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Acoustic detections of beaked whales, narrow-band high-frequency pulses and other odontocete cetaceans in the Southern Ocean using an autonomous towed hydrophone recorder

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ABSTRACT

Encased in a streamlined, flooded housing, a SoundTrap ST300HF hydrophone recording system was towed on voyages to South Georgia Island and the South Sandwich Islands and to the Antarctic Peninsula in December 2019–February 2020. Recordings were analyzed to identify acoustic detections of cetacean species. Acoustically identified species included sperm whales (*Physeter macrocephalus*), southern bottlenose whales (*Hyperoodon planifrons*), Arnoux's beaked whales (*Berardius arnuxii*), killer whales (*Orcinus orca*), and long-finned pilot whales (*Globicephala melas*). Acoustic detections also included several recognized types of beaked whale echolocation pulses (BW37/39 and BW58) as well as two likely beaked whale echolocation pulse types that do not match any previous descriptions. Narrow-band high-frequency echolocation signals (NBHF) (typical of porpoises and some dolphin species) were detected in many locations, and one of these coincided with a sighting of hourglass dolphins (*Lagenorhynchus cruciger*). This study shows the utility of an autonomous towed hydrophone system on a vessel of opportunity to study the distribution of cetaceans in rough seas that are difficult to study by visual survey methods.

1. Introduction

Much of what is known about odontocete cetacean distributions in the Southern Ocean has come from visual sighting surveys conducted as part of the International Whaling Commission's (IWC) Southern Ocean Whale and Ecosystem Research Programme (SOWER) from 1978 to 2009. These surveys were primarily focused on the distribution and abundance of baleen whales such as blue whales (Branch et al. 2004, 2007) and Antarctic minke whales (Branch and Butterworth 2001). However, the SOWER surveys also produced estimates of the density and abundance of the most commonly seen odontocetes (sperm whales (*Physeter macrocephalus*), killer whales (*Orcinus orca*), long-finned pilot whales (*Globicephala melas*), hourglass dolphins (*Lagenorhynchus cruciger*), and a collective category of all beaked whales (family Ziphiidae)) (Kasamatsu and Joyce 1995). The southern bottlenose whale (*Hyperoodon planifrons*) was by far the most commonly identified beaked whale in that study. However, those surveys concentrated on waters south of 60° S, and there is a shortage of species-specific distribution information on odontocetes in offshore regions of 40–60° S.

Passive acoustic surveys using towed hydrophones are a potential alternative to visual sighting surveys for distributional studies of odontocetes. Typically, towed hydrophone surveys have been conducted using a short, linear array of hydrophones towed behind a vessel (Heineman et al., 2016; Rankin et al., 2017). Odontocete acoustic signals received by the hydrophones are typically transmitted via a conducting tow cable back to the vessel for recording and/or real-time processing. Such systems have been used to study sperm whales in the Southern Ocean (Pierpoint et al., 1997; Gillespie et al., 1997; Leaper and Scheidat 1998; Leaper et al., 2000). Although this approach is effective, it requires a large quantity of specialized equipment and skilled operators. Here we describe the use of a simpler system with an integrated hydrophone recording system towed with a rope line. The simplicity of this system allows it to be more easily deployed from vessels of opportunity by personnel with minimal training.

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The use of towed hydrophone systems to study odontocete species distribution requires that species can be recognized by their acoustic signals. Although the echolocation clicks of sperm whales have been well characterized (Gould and Jones 1995), the species-specific recognition of the acoustic signals of beaked whales, dolphins and porpoises is still being developed (Baumann-Pickering et al., 2013; Rankin et al., 2017).

Beaked whales can be recognized from their characteristic echolocation pulses (or chirps) that include a frequency-modulated (FM) upsweep (Baumann-Pickering et al., 2013). To date, all beaked whale species have been found to produce a single unique FM pulse type that is diagnostic for that species (Baumann-Pickering et al., 2013; DeAngelis et al., 2018). In the Southern Ocean, five distinctive types of beaked whale pulses have been described (BW29, BW37, BW39, BW53, and BW58) and named based on their peak frequency in kHz (Trickey et al., 2015; Baumann-Pickering et al., 2015; Giorli et al., 2018). Based on its similarity to the echolocation pulse of the northern bottlenose whale (*Hyperoodon ampullatus*), BW29 is believed to be made by the southern bottlenose whale (*Hyperoodon planifrons*) (Baumann-Pickering et al., 2015). The other pulse types are likely from species in the genus *Mesoplodon* (Trickey et al., 2015; Baumann-Pickering et al., 2015; Giorli et al., 2018). Additional work is needed to determine whether BW37 and BW39 are truly unique or might be from the same species (Giorli et al., 2018). Echolocation pulses with a peak frequency of 16 kHz were recorded in the vicinity of Arnoux's beaked whales (*Berardius arnuxii*) in the Antarctic (Rogers and Brown 1999), but the recording bandwidth was limited and this should not be considered to be a complete description for that species. With at least 10 species of beaked whales in the Southern Ocean (MacLeod et al., 2006), more beaked whale FM pulses remain undescribed.

Dolphins and porpoises produce a variety of echolocation clicks and pulses which differ among taxonomic groups (Morisaka and Connor 2007). Most delphinid cetaceans produce short clicks that have a broad frequency bandwidth, along with whistles and burst pulses. All porpoise species, some dolphin species (in the genera *Cephalorhynchus, Lagenorhynchus,* and *Pontoporia*), and dwarf and pygmy sperm whales (*Kogia* spp.) produce narrow-band high-frequency (NBHF) echolocation pulses (Madsen et al., 2005). Although at least some acoustic signals have been described for most small cetaceans in the Southern Ocean (Kyhn et al. 2009, 2010; Gotz et al., 2010; Tougaard and Kyhn 2010), the full vocal repertoire has likely not been fully described for any species.

In this paper we describe the use of an autonomous towed hydrophone recording system to study odontocete acoustic signals in the Southern Ocean during a small yacht research charter voyage to South Georgia and the South Sandwich Islands and an expeditionary ecotourist voyage to the Antarctic Peninsula. High-quality recordings from this system were used to identify the acoustic detection locations of several beaked whale and other cetacean species based on previously described acoustic signals. Two likely beaked whale pulse types are described based on these recordings which appear to be unlike any that have been previously described. The autonomous towed system has the advantage of being self-contained and easy to deploy and retrieve with a minimum of training. This approach facilitates sampling of seldom studied areas, like the waters around the South Sandwich Islands, using vessels of opportunity.

2. Methods

2.1. Autonomous towed hydrophone system

Design details for our flooded towbody are given in Barlow (2021). A compact SoundTrap® ST300HF hydrophone recording system (Ocean Instruments, Auckland, New Zealand) was secured with set screws inside a 66.6 mm ID x 76.2 mm OD (2 5/8″ ID x 3″ OD) polycarbonate tube approximately 50 cm long (Fig. 1). The tapered end-caps were grooved to allow the tube to flood when towed. The ST300HF was mounted with the integrated hydrophone end pointing aft, away from the tow vessel. The first 360 m of towline was 4.8 mm (3/16″) Dyneema® (high modulus polyethylene). The last 3 m of tow line was 9.5 mm (3/8″) Dyneema® that was wrapped with 4.5 kg (10 lbs) of 4.8 mm (3/16”) lead wire to provide weight to sink the tow body. The ST300HF was programmed to record continuously at a 576 kHz sampling rate with a 400 Hz high-pass filter. With these settings, the instrument has a flat frequency response (±3 dB) from 500 Hz to 150 kHz. The depth of the tow body was measured with a Sensus Ultra® data recorder mounted inside the tube.

