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Exploring and verifying the acoustic presence of southern right whales (Eubalaena australis) off Elephant Island, Antarctica

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ABSTRACT:
Passive acoustic monitoring (PAM) can be used to monitor acoustic presence and behaviour of cetaceans, providing continuous, long-term, and seasonally unbiased data. The efficiency of PAM methods, however, depends on the ability to detect and correctly interpret acoustic signals. The upcall is the most prevalent vocalization of the southern right whale (*Eubalaena australis*) and is commonly used as a basis for PAM studies on this species. However, previous studies report difficulties to distinguish between southern right whale upcalls and similar humpback whale (*Megaptera novaeangliae*) vocalizations with certainty. Recently, vocalizations comparable to southern right whale upcalls were detected off Elephant Island, Antarctica. In this study, these vocalizations were structurally analyzed, and call characteristics were compared to (a) confirmed southern right whale vocalizations recorded off Argentina and (b) confirmed humpback whale vocalizations recorded in the Atlantic Sector of the Southern Ocean. Based on call features, detected upcalls off Elephant Island could be successfully attributed to southern right whales. Measurements describing slope and bandwidth were identified as the main differences in call characteristics between species. With the newly gained knowledge from this study, additional data can be analyzed providing further insight into temporal occurrence and migratory behaviour of southern right whales in Antarctic waters. https://doi.org/10.1121/10.0019633

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I. INTRODUCTION

Since acoustic signals play a major role in cetacean ecology (Clark, 1990), passive acoustic monitoring (PAM) methods can be used to monitor underwater vocalizations of cetaceans and even help to investigate related behaviors (Clark, 1982; Van Parijs *et al*., 2009). Over the last decades, continuously improving technologies increased the possibility of passive acoustic data collection over large spatial and temporal scales (Van Parijs *et al*., 2009), providing continuous, long-term, and seasonally unbiased data of sound-producing marine fauna in different types of marine environments (Mellinger *et al*., 2007). These features make PAM invaluable for studies on marine mammals in logistically challenging areas (Ahonen *et al*., 2019; Calderan *et al*., 2021; Frouin-Mouy *et al*., 2019). Within recordings, vocalizations are identified based on variations in signal duration, frequency range and bandwidth, and their general visio-aural appearance in spectrographic images, thereby allowing the differentiation of species, and in some cases even of populations or individuals (Janik and Sayigh, 2013; Mellinger *et al*., 2007). The efficiency of PAM methods depends on the ability to detect and correctly attribute acoustic signals to certain species, relying on baseline information on the species-specific signature features and acoustic behavior (Mellinger *et al*., 2007; Van Parijs *et al*., 2009). Such knowledge, in most cases, is obtained from concurrent acoustic and visual observations of the species. The bio-duck sound, for example, was an unidentified sound for several decades in the Southern Ocean before it was successfully attributed to the Antarctic minke whale through the deployment of dTAGs (*Balaenoptera bonaerensis*; Risch *et al*., 2014).

In some cases, similarities in vocalization parameters of sympatric species are problematic for PAM studies, as this may cause difficulties in correctly identifying species based on their vocalizations with certainty (Gillespie, 2004). For instance, the effective acoustic detection and discrimination of blue whale (*Balaenoptera musculus*) D-calls, fin whale (*Balaenoptera physalus*) 40 Hz-calls, and sei whale (*Balaenoptera borealis*) downsweeps in PAM recordings was reported as being not a trivial task, since all three vocalizations represent a downsweep over a similar frequency range (Huang *et al*., 2016; Ou *et al*., 2015). Recently, Ross-Marsh *et al*. (2022) proposed that humpback whales (*Megaptera novaeangliae;* hereafter referred to as HW) also produce high-intensity vocalizations similar to the so-called gunshots, which so far only have been attributed to right whales (*Eubalaena spp*.; Parks and Tyack, 2005), possibly causing problems in correct species identification for PAM studies. Additionally, Gillespie (2004) indicates difficulties to distinguish between right whale upcalls, the most

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commonly detected right whale call (e.g., Clark, 1982; Parks and Tyack, 2005; Urazghildiiev *et al.*, 2009; Calderan *et al.*, 2021), and similar vocalizations of HWs, since the acoustic characteristics of these signals overlap (Gillespie, 2004; Wild and Gabriele, 2014). In the context of understanding long-term species-specific distribution patterns and ecological niches, it is relevant to develop robust methods to acoustically distinguish species, without the need for simultaneous visual observation.

The waters off Elephant Island (hereafter EI, 61 °S 55 °W), which is part of the South Shetland Islands and located at the tip of the Antarctic Peninsula (Orsi *et al.*, 1995), are considered to represent an important foraging ground for baleen whales (Santora *et al.*, 2010; Santora and Veit, 2013; Burkhardt *et al.*, 2021). The presence of southern right whales (*Eubalaena australis*; hereafter referred to as SRW) has not been acoustically verified at EI to date, but opportunistic sighting and tagging data indicate at least sporadic presence (Vermeulen *et al.*, 2021; Zerbini *et al.*, 2018). Previous analyses by Schall *et al.* (2020) detected unknown vocalizations similar to SRW upcalls (Calderan *et al.*, 2021; Clark, 1982; Urazghildiiev *et al.*, 2009; Webster *et al.*, 2016) in passive acoustic data from EI from 2013. Therefore, the aim of this study was to investigate available acoustic datasets for the potential acoustic presence of SRWs off EI, by comparing upcalls of SRWs and HWs and developing a reliable decision structure to distinguish these species acoustically.

