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NOTE

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Acoustic occurrence, diel-vocalizing pattern, and detection ranges of southern right whale gunshot sounds off South Africa's west coast

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Southern right whales (SRWs), *Eubalaena australis*, have a cosmopolitan distribution in the Southern Hemisphere but are known to overwinter in four coastal breeding grounds off Argentina, Australia, New Zealand, and South Africa (International Whaling Commission [IWC], 2001; Jackson et al. 2016; Jefferson et al., 2015; Webster et al., 2019). SRWs perform seasonal migrations southwards in summer to Antarctic and sub-Antarctic waters where they feed mostly on copepods and krill (euphausiids), and northwards in winter to warm waters of the low latitudes for mating, calving, and nursing (Bannister et al., 1999; Best, 2007; IWC, 2001; Jefferson et al., 2015; Mate et al., 2011). However, Best (2006) and Mate et al. (2011) showed that the coastal waters of the South African west coast are also used as an austral spring/summer feeding ground by the portion of the population that remains there year-round. Seasonal acoustic occurrence of SRWs in South African waters is currently based on short-term shallow coastal (adjacent to the coast and within the 100 m isobath) research (Figure 1; Hofmeyr-Juritz, 2010; Vinding-Petersen, 2016). An expansion of such acoustic work to more offshore waters (Figure 1) and more long-term programs is useful for a more comprehensive understanding of the species' seasonal occurrence patterns.

Twelve call types of SRWs have been defined to date in South African waters (Hofmeyr-Juritz, 2010; Hofmeyr-Juritz & Best, 2011). Additionally, SRWs produce a short, distinctive broadband explosive sound termed the gunshot sound (Clark, 1983; Hofmeyr-Juritz & Best, 2011; Webster et al., 2016). The gunshot sound is termed so "because of

[Correction added on 20th May 2022, after first online publication: The copyright line was changed.]

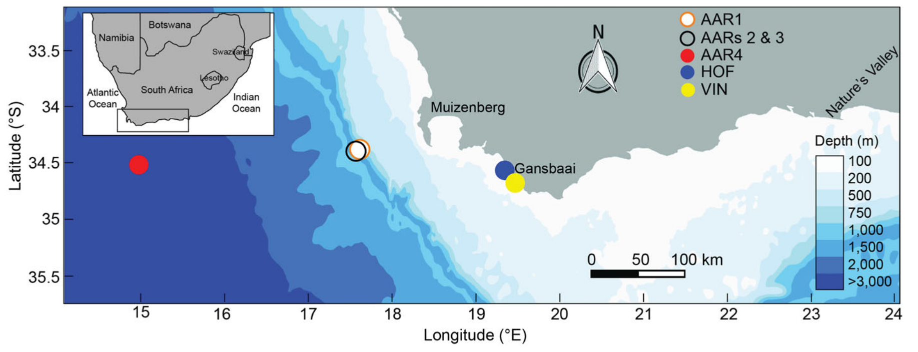

FIGURE 1 Map showing deployment positions of our autonomous acoustic recorders (AARs) off the west coast of South Africa, Atlantic Ocean. Locations of hydrophones for previous two acoustic studies in South Africa are also indicated, where HOF is for Hofmeyer-Juritz and Best (2011), and VIN is for Vinding-Petersen (2016).

its acoustic similarity to the sound of a rifle being fired" (Parks et al., 2005). North Pacific right whales (NPRWs), *Eubalaena japonica*, produce these sounds as songs (Crance et al., 2019). Both male and female right whales produce gunshot sounds using an unknown mechanism (Clark, 1983; Crance et al., 2017; Gerstein et al., 2014; Parks et al., 2005, 2012). Functions of the gunshot sound are hypothesized to include male acoustic reproductive advertisements directed at females and agonistic signals directed at other males that are not necessarily related to reproductive advertisement (Crance et al., 2019; Matthews et al., 2014; Parks et al., 2005). Gerstein et al. (2014) demonstrated that North Atlantic right whale (NARW), *Eubalaena glacialis*, adult females with newborn calves produced gunshot sounds for maternal alarms and for communication with their calves. It is also suggested that the gunshot sound could be used for echolocation, specifically to navigate, forage, and find other silent whales (Parks et al., 2005); however, there is currently no direct evidence to support such sound functions (Crance et al., 2017, 2019; Parks et al., 2005).

Parks et al. (2005) found the NARW gunshot sound to contain an initial signal (believed to be the direct path from the whale to the hydrophone) followed by an echo with prolonged reverberation of the signal (Figure 2) as a reflection of the original signal off the seabed (multipath arrival). SRW gunshot sounds have been reported previously without echoes from two coastal areas on the southwest coast of South Africa (Figure 1): Walker Bay, Gansbaai area (<30 m water depth and 5 m hydrophone depth; Hofmeyer-Juritz & Best, 2011) and Greater Dyer Island, Gansbaai area (<100 m water depth and 15 m hydrophone depth; Vinding-Petersen, 2016). Gunshot sound 100% duration of South African SRW population was previously reported to be 0.36 ± 0.15 s (mean ± standard deviation), and have a starting frequency of 80 ± 46 Hz and an end frequency of 20 ± 14 kHz (Vinding-Petersen, 2016). The 100% duration of the South African SRW gunshot is longer than 0.2 ± 0.01 s of SRWs off New Zealand (Webster et al. 2016), NARWs of 0.04 ± 0.02 s by Parks et al. (2005), and 0.09 ± 0.07 s by Trygonis et al. (2013).

We used passive acoustic monitoring data to study a SRW population that is recently of high concern in South African waters due to its low calf counts in the recent years (e.g., Findlay et al., 2017; Vermeulen et al., 2019). This study describes both the seasonal acoustic occurrence and diel-vocalizing pattern, while modeling the detection ranges of SRW gunshot sounds off the west coast of South Africa.