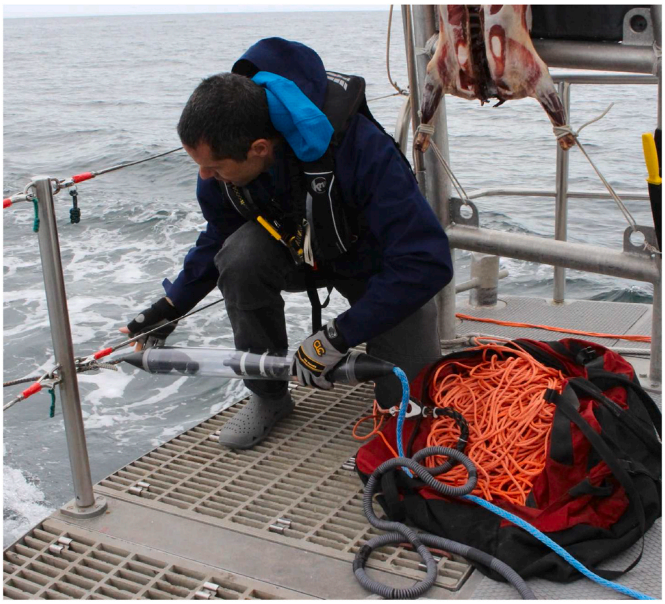

Fig. 1. One of the authors (TC) deploying the SoundTrap ST300HF hydrophone recorder (inside a streamlined towfish) from the stern of the *Pelagic Australis*. Photograph by Skip Novak.

2.2. Deployments

The towed hydrophone recording system was deployed on a not-to-interfere basis during transits of the 23-m sailing yacht *Pelagic Australis* during a round-trip expedition from the Falkland Islands to the South Sandwich Islands and South Georgia from December 30, 2019 to January 29, 2020 (Leg 1) and on the 26-m eco-tourism vessel *Hans Hansson* from King George Island to Puerto Williams, Chile via the Antarctic Peninsula from February 11 to 27, 2020 (Leg 2). The *Pelagic Australis* was always under sail during deployments, usually with auxiliary engine power as well; the *Hans Hansson* was powered by a diesel engine. The system was deployed 360 m behind the vessels by hand and towed at speeds of 2–10 kts (3.7–18.5 km h^{-1}). The system was retrieved by hand or with a manual winch.

2.3. Acoustic data processing

Acoustic recordings were downloaded from the ST300HF intermittently during both expeditions. Compressed files were converted to WAV files by SoundTrap® host software. Acoustic data were analyzed with PAMGuard v2_00_16e open-source software (Gillespie et al., 2009). The PAMGuard software created long-term spectral averages (LTSAs) and automatically detected impulsive sounds (e.g., echolocation clicks and pulses) using an energy detector. This software also classified each impulsive sound into categories of peak frequency using the click classification function within the click detection module. Prior to click detection and classification, the acoustic data were resampled to a sampling rate of 288 kHz. We used the same classification scheme as

Simonis et al. (2020) which initially classified clicks based on peak frequency ranges of 2–15, 15–30, 30–50, 50–80 and > 80 kHz. Within the primary frequency range of beaked whales (30–50 kHz), clicks with frequency sweeps were identified by zero-crossing analysis. After the initial processing by PAMGuard software, the resulting data files were re-processed using the click template classifier within PAMGuard Viewer software. Nine waveform templates were used based on: Cuvier's beaked whale (from the North Pacific), previously identified FM pulses from Antarctic beaked whales (BW29 & BW37 from Trickey et al., 2015), an FM pulse type identified in a preliminary review of our data (BW40V, see below), a 15 kHz pulse type identified in a preliminary review of our data and believed to be from Arnoux's beaked whale, a generic NBHF click type, a 117 kHz NBHF click type identified in a preliminary review of our data, sperm whale echolocation click, and a low-frequency delphinid echolocation click type. If the correlation between a detected signal and one of these waveform templates (at the sample lag that maximizes the correlation) was greater than a given threshold, PAMGuard Viewer labeled that encounter in its database.

Detections of potential cetacean echolocation pulses were identified manually in PAMGuard Viewer. Impulsive signals (clicks and pulses) were displayed as symbols in the click detector window, with the symbol color and shape coding based on peak frequency (from the click detector classifier) and on the results of the click template classifier. An experienced acoustic analyst (JB) reviewed results in 2-min time slices in the click detector's amplitude/time display. Additionally, JB reviewed the LTSA displays in 1-h time slices to detect cetacean signals that were missed in the review of the impulsive signals. Potential acoustic detections were recognized as patterns of high-amplitude pulses with similar symbols that were clustered together. Potential detections were examined in more detail by selecting a symbol on the screen to display the waveform, frequency spectrum, and Wigner-Ville representation of the pulse represented by that symbol. Contextual information, such as the presence of whistles, burst pulses, and various other sounds, was obtained by viewing a spectrogram representation of the acoustic data at the time of a potential detection. If a potential detection was viewed as likely to be from a cetacean, the impulsive signals were grouped as a detection "event" in PAMGuard, and events were labeled and stored for later analysis and scrutiny. Event labels could represent a recognized species (e.g., sperm whale), a previously identified echolocation type (e.g., "BW37" or "NBHF"), or an unidentified category (e.g., "delphinid" or "possible beaked whale"). New event labels were added in the course of the analysis as potentially new pulse types were identified.

Information on click and pulse events was extracted from PAMGuard databases and binary files using the R packages PAMpal and PamBinaries.[1] For each event, a histogram of inter-pulse interval (IPI), a plot of the average pulse frequency spectrum, and a concatenated spectrogram plot of pulses was created. Although missed detections and the presence of multiple animals can result in misleading IPI estimates, we assume that the peak in the IPI histogram represents the most likely IPI of an individual. These plots were used as aids (in addition to the PAMGuard displays) in the classification of detection events.

The final classification of acoustic events (as a species or as a recognized echolocation pulse type) was by unanimous agreement of two experienced analysts (JB and JST). Multiple traits were used to classify beaked whale FM pulse types including the presence of an upsweep, peak frequency, ancillary frequency peaks in the spectrum, and IPI. Sperm whales were recognized from their regular echolocation clicks that are short (typically only a few cycles), with a peak frequency less than 15 kHz and an inter-click interval greater than 0.4 s. Large delphinid species were recognized from their regular echolocation clicks that are short (typically only a few cycles), with a peak frequency greater than 15 kHz, and from contextual information in the spectrogram (such as burst pulses and whistles). NBHF species were recognized from their relatively long (many cycles), high-frequency (>100 kHz) pulses. If the two analysts disagreed about a classification, their final consensus classification was based on a higher level of taxonomy (such as "unidentified beaked whale").

3. Results

The hydrophone was towed at a nominal depth of 4–6 m for a total of 720 h and 5250 km on Leg 1 (to South Georgia and the South Sandwich Islands) and for a total of 408 h and 2455 km on Leg 2 (to the Antarctic Peninsula). The average speeds were 7.3 and 6.0 km h^{-1} (respectively). A total of 51 acoustic detection events were found in the analyses of Leg 1 recordings and 14 acoustic detection events were found in the analyses of the Leg 2 recordings (Table 1; Figs. 2–4).

