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Downsweep calls attributed to sei whales, *Balaenoptera borealis*, in Ilhabela, São Paulo, Brazil

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Baleen whales produce downsweep calls that are frequency-modulated signals with decreasing frequency over time (Ou et al., 2015). Downsweep calls from three baleen whale species (fin, sei, and blue whales) overlap in their frequency range from 150 to 35 Hz, and call duration in these species varies between 200 and 1,200 ms. In areas where blue whales co-exist with fin or sei whales, downsweep calls produced by one species could be easily confused with those from another. Fin whales produce downsweep calls in frequencies of 150 to 15 Hz (Thompson & Friedl, 1982). Fin whales also produce downsweep calls in a higher frequency range but are less frequent. McDonald and Fox (1999) reported a 35 Hz fin whale downsweep call sequence that appeared together with the 20 Hz sequence. Downsweep calls at even higher frequency ranges were also observed (center frequencies varying from 120 to 40 Hz) with more irregular repetition intervals (McDonald & Fox, 1999; Delarue et al., 2009). Nonetheless, fin whales are often identified by their 20 Hz call sequences. In addition, blue whales also produce downsweeps in the same frequency range that are categorized as D-calls (Ou et al., 2015). Here we focus on the downsweep calls of sei whales (*Balaenoptera borealis*), one of the least known baleen whales in the world. This cosmopolitan species is found mostly in more temperate waters when compared to other *Balaenoptera* species (Jefferson et al., 2015). It is the third largest species of the genus *Balaenoptera*, reaching a maximum length of 20 m and approximate weight of 30 ton, with females being slightly larger than males (Berta, 2015; Jefferson et al., 2015). The species occurrence is associated with the continental shelf break and deeper oceanic areas. Sei whales occur in the North Atlantic, North Pacific and in the Southern Hemisphere oceans, but there are no confirmed records in the Northern Indian Ocean (Santos, 2008; Andriolo et al., 2010; Iñíguez et al., 2010; Leonardi et al., 2011; Berta, 2015; Di Tullio et al., 2016; Heissler et al., 2016; Milmann et al., 2020; Weir et al., 2020). Sei whales migrate, staying in tropical and subtropical latitudes during the winter and, in the summer, they occur in temperate and subpolar regions (Horwood, 2009). Little is known about their movements among feeding and reproduction areas and their migratory routes (Cooke, 2018; Perry, 2002; Weir et al., 2020). In the Southern Hemisphere, the International Whaling Commission (IWC) has defined six geographic areas for management of sei whale populations, three of which overlap in the South Atlantic: Area I (60° W–120° W), Area II (0° W - 60° W), and Area III (0° E – 70° E). Japanese whale catches and visual surveys during the 1960s and 1970s recorded the highest densities of sei whales in mid-latitudes (30° S - 50° S) of Areas II and III, particularly between 40° S and 50° S (Masaki, 1980). In the South Atlantic Ocean, sei whale occurrence is limited around 40° to 50° S. In Brazil, the distribution along the coast is restricted below 6° S of latitude (Rosa & da Rocha, 2018). Among the species of the *Balaenoptera* genus, singing is assumed to be a male-only behavioral trait, sei whales alike (Tremblay et al., 2019). Sei whale males produce descending and low frequency vocalizations sweeps (< 100 Hz) (Zimmer, 2011), ranging from 82 Hz to 34 Hz with a duration of 1.4 s, typically in sets of 7 to 10 sweeps, with

