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Animal-borne tags provide insights into the acoustic communication of southern right whales (*Eubalaena australis*) on the calving grounds

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Abstract: This study investigated the repertoire, call-type variability and call rates of southern right whales on a calving ground off Brazil in the western South Atlantic. Acoustic tag data were collected from four lactating females and one juvenile. Pulsive, hybrid, and upcalls showed the greatest variability among call-types with up to 23% of non-standard forms detected. Quiet sounds (grunt, single, and double pulse) were detected for the first time in this species on the calving grounds. Although the sample size was limited, results suggest that social interaction increased call-type diversity and call rates, in line with other acoustic studies on right whales.

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1. Introduction

The acoustic communication of right whales (North Atlantic right whales: *Eubalaena glacialis*, NARWs; North Pacific right whales: *Eubalaena japonica*, NPRWs; and southern right whales: *Eubalaena australis*, SRWs) has been extensively investigated over the past four decades due to increasing use of passive acoustic monitoring (PAM) to investigate and monitor the species across different habitats.[1] The acoustic repertoire of right whales is comprised of calls along a continuum of sounds that can be classified into broad call-type categories based on aural and visual characteristics.[2,3] Clark[4] defined six call-types (upcall, downcall, constant, high, hybrid, pulsive) and two non-vocal sounds (blows and slaps). Subsequent studies showed that all right whale species share call types in their repertoire, including the "upcall," an up-sweep tonal sound commonly used in PAM studies.[5] Over the years, authors adapted call-type classification to broader and more parsimonious categories. For example, Parks and Tyack[6] grouped hybrid, pulsive, and high calls in one category: "scream," which minimized the number of call-types described. Manual categorization of a continuous repertoire has drawbacks[7] as the assumption that calls must fit within predetermined categories or that all calls in one category will always look and sound the same may be inaccurate. Consequently, important information on variability in call types that compose the repertoire of right whales may be lost. This could have consequences when interpreting call rate data, increasing uncertainty when applying this information in density estimation or call function studies.[5,7]

Investigating right whale bioacoustics using animal-borne sensors has allowed better understanding of right whale communication.[8–10] On the calving ground off Florida and Georgia, low-amplitude call types were recently described from tagged NARWs. Lactating females[9,10] produced brief single- and double-pulse sounds while both juveniles and lactating females produced short-duration low-amplitude grunts.[9,10] These low-amplitude calls on tag recordings were not detectable by fixed bottom-mounted sensors or towed arrays.[9] Parks *et al.*[9,10] and Nielsen *et al.*[8] found that lactating females on the calving grounds produced calls with lower

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received levels and that call rates were lower than in other habitats for both NARWs and SRWs. In the South Atlantic, the repertoire of SRWs on the calving grounds has been described exclusively based on recordings from bottom-mounted sensors and hydrophone arrays.[4,11] Therefore, to fully explore the SRW repertoire, studies including animal-borne acoustic sensors are necessary. The objective of this study was to increase our understanding of the call types and call rates of SRWs off Brazil using recordings obtained from animal-borne acoustic tags.

2. Methods

2.1 Data collection

During the austral winters of 2018 and 2019 we conducted tagging on a SRW calving ground in the western South Atlantic off Brazil, in the state of Santa Catarina. In 2018, we collected data in Ribanceira/Ibiraquera Bay (28°11′26.0952″S/48°39′42.318″W), a location that consistently had the highest sightings of SRW mother-calf pairs along the Brazilian coast.[12] In 2019, due to rough sea state conditions, tagging was conducted at Itapirubá Norte (28°19′48.3″S 48°42′30.8″W) an embayment with similar oceanographic characteristics to Ribanceira/Ibiraquera where right whales are consistently sighted throughout the season.[12]

Tagging was conducted from rigid hull inflatable boats using a hand-held carbon-fiber pole to attach Digital Acoustic Recording Tag (DTAGs)[13] (version 3 and 4) with suction cups to SRWs. Before a tagging attempt, we observed whale behavior for ≥10 min within 300 m of the group, and collected photographs for individual identification (photo-id). We determined the reproductive state of tagged individuals based on field observations and data from the photo-id catalog maintained by Instituto Australis. We defined lactating females as adult individuals, presumed to be females, accompanied by a significantly smaller individual (∼1/3 adult body length), presumed to be her calf. Juveniles were identified as unaccompanied individuals evidently smaller than adults.[14] After losing suction before the actual program detachment time, tags floated to the surface. Using VHF telemetry, we tracked the tags and recovered the devices either floating in the water or washed up on the beach.