Bioacoustic data were collected between 2014 and 2017 at three different sites off the west coast of South Africa (Figure 1, Table 1) as part of the South African Blue Whale Project (SABWP) to study the acoustic occurrence and behavior of Antarctic blue whales, *Balaenoptera musculus intermedia* (Findlay et al., 2012; Shabangu & Findlay, 2014; Shabangu et al., 2019). Four autonomous acoustic recorders (AARs) of Autonomous Underwater Recorder for Acoustic Listening (AURAL; Model 2 version 04.1.3, Multi-Électronique Inc., Rimouski, Canada) were used to record the acoustic data. These AARs were deployed on oceanographic moorings, and locations, deployment information, and recording parameters of each AAR are specified in Table 1. Temperature of the water column was

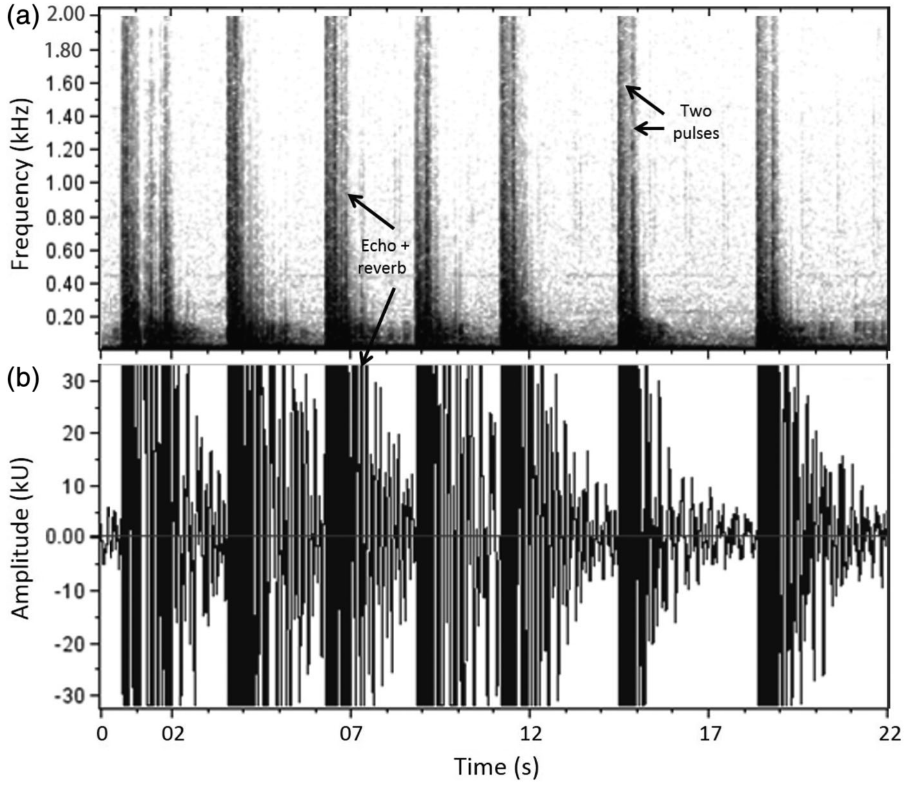

FIGURE 2 Spectrogram of gunshot sounds composed of two pulses together with their echoes and reverberation (a), amplitudes (kU is kilo unit, uncalibrated data) showing clipped waveforms of gunshot sounds (b) recorded by AAR1 on 10 October 2014. Spectrogram parameters: frame size 0.125 s, 50% overlap, FFT size 512 points, Hann window.

collected from 40 to 200 m using Star-Oddi Starmon Mini temperature sensors (Star-Oddi, Gardabaer, Iceland) deployed on AAR1 mooring. For AARs 2 and 3 moorings, water temperature measurements were available from 500 m downwards, but the upper water temperatures for these moorings should be comparable to measurements from AAR1 mooring given their close proximity (5 km). Water temperature profile was plotted in Ocean Data View (version 3.4.3; Schlitzer, 2009) using VG gridding (Schlitzer, 2002). Further acoustic data were collected by an AAR deployed through the SABWP on the Maud Rise (65°S, 2.5°E), eastern Weddell Sea, Antarctica, over the period January 12, 2014 to January 17, 2015 at water depth of 1,267 m and recorded a total of 2,479 hr of recordings (Shabangu & Charif, 2020; Shabangu, Andrew, et al., 2020; Shabangu, Findlay, et al., 2020). However, no gunshot sounds or other SRW call types were detected from this AAR in Antarctica, so this AAR was not included in further analyses. AAR1 was deployed approximately 70 km from the nearest coastline, whereas AARs 2 and 3 were deployed on the same oceanographic mooring that was 75 km from the nearest coastline (Figure 1). AARs 1 and 2 recorded simultaneously for three months (September through December) in 2014. AAR4 was deployed ~310 km from the nearest coastline and was ~240 km farther offshore from the location of AARs 1, 2, and 3 (Figure 1).

All audio files from 1,375 days of recording were reviewed manually in Raven Pro (Bioacoustics Research Program, 2017) for gunshot sounds through visual review of spectrograms and confirmed aurally when detected. No other call types of SRWs were detected from our acoustic data set. Gunshot sounds were detected to the Nyquist frequency (maximum recorded frequency), which was either 2,048 or 4,092 Hz as per set sampling rate (Table 1). Gunshot sounds were distinguished from broadband-pulsed clicks of humpback whales as the latter has a starting frequency of ~300 Hz and low-frequency energy below 500 Hz before upsweeping to higher frequencies (Cerchio

TABLE 1 Details of the deployment and settings of the four AARs used in this study. AARs are numbered according to order of their chronological deployment. ID is for identification.

AAR ID	Latitude (S)	Longitude (E)	Water depth (m)	AAR depth (m)	Sampling rate (Hz)	Sampling protocol (min/hr)	Start recording date	End recording date	Number of days recorded
AAR1	34°22.21′	17°37.69′	855	200	4,096	30	July 24, 2014	December 1, 2014	131
AAR2	34°23.64′	17°35.66′	1,118	300	4,096	20	September 16, 2014	December 1, 2015	442
AAR3	34°23.64′	17°35.66′	1,118	300	8,192	25	December 4, 2015	January 1, 2017	395
AAR4	34°30.36′	14°58.81′	4,481	200	8,192	25	December 4, 2015	January 13, 2017	407

et al., 2001). Additionally, broadband megapclicks of humpback whales have a longer minimum duration (0.5 s; Stimpert et al., 2007) than gunshot sounds of SRWs. Gunshots are similar to broadband abiotic sounds (e.g., anthropogenic and weather-related noises; Wenz, 1962); however, we consider these sounds to originate from SRWs since their acoustic characteristics (e.g., 100% duration range of 0.07–0.47 s, mean 100% duration = 0.20 ± 0.07 s, n = 103) are very similar to gunshot sounds that are known to be produced by SRWs (Webster et al., 2016).

Echoes and prolonged reverberation of the original signals trailed some signals (Figure 2), and echoes were determined by measuring the time delay between the original signal and echoes. Furthermore, echoes generally had lower intensities than the original signal, and those were not considered during gunshot sound counts. The presence of these echoes indicates that SRWs were close enough to the recorder (within one or two water depths) to enable multipath reception since echo strength tends to decline with distance from the sound source (Grinnell, 1995; Jen, 2010). Crests and troughs of waveforms were truncated through clipping (Figure 2b) for some signals, which occurred when the magnitude of the original waveform from a received sound exceeded the maximum magnitude that a hydrophone digitizer can characterize and record within its bit depth (Charif et al., 2010). Waveform clipping can also occur even when the maximum magnitude of the digitizer is not exceeded but when a component of the preamplifier is exceeded (Stirling & Siniff, 1979). Waveform clipping suggests that the vocalizing animal was close to the recorder to "distort" the recordings (Stirling & Siniff, 1979).