3.1. Beaked whales

Sixteen of the acoustic detections had FM pulses with the characteristic frequency upsweep that has been used to identify beaked whales in other studies (Baumann-Pickering et al., 2013) (Table 2). Two others had long echolocation pulses with peak frequencies of 15–16 kHz and no evidence of an upsweep, matching the previous, bandwidth-limited recordings of Arnoux's beaked whales (Rogers and Brown 1999) (Table 2). One of these two occurred ~5 km from a sighting of Arnoux's beaked whales in Gerlache Strait during Leg 2 (approximately 1 h after that sighting). Both were classified as Arnoux's beaked whales. Table 2 gives the median frequency characteristics of all beaked whale acoustic detections.

The majority (n = 11) of the 16 acoustic detections with FM pulses were labeled by both analysts as BW29 and were therefore classified as southern bottlenose whales. Of the remaining 5 detections, two closely matched two previously described echolocation pulse types (BW37/39 and BW58) (Fig. 5). One of the others was not sufficiently distinctive to classify as a previously described pulse type or as a new pulse type and is listed in Table 2 as an unidentified beaked whale. The FM pulses associated with the other two detections were sufficiently distinctive to justify new names for these signal types (BW40V and BW41).

Our BW37/39 FM pulse type (Table 2, Fig. 5) shares characteristics with both the previously described BW37 and BW39 pulse types. The peak frequency is closer to the 39 kHz FM pulse described by Giorli et al., (2018), but the IPI (0.15 s) is intermediate between the value they measured (0.22 s) and that measured by Trickey et al. (2015) for BW37 (0.12 s). Like the other two FM pulse types, our BW37/39 pulse had a secondary frequency peak between 20 and 30 kHz.

Our BW58 FM pulse type has a lower peak frequency (53 kHz) than that described for BW58 (Baumann-Pickering et al., 2015), however both studies found a broad, flat peak at 50–60 kHz, significant energy up to 100 kHz, and a strong secondary peak at 25–28 kHz. The relative amplitude of this secondary peak is less than 10 dB below than the primary peak. The IPI in that study (0.26 s) is also similar to the value we measured (0.29 s).

The BW40V FM pulse type has a frequency valley at 40 kHz between two almost equal frequency peaks (at 34 and 48 kHz) (Fig. 5) and a median IPI of 0.48 s. This name follows the nomenclature used by Griffiths et al. (2019) to describe the BW37V beaked whale pulse type which has a frequency valley at 37 kHz between two almost equal frequency peaks at 36 and 48 kHz. This FM pulse type was found only once, on Leg 1 (Fig. 3).

The BW41 FM pulse type had peak and center frequencies of 41 kHz (Fig. 5) and a median IPI of 0.45 s. This name follows the usual nomenclature used for beaked whales with a single peak frequency; however, a secondary frequency peak at 25–27 kHz was frequently observed with an amplitude of ~10 dB less than the primary peak (Fig. 5). This FM pulse type was found only once, on Leg 1 (Fig. 3).

The signals attributed to Arnoux's beaked whales were quite variable but all had a low peak frequency (15–16 kHz) and a narrow −3 dB

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[1] https://github.com/TaikiSan21.

Table 1
Locations and times of acoustic detection events that include odontocete echolocation signals detected on towed hydrophone surveys to the South Sandwich Islands and South Georgia, and to the Antarctic Peninsula. Acoustic event types are classified to species if possible. Other acoustic event types are explained in the text.

Event sequential number	Event ID	Start date/time (UTC)	Event type	Number of echolocation signals	South latitude	West longitude
Leg 1: South Sandwich Islands and South Georgia Voyage						
1	31	12/31/2019 02:27	NBHF	49	52.4718	55.1660
2	33	12/31/2019 03:55	NBHF	28	52.5505	54.8724
3	13	12/31/2019 07:30	BW37	13	52.7168	54.2125
4	37	1/1/2020 03:43	NBHF	247	53.9509	49.9782
5	90	1/1/2020 07:43	NBHF	6	54.0943	49.1083
6	7	1/1/2020 15:44	Southern bottlenose whale	15	54.5590	47.3655
7	8	1/1/2020 15:56	Southern bottlenose whale	27	54.5721	47.3140
8	91	1/1/2020 17:18	BW40V	5	54.6607	46.9659
9	38	1/1/2020 23:52	NBHF	13	55.0810	45.2329
10	17	1/2/2020 05:50	BW41	80	55.4101	43.7704
11	9	1/2/2020 21:05	Southern bottlenose whale	497	56.1299	40.1339
12	75	1/2/2020 21:44	Sperm whale	668	56.1584	39.9752
13	39	1/2/2020 23:38	NBHF	8	56.2385	39.5220
14	40	1/3/2020 05:08	NBHF	3	56.4750	38.1149
15	41	1/3/2020 08:25	NBHF	2	56.6045	37.2907
16	15	1/3/2020 13:21	Possible beaked whale	10	56.7419	36.0075
17	101	1/3/2020 17:54	Southern bottlenose whale	3	57.0337	34.8374
18	102	1/3/2020 18:59	Southern bottlenose whale	6	57.1104	34.5605
19	92	1/5/2020 00:24	Possible delphinid	258	57.7078	26.6829
20	67	1/10/2020 17:46	Arnoux's beaked whale	45	59.2584	26.9539
21	93	1/10/2020 23:17	Killer whale	78	58.7656	26.7886
22	21	1/11/2020 00:32	Southern bottlenose whale	4	58.5792	26.8137
23	87	1/11/2020 02:46	Killer whale	1620	58.2572	26.8648
24	94	1/12/2020 19:28	Unidentified odontocete	17	56.9918	26.8253
25	44	1/13/2020 21:13	NBHF	7	55.7883	30.1367
26	23	1/14/2020 10:26	Southern bottlenose whale	14	55.6117	32.6583
27	24	1/14/2020 15:28	Southern bottlenose whale	371	55.3083	33.4550
28	6	1/14/2020 16:38	Southern bottlenose whale	32	55.2033	33.7783
29	104	1/25/2020 23:47	Southern bottlenose whale	3	53.8500	39.6317
30	95	1/26/2020 01:53	Killer whale	97	53.8050	40.2650
31	96	1/26/2020 04:07	Unidentified delphinid	107	53.7367	40.7000
32	47	1/26/2020 06:35	NBHF	12	53.6533	41.3733
33	48	1/27/2020 01:40	NBHF	5	53.3450	45.2550
34	49	1/27/2020 02:26	NBHF	24	53.3450	45.2550
35	97	1/27/2020 03:22	Long-finned pilot whale	32	53.3250	45.5133
36	98	1/27/2020 03:34	Long-finned pilot whale	659	53.3067	45.7367
37	99	1/27/2020 04:09	Long-finned pilot whale	1297	53.3067	45.7367
38	51	1/27/2020 09:45	NBHF	9	53.1650	47.1317
39	72	1/27/2020 09:47	NBHF	47	53.1650	47.1317
40	100	1/27/2020 09:47	Unidentified delphinid	247	53.1650	47.1317
41	52	1/27/2020 10:47	NBHF	693	53.1317	47.3683
42	54	1/27/2020 11:17	NBHF	10	53.1317	47.3683
43	107	1/27/2020 11:18	Unidentified odontocete	4	53.1317	47.3683
44	56	1/27/2020 12:15	NBHF	19	53.1033	47.6200
45	105	1/27/2020 21:01	Unidentified large delphinid	1465	52.8783	49.7517
46	89	1/28/2020 03:39	Unidentified large delphinid	9430	52.6987	51.2900
47	57	1/28/2020 05:59	NBHF	191	52.6400	51.7467
48	59	1/28/2020 09:50	NBHF	6	52.4967	52.7600
49	106	1/28/2020 12:08	NBHF	90	52.4167	53.2333
50	60	1/28/2020 19:49	NBHF	15	52.2250	55.1850
51	61	1/29/2020 05:13	NBHF	4	51.8350	56.9667
Leg 2: Antarctic Peninsula Voyage						
1	39	2/16/2020 16:33	Possible delphinid	349	64.6523	62.2670
2	38	2/17/2020 19:06	Arnoux's beaked whale	4	64.7639	62.8748
3	40	2/24/2020 10:57	NBHF	10	63.5593	65.7100
4	9	2/24/2020 11:25	NBHF	75	63.5157	65.7827
5	10	2/24/2020 11:50	NBHF	8	63.4741	65.8505
6	37	2/24/2020 13:40	Killer whale	771	63.2616	65.9872
7	6	2/24/2020 19:56	Southern bottlenose whale	9	62.4652	66.1428
8	41	2/25/2020 00:21	BW58	49	61.9277	66.2751
9	11	2/26/2020 03:48	NBHF	11	58.6049	67.2791
10	42	2/26/2020 03:48	Unidentified delphinid	101	58.6049	67.2791
11	12	2/27/2020 03:17	NBHF	5	55.7031	66.5610
12	13	2/27/2020 04:04	NBHF	8	55.5934	66.5085
13	14	2/27/2020 04:12	NBHF	46	55.5741	66.4991
14	15	2/27/2020 04:20	NBHF	32	55.5576	66.4912

