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ORIGINAL PAPER

High-Frequency Modulated Signals Recorded Off the Antarctic Peninsula Area: Are Killer Whales Emitting Them?

M. V. Reyes Reyes[1,2] · S. Baumann-Pickering[3] · A. Simonis[3] · M. L. Melcón[1] · J. Trickey[3] · J. Hildebrand[3] · M. Iñíguez[1,4]

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Abstract High-frequency modulated signals with a stereotyped down-swept contour were recorded in the northwestern Antarctic Peninsula using an autonomous recorder and a towed hydrophone array. Signals have a mean start frequency at 21.6 kHz, end frequency at 15.7 kHz, −10 dB bandwidth of 5.9 kHz, and duration of 65.2 ms. Bouts of signals were generally recorded with a median inter-signal interval of 2.1 s. HFM signals partially modulated in the non-ultrasonic range similar to the ones described in this paper have already been reported for killer whales in the North Pacific, Western South Atlantic and Western Australian coast. The HFM signals were recorded in the presence of other odontocete sounds such as whistles, echolocation clicks and burst-pulsed sounds. The similarities of these sounds with vocalizations described for killer whales in the Western Australian coast lead us to strongly believe that the described HFM signals were produced by Antarctic killer whales. This paper described for the first time HFM signals in Antarctica and discussed evidence suggesting that Antarctic type A killer whales are the most probable candidates to produce such signals. However, a visual confirmation is still needed and the function of the HFM signals remains unknown.

Keywords High-frequency modulated signals · Antarctic killer whale morphotype · *Orcinus orca*

1 Introduction

Killer whales (*Orcinus orca)* are distributed throughout global oceans, and several populations demonstrate distinct morphological and genetic variations, as well as different behaviors, social structures, and diet preferences. Distinctive sympatric ecotypes are recognized in some regions [1–3] with low or no current gene flow among them [4,5], although the killer whale is still considered a single cosmopolitan species.

In Antarctic waters, five killer whale morphotypes [type A, type B (two forms), type C, and sub-Antarctic type D] have been described, with distinct morphological, ecological, and physiological adaptations [2,6,7]. Antarctic type A killer whales occur in open waters and have a circumpolar distribution around Antarctica, but are usually seen in ice-free waters and commonly around the Antarctic Peninsula [2]. They mainly feed on minke whales and occasionally on elephant seals. Type B killer whales also have a circumpolar distribution but appear to be common in the Antarctic Peninsula area and prefer nearshore waters. Type B killer whales can be divided into "pack ice" killer whales (large type B), which forage mainly in loose pack ice where they prey on seals, and also "Gerlache" killer whales (small type B) that are very common in the Gerlache Strait and have been seen feeding on penguins. Type

✉ M. V. Reyes Reyes
vanesa.reyes@cethus.org

1 Fundación Cethus, Gdor Luis Monteverde, 3695 (B1636AEM), Olivos, Provincia de Buenos Aires, Argentina

2 Whale and Dolphin Conservation, Brookfield House, 38St Paul Street, Chippenham, Wiltshire SN151LJ, United Kingdom

3 Scripps Institution of Oceanography, University of California, 9500 Gilman Drive 0205, La Jolla, San Diego, California 92093-0205, USA

4 Whale and Dolphin Conservation, 7 Nelson Street, Plymouth, MA 02360, USA

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C killer whales occur deep in the pack ice in eastern Antarctica, especially the Ross Sea, and feed on fish [2,8,9]. A fifth morphotype, type D, has a circumglobal distribution in sub-Antarctic waters, is sometimes associated with islands, and has been recorded interacting with toothfish longliners, suggesting that its diet probably includes fish [7,10].

Several studies have demonstrated differences in the structure and use of acoustic signals among different killer whale populations [11–14], and also of different dialects among different groups of the same population [15–17]. The acoustic repertoire of killer whales is diverse, including short duration (<0.25 ms), broad-band (10–100 kHz) echolocation clicks used for foraging [18–21] as well as low-frequency whistles, generally from 1 to 18 kHz [12,22–24] and pulsed calls used for communication [12]. In recent years, high-frequency modulated (HFM) signals or whistles have been described for several populations of killer whales. Samarra et al. [25] reported high-frequency whistles with fundamental frequencies ranging from 16.9 to 74.7 kHz in three eastern North Atlantic killer whale populations. HFM signals were also reported from recordings of eastern and western North Pacific killer whales, specifically the eastern North Pacific offshore ecotype of killer whales [26,27]. More recently, Andriolo et al. [22] described HFM signals for killer whales in the western South Atlantic Ocean off the coast of Brazil, and Wellard et al. [23] also described HFM signals for killer whales in Australian waters, a whistle group that they called BC04.