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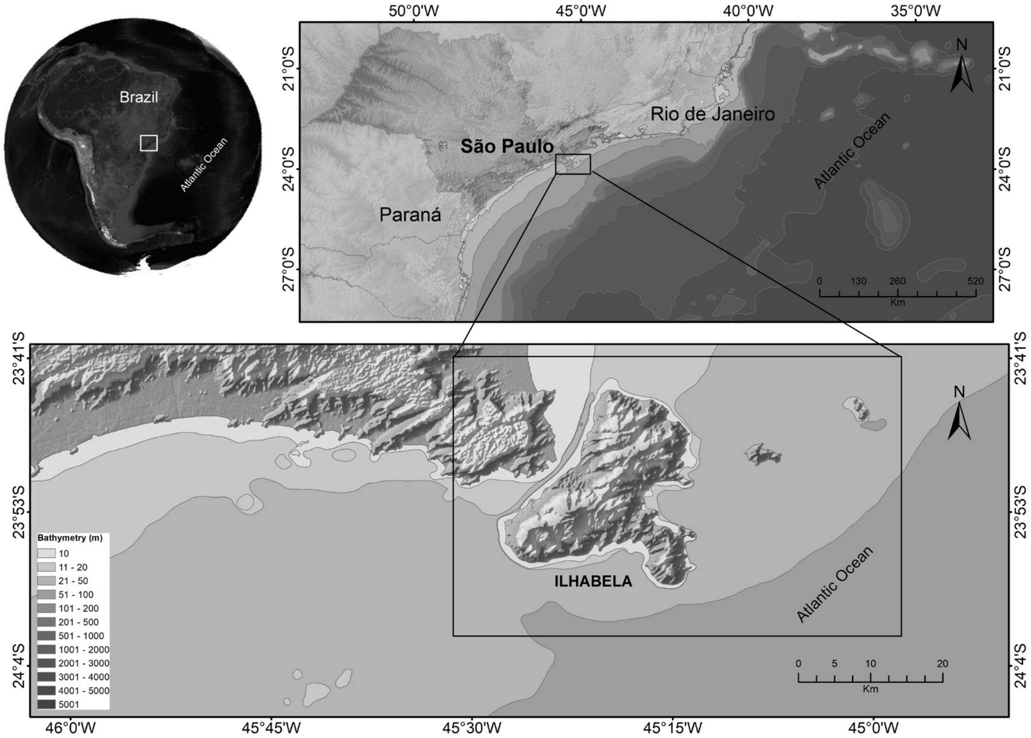

Figure 1. The circle shows the location of the recording site calls attributed to sei whales, *Balaenoptera borealis,* and triangles show records of sightings, georeferenced data from tag (satellite transducer), and strandings between 2001 and 2018 of the same species (Cabral & Barreto, 2022).

pulses of 0.7 s of duration with maximum frequencies of 3 kHz (Calderan et al., 2014; Tremblay et al., 2019). Sei whales have a diverse, song-like repertoire in the North Atlantic Ocean region (Tremblay et al., 2019). These sei whale vocalizations were characterized by an initial frequency of 50 Hz descending to 30 Hz. Tremblay et al. (2019) also discriminated these song-like vocalizations into types A, B, C, and D. Type A is composed of a unit starting at a frequency of 82 Hz and ending at 34 Hz. The A type vocalization is found in other geographical regions and is typically produced in pairs (Tremblay et al., 2019). The type B vocalization is somewhat shorter in duration (1.68 s), steeper in frequency modulation (52.75 Hz to 31.59 Hz) and generally has a higher dominant frequency (35.97 Hz) compared to the type C vocalization, which is longer (1.94 s), less modulated (49.36 Hz to 29.94 Hz) and with a lower dominant frequency (35.0 Hz). The type D vocalization is of low frequency (49.05 Hz to 29.6 Hz) with a duration of 0.6 s and dominant frequency of 36.69 s. Types A, B, C, and D vocalizations frequently occur in a repeated pattern, forming an "AABCDBD" song, but the sequence order may vary, like in humpback whales (Cholewiak et al., 2013). This study characterizes the 'type D' downsteep calls attributed to sei whales, *B. borealis*, in Brazil.

Recordings were conducted opportunistically south of Ilhabela, São Paulo, Brazil (23º58'32" S, 45º28'18" W) (Fig. 1), on 11 August 2020, in a 2.5 m Flexboat SR500 named Indaiauba III with an 115 HP outboard engine between 14:23 and 14:49 hours. Sound records containing likely sei whale signals were collected at a water depth of 43 m, temperature around 23°C, and Beaufort Sea state between 1 and 2. No visual observations of sei whales were made on the occasion. One dipping hydrophone (HTI-SSQ-94 model with −170 dB sensitivity and 5 Hz–30 kHz of flat frequency response) with a 20 m cable connected to a battery powered TASCAM DR-40 digital audio recorder was deployed off the side of the boat to record sounds produced by marine fauna and associate those sounds to any visual observations. The recorded signals were sampled at 96 kHz frequency rate and 24 bits resolution. The frequency flat response of the recording system was 20 Hz – 30 kHz and emissions were analyzed using the Raven Pro© v1.6 software. A total of 22 minutes and 42 seconds of recording time were analyzed. For all downsweep