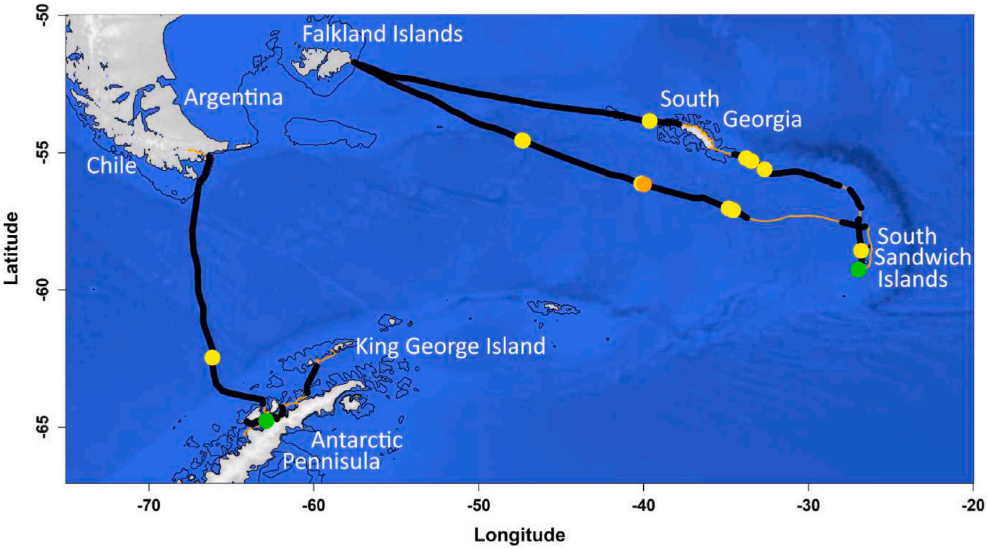

Fig. 2. Acoustic detection locations (colored circles) for southern bottlenose whales (yellow), Arnoux's beaked whales (green), and sperm whales (orange). Vessel transects include periods with towed hydrophone recordings (bold black lines) and without recordings (thin orange lines). Shelf waters (<200 m depth) are delimited by a thin black line. Negative values indicate south latitudes and west longitudes.

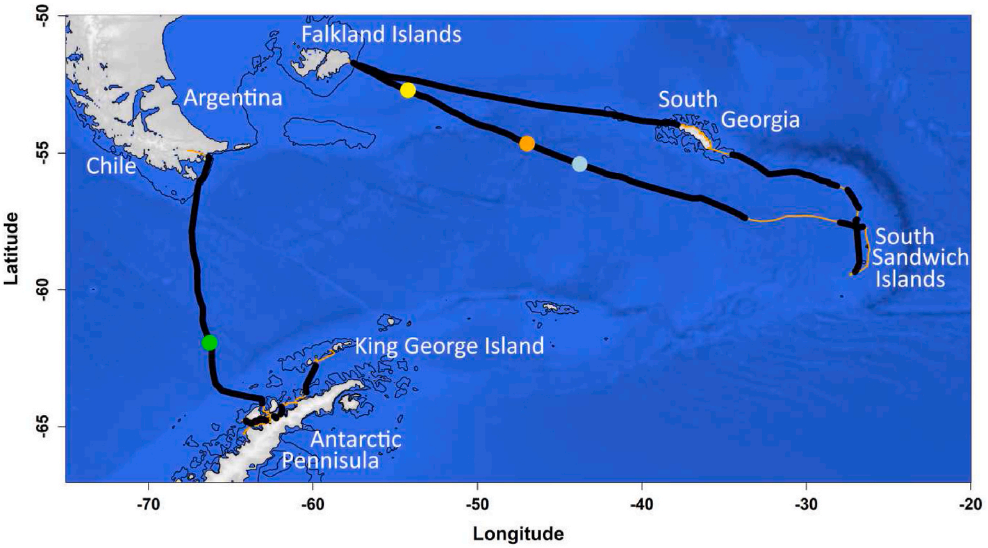

Fig. 3. Acoustic detection locations (colored circles) for beaked whale pulse types BW37/39 (yellow), BW58 (green), BW40V (orange), and BW41 (blue). Other features are as in Fig. 2.

bandwidth (2.3–3.3 kHz) (Table 2, Fig. 5). A high signal-to-noise ratio (SNR) pulse recorded near the sighting of this species in the Gerlache Straight had a sudden onset (like a delphinid echolocation click) followed by an apparent downsweep (Fig. 5). The highest SNR pulse of the other acoustic detection, at the south end of the South Sandwich Islands, was a long signal with a relatively constant frequency throughout (Fig. 5). Pulses from both detections showed secondary frequency peaks at 28–29 kHz.

3.2. NBHF species

A total of 30 acoustic events were detected with NBHF signals (Fig. 4, Table 3). The mean peak frequency for the median values for each event was 127.7 kHz (range = 122.0–131.0 kHz). A bivariate plot of peak frequency and −3 dB bandwidth did not show any obvious clustering of values that might be used to discern species (Fig. 6). One of the NBHF events (ID = 54) with a peak frequency of 129 kHz was recorded at the same time as a sighting of hourglass dolphins. Another of the NBHF events (ID = 72) with a peak frequency of 124 kHz occurred at the same time as delphinid burst pulses (ID = 100) with a peak frequency of 43 kHz. These two signal types overlapped in time, but it is not known if they were made by the same species.