Some features of the acoustic repertoires may be culturally transmitted; however, the general structure of vocalization is likely to be genetically transmitted [28]. Thus, understanding similarities and dissimilarities among vocalizations produced by different populations around the world might reflect long-range dispersal movements among oceans and hemispheres in the past as supported by phylogeographic studies [29]. In addition, for a thorough characterization of the acoustic signals it is necessary to use passive acoustic monitoring, which can provide valuable information on the year-round distributions, behaviors and densities of these populations. This is especially important in such remote areas as Antarctic waters where visual observations are mostly restricted to the austral summer seasons. To date, descriptions of Antarctic killer whale acoustic repertoires are limited to two studies that characterized sounds from Antarctic killer whale in the Ross Sea, possibly from type B or C killer whales [30,31], and a recent study on type C killer whales in the eastern Weddell Sea coast [32]. In this study, HFM signals recorded in the northwestern Antarctic Peninsula are described and compared to the HFM signals previously reported for other regions.

2 Methods

2.1 Data Collection

HFM signals were examined in acoustic recordings from the Southern Ocean, north of Elephant Island. Recordings were collected with an autonomous High-Frequency Acoustic Recording Package (HARP, [33]) and a towed hydrophone array.

The HARP was bottom-moored in a packaged configuration, consisting of a redundant acoustic release system, data logger and battery cases, and a hydrophone suspended approximately 10 m off the sea floor. Its position was 60°53.2′S and 55°57.2′W in 760 m water depth (Fig. 1). The recorder sampled at a frequency of 200 kHz with 16-bit quantization from March 5, 2014 to July 17, 2014. The recording schedule was duty-cycled, and sampling occurred for 5 min within each 6-min cycle period. The recorder was equipped with a bundle of six cylindrical sensors (AQ-1, Teledyne Benthos, Falmouth, MA) for low-frequency signals from 10 to 3000 Hz, and also an omnidirectional sensor (ITC-1042, International Transducer Corporation, Santa Barbara, CA) for higher-frequency signals from 3 to 100 kHz. The sensors were connected to a custom-built preamplifier board.

The custom-built 4-element oil-filled hydrophone array was equipped with omnidirectional sensors (BII-7011 Type 3, Benthowave Instrument Inc., Collingwood, Ontario, Canada) with an approximately flat (±2 dB) hydrophone sensitivity from 30 Hz to 200 kHz of −204 dB re V/μPa. Each sensor was connected to a custom-built preamplifier board and bandpass filter. The preamplifiers were designed to flatten the frequency response of the ambient ocean noise, which provided greater gain at higher frequencies at which ambient noise levels are lower and sound attenuation is higher [33]. Each pre-amplified element was high-pass-filtered at 300 Hz to decrease flow noise at low frequencies. Three mid-frequency hydrophone channels were recorded at a 192 kHz sampling frequency using a MOTU 896HD. One high-frequency channel was recorded at a 500 kHz sampling frequency using an Avisoft Ultrasound-Gate USB 116 (Avisoft Bioacoustics e.K., Glienicke/Nordbahn, Germany). Both analog-to-digital converters had a 16-bit quantization. Towed array data were recorded directly to a computer hard-disk drive. The array was towed about 300 m behind the vessel during daylight and nighttime hours of February 19, 20, 23, 24, 25, 27, and March 1 and 2, 2014. During daylight hours, an acoustic technician visually monitored the incoming signals from the towed array by scanning a real-time scrolling spectrogram in Ishmael 2.0 (Mellinger, Oregon State University, Newport) and listening with headphones. The start and end times of acoustic encounters were noted, and the GPS position and track were logged. Visual observations were conducted when the ship was underway during

