Unknown beaked whale echolocation signals recorded off eastern New Zealand

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Abstract: The echolocation signals of most beaked whale species are still unknown. In fact, out of the 22 species comprising the family Ziphiidae, only the echolocation pulses for 7 species have been clearly described. This study describes two distinct beaked whale echolocation signals recorded in the Cook Strait region using passive acoustic technology. These signals differ from previously described Ziphiid species clicks. A description of the time-frequency characteristics of the two signals is provided. Understanding the characteristics of these signals is necessary to correctly identify species from their echolocation signals and enables future monitoring of beaked whales using passive acoustics techniques.

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1. Introduction

The echolocation signals of most beaked whale (BW) species are still unknown. Out of the 22 species comprising the family Ziphiidae, species-specific variations in the time-frequency characteristics of echolocation signals have been described for Baird's (*Berardius Bairdii*) (Dawson *et al.*, 1998), Blainville's (*Mesoplodon densirostris*) (Johnson *et al.*, 2006; Madsen *et al.*, 2005), Cuvier's (*Ziphius cavirostris*) (Zimmer *et al.*, 2005), Longman's (*Indopacetus pacificus*) (Rankin *et al.*, 2011), Northern bottlenose whale (*Hyperoodon ampullatus*) (Wahlberg *et al.*, 2011), Arnoux's (*Berardius arnouxii*) (Rogers and Brown, 1999) and Gervais' (*Mesoplodon europaeus*) (Gillespie *et al.*, 2009) BWs. Other distinct BW click types await species identification (Baumann-Pickering *et al.*, 2013c). A common feature of all the BWs' echolocation signals is the presence of a frequency modulated upsweep (Zimmer *et al.*, 2005). This finding has been used for the development of automated algorithms for detecting and monitoring the presence of BWs using passive acoustics techniques (Klinck and Mellinger, 2011).

Passive acoustic monitoring has provided the ability to study BWs in different parts of the ocean (Giorli *et al.*, 2015, 2016) and the opportunity to discover new BW-like signals. Passive acoustic data collected at the Cross Seamount near the Hawaiian Archipelago revealed the presence of an unknown BW signal labeled BWC (Johnston *et al.*, 2008; McDonald *et al.*, 2009). At Palmira Atoll, BW-like echolocation signals were recorded (Baumann-Pickering *et al.*, 2010) and the authors hypothesized that the source could be Deraniyagala's BW (*Mesoplodon hotaula*). Three unknown BW signals, called BW29, BW58, and BW37, have been discovered near the Antarctic Peninsula (Trickey *et al.*, 2015; Baumann Pickering *et al.*, 2015), and others labelled BW40, BW43, BWG, and BW70 (Baumann-Pickering *et al.*, 2013c) were recorded at different locations in the North Pacific Ocean and Gulf of Mexico. Data from the

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Aleutian Islands revealed the presence of another unknown type of BW echolocation signal that the authors hypothesized belonged to Stejneger's BWs (*Mesoplodon stejnegeri*) (Baumann-Pickering *et al.*, 2013a). Most of these studies were conducted in the Northern Hemisphere, and there is limited data available for BW species living in the Southern Hemisphere.

In New Zealand, the Cook Strait divides the North and South Islands and has been a key area for fishing, aquaculture, and whaling. Recently, a growing interest in mineral extraction in this region has raised questions about the occurrence of BWs in the area, motivated by their sensitivity to anthropogenic noise (Cox *et al.*, 2006; Nowacek *et al.*, 2007).

The scope of our work was to study BW occurrence in the Cook Strait region using passive acoustic techniques. In this paper, we present a description of the time-frequency characteristics of two BW echolocation signals from unknown species, and compare them to other unknown signals previously described in the literature.

2. Methods

2.1 Data collection

Three Autonomous Multichannel Acoustic Recorders (model G3; JASCO Applied Sciences, Halifax, Canada) were deployed east of the Cook Strait region in deep waters (∼1250–1480 m) (Fig. 1) between June and December 2016. The recorders were fitted with an M36-V35–100 omnidirectional hydrophone (GeoSpectrum Technologies Inc., Dartmouth, Nova Scotia, Canada; −164 dB re 1 V/μPa sensitivity) and recorded at a sampling rate of 250 kHz for 125 s every 775 s.