II. MATERIAL AND METHODS

A. Study area and sampling

Passive acoustic data from EI (hereinafter referred to as unidentified upcalls) were obtained using a SonoVault autonomous recorder (Develogic GmbH, Hamburg, Germany, Reson TC4037-3 hydrophone, −193 dB re1 V μPa^{-1} hydrophone sensitivity, 48 dB amplification gain, 24-bit resolution), which continuously recorded at a sampling frequency of 5333 Hz (Fig. 1 and Table I) from 15 January 2013 to 09 November 2013. The recorder was attached to a mooring at 212 m depth. As baseline data for SRW upcalls (hereinafter referred to as confirmed SRW upcalls), passive acoustic recordings with visual confirmation of SRWs gathering in Bahía San Antonio (BSA), Argentina, were analyzed (Fig. 1). Acoustic data were recorded using an array of six SoundTrap 202 STD recorders (Ocean Instruments, New Zealand, −205 dBV re 1 μPa sensitivity, max level before clipping of 186 dB re 1 μPa gain, 16-bit successive approximation resolution) at a 4000 Hz sampling frequency, for 14 days from 24 August to 6 September 2015. HW song including similar vocalizations to SRW upcalls were recorded in the Southern Ocean along the Greenwich Meridian (GM1, GM2, and GM3, summarized as GM) in 2011 and were also obtained with SonoVaults using the identical recording setting as EI (see Table I for deployment information).

B. Data processing

1. Data selection

Information on the presence of unidentified upcalls was available for EI through previous work within the Ocean Acoustics Group of the Alfred-Wegener-Institute. In previous analyses of passive acoustic data from EI from 2013 the "low frequency detection and classification system," (LFDCS; Baumgartner and Mussoline, 2011) and a custom-made acoustic-context filter to detect HW vocalizations were used. The detector found vocalizations allegedly produced by HWs, but which could not be visually confirmed as such in the spectrogram by a human analyst (Schall *et al.*, 2020). With this method, only even hours of the full dataset of EI recordings were previously analyzed, therefore only even hours containing detections of unidentified upcalls, and the adjacent odd hours were considered in this study. For the multi-channel BSA data, only one of the six channels was used for analysis in this study to avoid logging the same vocalization multiple times. Of the 14 recorded days, only

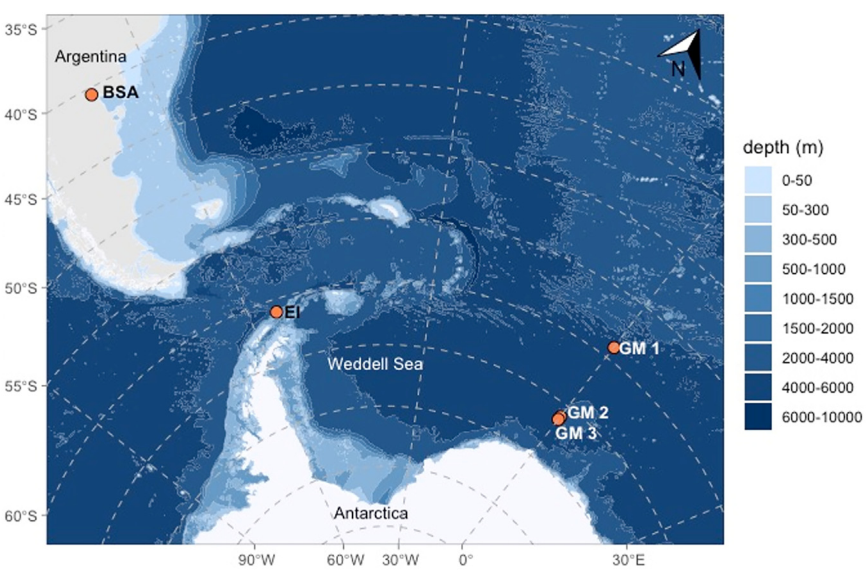

FIG. 1. (Color online) Bathymetric map of the southern Atlantic and the Southern Ocean including the geographical locations of the five acoustic recorders used in this study. Bathymetry data from Amante and Eakins (2009).

TABLE I. Deployment information on passive acoustic recordings.

Recording ID	Latitude	Longitude	Sampling frequency (Hz)	Recorder depth (m)	Duration of recordings
EI - AWI251-01_SV1008	61 0.88 °S	55 58.53 °W	5333	212	2013-01-15 – 2013-11-09
BSA - Argentina	40 48.46 °S	65 58.20 °W	4000	10–25	2015-08-24 – 2015-09-06
GM1 - AWI227-11_SV0002	59 3.02 °S	000 6.63 °E	5333	1007	2010-12-11 –2011-08-22
GM2 - AWI230-07_SV1001	66 1.9 °S	000 3.25 °E	5333	934	2010-12-16 – 2012-09-17
GM3 - AWI231-09_SV1002	66 30.71 °S	000 1.51 °W	5333	1083	2010-12-17 – 2011-08-14

ten days (i.e., from 25 August to 05 September) were considered to avoid effects of noise pollution caused by deployment and retrieval of equipment. The passive acoustic data of GM recorders in the Atlantic sector of the Southern Ocean (ASSO) had also been pre-processed for song structure analysis of HW songs in a previous study by Schall *et al*. (2021). Seven days of song recordings with confirmed HW song units from the ASSO, were chosen for this study. The recordings are assumed to be of different HW individuals (see Schall *et al*., 2021b for details on singer differentiation) and song units include vocalizations which can be described as upcalls.

2. Manual data processing

The upcall is produced by all age classes and both sexes, on both breeding and foraging grounds (Calderan *et al*., 2021; Clark, 1982; Dombroski *et al*., 2016) and can therefore be used as a reliable indicator of SRW (acoustic) presence. The SRW upcall represents a social, low-frequency signal rising in frequency from a mean low of 50 Hz, to a mean high frequency of 200 Hz as described by Clark (1982) and was identified in the recordings as such.