Acoustic presence of SRWs was defined as the detection of at least one gunshot sound within a sampling interval. Acoustic occurrence (in percentage) was defined as the number of sampling intervals with gunshot sounds divided by the total number of sampling intervals recorded per month (seasonality) or hour (diel variability) for each AAR. A sampling interval was defined as the period of time each hour during which acoustic data were recorded. The duration of a sampling interval varied depending on the sampling protocol (Table 1); for example, 30 min of acoustic data were recorded per hour for AAR1. Gunshot rates of each AAR were calculated as the number of gunshots within a sampling interval divided by the duration of the AAR sampling interval. Different diel light regimes were classified over different seasons in accordance with the altitude of the sun: dawn (nautical twilight), daytime, dusk (nautical twilight), and nighttime by averaging hourly sun altitudes over the austral seasons (Shabangu, Andrew, et al., 2020). Austral seasons are summer (December to February), autumn (March to May), winter (June to August), and spring (September to November). Hourly sun altitudes for each day of the year from 34°22′S, 17°37′E were used for all AAR locations because all AARs were on a similar latitudinal plane. Sun altitudes were obtained from the United States Naval Observatory Astronomical Applications Department (http://aa.usno.navy.mil). Because time of day is a circular variable, diel mean gunshot occurrence per season and diel gunshot rates for spring at AAR1 were smoothed through penalized cyclic cubic regression splines (Wood, 2017) in generalized additive models (GAMs; Guisan et al., 2002) using the "mgcv" package (Wood, 2001) in R (version 4.0.1; R Core Team, 2020). GAMs with Gaussian distribution were also fitted to evaluate if sound occurrence and gunshot rates varied significantly between daylight regimes (dawn was used as a GAM reference for daylight regime) for spring 2014 of AAR1 since there were little to no occurrence and rates of gunshots for other seasons of other AARs.

To investigate discrepancies in sound detections between the closely positioned AARs 1 and 2 during the time of recording overlap (September to December 2014) and to establish transmission loss estimates for each AAR, we estimated detection ranges for gunshots detected off the west coast of South Africa. A detection was defined by signals with signal-to-noise ratios (SNRs) of 0 dB or greater (Au et al., 2001; Miller et al., 1951) since there are no established SNR thresholds for SRW sounds. Calculations were carried out for four scenarios, coinciding with data sets from the four AAR deployments. The signals were defined so as to represent the characteristics of gunshots as observed in the recorded data. The signals were therefore assumed to occupy the frequency band from below 1,000 Hz to the Nyquist frequency of the receiver. The low end of the frequency band was defined at 300 Hz as the acoustic data were high pass filtered to eliminate mooring noise below this frequency, which is below the 795 ± 65 (± standard error) Hz peak frequency estimated for SRW gunshot sounds by Webster et al. (2016). We used an average peak-to-peak source level (SL) of NARWs of 196 dB re 1 μPa for all AARs (Parks et al., 2005), because there are currently no estimated SLs for the SRW gunshot sound in the literature. Little difference is expected between the

SLs of the two populations as their gunshot sounds have similar acoustic properties (e.g., Hofmeyr-Juritz & Best, 2011; Parks et al., 2005; Vinding-Petersen, 2016).

The received level was computed using the SL and the transmission loss in BELLHOP beam tracing model (Porter, 2011). The ray tracing approach was used as ray theory is adequate when the water depth is more than (roughly) 10 wavelengths of the signal. The environmental parameters used in the BELLHOP model were an annual average sound speed profile from World Ocean Atlas 2013 (WOA2013; Boyer et al., 2013), bathymetry from the Smith-Sandwell database (Smith & Sandwell, 1997), and Thorp attenuation (Focke et al., 1982; Thorp, 1967). The vocalizing whale was assumed to be at a depth of 5 m (Trygonis et al., 2013); AARs were at either 200 or 300 m, depending on the mooring (Table 1). Transmission loss curves were computed at each kilometer along 16 radials starting at the receiver location and spaced every 22.5° in azimuth. Reciprocity was used to assume that the loss from the receiver to the whale (the direction BELLHOP model used) was equivalent to the loss from the whale to the receiver.

Among other factors, the SNR depends on the source signal level and the ambient noise level at the receiver. The representative ambient noise level was estimated using calibrated records from different months of the year that had no apparent short-term anthropogenic contributions such as shipping or seismic surveying but consisted of purely continuous noise (Table 2). The ambient noise was a function of frequency, with the levels near 300 Hz as much as 17 and 23 dB louder than at 2,000 and 4,000 Hz, respectively (Table 2).

The detection statistic should formally compare the signal energy integrated over the frequency band to the noise energy also integrated over the frequency band. As a proxy for this calculation, the detection statistic was computed at 300 Hz and at the Nyquist frequency. These calculations assumed a frequency-independent source spectral level equal to the average level divided by the bandwidth. Effect of ambient noise was dominant at the lower frequency, which suggests that the detection range computed at the higher frequency is a more reliable measure of range based on a fully integrated statistic.

A total of 13,135 hr of acoustic files were recorded from the four AARs, with the number of hours recorded by each AAR specified in Table 3. The shallowest listening station (AAR1) detected the highest number (313 hr) and percentage (20%) of hours with gunshot sounds (Table 3). AAR4 detected the second highest number (11 hr) and percentage (0.27%) of hours with gunshot sounds, while AARs 2 and 3 detected 8 and zero hours with gunshot sounds, respectively (Table 3). Overall, the deepest listening station (AAR4) recorded the highest number of hours of audio files while AAR1 recorded the lowest number of hours (Table 3).

Echoes of the gunshot sound were only detected in the acoustic data from AAR1, and time delay between the signal and the echo ranged in 100% duration from 0.18 to 1.09 s with an average delay duration of 0.56 ± 0.26 s (n = 19). When using the estimated average sound speed of 1,500 m/s around AAR1 and whales vocalizing right

TABLE 2 Hydrophone sensitivities provided by the manufacturer, measured noise levels at 300 and 2,000/4,000 Hz, average peak-to-peak SL derived from Parks et al. (2005), and calculated SL density of each AAR used in this study. SL density is the source level normalized by the bandwidth, where the bandwidth is 2,000–300 Hz for AARs 1 and 2, and 4,000–300 for AARs 3 and 4. (In dBs, this is 196–$10\log_{10}$(2,000–300) for AARs 1 and 2; 196–$10\log_{10}$(4,000–300) for AARs 3 and 4.)