3.3. Other species

Other acoustic detection events included four killer whale encounters with peak frequencies of 18–25 kHz, three long-finned pilot whale encounters with peak frequencies of 39–49 kHz (all within a 1-hr period), one sperm whale encounter with a peak frequency of 14 kHz (lasting 46 min), and several possible/unidentified delphinid encounters without NBHF pulses (Tables 1 and 4). All of the killer whale detections and two of the long-finned pilot whale detections included burst pulses as well as delphinid-type echolocation clicks. Two of the killer whale detections also included whistles. The sperm whale detection had a

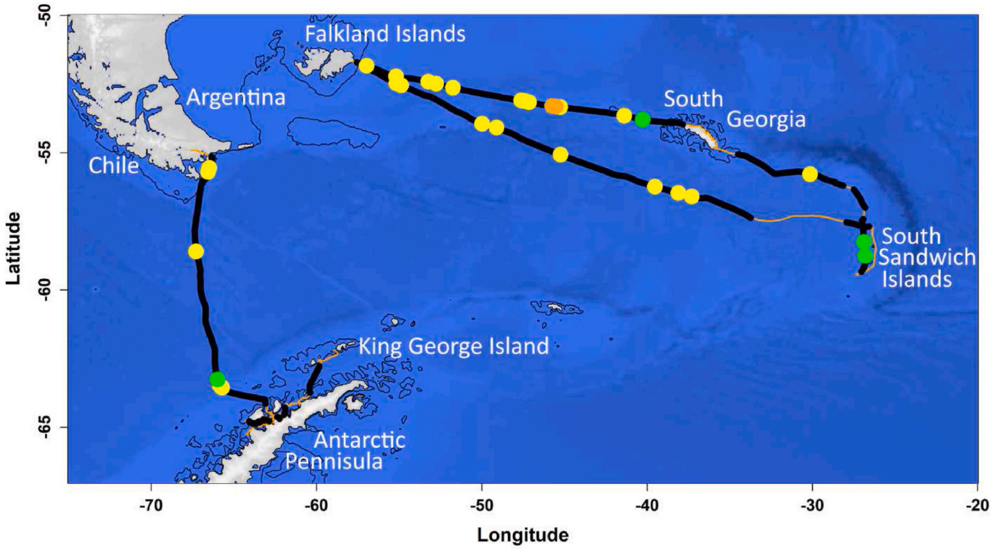

Fig. 4. Acoustic detection locations (colored circles) for narrow-band high-frequency (NBHF) species (yellow), killer whales (green), and long-finned pilot whales (orange). Other features are as in Fig. 2.

median inter-click interval of 0.75 s.

4. Discussion

Our study demonstrates the utility of autonomous towed hydrophones to study the distribution of odontocetes from vessels of opportunity with a minimum of effort. The number of odontocete acoustic detections ($n = 65$) is much higher than the number of concurrent odontocete sightings ($n = 2$) in these rough waters. Our study benefitted from the relatively slow transit speed of the two vessels we used (less than 15 km h^{-1}). Although towed hydrophone surveys for odontocetes have been routinely used as speeds of up to 10 kts (18 km h^{-1}) (Rankin et al., 2017), greater speeds might be problematic. At higher speeds, propeller cavitation noise is a greater problem, but that can be mitigated to some degree by using properly maintained low-cavitation propellers (Chekab et al., 2013). Another noise problem occurs when the hydrophone strikes air bubbles entrained by breaking waves in the upper water layer. At higher speeds, more weight is required to get a towed hydrophone below this bubble layer. Higher speeds also contribute to greater flow noise. Towed hydrophone surveys like ours may not be possible on vessels of opportunity that transit at speeds greater than 10 kts.

We were conservative in our classification of species or pulse type from acoustic events found in our recordings. We based classifications on the closest match to previous descriptions. When in doubt, we labeled the events as unidentified odontocetes. We described potentially new sound types only when a signal clearly did not match any previously described cetacean signals. Although this approach is common practice, it is not entirely satisfactory. Because classifications are subjective, it is difficult to quantify the errors in classification. All classification methods are likely to have some errors, but it takes a large dataset with known species to quantify misclassification error. Ultimately, studies like this should base species and other classifications on objective, well-validated classification methods with known error rates, such as that developed recently by Rankin et al. (2017). Until enough data are available to make this feasible, it is important to consider that some species classification errors are likely and that the reliable characterization of new signal types can only occur from replicated observations.

4.1. Beaked whales

The two beaked whale species that were classified with a high degree of confidence were the southern bottlenose whale and Arnoux's beaked whale. Southern bottlenose whales were the most commonly seen odontocete species on the IWC's circum-Antarctic sighting surveys (Kasamatsu and Joyce 1995), which matches our observation as the most-frequently recorded beaked whale in our acoustic data. The other likely beaked whale species in the Southern Hemisphere include Shepherd's beaked whale (*Tasmacetus shepherdi*), Cuvier's beaked whale (*Ziphius cavirostris*) and five species in the genus *Mesoplodon*: the strap-toothed beaked whale (*M. layardii*), Gray's beaked whale (*M. grayi*), Hector's beaked whale (*M. hectori*), Andrew's beaked whale (*M. bowdoini*), and the spade-toothed beaked whale (*M. traversii*) (MacLeod et al., 2006).

Of the Southern Hemisphere beaked whale species found in cold waters, recordings in the near vicinity of confirmed sightings have only been made for Arnoux's beaked whale and Shepherd's beaked whale. Our recordings in the Gerlache Strait (near a sighting of Arnoux's beaked whales) and south of the South Sandwich Islands matched the 16 kHz signals that were previously described for Arnoux's beaked whales (Rogers and Brown 1999). Unlike the previous recordings of Rogers and Brown (1999), our recordings at a sampling rate of 576 kHz were not bandwidth-limited and show additional detail not seen in these previous recordings. In addition to a strong frequency peak at 15–16 kHz, our recordings show faint secondary peaks at 28 and 34 kHz and some energy above ambient noise up to 40 kHz (Fig. 5). Leunissen et al. (2018) recorded broadband echolocation clicks with a 19 kHz peak frequency in the vicinity of Shepherd's beaked whales. None of our beaked whale acoustic events matched those signals; however, because these broadband clicks do not match our expected pattern of FM pulses, we might not have recognized these as a beaked whale in our recordings.

Previously described beaked whale FM pulses that are not yet be attributed to a sighted species include BW29, BW37, BW58, BW39, and BW53. Of these, BW29 and BW37 were previously recorded near the South Scotia Ridge (Trickey et al., 2015) and Elephant Island (Baumann-Pickering et al., 2015). BW58 was only recorded near Elephant Island (Bauman-Pickering et al., 2015). BW39 and BW53 were only recorded east of Cook Strait in New Zealand (Giorli et al., 2018). We add two new FM pulse types to this previous list of five: BW40V and BW41.

We agree with previous authors (Trickey et al., 2015; Baumann-Pickering et al., 2015) that based on its distribution, common occurrence, and similarity to the FM pulse signal produced by northern bottlenose whales, BW29 are highly likely made by southern bottlenose whales. Gray's and strap-toothed beaked whales have been described as

Table 2
Frequency characteristics of beaked whale acoustic detections. Median values of peak frequencies and bandwidth metrics (at −3 dB and −10 dB re: peak) are given for all pulses that were at least 15 dB above the noise level at the peak frequency. Event IDs correspond to events in Table 1.