Compared to SRWs, HWs are known to produce social sounds and songs (D'Vincent *et al*., 1985; Payne and McVay, 1971; Silber, 1986). One specific HW vocalization, in the literature described as "wop," "whup," or "upsweep" (hereafter also referred to as upcall; Dunlop *et al*., 2007; Wild and Gabriele, 2014) also represents a tonal signal rising in frequency with mean low and high frequency limits of 52 and 743 Hz, respectively. As the HW upcall is used in a broad range of contexts (Wild and Gabriele, 2014), it is often produced as social sound (Dunlop *et al*., 2007), but is also found in HW song (Payne and McVay, 1971). In order to ensure that only HW upcalls (hereinafter referred to as confirmed HW upcalls) were considered for the comparative analyses, only upcalls from HW songs were analyzed (see Schall *et al*., 2020).

All passive acoustic recordings were analyzed using the sound analysis software Raven Pro 1.6 (The Cornell Lab of Ornithology, Center for Conservation Bioacoustics, Ithaca, NY), with which spectrograms were calculated and visually scanned for upcalls. The upcalls for acoustic measurements were chosen based on the visibility within the spectrogram. We did not filter out vocalizations according to their signal-to-noise ratio (SNR) because topographic features and therefore acoustic propagation were different at each sampling site (Forrest, 1994; McKenna *et al*., 2021). Instead, we focused on finding the largest number of upcalls in the recordings in order to produce a robust acoustical characterization of the different upcall groups. All analyses were performed using smoothed spectrograms in a Hanning window, with 50% overlap. To allow for a precise comparison of acoustic measurements from spectrograms between the different sampling rates of the recorders, window sizes for spectrogram calculation were adjusted for each recording position (see Table SII in the supplementary material[1]). A series of acoustic parameters were automatically extracted using available measurements in Raven Pro 1.6, to allow for numeric comparisons among vocalizations and with other studies (Table II).

C. Statistical analysis

Selection tables containing quantitative acoustic measurements were exported from Raven Pro 1.6 and imported into RStudio Version 2021.09.02 (RStudio Team, 2020) for statistical analysis. To attempt to statistically verify the influence of the factor "group" (the different upcall classes detected off EI, BSA, and GM, respectively) on the variability of acoustic measurements, several non-parametric statistical approaches within the R package "vegan" were implemented (Oksanen *et al*., 2020). An analysis of similarities (ANOSIM) based on the rank order of dissimilarities using the function "anosim" and a permutational analysis of variance (PERMANOVA) using the function "adonis" were performed to examine if the groups are different from each other (we performed both tests, since the sensitivities towards particular assumptions are different). Both tests were performed with 10 000 permutations, using the Bray-Curtis and the Euclidean distance as distance measures. Further, a pairwise comparison using the packages "vegan" and "pairwiseAdonis" (function "pairwise.comparison") was conducted to determine which groups' vocalizations were different based on their acoustic characterization (Martinez Arbizu, 2020). Additionally, to avoid biased results through an un-balanced design, all three tests were also performed with ten random subsets of 350 samples each from the EI dataset, using the original dataset-sizes from BSA and GM (i.e., $n_{BSA} = 348$, $n_{GM} = 354$). Furthermore, a Similarity Percentage (SIMPER) analysis within the package "vegan" was applied (function "simper") using the Bray-Curtis distance measure to determine the contribution of each acoustic measurement to the dissimilarities between groups. To visualize groupings of samples based on the quantitative acoustic measurements, a non-

TABLE II. Quantitative measurements to describe detected upcalls of southern right and humpback whales in Argentina and the Atlantic sector of the Southern Ocean. Parameters were calculated according to the temporal and spectral limits of the respective vocalizations by drawing selection boxes around detected vocalizations. Details on measurements according to the Raven Pro 1.4 User's Manual (Charif *et al.*, 2010).

Measurement	Description
Low frequency	Lower frequency limit of the selection box in Hz.
High frequency	Upper frequency limit of the selection box in Hz.
Delta frequency	The difference between the upper and lower frequency limits of the selection box in Hz.
Center frequency	The frequency that divides the selection into two frequency intervals of equal energy in Hz.
Frequency 25%	The frequency that divides the selection into two frequency intervals containing 25% and 75% of the energy in Hz.
Frequency 75%	The frequency that divides the selection into two frequency intervals containing 75% and 25% of the energy in Hz.
Frequency 5%	The frequency that divides the selection into two frequency intervals containing 5% and 95% of the energy in Hz.
Frequency 95%	The frequency that divides the selection into two frequency intervals containing 95% and 5% of the energy in Hz.
Delta Time	The difference between begin time and end time of the selection in s.
Duration 90%	The difference between the point in time that divides the selection into two time intervals containing 5% and 95% of the energy (Time 5%) and the point in time that divides the selection into two time intervals containing 95% and 5% of the energy in the selection in s.
Slope	The slope of the selection, calculated as delta frequency divided by delta time in Hz/s.

metric multidimensional scaling (NMDS) was used to reduce the multiple dimensions of conducted measurements to two dimensions within the R package "vegan."

D. Automatic classification of vocalizations

To evaluate the discrimination potential of conducted measurements we used a random forest classification model in RStudio (Breiman, 2001), a supervised machine learning algorithm. The Boruta algorithm (Kursa and Rudnicki, 2010) was additionally applied to identify relevant measurements as predictor variables for the classification model. We used the Boruta function in the R Boruta package (Kursa and Rudnicki, 2010). To develop the random forest model, we used the randomForest function from the randomForest package (Liaw and Wiener, 2002). The training data set consisted of the measurements from vocalizations detected off BSA and GM, while the validation data set consisted of the ones from EI. We grew 500 trees with a node size of 1 and tested three predictor variables at each split.

III. RESULTS

In the total amount of 496.5 analyzed hours of acoustic recordings 1827 upcalls were logged and measured. From a total of 102 h of EI data, 1125 unidentified upcalls were logged. Upcall vocalizations off EI were detected from January to May and in August. While 1120 upcalls were detected in austral summer with a peak in April, only five upcalls were detected during the austral winter month of August (see Fig. S3 in the supplementary material[1]). For comparison, 348 and 354 confirmed upcalls from SRWs and HWs were logged in the 226.5 h of BSA and 168 h of GM data, respectively.