AAR ID	Hydrophone sensitivity (dB re 1 V/μPa)	Date of source file	Noise levels (dB re 1 μPa^2/Hz)		SL (dB re 1 μPa)	SL density (dB re 1 μPa/Hz)
			300 Hz	2,000/4,000 Hz		
AAR1	−164.20	July 2014	77.3	61.6 (2,000)	196	163.7
AAR2	−163.90	October 2014	75.2	58.1 (2,000)	196	163.7
AAR3	−164.10	April 2016	70.6	50.8 (4,000)	196	160.3
AAR4	−164.20	January 2016	76.2	53.5 (4,000)	196	160.3

TABLE 3 Number and percentage of hours and days of acoustic files containing gunshot sounds from each AAR. Number of days with gunshot sounds represents days when one or more gunshot sound was detected for a given sampling intervals. Sampling intervals were summed to constitute hours.

AAR number	No. of hours recorded	No. of hours with gunshot sounds	% of hours with gunshot sounds	No. of days with gunshot sounds	% of days with gunshot sounds	No. of gunshot sounds
AAR1	1,567	313	20	57	44	1,895
AAR2	3,490	8	0.23	1	0.2	18
AAR3	3,982	0	0	0	0	0
AAR4	4,096	11	0.27	4	1	16

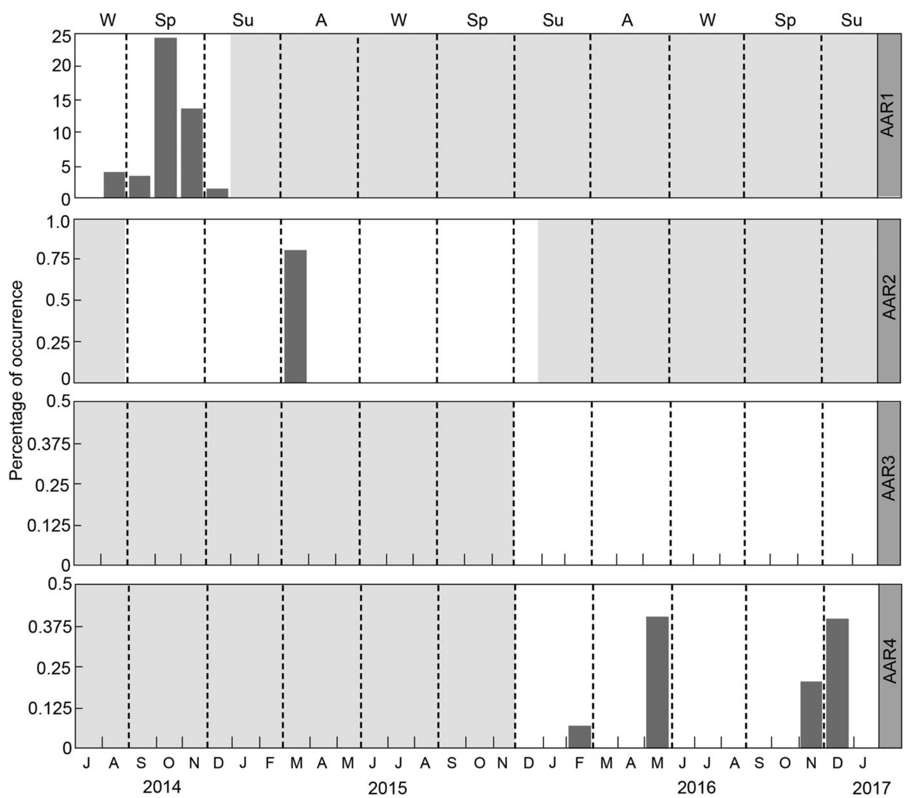

FIGURE 3 Monthly percentage of SRW gunshot sound occurrence from each AAR. Note the scales of *y*-axes are different. Gray shaded areas indicate periods without recording effort. Letters on the *x*-axis represent months. Seasons (Su: Summer, A: Autumn, W: Winter, and Sp: Spring) are shown on the top axis and outlined by dashed vertical lines.

above the mooring, a maximum distance of 1,635 m is traveled by the signal within the maximum delay time of 1.09 s, which is more than twice the distance (655 m) from the AAR depth to the seabed. From the average delay time of 0.56 s, the maximum distance of 840 m is traveled by the signal within the delay time. Given such distances traveled by the sound, the detected echoes were likely reflected off the seabed, although our sample size is considerably smaller than 407 echoes of Parks et al. (2005).

Gunshot sounds were detected from August through December 2014 by AAR1, and the sound occurrence peak was in October (Figure 3). On AAR2, gunshot sounds were only recorded in March 2015 (Figure 3). Although AARs

1 and 2 both recorded simultaneously for 3 months (September–December 2014), gunshots were only detected on AAR1 during the period of overlap (Figure 3), despite their close proximity. No SRW sounds were detected on AAR3 (Figure 3). For AAR4, gunshot sounds were detected on single days in February, May, November, and December 2016 (Figure 3). Seasonal gunshot detections varied between AARs: AAR1 detected sounds in austral late-winter through early summer (August through December), AAR2 detected sounds in autumn (March), and AAR4 detected gunshots in summer (December and February), autumn (May) and spring (November) (Figure 3).

Diel vocalizing patterns of sound occurrence were observed in winter and spring from AAR1 (Figure 4). For spring of AAR1, there was a general pattern of increased vocal activity in the early predawn hours as well as from afternoon to midnight, with decreased vocal activity at mid-day (Figure 4). GAM results indicated significantly lower sound occurrence during the day ($p < .05$) than other daylight regimes ($p > .05$) for AAR1 in the spring. At AAR1, winter detections followed a similar diel pattern as spring but slightly delayed where there was an increased vocal activity from early predawn through late morning hours as well as from dusk to midnight, with decreased vocal activity in the afternoon (Figure 4). Although no obvious diel patterns were established at AARs 2 and 4 due to low gunshot sample sizes, there were very small increase in vocal activities at early morning, mid-morning, afternoon, and nighttime (Figure 4). Higher monthly gunshot rates were observed from AAR1 in October and December 2014 (Figure 5a), and gunshot rate medians and interquartile widths for the other three AARs were zeroes. December 2014 had the highest gunshot median rate of 12 gunshots/hr (Figure 5a). Overall, October 2014 from AAR1 had the highest recorded gunshot rate of 354 gunshots/hr (Figure 5a). Diel pattern of smoothed mean gunshot rates for spring 2014 (Figure 5b) resembled the pattern of the percentage of gunshot occurrence in spring (Figure 4) except for the decrease in gunshot rates from dusk through midnight, and GAM analyses indicated significant change in call rates at nighttime ($p < .05$) than during other daylight regimes ($p > .05$).