DTAGs were equipped with 3-axis accelerometer and magnetometer, temperature and pressure sensors, as well as hydrophones.[13] DTAG-4s were equipped with archival GPS. Sensor data were collected at 50 and 100 Hz in 2018 and 2019, respectively. To minimize flow-noise, a single-pole 400 Hz Butterworth high-pass filter was applied to all acoustic recordings. In 2018, DTAG-3s and 4 s recorded audio at a sampling rate of 120 kHz. In 2019, DTAG-4s recorded audio at 64 kHz.

2.2 Data analysis

Acoustic recordings were decimated to 16 kHz sampling rate using Sound eXchange,[15] yielding an analysis bandwidth up to 8 kHz. Recordings were manually browsed for SRW sounds using Raven Pro 2.0.[16] Spectrograms were calculated with a 1024 Fast Fourier Transform (FFT) point Hann window with 90% overlap. Deployment duration was determined from a combination of acoustic cues and the pressure record from the DTAGs.

Call types. We classified call types based on acoustic and visual characteristics according to Clark[4] and Parks *et al.*[9] All calls with a signal-to-noise ratio (SNR) ≥6 dB were included for further analysis. We determined the SNR based on an average energy of the call and ambient background selections as described in Dombroski *et al.*[11] Raven software automatically extracted time and frequency parameters of calls (see Table S1 in the supplementary material[21]).

Call rate. We used transmission loss data and acoustic evidence of interactions with other individual(s) to assign calls to the tagged whale (focal) or nearby individuals (non-focal). We assessed the probability of detecting high SNR calls from non-focal whales on the tag record by estimating the transmission loss for the center frequency of SRW upcalls (102 Hz) in this habitat using the Monterey-Miami Parabolic Equation (MMPE) model.[17] Evidence of social interactions with other individuals from the audio record was based on the detection of splash and blow sounds when the tagged whale was submerged (>0.5 m), as well as detection of overlapping calls. We used the pressure data from the DTAGs (±0.5 m) to determine the depth of the tag when calls were detected. Call rates were calculated based on the total number of presumed focal calls detected on the tag audio divided by the total duration of the deployment.

3. Results

3.1 Data collection

We deployed DTAGs on five SRWs (4 lactating females and 1 juvenile) between July and August in 2018 and 2019 totaling 22.7 h of tag data. Mean [± standard deviation (SD)] attachment duration was 4.5 h ± 3.6 h (Table 1).

Table 1. Call rates (call h^{-1}) of single and double pulses (S-D pulse), upcall, and overall calls (upcall, downcall, constant, high, hybrid, pulsive, and variations combined) per deployment. Deployment id has a two-letter species abbreviation from its Latin name, two digits of the year in which tagging occurred followed by the Julian day on which tagging occurred, and a letter that corresponds the deployment order on that day.

Deployment id	Reproductive state	Deployment duration (h)	S-D pulse rate (call h^{-1})	Upcall rate (call h^{-1})	Overall call rate (call h^{-1})
ea18_202a	Lactating	0.98	2.04	2.04	19.38
ea18_202b	Lactating	6.44	1.08	0.15	0.31
ea18_228a	Juvenile	8.30	0.24	22.65	47.83
ea19_220a	Lactating	0.16	0	0	0
ea19_220b	Lactating	6.78	2.65	0.29	1.03