A. Manual data processing

The frequency of unidentified upcalls recorded off EI rose from a mean minimum of 113 Hz to a mean maximum of 181 Hz. Vocalization frequency in some cases did range from a minimum low frequency of ∼44 Hz to a maximum high-frequency value of ∼401 Hz. EI upcalls had a mean bandwidth of ∼67 Hz and an average duration of 0.56 s. The detected vocalizations were characterized by a mean slope of ∼137 Hz/s. Confirmed SRW vocalizations detected in the BSA had a mean low frequency of ∼75 Hz and a mean high frequency of ∼162 Hz. The slope of the vocalization averaged to 104 Hz/s with a mean bandwidth of ∼86 Hz and a mean duration of 0.89 s. Frequencies of the HW vocalizations detected at GM ranged on average from 116 to 568 Hz, while the mean duration was 0.51 s. The mean bandwidth was 452.27 Hz resulting in a mean slope of ∼1024 Hz/s (Fig. 2 and Table III).

When scaling the various acoustic measurements with the NMDS method, two dimensions were chosen to collapse information. The measurements are arbitrarily represented in the dimensions to optimally display the dissimilarities in the ranked data. A low stress value ($<0.1 = $ good) indicates the distances are well represented in only two dimensions. Accordingly, the stress value of 0.037 indicates an excellent fit of ordination (Clarke, 1993). All analyzed vocalizations are clearly split into two groups, namely, the EI and BSA vocalizations as a single group and the GM vocalizations as a separate group (Fig. 3).

For brevity, only the results of the ANOSIM and PERMANOVA that were based on the Bray-Curtis distance measures on the whole data set will be reported here, since statistics using the Euclidean distance measures, as well as multiple random subsamples resulted in similar outputs and lead to the same conclusions as the statistical results presented here. The ANOSIM applied to the complete data set (R-value $= 0.8174$ and p-value $= 9.999 \times 10^{-05}$) suggested greater dissimilarities between than within groups, with a high significance level. The F-value of the performed PERMANOVAs (F-value $= 3148.1$, p-value $= 9.999 \times 10^{-05}$ and $R^2 = 0.77537$) demonstrates a significant group separation, while the determination coefficient value indicates a good fit for the variation explained by groups. Since the assumption of homogeneity was violated when conducting

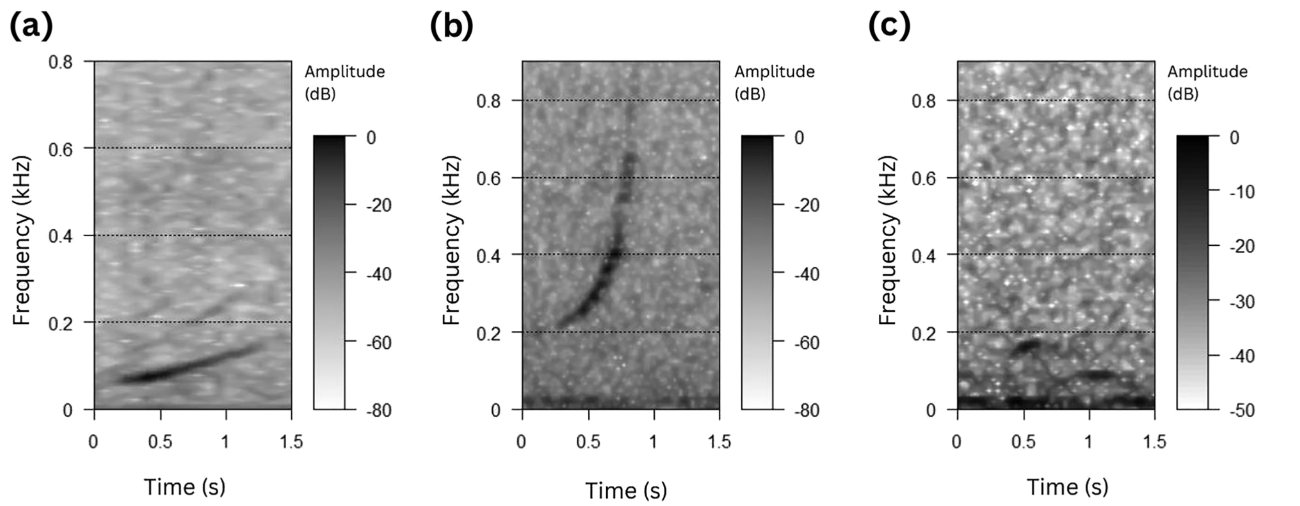

FIG. 2. Spectrograms of analyzed upcalls. (a) Southern right whale upcall detected off BSA, (b) humpback whale upcall detected at the GM, and (c) unidentified upcall detected off EI. Spectrograms calculated with fast Fourier transform (FFT) 740 (a,b), and FFT 850 (c), a Hanning window and 50% overlap.

TABLE III. Summary statistics of measured upcall vocalization characteristics: minimum (min), mean, maximum (max) values, and standard deviation (sd), shortened to a single decimal digit. Explanations on how the different measurements were conducted can be found in Table II.