In general, the strength of the ambient noise at 300 Hz drowned out the signal except at short distances, less than 30 km for all AARs (Figure 6a, c, e, g). At the other extreme, the quieter ambient noise levels in the mid-

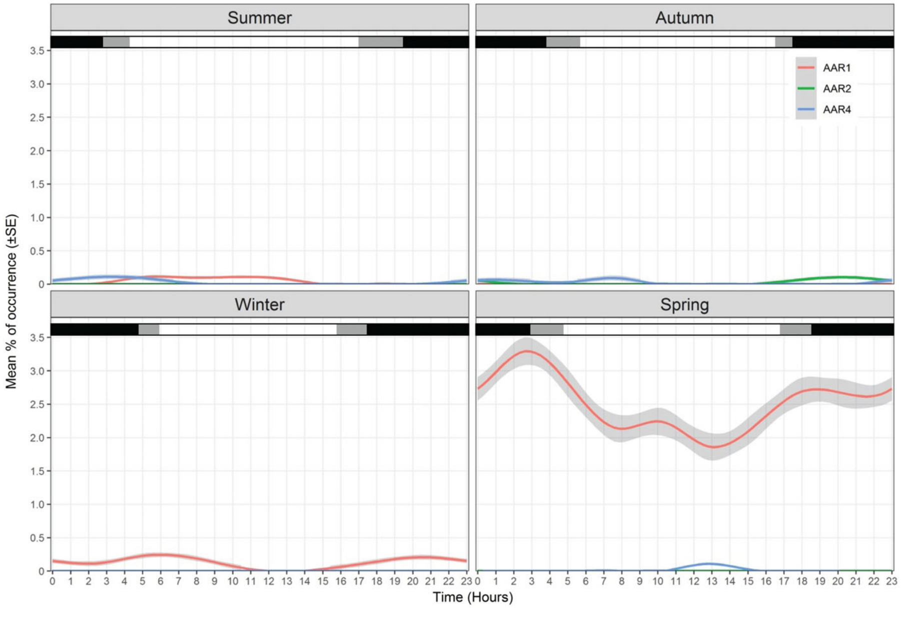

FIGURE 4 Circular smoothed diel percentage of gunshot occurrence per season. No acoustic data were recorded in autumn for AAR1, and no gunshot sounds were detected from AAR3; hence, none are plotted here. Horizontal diel bar shading: black represents average nighttime hours, gray represents average twilight hours, and white represents average daytime hours. Gray shaded regions represent the standard error of the mean. All times presented in Coordinated Universal Time (UTC).

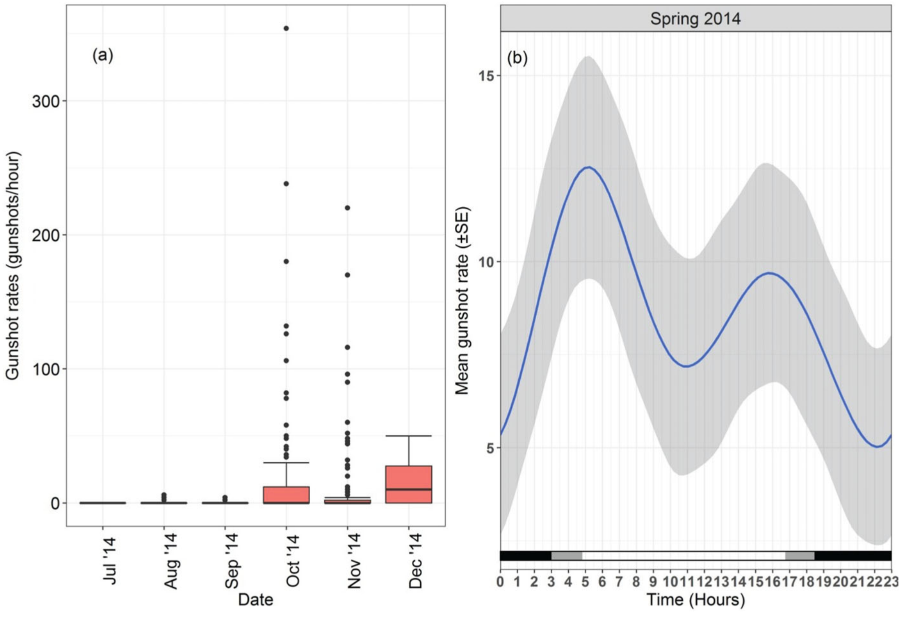

FIGURE 5 Box and whisker plot of monthly gunshot rates (a) and circular smoothed mean diel gunshot rates (blue line) for spring 2014 (b) at AAR1. Boxes in the box and whisker plot represent the first to third quartiles (interquartile range), and the black lines inside the boxes are the medians. Whiskers outline 1.5 times the interquartile width, and closed circles are observations that are outside the range covered by the whisker. Horizontal diel bar shading in (b) is the same as described in the caption of Figure 4. Gray shaded region in (b) represents the standard error (SE) of the mean (line plot). Time in (b) is referenced to UTC.

frequency (2,000–4,000 Hz) region supported a much longer detection range, from 30 km to as much as 80 km (Figure 6). The polar plots show a loss of detection range in the eastern direction for AARs 1, 2, and 3 (Figure 6a–f), possibly due to bathymetric effects up onto the shelf, but uninterrupted detection ranges in all directions for AAR4 (Figure 6g, h). At the 2,000 Hz frequency band, the maximum detection ranges were 40 km for AAR1 (Figure 6b) and 60 km for AAR2 (Figure 6d) in most of the BELLHOP model radials. At the 4,000 Hz frequency band, the maximum detection range was 50 km for AAR3 (Figure 6f) and 70 km for AAR4 (Figure 6h) in most of the BELLHOP model radials. AARs 2 and 3 had different maximum detection ranges even though they were deployed on the same mooring and depth, likely due to varying seasonal noise levels (Table 2) and environmental conditions. A convergence zone structure is evident in AAR4 at 300 and 4,000 Hz (Figure 6g, h). Convergence zones are compact regions in range where downward-radiating portions of the whale's sound refract back up to receivers in the near-surface region. These regions, where detections may be good, are usually buttressed by regions where refraction has bent forward-radiated sound away from the surface, the whale sound is inaudible and, consequently, detections are poor. The maximum detection range should include the farthest convergence zone, although this definition may include regions at shorter ranges that will not have detections.

Gunshot detection ranges of this study are greater than a maximum detection range to localized calls of 33 km estimated for NARW gunshot sounds (Laurinolli et al., 2003), but less than 120 km theoretical maximum ideal detection range estimated for NPRW gunshot sounds by Crance et al. (2019). Our results are comparable to Crance et al. (2019) since similar theoretical ideal detection ranges were estimated in both studies. Differences in the whale detection ranges between different studies are typically caused by varying transmission loss in the ocean, sea state conditions (noise levels), SLs, recorder types, recorder depths, SNR thresholds, sound propagation models used, and bathymetric properties of different regions (e.g., André et al., 2017; Medwin & Clay, 1998; Mathias et al., 2013).

