Risch et al. (2014) recorded bioduck calls from multi-sensor suction-cup tags equipped with hydrophones (sampling at 25.81 kHz) that were attached on Antarctic minke whale's body, bioduck calls from their recorded sound files contained in the supplementary information of that paper do not contain harmonics above 1 kHz. The lack of harmonics above 1 kHz in Risch et al. (2014) research could be due to directivity of the bioduck calls relative to the hydrophone on the dorsal part of the whale. Alternatively, harmonics above 1 kHz could be unique to bioduck B2 as those have not been report on other Antarctic minke whale bioduck call-types.

4.1. Conclusion

Seasonal acoustic occurrence, diel-vocalizing patterns and call-type composition of Antarctic minke whales in Antarctic and South African waters were described using passive acoustic monitoring. Antarctic minke whales were acoustically detected during most of the 9-month recording period in Antarctica. In South African waters, Antarctic minke whale calls were detected seasonally and there was a strong intra-annual variability in bioduck call occurrence. According to RF model outputs, Antarctic minke whales were more vocally active during the day in Antarctica, but no diel-vocalizing pattern was observed in South African waters although high call rates of bioduck B2 were observed at night in spring. Our estimated call rates of bioduck B2 cannot compared to call rates of other bioduck call-types since no call rates have been estimated for those according to our best knowledge. Bioduck A2 call-type was the most dominant Antarctic minke whale call-type detected in all our recording stations. A new subtype of bioduck B call termed bioduck B2 is described here, which has harmonics that extend as high as 2 kHz and likely exceed this frequency. Both the Maud Rise and west coast of South Africa are important habitats of Antarctic minke whales given the dynamic seasonal bioduck call occurrence and call-type compositions. This is the first study to describe the acoustic occurrence, diel-vocalizing patterns and call-type composition of Antarctic minke whales off South African west coast and eastern Weddell Sea where and when visual survey effort is not possible due to darkness, ice cover, inclement weather or costs.

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