Call types. A total of 454 high-SNR calls were detected. Examples of call types with the most within-category variation are shown in Fig. 1. These variations included non-stereotyped upcalls with a variety of frequency slopes as well as down-up and up-down frequency sweeps comprising 23% of upcalls (Mm. 1—examples of up, down-up, and up-down sweeps classified as upcalls), hybrid calls with several combinations of alternating tonal and pulsive structure totaling ~8% of hybrid calls, and pulsive calls with a wide range of durations (from 0.24 s to 12.28 s). According to the MMPE model output (see the supplementary material[21]), transmission loss in this shallow habitat ranges between 40 dB and 50 dB at 1 m depth at a 300 m range and over 70 dB at 1 m at a 1 km range. Based on previous studies, typical spacing between female-calf pairs and other pairs and whale groups on the calving grounds in the South Atlantic is >300 m,[12,18] suggesting that it is highly unlikely to detect high SNR calls from distant whales on the tags of lactating females. As there was no acoustic evidence of interactions with other whale groups (see Sec. 2) we found that all calls detected on tags from lactating females were likely to be produced by the tagged whale or the associated calf. For the juvenile tag, however, blows, splashes, and overlapping calls suggest that non-focal whales were within close-range (<300 m) of the focal whale for periods of the record. Therefore, it is possible that some of the high SNR calls detected were produced by non-focal animal(s) during these social interactions on the juvenile tag recordings.

Lactating females showed overall low call production, including one short (9.6 min) deployment having no calls. The lactating females produced isolated single and double pulse sounds (examples included in Mm. 2) and ea19_220b produced sequences of pulses (Fig. 2). We also detected tonal and hybrid calls on the acoustic record of ea18_202a and upcalls on ea19_220b. In contrast, for the juvenile's tag (ea18_228a) we found the greatest diversity of call types, including pulsive, hybrid calls, tonal calls, upcalls, and paired grunts. Paired grunts were detected before upcalls, pulsive, and tonal calls and after upcalls (Fig. 2; examples of paired grunts before and after upcalls included in Mm. 3). Single pulses were also detected in the acoustic record of ea18_228a and it is unclear if these sounds were produced by the tagged whale as they were detected during social interactions with other whales. The overall number of calls by call-type on each tag can be found on Table 2. Acoustic parameters (average ±SD) for call types are included in Table S1 in the supplementary material.[21]

Mm. 1. Upcalls forms (standard, down-up, up-down) found on the acoustic record of DTAGs deployed on SRWs off Brazil. This is a file of type "mp3" (24.8 Kb).

Mm. 2. Double and single pulse sounds detected on the acoustic record of DTAGs deployed on SRWs off Brazil. This is a file of type "mp3" (9.7 Kb).

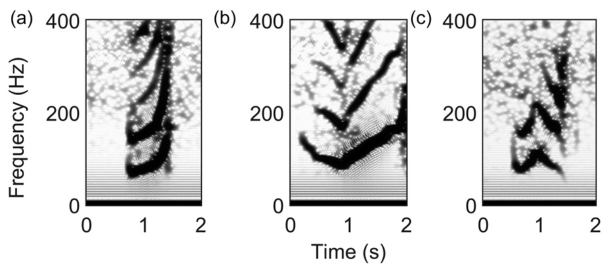

Fig. 1. Upcall types detected on the acoustic record of DTAGs deployed on SRWs off the calving ground in Brazil. Upcalls were found as (a) standard, (b) down-up, and (c) up-down forms. Spectrograms were calculated using Hann window, 1024 FFT points, and 90% overlap.

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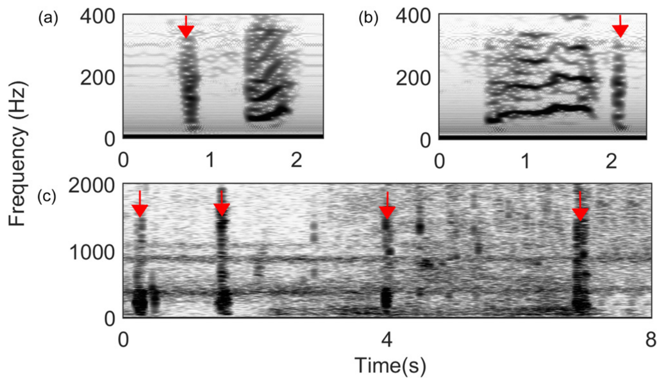

Fig. 2. (Color online) Low amplitude right whale calls detected on the acoustic record of DTAGs deployed on SRWs on the calving grounds off Brazil. Paired grunts were detected on the juvenile tag ea18_228a (a) before and (b) after calls as marked with arrows. In one lactating female tag (ea19_220b) we found (c) a sequence of single and double pulses where pulses are marked with an arrow. Spectrograms were calculated using Hann window, 1024 FFT points, and 90% overlap.