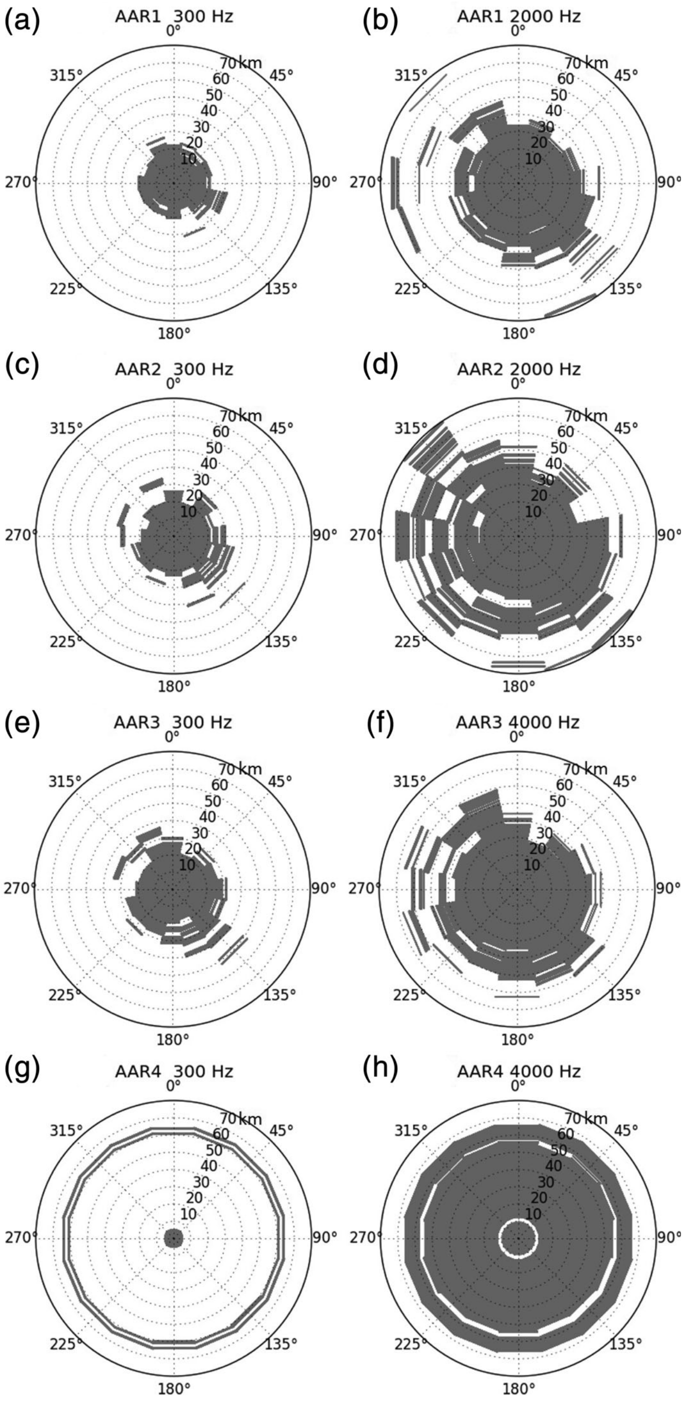

FIGURE 6 Polar plots of BELLHOP model detection range estimates of gunshot sounds for AARs 1 (a, b), 2 (c, d), 3 (e, f), and 4 (g, h) at different bearings (degrees) and frequency bands (300 Hz vs 2,000/4,000 Hz). Gray patches represent regions from which a gunshot sound would be detectable at the hydrophone location (center of plot).

The discrepancy between AARs 1 and 2 observations was pursued by additional ambient noise analysis and modeling for the period when the mooring deployments overlapped. Noise levels decreased from September to November and then increased slightly in December for AAR1 at 300 Hz with the highest difference of 20 dB re 1 μPa^2/Hz between months (Figure 7a); however, noise levels fluctuated between months at 2,000 Hz for this AAR

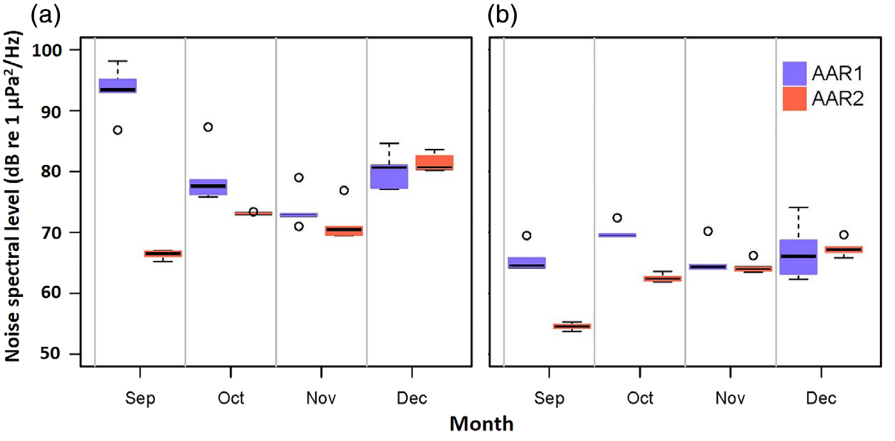

FIGURE 7 Monthly comparison of noise levels at 300 (a) and 2,000 (b) Hz between AARs 1 (purple) and 2 (red). Box and whisker plots are the same as described in the caption of Figure 5, and open circles are observations that are outside the range covered by the whisker.

with the highest difference of ~5 dB re 1 μPa^2/Hz (Figure 7b). For AAR2, noise level trends at both 300 and 2,000 Hz increased by about 12–14 dB re 1 μPa^2/Hz from September to December (Figure 7). In general, when there were no nearby ships, noise levels varied from hr to hr by 1 or 2 dB re 1 μPa^2/Hz. A nearby ship raised the noise levels by as much as 10–20 dB re 1 μPa^2/Hz for a short time. Overall, AAR1 (positioned at 200 m in the water column) had higher noise levels than AAR2 (positioned at 300 m in the water column) for all months except for December at 300 Hz (Figure 7a). AAR1 had higher noise levels than AAR2 at 2,000 Hz for September and October, but had comparable levels for November and December (Figure 7). The 10–20 dB re 1 μPa^2/Hz shift in noise level over months could have roughly reduced the detection range by a factor of 10–20.

The difference in noise levels between months at 300 Hz is substantial, indicating that these AARs were located close to a shipping route where noise levels vary considerably from one month to the next. Furthermore, the noise levels are much higher for these AARs than could be caused by the environmental, meteorological, oceanographic, and biological processes alone (Wenz, 1962), suggesting that the recorded noise emanated from nearby ships. Given that AAR2 had lower noise levels than AAR1 during overlapping deployment periods, AAR2 had longer detection ranges at all bearings than AAR1 at their quietest months (Figure 8). The increase in ambient noise at AARs from September to December is actually quite large compared to measurements in other oceans (e.g., Estabrook et al., 2016), and consequently the detection range decreases by almost half. Nonetheless, the detection range difference does not explain the difference in sound detections between these closely spaced AARs during periods of concurrent recordings as these detection ranges should have allowed an overlap and coincidental detection of sounds.