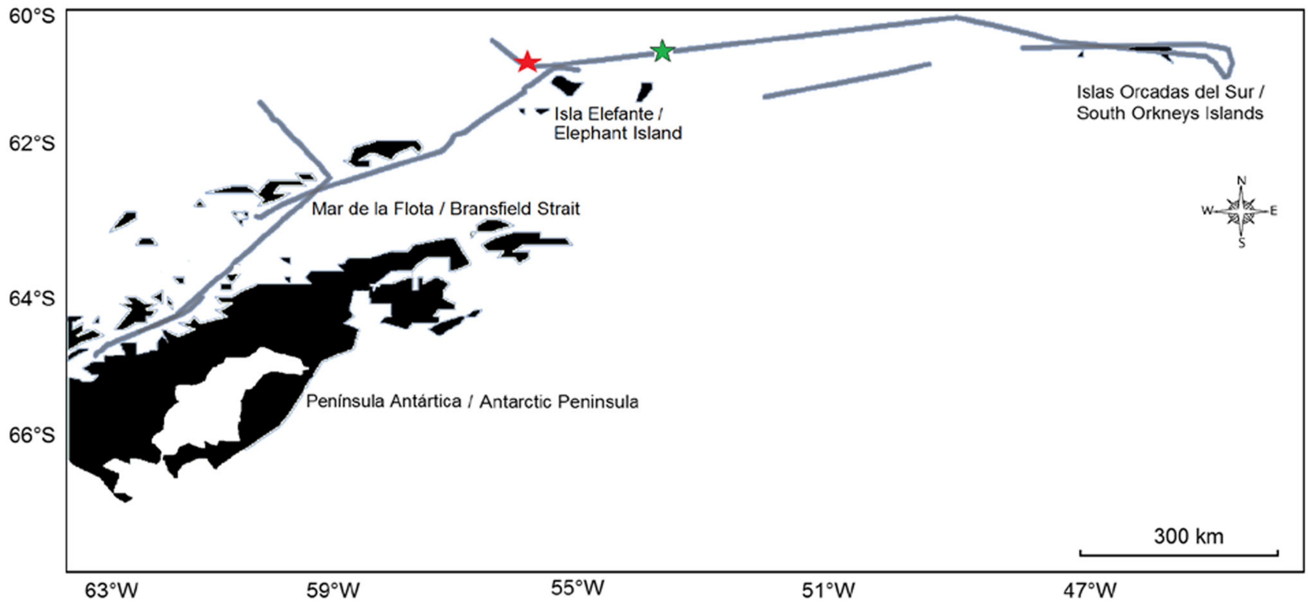

Fig. 1 Map showing the location of HARP deployment (*red star*) and the killer whale HFM signal detection in the towed array data (*green star*). *Gray line* indicates the towed array tracklines