2.2 Detection of BWs' echolocation signals in the dataset

Recordings containing echolocation clicks from BWs were extracted from the dataset in two steps. First, an automated algorithm detector was applied. The algorithm high-pass filtered the data to remove energy below 8 kHz and identified click events using a Teager-Kaiser energy detector. The algorithm then extracted waveform parameters, including the number of zero crossings (zc), time separation between zc, and the slope of the change in time separation between zc. A click was classified as a given BW signal type if the Mahalanobis distance between the extracted parameters and the corresponding click template parameters was the lowest (Martin *et al.*, 2015).

In a second step, trained researchers visually analyzed 1% of the automated detections to validate the detector performance. This analysis provided a dataset of validated echolocation clicks, which were further analyzed.

2.3 Data analysis and signal processing methods

The visually validated recordings were analyzed to compute time-frequency characteristics of the BWs' echolocation clicks using a custom MATLAB User Interface (UI). After

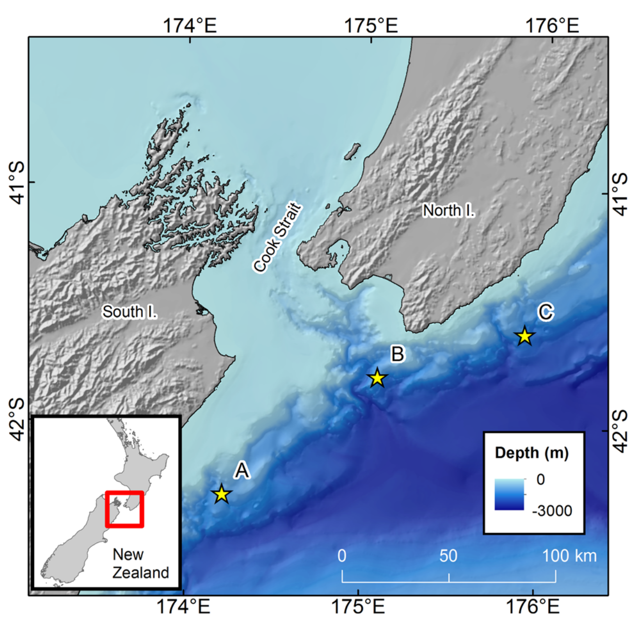

Fig. 1. (Color online) Map of the Cook Strait region with the location of the three acoustic moorings indicated by the star symbol.

determining that most of the signals had no energy below 20 kHz, data were filtered with an eighth order Butterworth bandpass filter with cutoff frequencies of 15 and 122 kHz. The operator selected a click train in the recorded time-series and a spectrogram of the click train was generated (90% overlap). The spectrogram was analyzed to verify the click train was from a BW. The operator then proceeded to a click-by-click analysis of time-frequency characteristics of each click. The operator selected a click, and the UI searched for the maximum amplitude in a 10 ms time window around the selection point. The window was resized to 1.5 ms and centered on the point of maximum click amplitude. The window was set to 1.5 ms to include the entire echolocation click as BW clicks have duration between ∼180 and 800 μs (Baumann-Pickering *et al.*, 2013c). The algorithm then computed time-frequency characteristics of the 1.5 ms click time-series. Time-frequency parameters measured were −3 dB bandwidth, −10 dB bandwidth, peak frequency, center frequency, click duration, $Q_{-3\,\mathrm{dB}}$, and frequency modulation rate (FM rate). The program also stored the 1.5 ms click time-series, its dB spectrum and its spectrogram. Click spectra were computed with a frequency resolution of 0.3 Hz and zero normalized and the spectrograms were computed with a frequency resolution of 1 Hz (90% overlap). The center frequency was calculated using the following equation from Au (1993):

$$f_0 = \frac{\int_{-\infty}^{\infty} f\,|S(f)|^2 df}{\int_{-\infty}^{\infty} |S(f)|^2 df}, \tag{1}$$

where *S*(*f*) is the Fourier transform of the 1.5 ms click time-series. The $Q_{-3\ \mathrm{dB}}$ was obtained by dividing the center frequency by the −3 dB bandwidth (Au, 1993). The click duration was the time interval between the 5th and 95th percentiles of the energy obtained by integrating the square pressure over the 1.5 ms window. The FM rate (in kHz/ms) was calculated as follows: the maximum value in each time bin of the spectrogram was determined and the start and end points of the upsweep were defined as the points within −6 dB from the greatest of the maximum values. The upsweep rate was then computed by calculating the angular coefficient of the regression line that fitted the remaining maxima.