Group	Measurement	Mean	SD	Min	Max
EI	Low freq (Hz)	113.9	24.3	44.0	353.4
	High freq (Hz)	181.9	21.3	103.6	401.2
	Delta freq (Hz)	68.0	19.3	23.6	154.8
	Duration (s)	0.6	0.3	0.18	2.4
	Center freq (Hz)	146.4	25.1	72.9	375.0
	Freq 25 (Hz)	134.3	25.9	62.5	369.8
	Freq 75 (Hz)	159.0	23.1	83.3	380.2
	Freq 5 (Hz)	121.2	25.2	46.9	364.6
	Freq 95 (Hz)	172.2	21.6	93.7	390.6
	Dur 90 (s)	0.4	0.2	0.1	20.2
	Slope (Hz/s)	137.3	51.3	34.6	418.6
BSA	Low freq (Hz)	75.7	38.3	42.4	321.5
	High freq (Hz)	162.3	46.7	99.0	442.9
	Delta freq (Hz)	86.6	24.3	36.0	177.8
	Duration (s)	0.9	0.3	0.3	1.7
	Center freq (Hz)	103.8	42.0	66.4	371.1
	Freq 25 (Hz)	93.0	40.2	62.5	339.8
	Freq 75 (Hz)	117.0	43.6	70.3	382.8
	Freq 5 (Hz)	83.6	39.0	50.8	332.0
	Freq 95 (Hz)	137.5	44.7	82.0	410.2
	Dur 90 (s)	0.6	0.2	0.1	1.3
	Slope (Hz/s)	104.4	41.7	33.9	370.3
GM	Low freq (Hz)	116.6	55.5	30.2	464.9
	High freq (Hz)	568.8	147.4	238.4	1006.6
	Delta freq (Hz)	452.3	139.7	109.7	910.5
	Duration (s)	0.5	0.2	0.1	0.9
	Center freq (Hz)	252.2	76.5	72.9	593.7
	Freq 25 (Hz)	198.7	65.9	52.1	531.2
	Freq 75 (Hz)	317.1	87.0	104.2	677.0
	Freq 5 (Hz)	146.3	59.4	31.3	510.4
	Freq 95 (Hz)	434.4	112.8	187.5	812.5
	Dur 90 (s)	0.3	0.1	0.3	0.7
	Slope (Hz/s)	1024.5	508.4	336.5	3090.6

the previously listed tests, the reported statistical results have to be interpreted with caution. Therefore, we also describe in the following the visual comparison of vocalization characteristics in the form of boxplots and a random forest analysis, which does not rely on the assumption of heterogeneity.

To better reveal the drivers of similarities and dissimilarities between the groups, the median and range values of the calculated measurements were compared (Fig. 4). In conjunction with the boxplots, we examined the median, since it is unaffected by extreme outliers in the data. Low-frequency measurements of upcalls from EI had similar overall ranges compared to BSA but with a higher median and interquartile range at EI. In comparison to EI, the low-frequency limits of vocalizations recorded at GM had a greater overall range. High-frequency limits of EI

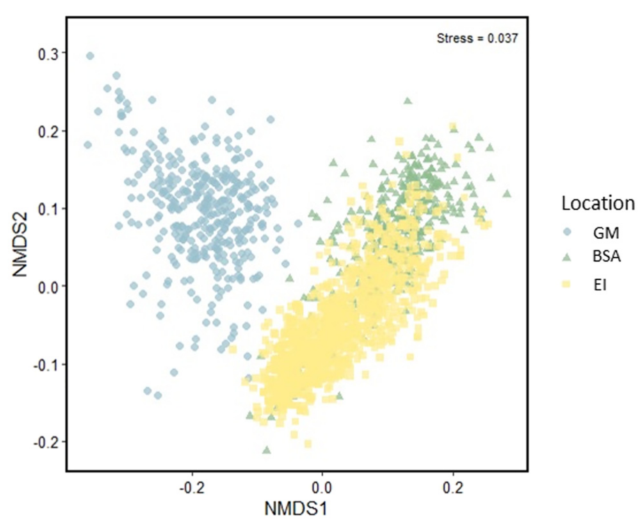

FIG. 3. (Color online) NMDS plot representing the two-dimensional grouping of analyzed vocalizations. Stress value = 0.037. (GM, confirmed humpback whale upcalls; BSA, confirmed southern right whale upcalls; EI, unconfirmed upcalls).