Mm. 3. Paired grunts were detected on deployment ea18_228a (juvenile SRW tagged off Brazil) before and after calls. This is a file of type "mp3" (15.9 Kb).

Call rate. Overall call rates and upcall rates of lactating females were lower than the call rate of the juvenile (Table 1). Despite the high overall call rate (47.83 call h^{-1}) for the juvenile, we did not find calls throughout the tag deployment. Instead, we noticed periods of intense vocal activity from 0 to 1.5 h and from 6.1 to 8.3 h of the deployment. Based on evidence of surface social activity detected in the acoustic record, this whale was involved in social interactions with at least one other individual during the second period of intense vocal activity. For the first period of intense acoustic activity we did not find evidence of interactions with other individuals. These periods of elevated call rates were separated by an interval with only 2 calls detected in ~4.6 h (Fig. 3). Double and single pulse rates were higher for lactating females. These calls were found in bouts and the tags had long periods in which no calls were detected. Average ±SD depth of the tag on ea18_228a (juvenile tag) was 1.7 m ± 0.8, max depth of 4.5 m and average tag depth where calls were detected was 1.4 m ± 0.9. For tagged females that produced calls (ea18_202a, ea18_202b, ea19_220b), average ±SD depth of the tag was 0.5 m ± 0.5 with max depth of 5.1 m and average call depth was 0.8 m ± 0.6.

4. Discussion

Among the previously described SRW sounds detected on the acoustic record of tags deployed off Brazil, we found standard and variable forms of call-types. The greatest diversity of calls, as well as call-type variations, coincided with acoustic evidence of assumed interactions with other individuals supporting findings from previous studies suggesting that social behavior can, among other factors, drive the use of larger and more diverse repertoire.[4,6,19] Call-types with greater variability included hybrid, pulsive, and the upcall. The upcall is a contact-call used as the primary acoustic cue to detect right whale presence and to estimate cue rates for acoustic density estimation in PAM studies.[1,4,5] In our study, we classified the standard upsweep, the up-down sweep, and the down-up sweep as upcalls. In NPRWs, down-up and up-down sweep calls were also included in the upcall call-type.[20] In contrast, a previous study of SRWs classified the down-up sweep separately from upcalls as "V-call."[11] Excluding non-standard upcalls from call rate estimates can affect conclusions about call usage and applications of PAM to monitor the species.[7] As failure to report variations within call-type classification prevents valid comparisons across

Table 2. Summary of call-types found on the acoustic record of DTAGs attached to SRWs off Brazil.

Deployment id	Calf	Upcall	Downcall	Constant	High	Hybrid	Pulsive	Gunshot	Paired grunt	S/D Pulse	Total calls
ea18_202a	5	2	1	0	1	10	0	0	0	2	21
ea18_202b	0	1	0	1	0	0	0	0	0	7	9
ea18_228a	0	188	17	29	10	58	79	2	14	2	399
ea19_220a	0	0	0	0	0	0	0	0	0	0	0
ea19_220b	0	2	0	4	0	0	1	0	0	18	25
Total	**5**	**192**	**18**	**34**	**11**	**61**	**80**	**2**	**14**	**29**	**454**