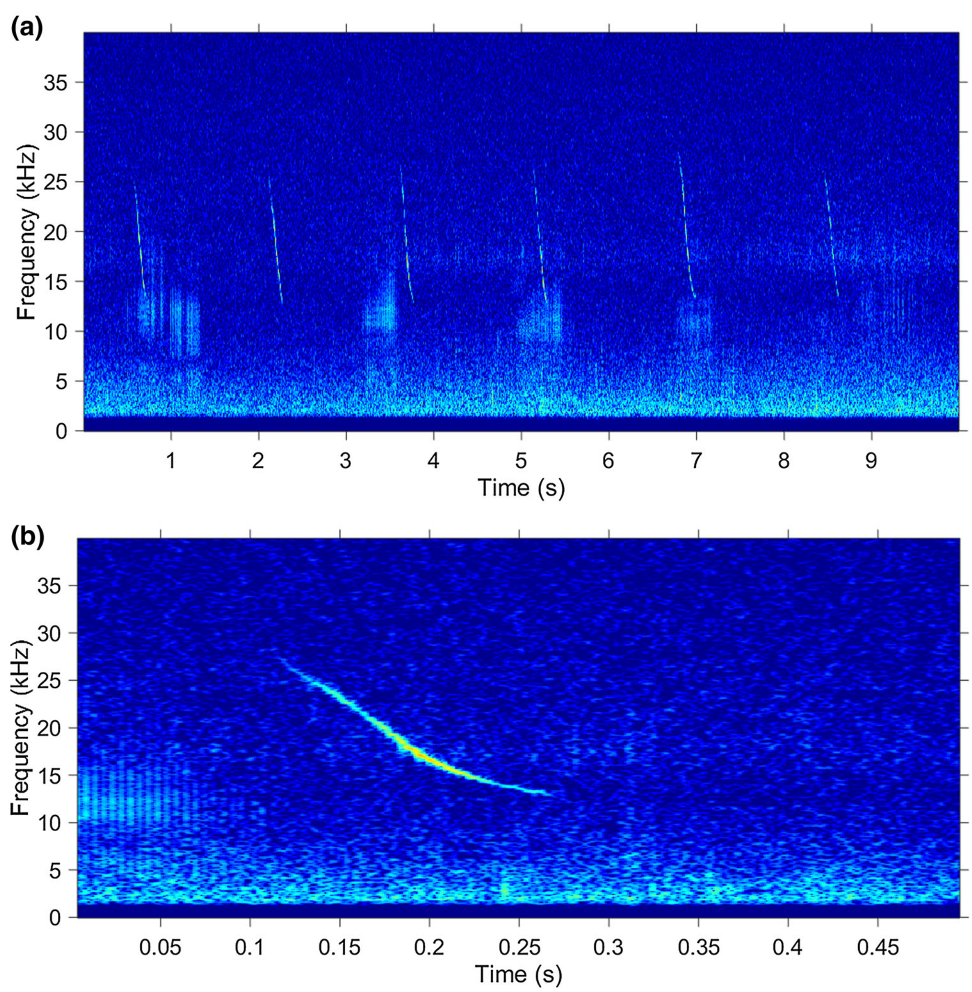

Fig. 2 Spectrogram of **a** a HFM signal bout, and **b** a single HFM signal (4096-point FFT, 90% overlap, Hanning window, high-pass filter with corner frequency at 2 kHz)

Table 1 Descriptive statistics of high-frequency modulated signals analyzed in this study, compared to [22,23,25,37]

Location	Antarctica ($n = 130$)	Brazil ($n = 19$)	North Pacific ($n = 159$)	Iceland ($n = 548$) Iceland > 48kHz ($n = 22$)	Norway ($n = 234$) Norway >48 kHz ($n = 23$)	Western Australia ($n = 61$)
Start freq (kHz)	21.6 ± 2.4 [15.0–27.0]	23.8 ± 2.5 [21.1–27.5]	29.6 ± 5.1 [19.3–44.0]	31.3 ± 6.7 [16.9–47.3]	31.7 ± 6.1 [17.6–45.2]	[3.9–27.0]
				64.0 ± 2.7 [60.6–71.2]	64.3 ± 3.6 [56.6–71.0]	
End freq (kHz)	15.7 ± 1.5 [12.3–21.0]	14.4 ± 2.6 [12.1–17.8]	20.8 ± 3.2 [17.1–33.4]	37.0 ± 6.3 [19.4–50.5]	35.3 ± 6.4 [19.8–46.6]	[5.7–29.1]
				68.5 ± 3.2 [60.0–74.7]	58.1 ± 5.4 [47.1–68.3]	
Mid freq (kHz)	16.6 ± 4.2 [11–33.6]	17.5 ± 2.5 [14.4–20.8]	25.3 ± 4.3 [18.4–39.4]	32.5 ± 5.8 [17.6–45.2]	32.1 ± 5.8 [19.0–42.8]	17.5 ± 62.5
				65.9 ± 2.3 [58.1–68.8]	59.2 ± 3.3 [53.3–64.3]	[14.4–20.8]
Min freq (kHz)	15.7 ± 1.5 [12.3–21.0]	14.4 ± 2.5 [12.1–17.8]	20.8 ± 3.2 [17.1–33.4]	30.4 ± 5.9 [16.9–44.5]	30.7 ± 5.9 [17.4–42.3]	[3.9–15.0]
				63.1 ± 2.8 [55.6–68.3]	55.9 ± 4.0 [47.1–64.3]	
Max freq (kHz)	21.6 ± 2.4 [15.0–27.0]	23.9 ± 2.5 [21.2–27.4]	20.8 ± 3.2 [17.1–33.4]	37.2 ± 6.4 [19.4–50.5]	35.7 ± 6.0 [22.3–46.6]	[9.1–29.3]
				68.7 ± 3.0 [61.9–74.7]	65.1 ± 3.4 [57.9–71.0]	
Peak freq (kHz)	17.7 ± 1.8 [14.5–23.3]	16.2 ± 3.3 [13.0–19.7]	–	–	–	–
Bandwidth (kHz)	5.9 ± 2.5 [0.9–12.1]	9.4 ± 3.8 [5.9–14.5]	8.9 ± 3.8 [1.6–20.2]	6.8 ± 3.7 [0.8–21.2]	5.0 ± 2.5 [1.0–19.9]	[0.3–20.3]
				5.6 ± 2.4 [0.7–10.4]	9.1 ± 4.1 [3.6–19.5]	
Duration (ms)	65.2 ± 25.9 [20.0–157.0]	210.3 ± 110.1 [69.8–366.2]	142.6 ± 74.2 [37.8–371.2]	140 ± 140 [8–810]	170 ± 300 [10–4200]	[50–1400]
				40 ± 70 [6–250]	40 ± 30 [20–140]	
ISI (s)	2.3 ± 1.1 [0.3–5.0]	2.4 ± 1.2 [1.0–1.9]	–	–	–	–
Sweep rate (Hz/ms)	95.2 ± 32.3 [11.2–166.7]	57.1 ± 31.2 [21.4–112.2]	Variable	–	–	–