			Bandwidth @ −3 dB				Bandwidth @ −10 dB			
Event ID	Event Type	Peak frequency (kHz)	Center frequency (kHz)	Bandwidth (kHz)	Lower frequency (kHz)	Upper frequency (kHz)	Center frequency (kHz)	Bandwidth (kHz)	Lower frequency (kHz)	Upper frequency (kHz)
13	BW37/39	39.0	38.8	5.8	35.7	41.9	39.2	10.9	33.6	44.8
7	Southern bottlenose whale	28.5	28.9	5.6	25.7	31.5	32.2	15.0	23.3	40.0
8	Southern bottlenose whale	29.0	29.0	5.8	26.6	32.0	30.8	13.8	23.6	38.1
91	BW40V	48.0	47.6	6.5	43.8	51.3	41.3	23.3	29.6	53.2
17	BW41	41.0	41.5	3.0	39.5	42.9	40.6	13.7	33.5	47.3
9	Southern bottlenose whale	33.5	32.8	4.5	30.1	35.6	33.7	14.7	25.4	41.8
15	Possible beaked whale	39.0	38.7	3.6	37.0	40.2	38.3	6.7	35.1	41.7
101	Southern bottlenose whale	28.5	29.2	8.1	25.1	33.2	30.7	15.6	22.9	38.5
102	Southern bottlenose whale	31.0	30.1	5.5	26.4	34.1	31.1	14.3	23.5	38.9
67	Arnoux's beaked whale	15.0	15.0	2.3	13.8	16.4	15.0	5.0	12.9	17.3
21	Southern bottlenose whale	31.0	30.2	7.3	26.5	34.6	33.1	17.1	24.5	41.7
23	Southern bottlenose whale	37.0	36.6	4.4	33.3	40.2	33.9	22.9	22.7	45.4
24	Southern bottlenose whale	34.0	33.8	4.8	30.4	36.6	35.7	18.7	25.2	46.3
6	Southern bottlenose whale	28.0	28.4	5.1	25.7	31.6	29.1	10.6	24.0	34.2
104	Southern bottlenose whale	29.0	30.3	8.3	26.2	34.5	32.7	17.4	24.1	41.4
38	Arnoux's beaked whale	16.0	17.3	3.3	13.9	20.3	18.8	5.6	13.1	21.5
6	Southern bottlenose whale	29.0	29.1	5.9	25.7	32.9	31.6	15.9	22.3	41.0
41	BW58	53.0	53.4	6.1	49.1	57.7	52.5	17.3	42.9	61.8

likely sources for four FM pulse types (BW37, BW58, BW39, and BW53) (Baumann-Pickering et al., 2015; Giorli et al., 2018). Our BW58 pulse type is clearly similar to that signal as described by Baumann et al. (2015). Giorli et al. (2018) suggests that BW37 and BW39 might represent natural variation within the range of a single species. Our measurements of BW37/39 are intermediate to those described for BW37 and BW39 and generally support this suggestion. If this is true and if each beaked whale species only makes one type of FM pulse (Baumann-Pickering et al., 2013), the five unattributed pulse types (BW37/39, BW53, BW58, BW40V, and BW41) likely correspond to the five species of *Mesoplodon* found in the Southern Ocean.

The geographic distribution of the five unattributed pulse types (or six, if BW37 and BW39 are different) may provide some clues about their source. Only two *Mesoplodon* species (Gray's and strap-toothed beaked whales) have been commonly seen south of the Antarctic Convergence (MacLeod et al., 2006). Given that BW37 and BW58 have been recorded well south of the Antarctic Convergence, they are likely produced by these two most southern of the *Mesoplodon* species. The other FM pulse types (BW53, BW40V and BW41) might therefore be made by the more northern *Mesoplodon* species (Andrew's, Hector's and spade-toothed beaked whales). Although Shepherd's beaked whales are known to make broad-band, dolphin-like echolocation clicks (Leunissen et al., 2018), they may also make one of these described FM pulses. Clearly more research is needed to attribute specific FM pulses to beaked whale species. This will require dedicated efforts to identify beaked whales at sea (visually, photographically or genetically) and to acoustically sample in the vicinity of those whales to record and characterize the echolocation pulses produced during their next foraging dive.

4.2. *NBHF species*

NBHF pulses are made by a diverse group of odontocete species that are not closely related taxonomically. The common use of 120–150 kHz signals may have developed in multiple taxa by convergent evolution as an approach to avoid being detectable by killer whales while maintaining sufficient echolocation range to detect their prey (Morisaka and Connor 2007). Although the frequency range used for NBHF pulses is small, there are still differences in signals between species that can be used to classify species. Kyhn et al. (2009) found that the duration of NBHF pulses of hourglass dolphins was approximately twice that of Hector's dolphins (*Cephalorhynchus hectori*) with no overlap in the ranges between species. Kyhn et al. (2010) found that Peale's dolphins