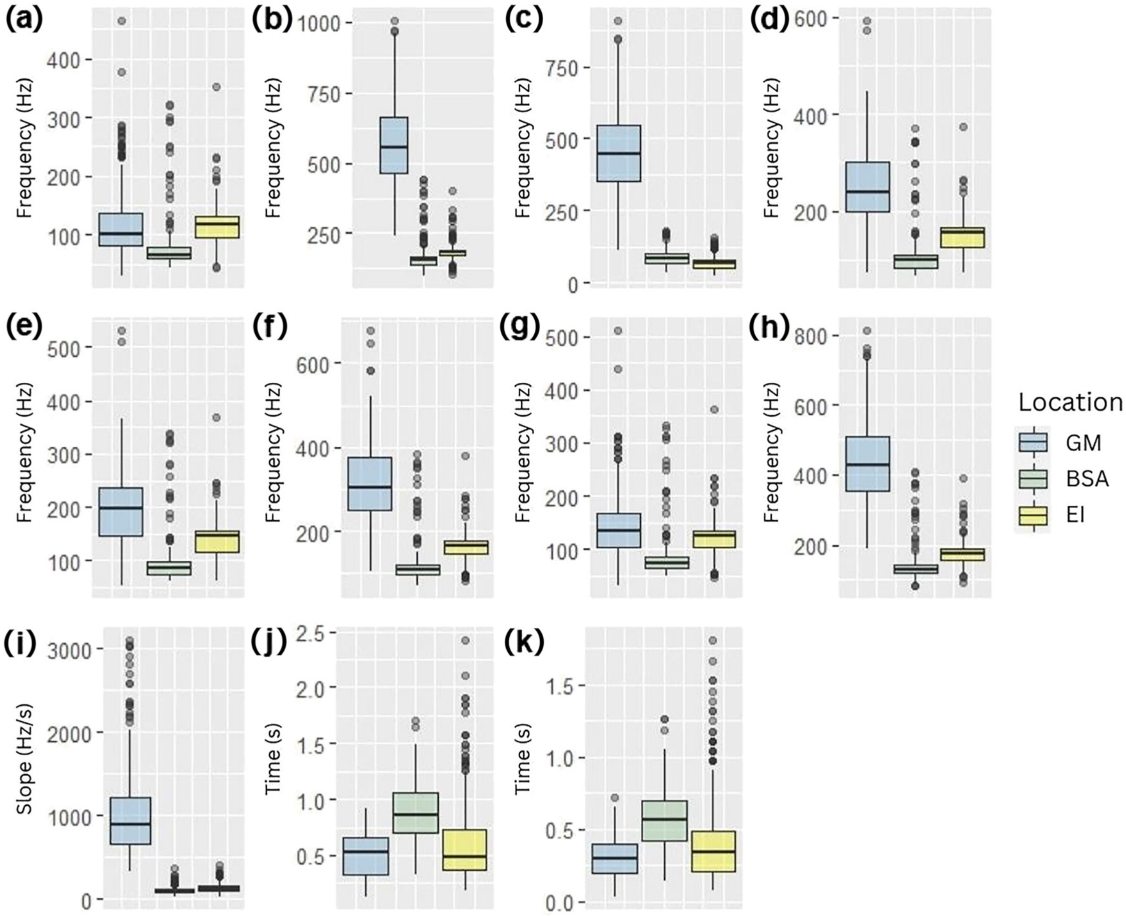

FIG. 4. (Color online) Boxplots representing quantitative acoustic measurements for the three groups GM, confirmed humpback whale upcalls; BSA, confirmed southern right whale upcalls; and EI, unconfirmed upcalls. (a) low frequency, (b) high frequency, (c) delta frequency, (d) center frequency, (e) frequency 25%, (f) frequency 75%, (g) frequency 5%, (h) frequency 95%, (i) slope, (j) duration, and (k) duration 90%.

vocalizations resulted in a relatively small interquartile range, also similar to BSA vocalizations, where slightly lower high frequencies were recorded. GM upcalls were characterized by a far greater overall and interquartile range of high-frequency limits than EI and BSA upcalls. The bandwidths of EI vocalizations resulted in a relatively small interquartile range similar to BSA measurements but had slightly lower values compared to vocalizations from BSA. However, bandwidths of GM vocalizations were spanning a larger overall and interquartile range. The remaining robust frequency measurements (center frequency, frequency 25%, frequency 75%, frequency 5%, frequency 95%) all indicated a very similar pattern. Robust frequency measurements of upcalls detected at EI had a comparable range to BSA vocalizations, while GM upcalls were characterized by a much greater range, including a greater and higher interquartile range, as well as a higher median. However, EI vocalizations had a higher and greater interquartile range than BSA vocalizations. The slope of analyzed vocalizations showed very similar and small ranges for EI and BSA upcalls, all located below 500 Hz/s, while the overall range of GM vocalizations was considerably different. Analyzed upcalls spanned from around 400 Hz/s up to over 3000 Hz/s, with a median of around 900 Hz/s. These median and range differences in frequency measurements are reflected in the performed pairwise comparison, which also indicated greater, but similar differences between GM vocalizations and detected vocalizations at EI and BSA, respectively (GM – EI SumOfSqs = 38.776119 and p-value = 0.001, GM – BSA SumOfSqs = 38.5435545 and p-value = 0.001). Temporal measurements of the vocalization (duration and duration 90%) showed similar patterns with respect to the parameter ranges of groups. The overall range for EI upcalls was comparable to BSA upcalls, but the median and height of the interquartile range was more similar to GM upcalls. These variations are reflected in the pairwise comparison between EI and BSA applied to the whole dataset (SumOfSqs = 6.143 and p-value = 0.001), which indicated small dissimilarities between EI and BSA upcalls. Consistent with these results are the outcomes of the performed SIMPER analyses, which indicated that the measurements slope, delta frequency and high frequency mainly drove differences between GM and EI, and GM and BSA. According to this analysis, the minor differences between EI and BSA were driven by slope, frequency 75%, and center frequency.

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B. Automatic classification of vocalizations

The random forest model using manual measurements successfully discriminated between SRW and HW upcalls and classified the vocalizations detected off EI as SRW upcalls. The average model out-of-bag (OOB) estimate of error rate was 0%, with HW and SRW vocalizations having a miss rate of 0%, resulting in a 100% accurate classification. While the conducted Boruta algorithm considered all performed manual measurements relevant for classification, the most important measurements to discriminate between species vocalization using the model were slope and delta frequency.

IV. DISCUSSION

A. Southern right whale vocalizations

Previously unidentified vocalizations recorded at EI, Antarctica in 2013 were characterized and successfully attributed to SRWs. The measured mean start frequency of the EI vocalizations was 113 Hz monotonically increasing to a mean end frequency of 181 Hz, with a mean slope of 137 Hz/s. These upcall characteristics are broadly similar to the measured characteristics of SRW vocalizations at BSA. Apart from a similar mean duration (EI, 0.56 s and GM, 0.52 s), EI vocalizations were notably different from HW vocalizations recorded at GM, with a mean slope of 1024 Hz/s and a mean bandwidth of 452 Hz as the main contributors to differences between groups, allowing to successfully differentiate SRW upcalls from HW vocalizations (Tables III and IV). We cannot exclude the possibility that the acoustic measurements are biased by the analyst's manual logging of individual vocalizations, but this method is widely used in the literature to investigate call parameters (e.g., Dombroski *et al.*, 2016; Webster *et al.*, 2016; Calderan *et al.*, 2021). Further, we extracted robust measurements (center frequency, frequency 25% and frequency 75%, frequency 5% and 95%, duration 90%) that do not entirely rely on time and frequency end points but on the energy distribution within the selection. Thus, small changes in borders of the selection should have little influence on the resulting robust measures (Charif *et al.*, 2010).