For Iceland and Norway, whistles with fundamental frequencies entirely above 48 kHz are listed in separate rows [18]. Sample sizes for each location are included in brackets. For each parameter, values given are mean ± standard deviation, with range in brackets, except for Brazil killer whales for which 10th and 90th percentiles are given in brackets

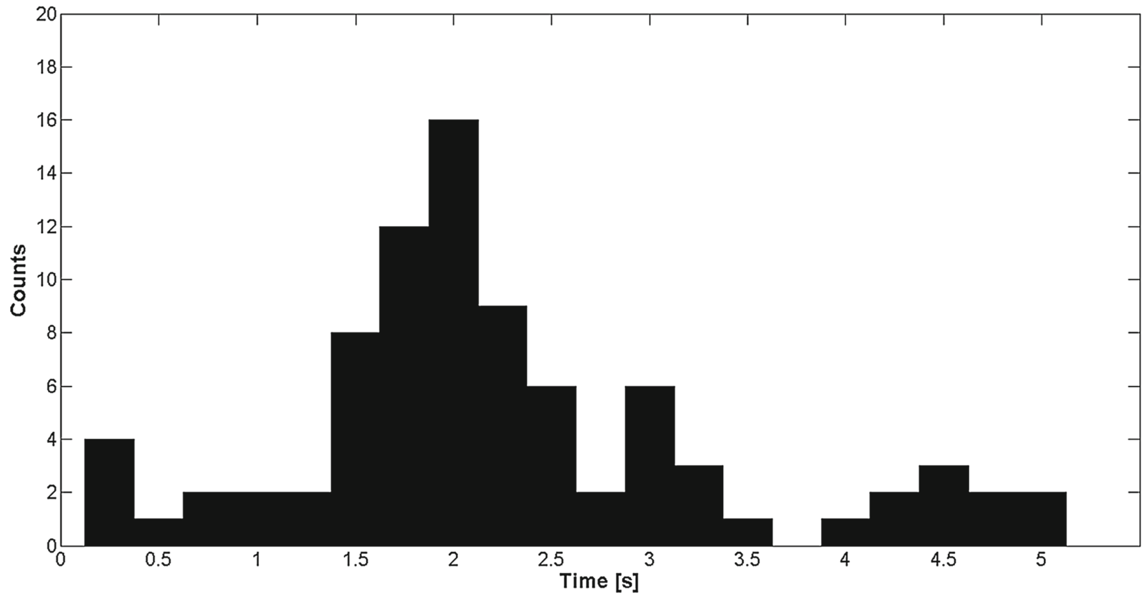

Fig. 3 Histogram of ISIs for all measured HFM signals

daylight hours, subject to weather and sea state conditions (Beaufort $\leq$ 4), and consisted of a team of two observers searching with 7$\times$ handheld binoculars and the unaided eye from the bridge and the exterior wings of the bridge. The acoustic technician notified the visual observers of any acoustic encounters via radio communications.