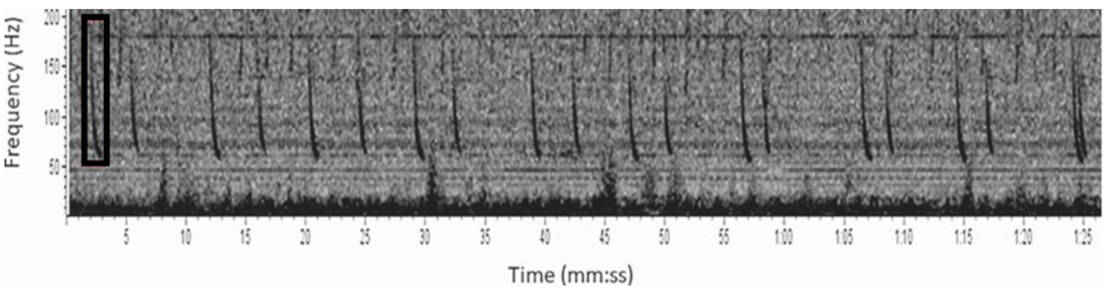

Figure 2. Spectrogram of sei whale (*Balaenoptera borealis*) calls sonogram recorded in Ilhabela, São Paulo, Brazil on 11 August 2020. Spectrogram parameters: 16384 FFT window size, 59.3% overlap, 5.86 Hz frequency resolution. Time resolution is 8.3 Hz and 100 ms, respectively, using the Hann window.

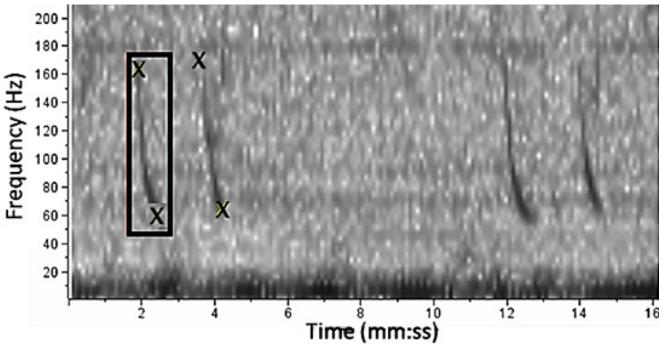

Figure 3. Detailed sound spectrogram of a call unit of the sei whales, *Balaenoptera borealis*, illustrating some of the measurements used in the quantitative analyses. The square shows the complete D-call. "X" marks the maximum and the minimum peak frequencies (Hz) of that call (n = 53). Spectrogram parameters: 16384 FFT window size, 59.3% overlap, 5.86 Hz frequency resolution. Time resolution is 8.3 Hz and 100 ms, respectively, using the Hann window.

D-calls found in this period of time the following six acoustic variables were extracted: start (SF) (Hz), end (EF) (Hz), delta (DF = EF – SF) (Hz), center (CF = frequency in the middle of the call) (Hz), peak frequency (PF = frequency with highest amplitude) (Hz) and delta time (DT) (duration in s). Spectrograms were generated with 16384 FFT window size, 59.3% overlap, 5.86 Hz frequency resolution. Time resolution was 8.3 Hz and 100 ms, respectively, using the Hann window.

A total 53 downsteep D-calls with high signal-to-noise ratio (SNR > 10 dB) identified as D-calls were attributed to sei whales based on similarities on the acoustic structure and contour of the signals as described in Tremblay et al. (2019). D-calls were

Table 1. Quantitative analysis of five acoustic parameters of 53 sei whales (*Balaenoptera borealis*) D-calls type A. Values in bold are similar (P > 0.05). Mean/SD are indicated by #, while median/IQR values are indicated by *. IQR = interquartile range.