Based on the manual measurements the random forest model was able to accurately (100%) discriminate between SRW and HW upcalls, and successfully attributed the unidentified EI upcalls to SRWs. Similar to other studies (Hannay *et al.*, 2013; Rankin *et al.*, 2017) our model is showing a high achieved accuracy. In general, the random forest approach ingesting the measurement's bandwidth and slope has a high potential to support and facilitate automated detections of right whale upcalls in PAM data.

The measured means of vocalization parameters of SRWs at EI and BSA are within the time and frequency ranges of right whale vocalizations first described by Clark (1982). The EI vocalizations' bandwidths are broadly similar to approximated bandwidths of SRW vocalizations detected off South Georgia (Calderan *et al.*, 2021), off the Auckland Islands (Webster *et al.*, 2016), and on breeding grounds off Brazil (Dombroski *et al.*, 2016). The measured mean of the upper frequency limit of EI upcalls is similar to upcalls recorded by Širović *et al.* (2006) off South Georgia (Table IV). The mean duration of analyzed EI upcalls is relatively short, compared to previously mentioned studies. Only Dombroski *et al.* (2016) describe SRW upcalls off Brazil with similar durations (0.6 s).

In addition to the evident similarities of the EI upcalls with other SRW upcalls, we found a remarkable increase in 21 Hz on average for the low frequency limit of EI upcalls compared to SRW upcalls from other regions (Calderan *et al.*, 2021; Širović *et al.*, 2006; Webster *et al.*, 2016). Comparable low-frequency limits have only been measured in North Atlantic right whale upcalls detected in the northwest Atlantic (Parks *et al.*, 2007), an area characterized by high levels of anthropogenic noise e.g., from shipping and fishing (Parks *et al.*, 2009; Parks *et al.*, 2011). Changes in background noise conditions are known to not only be possible drivers for changes in vocalization amplitudes, also known as the Lombard-effect (Helble *et al.*, 2020; Scheifele *et al.*, 2005), but also for changes in frequency limits of vocalizations, as well as their duration (Parks *et al.*, 2011; Parks *et al.*, 2016). Parks *et al.* (2016) found that the low-frequency limit of SRW vocalizations shifted to higher frequencies compared to baseline conditions, when dominant background noise at lower frequencies than SRW

TABLE IV. Selected acoustic characteristics of vocalizations of two right whale species and humpback whales from different studies. (Values in parentheses are standard deviations, not available for Webster *et al.*, 2016).

	Right whale								Humpback whale	
Species	This study - EI E. australis	This study - BSA E. australis	Calderan *et al.* (2021) E. australis	Webster *et al.* (2016) E. australis	Širović *et al.* (2006) E. australis	Dombroski *et al.* (2016) E. australis	Parks *et al.* (2007) E. australis	Parks *et al.* (2007) E. glacialis	This study - GM M. novaeangliae	Wild and Gabriele (2014) M. novaeangliae
Area	Elephant Island	Bahía San Antonio	South Georgia	Auckland Islands	South Georgia and Scotia Sea	Brazil	Argentina	Bay of Fundy	Greenwich Meridian, ASSO	Southeastern Alaska
Mean duration	0.56 (0.27)	0.89 (0.26)	0.8 (0.27)	0.9	0.7 (0.1)	0.6 (0.2)	0.82 (0.23)	0.87 (0.27)	0.51 (0.2)	0.2 (0.1)
Mean low frequency	113.97 (24.26)	76.67 (38.28)	86 (10)	87	92 (11)	58 (22)	78 (15)	101 (22)	116.57 (55.48)	52 (13)

vocalizations was present. This phenomenon has also been studied in other species (e.g., *Parus major*; Slabbekoorn and den Boer-Visser, 2006) and in *Stenella coeruleoalba* (Papale *et al.*, 2015). Background noise conditions are not only influenced by anthropogenic noise but also by biological sound sources (e.g., fish chorus). To avoid acoustic competition among species sharing the same acoustic environment, many animal species are thought to adapt to specific acoustic niches (i.e., timespans and frequency bands with comparatively little overlap with other species). This niche can be extended through frequency modulation, for example, when an (acoustic) invasion of another species occurs (Both and Grant, 2012; Mossbridge and Thomas, 1999). Off EI, fin whales are known to produce a variety of low-frequency, but high-intensity vocalizations within frequency limits of 15–89 Hz (Burkhardt *et al.*, 2021; Širović *et al.*, 2004). Fin whales aggregate in great numbers off EI from mid-February to August, during the same time period as SRWs are acoustically present in our data. Since this is resulting in high amplitude levels within the frequency bands used by the local fin whales (Burkhardt *et al.*, 2021), they may compete for acoustic space with SRWs off EI, possibly leading to shifts in SRW vocalization parameters. An acoustic energy analysis in the typical fin whale frequency bands of 13–28 and 84–89 Hz for the analyzed recording snippets from this study shows different energy levels in background noise at the three different locations. The results suggest that fin whales are a significant source of background noise at EI in comparison to the other two locations, which may be the cause for a shift of the low frequency limit of SRW upcalls. The shift in frequencies might be a short-term adjustment of the Argentinian SRW population, since a study by Zerbini *et al.* (2018) shows SRWs migrating from Argentinian breeding grounds to feeding grounds off South Georgia and even further south. However, this short-term adjustment could not only be triggered by acoustic presence of fin whales but also through a functional change of the vocalization on the feeding ground in comparison to on breeding grounds or the competition for an acoustic niche with other sound sources, including anthropogenic noise (while no other potentially interfering sounds could be identified in the data). The clarification of this phenomenon requests further research.