2.2 Acoustic Analysis

Acoustic signal processing was performed using the MATLAB-based (Mathworks, Natick, MA) custom software program *Triton* [33], as well as other custom MATLAB routines. The calibrated system response of the sensors connected to the preamplifier was applied to recordings during analysis. Long-term spectral averages (LTSAs, [33]) were examined to identify acoustic encounters with HFM signals, as well as other sounds recorded at the same time. An acoustic encounter was defined as a sequence of any of these signal types separated from others by 30 min or more. LTSAs averaged 500 discrete Fourier transform spectra from non-overlapping 10 ms Hanning-windowed frames, arranged sequentially to create a spectrogram with a resolution of 100 Hz for every 5 s. When HFM signals were detected in the LTSAs, the waveform and spectrogram were inspected in detail, and the start and end points of each signal were logged. Time series of 500 ms for each signal were digitally filtered with a 10-pole Butterworth bandpass filter with a pass-band between 10 and 60 kHz, and spectrograms were calculated (Hanning window, 2048 and 5120-point FFT for 200 and 500 kHz sampling frequencies, respectively, 90% overlap). For each time bin, the frequency bin with the highest amplitude was selected to trace the contours of each signal. The following parameters were calculated: minimum frequency, maximum frequency, start frequency, end frequency, mid-frequency (measured at the half-way point of the duration of the contour), peak frequency (measured at the maximum amplitude), bandwidth (maximum–minimum frequency), 10 dB duration, sweep rate, inter-signal interval (ISI), and number of inflection points. To account for a variety of signal-to-noise ratios, analyses were restricted to within -10 dB of the peak-amplitude along each contour. Only HFM signals with clearly visible contours in the spectrogram and without overlap with other sounds were included in the analysis. The other sound types were not thoroughly analyzed in this study, but were qualitatively inspected to assist in species identification.

3 Results and Discussion

HFM signals were recorded in four encounters: February 19, 2014 from 23:12 to 23:51 ($n = 3$; towed array; 60°41.4′S 53°41.8′W; Fig. 1), April 4, 2014 ($n = 3$; HARP) from 16:13 to 16:22, May 16, 2014 ($n = 40$; HARP) from 10:38 to 11:05, and May 31, 2014 ($n = 84$; HARP) from 11:22 to 13:19. All times are given in local time (GMT-3). The signals were very stereotyped with a frequency down-swept contour without inflection points (Fig. 2; Table 1). The mean start frequency was at 21.6 kHz and mean end frequency at 15.7 kHz. The mean -10 dB bandwidth was 5.9 kHz, the mean duration was 65.2 ms, and the mean sweep rate was 95.2 Hz/ms. Signals were generally emitted in bouts with a mean number of HFM signals of 6.0 $\pm$ 2.7, and a median inter-signal interval (ISI) of 2.1 s (Fig. 3).