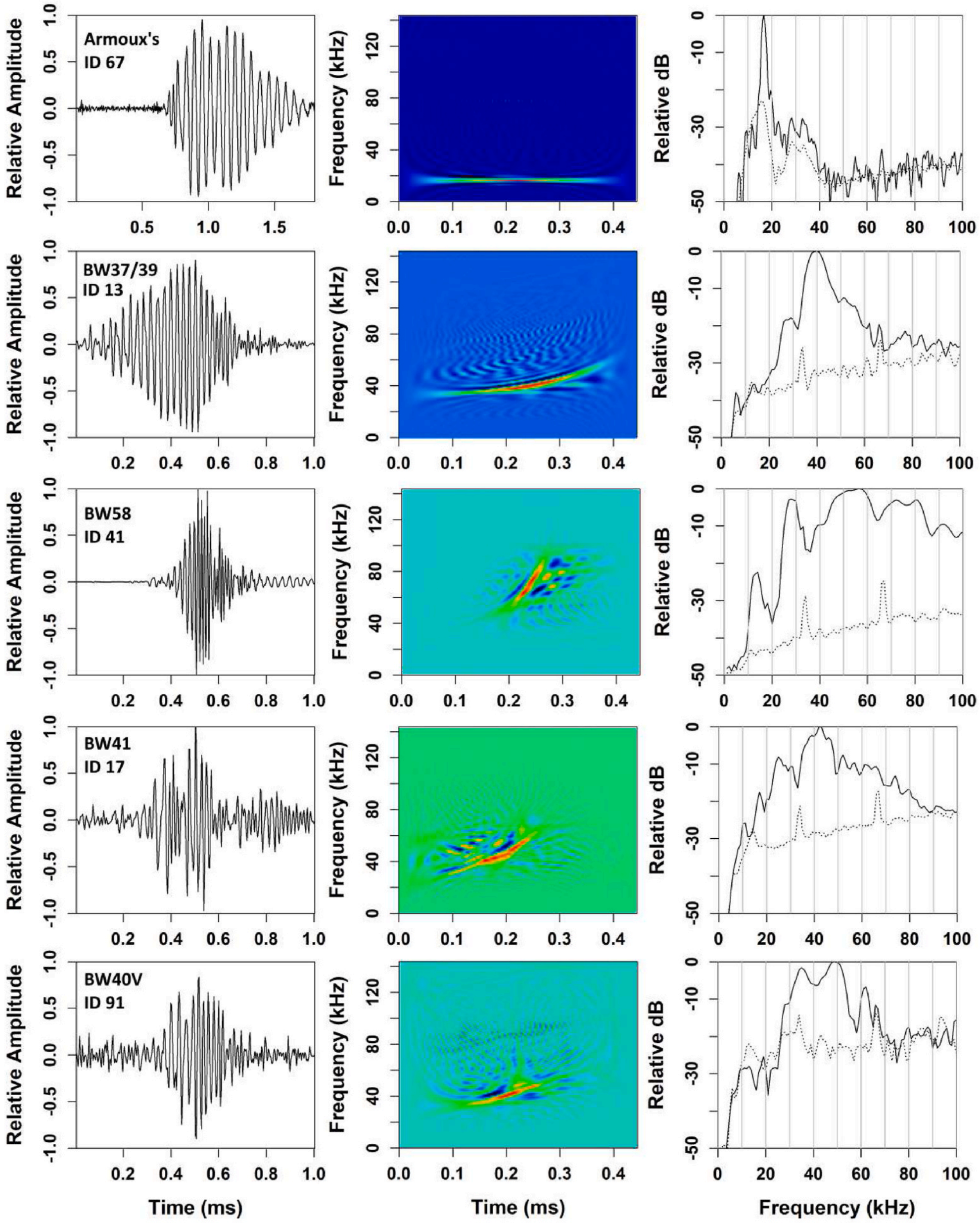

Fig. 5. Acoustic characteristics of five beaked whale FM pulse types. Panels include waveform (left) and Wigner-Ville tranformations (center) of the loudest click for each detection event and the mean spectrum of all clicks with a SNR >20 dB at the peak frequency (right). Noise levels in the spectrum plot (dotted line) are based on the prior sampling window (of the same size as the waveform window).

(*Lagenorhynchus australis*) and Commerson's dolphins (*Cephalorhynchus commersonii*) could be largely distinguished based on centroid frequency even though mean values differed by only 4 kHz. Griffiths et al. (2020) used multivariate clustering to identify three NBHF pulse types: two of which likely corresponded to Dall's porpoises (*Phocoenoides dalli*) and one to pygmy sperm whales (*Kogia breviceps*).

Most of the NBHF detections in our study occurred in deep pelagic waters far from a coastal shelf (Fig. 4). Pelagic species that produce NBHF pulses in the Southern Ocean include hourglass dolphins and spectacled porpoises (*Phocoena dioptrica*). It is likely that our NBHF detections are from these two species. Echolocation has not been studied in spectacled porpoises (Erbe, 2004), so there is insufficient information at this time to distinguish between these species in our data. A simple bivariate plot of peak frequency and bandwidth of NBHF signals did not show any obvious clustering in our data (Fig. 6). Multivariate clustering techniques may have more power to discern clusters that could help in species classifications (Griffiths et al., 2020). Ultimately, recordings are needed in the presence of spectacled porpoises to validate clustering methods for species classifications.

The echolocation signals associated with a sighting of hourglass dolphins (acoustic event ID = 54) had bandwidths (at −3 and −10 dB) and a peak frequency that are within the range of values measured by Kyhn et al. (2009) for this species. In fact, all the NBHF events we recorded (Table 3) had median peak frequencies within this published range for hourglass dolphins and the vast majority also had −3 and −10 dB bandwidths within the published ranges for this species.

4.3. *Sperm whales*

Sperm whales were detected only once in our study, albeit almost continuously for 46 min. In contrast, sperm whales were seen much more frequently than killer whales and pilot whales on Antarctic

Table 3

Frequency characteristics for detections of odontocetes with narrow-banded high-frequency (NBHF) echolocation pulses. Median values of peak frequencies and bandwidth metrics (at −3 dB and −10 dB re: peak) are given for all pulses that were at least 15 dB above the noise level at the peak frequency. Event IDs correspond to events in Table 1.

		Bandwidth @ −3 dB				Bandwidth @ −10 dB			
Event ID	Peak frequency (kHz)	Center frequency (kHz)	Bandwidth (kHz)	Lower frequency (kHz)	Upper frequency (kHz)	Center frequency (kHz)	Bandwidth (kHz)	Lower frequency (kHz)	Upper frequency (kHz)
31	130.0	130.2	4.8	126.5	133.0	130.3	12.3	124.6	137.3
33	126.0	126.1	4.2	124.0	128.3	127.2	9.5	122.6	132.0
37	125.0	124.4	6.6	117.1	129.3	123.6	19.2	113.7	133.5
90	122.0	122.3	4.6	119.9	124.7	123.1	9.1	118.5	127.5
38	127.0	126.8	4.8	124.5	129.2	127.6	9.3	122.9	132.2
39	126.0	126.2	5.1	123.6	127.9	126.6	11.3	121.6	131.1
40	129.5	128.8	6.6	125.5	132.0	128.9	9.9	123.9	133.8
41	131.0	130.8	7.3	127.1	134.4	130.3	13.4	123.5	137.0
44	128.5	128.5	6.1	125.6	131.7	129.0	11.5	123.2	134.4
47	127.0	127.0	5.9	124.0	129.4	127.0	10.5	122.0	132.2
48	129.5	130.0	6.7	126.4	133.5	129.7	13.6	122.9	136.5
49	128.0	128.2	4.9	125.5	130.8	127.6	10.1	122.5	132.7
51	130.5	130.3	4.2	127.2	133.7	132.1	13.6	124.1	138.3
72	124.0	123.5	4.0	121.4	125.5	123.6	8.1	119.5	127.5
52	124.0	124.5	6.1	121.2	127.7	124.6	11.5	118.8	130.5
54	129.0	129.5	7.4	125.7	133.3	130.4	12.0	124.4	136.5
56	128.0	128.0	6.3	125.0	130.7	128.8	10.7	123.4	134.0
57	128.0	127.6	7.8	123.4	132.0	126.6	18.0	118.2	134.7
59	128.0	129.3	8.0	125.3	133.3	130.5	14.3	123.4	137.4
106	124.0	123.4	4.2	121.2	125.5	123.9	9.9	119.1	128.8
60	128.0	128.1	5.5	124.9	131.3	128.6	12.4	122.6	134.6
61	131.0	131.5	5.2	128.9	133.8	129.9	10.1	124.8	135.0
40	126.0	125.6	4.9	123.5	128.1	125.8	10.5	120.7	130.7
9	127.0	127.5	4.8	124.7	129.8	128.1	9.3	123.3	133.0
10	130.0	130.3	8.5	126.0	134.7	130.6	14.2	123.7	137.2
11	130.0	129.8	6.8	126.5	132.6	130.1	17.6	120.0	137.8
12	128.0	128.5	5.9	125.6	131.3	128.7	10.0	123.9	133.1
13	127.0	127.3	8.6	123.5	131.0	127.0	15.2	120.0	135.2
14	129.0	128.8	6.4	124.9	132.3	129.0	13.8	121.9	136.6
15	130.0	130.4	5.1	127.7	132.7	131.5	11.6	125.4	137.4