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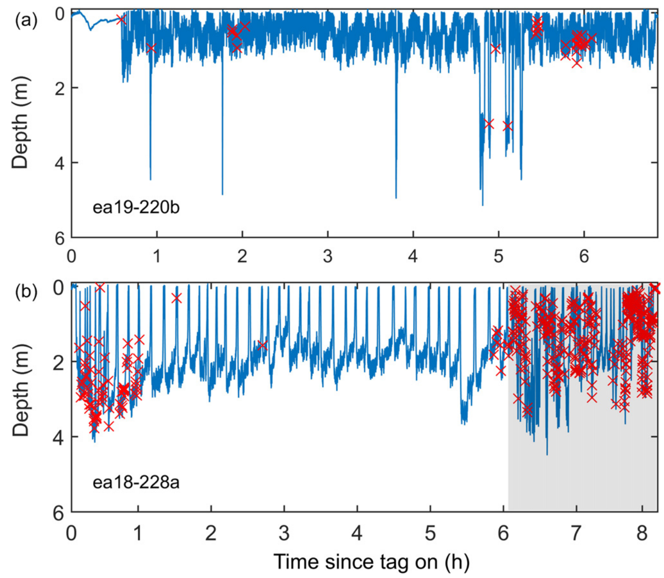

Fig. 3. (Color online) Dive profiles (depth vs time since tag on) of two SRWs tagged off Brazil. The "x" indicates time and depth when calls were detected for (a) a lactating female tagged in 2019 and (b) a juvenile right whale tagged in 2018. For both individuals, calls were produced in bouts and on the juvenile tag, periods on intense calling coincide with elevated surface activity level and potentially interactions with at least one other whale (gray area).

study areas and species,[7] we recommend authors be explicit about the variability of calls included in call-type classification in an effort to increase comparability of findings.

Lactating females tagged off Brazil produced the same low-amplitude pulses (single and double pulses) that were first described from acoustic tags on NARWs,[9] suggesting that these sounds are present in at least two right whale species. In SRWs, similarly to NARWs, these sounds were produced more frequently than other call types by lactating females.[8,10] It has been hypothesized that these low-amplitude sounds could be used for close-range, cryptic communication between lactating females and calves.[8–10] Interestingly, we also found single and double pulses on the acoustic record from a tag deployed on the juvenile whale. However, because there was acoustic evidence of close-range interactions with other individuals, it is unclear whether these signals were being produced by the tagged whale, or by another individual at close range from the focal whale. Paired grunts were detected in the acoustic record of the juvenile's tag (ea18_228a), before and after high amplitude calls. However, not all calls in ea18_228a were preceded or succeeded by paired grunts, even when no acoustic evidence of nearby individuals was found, suggesting greater variability in paired grunt production than previously described.[9] Finally, previous descriptions of the acoustic repertoire of SRWs off Brazil using bottom-mounted sensors did not include paired grunts, double, and single pulses.[11] We were only able to detect these low-amplitude calls by using animal-borne acoustic tags highlighting the importance of this tool to investigate basic questions about the acoustic communication in baleen whales.

By using animal-borne tags we were able to estimate call rates on the calving grounds off Brazil. The call rates of high amplitude calls on the juvenile tag were higher than for lactating females. However, this was a single tag deployment and we were unable to distinguish between focal and non-focal calls during social interactions for the juvenile tag. Despite a limited dataset, our results support a relationship between whale-group call rate and behavioral state as previously demonstrated for NARWs and SRWs.[4,19] At least one period of higher calling rates coincided with evidence of social and active behavior by the juvenile while no evidence of social interactions were detected during periods of low call rates. Clark[4] described similar results on SRWs off Argentina: rates of high, hybrid, pulsive calls were significantly higher during mild, full, and sexual behavior than during swimming and resting. For NARW female-calf pairs higher calling rates were detected during surface active and play behavior which comprised a small percentage of the pair's activity budget.[19] Low-energy behaviors such as resting accounted for the majority of NARW female-calf pair's activity budget which coincided with low call rates.[19] The low call rate reported here is consistent with tag data showing that female-calf pairs engaged predominantly in low-energy behavioral states. Therefore, when conducting PAM studies on the calving grounds, call rates and call types must be interpreted not only as indicative of the number of the right whales present, but also as a proxy for the predominant behavioral state displayed by whales in the area.

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[21]See supplementary material at https://doi.org/10.1121/10.0001391 for a list of acoustic parameters and definitions, for MMPE input parameters and output, and for a table with acoustic parameters extracted from calls types detected on tags deployed on SRWs off Brazil.