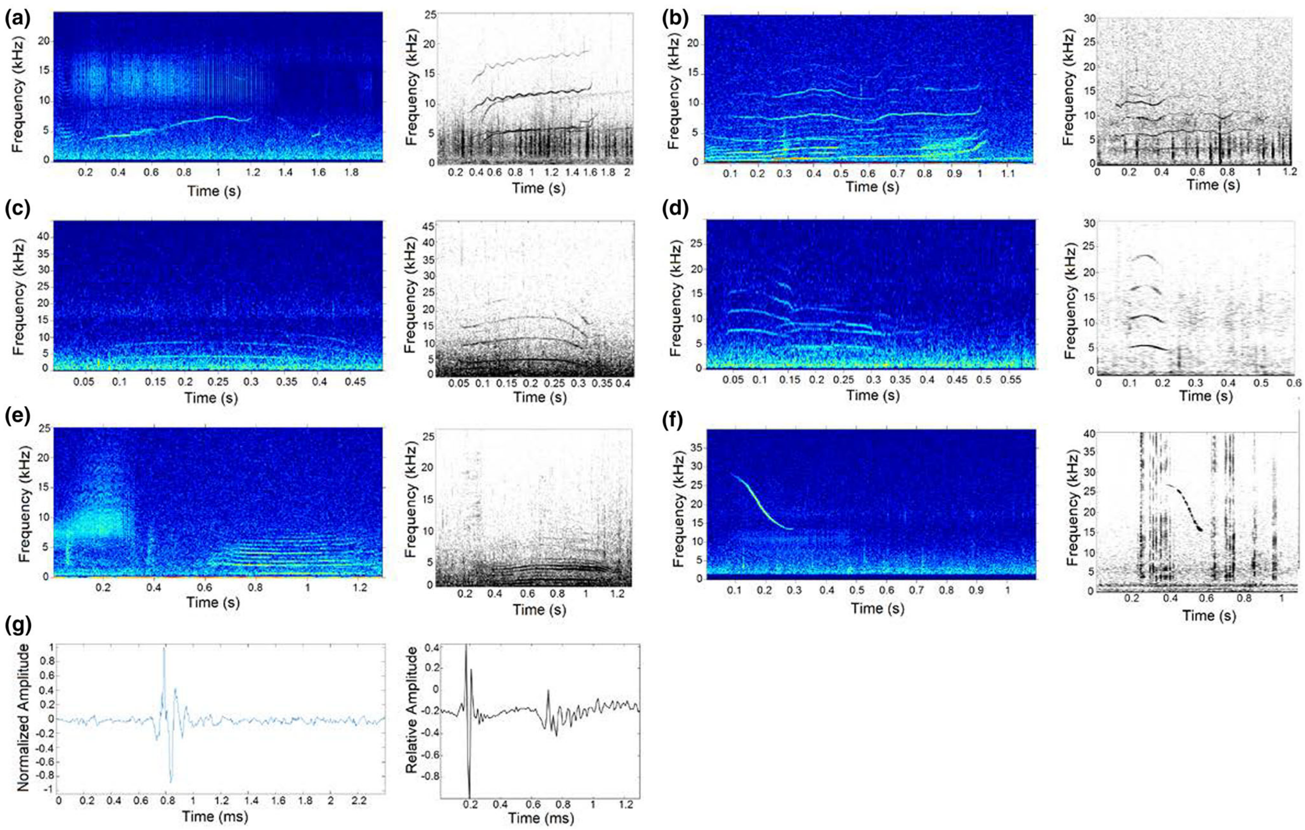

Fig. 4 Spectrograms of various call types recorded in the present study (*left panel* 90% overlap, Hanning window) compared to similar call types recorded from killer whales in Western Australia (*right panel*), **a** whistle with long duration (2048-point FFT, $fs = 500$ kHz), **b** whistle with high-frequency modulation (1024-point FFT, $fs = 200$ kHz), **c** whistle with a short duration and convex shape (1024-point FFT, $fs = 200$ kHz), **d** whistle of short duration and with a low number of extrema and inflection points (2048-point FFT, $fs = 500$ kHz), **e** Burst-pulse sound from Group BC05 showing little frequency modulation (2048-point FFT, $fs = 200$ kHz), **f** whistle from Group BC04 of short duration and high frequency (4096-point FFT, $fs = 500$ kHz), **g** single click of <200 µs duration. Group classification and figures for Australian calls were extracted from Wellard et al. [23]

Since this is the first time that HFM signals are recorded in Antarctica, and no concurrent visual observation was obtained for any of those events, we cannot accurately ascribe these sounds to a particular species. However, there is some evidence that leads us to strongly believe that the described HFM signals were produced by Antarctic killer whales. Each acoustic encounter of HFM signals also contained other odontocete sounds such as whistles, echolocation clicks and burst-pulsed sounds (Fig. 4). The odontocete species that are known to occur around the Antarctic Peninsula include at least five species of beaked whales, killer, long-finned pilot (*Globicephala melas*), and sperm whales (*Physeter macrocephalus*), as well as hourglass dolphins (*Lagenorhynchus cruciger*) [10,34,35]. Of these species, only killer and long-finned pilot whales have been described producing all the recorded sound types. In killer whales, ultrasonic whistles are known from the Northeast Atlantic [25], the North Pacific [26,27], the Western South Atlantic [22] and Western Australian coast [23] (Table 1). Recently, Vester et al. [36] described ultrasonic whistles in a frequency range of 24–40 kHz and above 60 kHz for long-finned pilot whales in northern Norway. However, stereotyped HFM signals with down-swept contours have only been described for killer whales [22,23,37]. Furthermore, HFM signals partially modulated in the non-ultrasonic range similar to the ones described in this paper have already been reported for killer whales in the North Pacific [26], Western South Atlantic [22] and Western Australian coast [23]. Killer whales in the South of Brazil and North Pacific produce bouts of HFM signals with ISIs similar to those reported in this study [22,26]. In addition, many of the low-frequency whistles and burst-pulsed sounds recorded along with the HFM signals were similar to the vocalizations described by Wellard et al. [23] for killer whales in Western Australian coast (Fig. 4). In Fig. 4f, the spectrogram of an Antarctic HFM signal is shown along with an example of the Australian whistle BC04 [23] to illustrate the high similarity in frequency and duration among both signals. Echolocation clicks were not analyzed extensively in this study, but the broad-band spectra with peak frequency around 12 kHz, and short duration <0.2 ms were consistent with clicks described for populations of killer whales [21,23]. Echolocation clicks from long-finned pilot whales have been shown to have higher peak frequencies than killer whales with a mean peak frequency at 50 kHz [38]. An example of the waveform of an echolocation click is shown in Fig. 4g for comparison with the sounds described for Australian killer whales.