Measurements	Maximum	Minimum	Range	Mean ± SD # Median/IQR *
Start Frequency (SF) (Hz)	174.3	47.2	127.14	132.95±23.08 #
End Frequency (EF) (Hz)	87.15	40.95	46.5	57.65 ± 8.15 #
Peak Frequency (PF) (Hz)	101.56	58.6	42.97	78.93+11,08 #
Center Frequency (CF) (Hz)	97.65	66.41	31.25	82,03 ± 8.54 *
Delta frequency (DF) (Hz)	134.88	37.88	97	89.54 ± 23.07 #
Delta Time (DT) (s)	1.00	0.42	0.60	0.78± 0.15 #

characterized according to frequencies and duration parameters present in Table 1. Figure 2 shows an example spectrogram generated in the Raven Pro 1.6© software.

Downsweep D-calls reported in this study had a mean frequency (start and end) of 132.95 Hz ± 23.08 (start) and 57.65 Hz ± 8.15 (end). These results show frequency values slightly higher than those found in North and Northwestern Atlantic and South and Eastern Pacific Oceans (Knowlton et al., 1991; Rawkin & Barlow, 2007; Baumgartner et al., 2008; Calderan et al., 2014; Romagosa et al., 2015; Español-Jiménez et al., 2019; Tremblay et al., 2019; Moreira, 2021) (Table 2). Regarding the South Atlantic Ocean, mean start and end frequencies are between the frequencies reported by Cerchio & Weir (2022) and Mc Donald et al. (2005) as shown in Table 2. These differences in acoustic parameters

Table 2. Comparison of the frequency (minimum and maximum in Hz) and duration in seconds of recorded D-calls of sei whales (*Balaenoptera borealis*) in the present study with studies in other areas along the years. Values are mean value ± standard deviation. ND: no data (the study did not include that information).

Ocean	Local	Year	N	Mean Start Freq (Hz)	Mean End Freq (Hz)	Mean Duration (s)	Reference
South Atlantic	Ilhabela, Brazil	2020	37	132.95 ± 23.08	57.65 ± 8.15	0.78 ± 0.15	This Study
South Atlantic	West Antarctica East Antarctica	2003	50 ND	433 570	192 170	0.45 ± 0.3 ND	McDonald et al. (2005)
South Atlantic	Falkland Island	2018 - 2019	113 44	104.6 ± 10.7 158.4 ± 23.9	29.9 ± 5.0 29.5 ± 4.8	1.20 ± 0.15 1.11 ± 0.13	Cerchio & Weir (2022)
North Atlantic	Canada	ND	ND	3,000	ND	0.7	Thompson (1979)
North Atlantic	Canada	1986 - 1989	ND	3,500	1500	0.5 - 0.8	Knowlton et al. (1991)
North Atlantic	New England	2006 - 2007	108	82.3 ± 15.2	34 ± 6.2	1.38 ± 0.37	Baumgartner et al. (2008)
North Atlantic	Maine. EUA	2008	100	49.05	29.6	0.6	Trembley et al. (2019)
North Atlantic	Azores, Portugal	2012	53	99.8 ± 13.6	37.4 ± 8.4	1.21 ± 0.33	Romagosa et al. (2015)
North Atlantic	Azores, Portugal	2010 - 2016	2,093	76.69 ± 11.05	33.3 ± 3.4	-	Moreira (2021)
North Atlantic	Canada	2015 - 2016	268	75.66 ± 9.29	34.22 ± 5.63	1.58 ± 0.31	Macklin (2022)
South Pacific	Auckland Island	2013	4 4 30	78.0 ± 2.0 83.3 ± 15.2 66.3 ± 10.7	69.0 ± 0.8 34 ± 6.2 36.6 ± 2.1	1.1 ± 0.0 1.38 ± 0.37 1.2 ± 0.3	Calderan et al. (2014)
North Pacific	Hawaii	2002	2 105	100.3 ± 11.1 39.4 ± 3.4	44.6 ± 2.9 21.0 ± 2.4	1.2± 0.007 1.2 ± 0.11	Rawkin & Barlow (2007)
South Pacific	Chile	2016 2017	5 6	105.3 ± 18.3 93.3 ± 10.9	35.6 ± 4.6 42.2 ± 5.6	1.6 ± 0.1 1.6 ± 0.3	Español-Jiménez et al. (2019)

might be due to differences in genetic population structure (Taguchi et al., 2021). Differences between sound emissions of cetaceans from contiguous areas and in the repertoire of the same species, but from distant geographic regions have been previously found (Moreira, 2021).

Our results show that downsweeps D-calls recorded attributed to sei whales in Ilhabela have a broader frequency range than those of other populations.

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