Different gunshot sound occurrence between the closely spaced AARs 1 and 2 during the time of recording overlap (September through December 2014) are likely due to the variation in water temperature where the thermocline was close to 200 m and stratification had weakened for September and October (Figure 9). The thermocline acts as an acoustic barrier for sounds produced by sources above or below its depth (Siderius et al., 2007; Song et al., 2010), but some energy leaks depending on the strength of the thermocline gradient (Song et al., 2010). Such sound leakage could have led to AAR1 detecting more gunshot sounds in other months than the deeper AAR2, as water mixing during a storm or high wind speeds could have resulted in thermocline disruption into greater depths (Siderius et al., 2007). Few gunshot sounds were detected in September despite the thermocline depth being deeper in that month, indicating that most of SRWs had not yet arrived at this location by then.

More calls of Antarctic blue and fin (*Balaenoptera physalus*) whale were detected by AAR1 during the time of recording overlap with AAR2 (Shabangu et al. 2019); these whales also vocalize in shallow water depths above 50 m

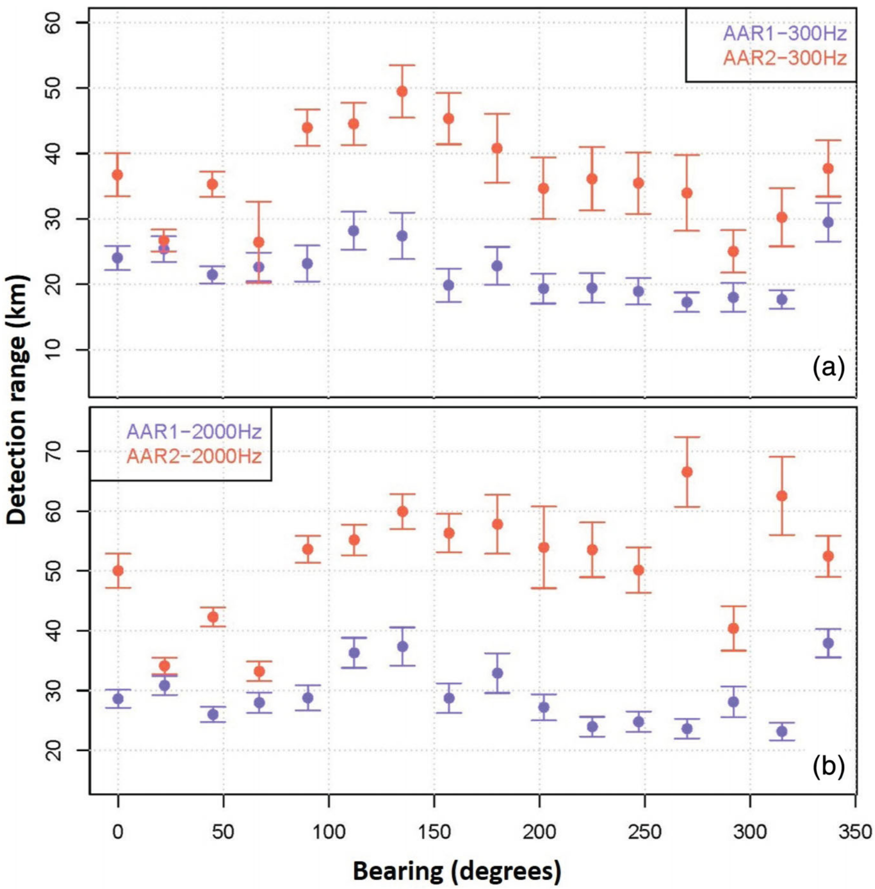

FIGURE 8 Comparison of theoretical maximum detection ranges of AARs 1 and 2 at different bearings. Closed circles represent the mean, and error bars represent the deviations of the data. Median noise levels at 300 Hz from October and September were used for AARs 1 and 2, respectively, and median noise levels at 2,000 Hz from September were used for both AARs (Figure 7).

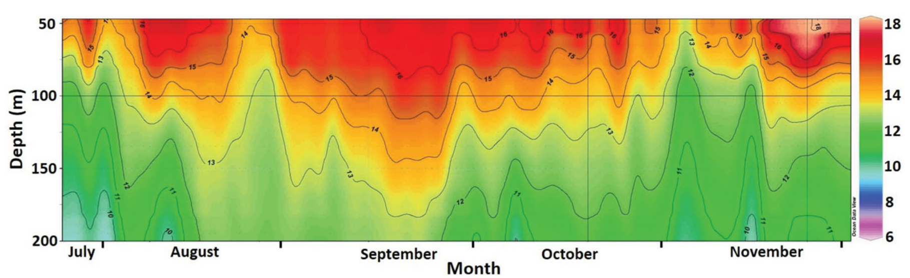

FIGURE 9 Daily temperature profile of the water column from 40 to 200 m measured from AAR1 oceanographic mooring in 2014. The colored shading as detailed in the key represents different temperature values in °C.

(e.g., Watkins et al., 1987; Oleson et al., 2007). However, different acoustic occurrence patterns were observed for Antarctic minke whales, *Balaenoptera bonaerensis* (Shabangu, Findaly, et al., 2020) and sperm whales (Shabangu & Andrew, 2020) where more calls were detected by AAR2 than AAR1 during time of recording overlap, since these whales vocalize in deeper waters (e.g., Watwood et al., 2006; Shabangu, Findlay, et al., 2020). The above results support previous findings that the sound source and hydrophone depth relative to the thermocline determine whether signals can be detected (Siderius et al., 2007; Song et al., 2010). The same interpretation is applicable to AARs 3 and 4 deployed at 300 and 200 m, respectively, as AAR4 detected more sounds than AAR3. The nonsmooth character (nontypical features) of the evaluated sound speed profiles (WOA2013) that lacked ducts or waveguides further indicates that the oceanography of this area is not well sampled and also key to understanding the lack of detections on AAR2.

Moreover, the high number of detections of gunshot sounds from AAR1 (the more coastal listening station deployed at 855 m water depth) could be due to high prey densities and favorable environmental conditions associated with that depth (Elwen & Best, 2004a, b; Prieto et al., 2017; Purdon et al. 2020; Shabangu et al., 2019). For example, areas shallower than the 1,000 m isobath on the west coast of South Africa are known to have elevated productivity to support high biomasses of prey due to increased upwelling (Andrews & Hutchings, 1980; Lamont et al., 2015, 2018). AAR1 is located within 1,000 m isobath and high numbers of gunshot sounds were detected, could indicate that whales were utilizing the highly productive coastal areas. Purdon et al. (2020) found bathymetry (<1,500 m) and distances to shore (<500 km) to have higher influence on the SRW distribution in summer, which corroborates our results. Alternatively, the high detections at AAR1 relative to AAR2 could be because the 855 m water depth is their established migratory paths. However, using our currently available acoustic data it is not possible to investigate the year-round acoustic use of this depth as our AAR deployment at this depth was experimental for only five months. No other AARs were deployed at this location or shallower due to SABWP's priorities, funding constraints and potential conflict with the deep-water fisheries.