Given the location of the acoustic recordings (north of South Shetland Islands/ Islas Shetland del Sur), Antarctic type C killer whales are the least likely to have produced these signals as they prefer East Antarctica and are generally found within pack ice [10]. Possible candidates for the HFM signals could be Antarctic type A, B, or D killer whales. The killer whales producing the HFM signals in Brazil [21] looked like the most common morphotype of killer whale seen worldwide (A. Andriolo, personal communication), as is the case for Antarctic type A killer whales. Also, the Australian killer whales recorded by Wellard et al. [23] had a phenotype consistent with Antarctic type A killer whales. Furthermore, the phylogenetic relationships shown by Morin et al. [29] cluster Antarctic type A with other populations that produce HFM signals, including the North Pacific offshore ecotype and North Atlantic killer whales, while Antarctic types B and C are clustered into a separate, single clade.

All the reasons stated above lead us to think that the HFM signals reported in this study were produced by Antarctic type A killer whales. Nevertheless, a concurrent visual observation with acoustic recordings of HFM signals is necessary to confirm this.

Similarities in the vocal repertoire between different populations may reflect their ancestry [28] and can be used in combination with genetic data to better understand their phylogenetic relationships. Compared to the signals from the Northern hemisphere, Antarctic HFM signals were more similar to those from North Pacific killer whales [26] than from North Atlantic killer whales [25,37] (Table 1). They shared a similar down-sweep contour shape, but were lower in frequency and shorter. This is consistent with the recent findings of Moura et al. [5], who suggest that killer whales expanded from the Southern Ocean into the North Pacific, with North Atlantic ecotypes diverging from North Pacific lineages, and the divergence between North Pacific ecotypes occurring locally in sympatry.

The lack of visual data concurrent with the acoustic recordings reported in this study precludes us to make any assumption on the behavioral context of those signals. Some hypotheses have been formulated in previous studies related to the function of the HFM signals, but up to date, it remains unknown. Samarra et al. [25] suggested a use in short-range communication while foraging or socializing, because Icelandic and Norwegian killer whales call most intensively during such contexts and are generally silent while traveling [39]. Filatova et al. [27] also recorded HFM signals from animals that were mostly foraging. Simonis et al. [26] found that HFM signals had higher source levels than whistles and pulsed calls suggesting a different function than typical whistles. The authors also discussed about the similarity between HFM signals from killer whales and the echolocation signals of some species of bats [40], as well as beaked whale echolocation signals [41,42], which suggests that killer whale HFM signals could be used for echolocation purposes. Finally, they concluded that given the larger time-bandwidth product which increases the processing gain of a signal [43], HFM signals are more suitable for long-range detection tasks than the typical echolocation clicks. Andriolo et al. [21] recorded HFM signals while killer whales were traveling and also suggested an echolocation function of these signals. This paper described for the first time HFM signals in Antarctica and discussed evidence suggesting that Antarctic type A killer whales are the most probable candidate producing such signals. Further research is needed in order to visually confirm whether Antarctic type A killer whales produce HFM signals, and also to characterize source properties of HFM signals which would allow a better understanding of the function of these sounds.

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