B. Potential applications using PAM

The upcall is the most prevalent and best-studied vocalization within the SRW's vocal repertoire, thought to be used as a contact call between individuals (Clark, 1982). Since upcalls are produced by both sexes, all age classes, and during a range of behavioural contexts (Parks *et al.*, 2011), it represents an adequate signal for the comprehensive assessment of acoustic presence of this species, therefore most commonly used for passive acoustic detection (Urazghildiiev *et al.*, 2009). The automated detection of upcalls can also serve as an indicator for the potential presence of other SRW vocalizations which can subsequently be identified and analyzed in more detail and provide additional information on group composition, breeding, feeding, or social behaviour (McDonald and Moore, 2002). In addition to behavioural insights, detections of right whale upcalls can provide information on single whale identity and age class, which are mainly dependent on spectral entropy and duration (McCordic *et al.*, 2016). In addition, acoustic cue counting using upcalls has proven successful in estimating right whale density in the northern Pacific (Marques *et al.*, 2011). In the northwest Atlantic, PAM is used for the real-time detection of North Atlantic right whale (*Eubalaena glacialis*) upcalls (Spaulding *et al.*, 2009; Van Parijs *et al.*, 2009) not only for information on their distribution but also for collision mitigation, as ship strikes are a major mortality cause for the highly endangered North Atlantic right whale (Campbell-Malone *et al.*, 2008). For all these applications of PAM, the ability to correctly detect vocalizations and distinguish between co-occurring species is essential. This study shows that especially frequency related measurements such as slope, delta frequency and high frequency can be applied to distinguish between SRW and HW upcalls in future acoustic studies.

In addition to a direct automated classification to discriminate between SRW and HW upcalls, another approach is to include the acoustic context (e.g., Kowarski *et al.*, 2023), which we applied for the confirmed HW upcalls in the GM data by only logging upcalls within HW song. However, HWs produce upcalls not only in the song context but also as social sounds (Dunlop *et al.*, 2007). Therefore, only relying on HW song patterns would not be a sufficient approach for the discrimination of upcalls. Moreover, in the case of the EI data, no other SRW vocalizations could be identified which could have been used for an acoustic context decision. This missing of other SRW vocalizations at EI could be due to shallow topography at the recording location leading to a complex acoustic propagation scenario (Burkhardt *et al.*, 2021; Forrest, 1994; Kularia *et al.*, 2016; McKenna *et al.*, 2021). Kowarski *et al.* (2023) considered upcalls to be produced by right whales, only, if there was not a HW vocalization confirmed or suspected within 2 h of the detection, or if it occurred with a right whale gunshot. However, since gunshots are thought to be produced by males only the acoustic presence of right whales would be sex-biased. Moreover, the approach by Kowarski *et al.* (2023) might miss right whales present at the same time as HWs. Therefore, we believe that an automated detection and classification approach for SRWs based on the acoustic features of upcalls is more likely to produce unbiased and comprehensive results for long-term and large-scale studies.

C. EI—A potential foraging ground

The combined investigation of environmental factors, anthropogenic impacts, and soundscapes including the specific identification of SRWs' and other species' vocalizations is of high interest to understand the future of Southern Ocean ecosystems. In order to protect and conserve species or populations as effectively as possible, the identification of areas of importance for the species or population is crucial. While current SRW breeding grounds are well-studied, contemporary data on feeding ground locations south of 40 °S are sparse. The identification of feeding grounds could lead not only to an improved understanding of SRWs spatiotemporal distribution but also to a better knowledge of environmental variables that may be linked to reproductive success. Thus, the identification of possible feeding grounds is a key part of the International Whaling Commission–Southern Ocean Research Programme (IWC-SORP) research theme 6 (Vermeulen *et al.*, 2021). Based on the analyzed vocalizations SRW presence off EI was detected in austral summer (January and February), austral autumn (March to May), and in austral winter (August; see Fig. S3 in the supplementary material[1]), with a peak of 775 detected upcalls on a total of 11 days in April. At EI, the SRWs' temporal acoustic presence is accompanied by phytoplankton blooms from January to March, and the waters are characterized by high krill densities, including Antarctic krill (*Euphausia superba*), a main food source of SRWs and other baleen whales (Siegel, 2005). Therefore, EI could not only be a key feeding ground for fin whales (Burkhardt *et al.*, 2021) and HWs (Schall *et al.*, 2020), but presumably also for SRWs.

V. OUTLOOK

Our study shows the feasibility of successfully and accurately distinguishing between SRW and HW upcalls, providing the vocalization parameters determining the main differences in call characteristics between species for future PAM studies, and facilitating the correct detection of SRW acoustic presence and behavior. The present analysis only provides the first insights into the spatiotemporal distribution of SRWs in the ASSO, and confirmed sightings are located not only around the Antarctic Peninsula but also in other sub-Antarctic and Antarctic areas (Vermeulen *et al.*, 2021), indicating that there is potential for future PAM studies. For example, all available acoustic data of the EI recorders since 2012, spanning nine years of recordings (Rettig *et al.*, 2013), should be analyzed for the presence of SRW upcalls using the newly gained knowledge on how to classify these vocalizations. Additional PAM effort should preferably overlap with sighting data presented in Vermeulen *et al.* (2021), and extend eastwards in a transect around 60 °S from EI. Since contemporary data on possible SRW feeding grounds south of 40 °S is scarce, more comprehensive analyses of acoustic recordings would help to understand SRWs spatiotemporal distribution and migration patterns. Joint analyses of environmental conditions and SRWs' distribution data could help to identify drivers of distribution patterns and habitat choice (Payne *et al.*, 2017). These analyses together with ecological knowledge of trophic relationships and a quantitative understanding of spatial and temporal lags between physical drivers and ecological response can be used to calculate forecasts on monthly, annual, or even decadal scales (Barlow and Torres, 2021). Such spatiotemporal predictions are vital for effective management implementations (Barlow and Torres, 2021; Williams *et al.*, 2006), such as marine protected areas, especially in a region like the Antarctic Peninsula facing one of the fastest regional warming rates on Earth (Rogers *et al.*, 2020; Vaughan *et al.*, 2003) and rising anthropogenic pressure (Morley *et al.*, 2020).

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[1]See supplementary material at https://doi.org/10.1121/10.0019633 for additional tables and figures.

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