Lack of or limited detections of gunshot sounds in the 2015 and 2016 recording periods coincided well with the observed but unexplained sharp decline of SRWs from annual aerial surveys across the coastal breeding grounds of the Southern Cape coast between Nature's Valley and Muizenberg (Figure 1) during the same period (Findlay et al., 2017). The absence of gunshot sounds from our AAR deployed in close proximity to the sea ice edge in Antarctica agrees with sighting survey results that these animals rarely migrate as far south as 65°S (Bannister et al., 1999; Best et al., 1993; IWC, 2001). Very few SRWs (19 animals) were harvested at such high latitudes (IWC, 2001; Tormosov et al., 1998) or recorded during the IWC's International Decade of Cetacean Research or Southern Ocean Whale Ecosystem Research cruises (Shabangu et al., in press).

Percentages of gunshot sound occurrence for AAR1 were high in October, which might indicate the arrival of whales in this region from sub-Antarctic waters or other regions as observed from SRW catches (Best, 2006; Townsend, 1935) and sighting surveys (Best, 2000; IWC, 2001; Roux et al., 2015; Vinding et al., 2015). The Mammal Research Institute Whale Unit, University of Pretoria, conducts its SRW aerial surveys around early October of each year to ensure that all calves have been born by the time the survey is carried out across the Southern Cape coast, South Africa (e.g., Best, 1990; Findlay et al., 2017; Vermeulen, 2017). However, Best and Scott (1993) defined the seasonal distributions of animals earlier in the year, where SRWs arrived around June, reach peak abundance around September, and depart around December or January. Hofmeyr-Juritz (2010) also observed increased SRW call rates with whale group sizes around September/October on the southwest coast of South Africa in the Walker Bay area. Gunshot detections from August through December by AAR1 could indicate that the shallow offshore (~850 m water depth) component of the west coast of South Africa is an important ecoregion for SRWs because they use this area from winter through summer as an overwintering and breeding ground with occasional feeding (Best, 2000, 2006; Mate et al., 2011; Peters et al., 2012). Low and absence of percentages of sound occurrence from AARs 2 and 3, respectively, could be due to the lack of whales, sound propagation effects or silent whales among other causes. Occurrence of gunshot sounds in February, May, November, and December 2016 from AAR4, suggest that this offshore region could also be used seasonally for transiting to the coastal areas or southwards to sub-Antarctic and/or Antarctic waters (Best, 2000, 2007).

The diel pattern of gunshot sound occurrence in winter and spring from AAR1 could indicate changes in behavioral states (e.g., mating, resting, and swimming activities) throughout the day (Clark, 1982; Parks & Tyack, 2005; Parks et al., 2005). For example, increased vocal activity at nighttime and early morning in winter and spring could reflect increased mating activities, or that animals used sounds for communication at night when there was limited visual contact as similarly observed for humpback whales (Au et al., 2000). Photographic evidence of SRWs mating behaviors during the day exists for Walker Bay, off the southwest coast of South Africa (Xplorio, 2018); however, there is currently no link between mating behaviors and sound types in South African waters according to our best knowledge. Low vocal activity during the day in both winter and spring could indicate that SWRs were involved in activities that require less vocal interactions, such as swimming or resting (e.g., Clark, 1982), and that the use of sound for mating during the day is limited as animals likely use visual cues to maintain contact with conspecifics (e.g., Webster et al. 2019).

The gunshot rate increase in spring could indicate an increase in whale numbers as SRW gunshot rates have been found to increase with whale numbers (e.g., Hofmeyr-Juritz, 2010; Matthews et al., 2001; Vinding-Petersen,- 2016). Webster et al. (2019) also detected more SRW gunshots at dusk and night, but the proportion of call types did not change throughout the day. NARW had higher gunshot rates in the late afternoon and evening, which the authors suggested were a result of potentially increased mating activities (Parks et al., 2012). Since gunshots are hypothesized to be also used for echolocation (e.g. Parks et al. 2005), the gunshot echoes detected in this study could be part of echolocation, although there is currently no proof for it. Thus, the observed diel-vocalizing patterns could also be associated with diurnal vertical migration of their zooplankton prey as observed of Antarctic blue and minke whales in South African waters (Shabangu et al. 2019, Shabangu, Findlay, et al., 2020). Our highest estimated gunshot rate of 354 gunshots/hr is lower than the maximum 836 gunshots/hr estimated for NPRWs (Crance et al., 2017) and ~750 gunshots/hr for NARWs (Matthews et al., 2001). Nonetheless, our estimated maximum gunshot rate is greater than the estimated 0.7 gunshots/hr for SRWs in Walker Bay, South Africa (Hofmeyr-Juritz and Best, 2011) and 15 gunshots/hr for SRWs off New Zealand (Webster et al., 2019).

To conclude, seasonal gunshot occurrence off the west coast of South Africa is established where gunshots were detected in different seasons of the year over the three years of passive acoustic monitoring, with the highest vocalization peak in October, revealing that SRWs are sporadically present throughout the year and that majority of animals are present in this area around spring. Site specific variation in propagation conditions and mooring configurations likely influenced the observed patterns in gunshot detections. Years (2015 and 2016) with low SRW gunshot sounds coincided with a decline in all SRW counts from annual aerial surveys. High percentages of gunshot occurrence at dusk and night likely indicate mating activities and the use of sound for communication with conspecific during periods of limited visibility. This study is the first to attempt to establish the offshore seasonal acoustic occurrence, detection ranges, and diel-vocalizing pattern of SRW for this poorly researched area of the southern African region. To expand our knowledge of the acoustic ecology (seasonal acoustic occurrence and diel-vocalizing patterns) and characteristics (detection ranges) of SRW sounds, more bioacoustics research is required in the offshore areas of the South African coast. Further acoustic research efforts should be invested to increase sample sizes of acoustic data throughout the spatial and temporal ranges of SRWs.

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AUTHOR CONTRIBUTIONS

Fannie Welcome Shabangu: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; validation; writing-original draft; writing-review and editing. **Rex Andrew:** Conceptualization; formal analysis; funding acquisition; investigation; validation; visualization; writing-original draft; writing-review and editing. **Ken Findlay:** Conceptualization; funding acquisition; investigation; project administration; writing-original draft; writing-review and editing.

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