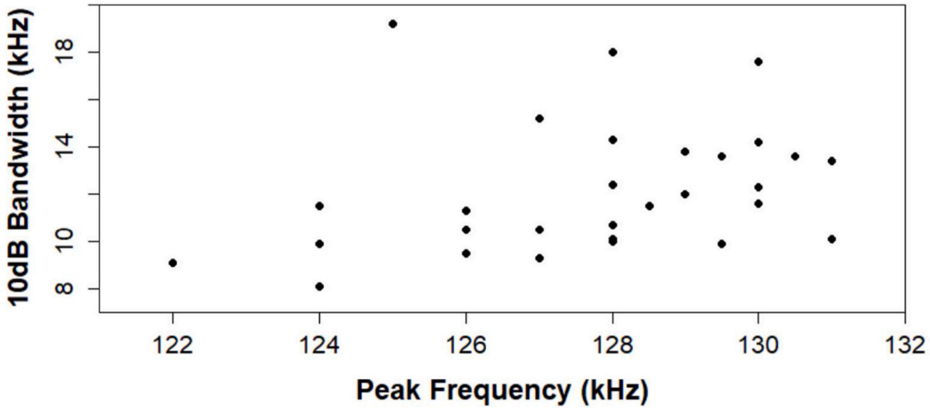

Fig. 6. Bivariate plot of median peak frequencies and bandwidths for all NBHF detection events.

sighting surveys (Kasamatsu and Joyce 1995) and were acoustically detected much more frequently on previous towed hydrophone surveys in the Southern Ocean (Pierpoint et al., 1997; Gillespie 1997; Leaper and Scheidat 1998; Leaper et al., 2000). These previous acoustic surveys used a linear array of two hydrophones which allowed the differentiation of individual whales based on their bearing angles relative to the array. We likely failed to detect sperm whales because, unlike these previous studies, we did not monitor our recordings aurally (which is the most effective way to discern faint sperm whale clicks, Gillespie (1997)) and we could not discriminate between sperm whale clicks and propeller cavitation using bearing angle. Using a hydrophone array, our 46-min detection almost certainly would have been comprised of multiple sperm whales. Sperm whales had a similar patchy distribution on these previous surveys and it was not uncommon for detections to be highly clustered (*op. cit.*). For effective sperm whale surveys using an autonomous towed system, we recommend that two hydrophones be used in a linear array and that stereo recordings be monitored aurally by analysts who are experienced in detecting sperm whale clicks. Based on their inter-click intervals (~0.75 s), the acoustically detected sperm whales were likely males (Goold and Jones 1995).

4.4. *Other species*

The most frequently detected large delphinids were killer whales and long-finned pilot whales, which match the species composition of sightings on the IWC circum-Antarctic surveys (Kasamatu and Joyce

Table 4
Frequency characteristics for detections of broadband echolocation clicks from delphinids. Median values of peak frequencies and bandwidth metrics (at −3 dB and −10 dB re: peak) are given for all pulses that were at least 15 dB above the noise level at the peak frequency. Event IDs correspond to events in Table 1.

			Bandwidth @ −3 dB				Bandwidth @ −10 dB			
Event ID	Event Type	Peak frequency (kHz)	Center frequency (kHz)	Bandwidth (kHz)	Lower frequency (kHz)	Upper frequency (kHz)	Center frequency (kHz)	Bandwidth (kHz)	Lower frequency (kHz)	Upper frequency (kHz)
92	Possible delphinid	45.0	46.0	5.7	42.2	49.4	44.3	22.1	31.9	57.0
93	Killer whale	25.0	23.0	6.7	16.9	27.8	23.7	23.4	11.3	35.2
87	Killer whale	18.0	18.6	7.3	14.6	22.1	22.5	21.7	11.6	33.4
95	Killer whale	24.0	22.4	6.8	16.3	28.3	24.4	23.8	11.4	36.1
96	Unidentified delphinid	47.0	46.6	5.5	43.8	49.2	51.4	33.1	33.5	70.1
97	Long-finned pilot whale	39.0	38.6	6.0	34.8	41.4	40.0	18.0	30.5	48.7
98	Long-finned pilot whale	41.0	40.7	4.3	38.4	42.7	41.2	15.2	33.2	50.7
99	Long-finned pilot whale	49.0	48.4	5.2	45.1	51.2	50.9	25.7	36.4	63.9
100	Unidentified delphinid	43.0	43.8	9.9	38.0	49.9	45.9	23.2	32.6	58.8
105	Unidentified delphinid	32.0	31.9	8.2	26.9	36.3	31.9	21.6	20.6	42.8
89	Unidentified delphinid	30.0	29.6	4.3	27.0	32.3	30.4	13.8	22.3	38.1
39	Possible delphinid	92.0	89.5	3.9	87.5	91.9	89.0	14.2	80.5	97.0
37	Killer whale	23.0	22.7	6.8	19.1	26.5	23.7	17.7	13.1	33.1
42	Unidentified delphinid	43.0	44.4	6.7	40.1	50.8	23.0	23.8	33.9	56.9

1995). The median peak frequencies of the echolocation clicks from the detections of killer whales (18–25 kHz, n = 4 detection events) and long-finned pilot whales (39–49 kHz, n = 3) were lower than the mean values (29 & 50 kHz, respectively) measured in a Norwegian fjord (Eskesen et al., 2011). This shift in peak frequency is likely caused by the loss of the higher frequency components in these broad-band signals due to propagation losses at greater ranges (Ainslie 2013). Although the detection range is not known for our samples, they are likely to be much greater than the 20–120 m range for the Norwegian measurements. The lower −10 dB bandwidth frequencies (11.3–13.1 kHz for killer whales and 30.5–36.4 kHz for short-finned pilot whales, Table 4) may be a more reliable metric to characterize the echolocation clicks for these species because it should be less prone to range-dependent frequency shifts than peak frequency.

5. Conclusions

Autonomous towed hydrophone recording systems can be used to effectively quantify the distribution of odontocete cetaceans in hard-to-study areas with relatively little cost or dedicated time. They can be deployed from vessels of opportunity without interfering with their primary missions. They are far easier to maintain than traditional towed hydrophone arrays which have long conducting cables and complicated computer recording systems, and operators require little acoustic or electronic expertise.

The use of autonomous towed hydrophone recorders is especially promising for studying the distribution of beaked whales and other small odontocetes that are hard to see on visual sighting surveys. Beaked whale FM pulses appear to be species-specific, but more information is needed to allow species classification from these signals. Dedicated studies are needed to link known species with the identified FM pulse types. Additional work is also needed to quantify the range of variation in these recognized FM pulse types. Similarly, dedicated research is needed to identify species of odontocetes from their NBHF echolocation signals. In particular, NBHF characterizations are needed for spectacled porpoises, and classification algorithms are needed to discriminate among all the Southern Hemisphere NBHF species.

The future use of autonomous towed hydrophone systems could be greatly aided by the addition of a second hydrophone, creating a two-element linear towed array. Bearing angles estimated from a two-element array would be helpful in estimating detection range from the convergence of bearing angles. A consistent progression of bearing angles is also helpful in discriminating true odontocete detections in a clutter of noise from random directions or from the ship.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Data was collected via a hydrophone deployed aboard two voyages as platforms of opportunity. One of the two voyages was a commercial tourism voyage operated by Cheesemans' Ecology Safaris owned by co-author Ted Cheeseman. The authors do not believe the arrangement has any impact on the integrity of the research.

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