The signal-to-noise ratio (SNR) of each click was computed with the following equation:

$$\mathrm{SNR} = 20 \times \log_{10} \frac{\sqrt{\frac{1}{T}\int_{T2}^{T3} s(t)^2\,dt}}{\sqrt{\frac{1}{T}\int_{T0}^{T1} n(t)^2\,dt}}, \tag{2}$$

where *s*(*t*) is the pressure time-series of the echolocation click, *n*(*t*) is the pressure time series at the beginning to the 1.5 ms window, *T*2 and *T*3 are the start and ending points of the echolocation click as previously determined, *T*0 is the time at the beginning of the 1.5 ms window, and *T*1 is the value at which *T*1–*T*0 is equal *T*3–*T*2. If the SNR was lower than 20 dB then the echolocation click was not included in the analysis. Once the operator analyzed all clicks in a train, the program computed the inter pulse interval (IPI). This analysis was repeated for all visually validated recordings. Outliers in the data were identified as any data point more than 1.5 interquartile ranges below the first quartile or above the third quartile (Ghasemi and Zahediasl, 2012) and excluded from the statistical analysis.

A Kruskal-Wallis test was used to assess whether the time-frequency parameters statistically differed between the two types of BW signals.

3. Results

The validation analysis of the automatic detector revealed the existence of three distinct BW echolocation signals in the dataset. One matched Cuvier's BW (*Ziphius cavirostris*) signals (Zimmer *et al.*, 2005), and will not be further discussed in this manuscript. The other two signals were labeled BW39 and BW53 (Fig. 2) in reference to their peak frequency. Analysis of the validated recordings resulted in 266 BW39 clicks (all recorded at Station B) and 813 BW53 clicks (314 at Station A; 229 at Station B; 270 at Station C) with a SNR higher than 20 dB (Table 1). The mean spectra and distributions of the measured time-frequency parameters of the two echolocation signals show distinct characteristics (Figs. 3 and 4).

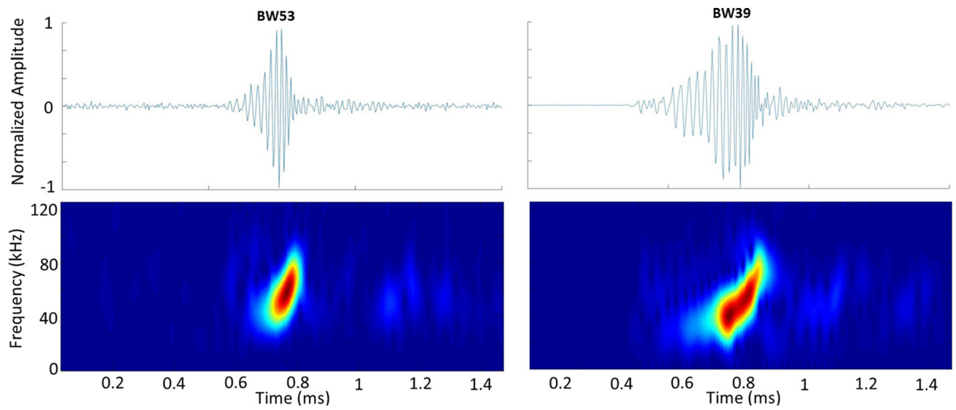

Fig. 2. (Color online) Click time series (top) and spectrograms (bottom) of the BW53 click type (left) and the BW39 click type (right).

The median values, as well as 10th and 90th percentiles of the time-frequency parameters computed on a click-by-click basis are shown in Table 1. The BW39 had a median peak frequency of 39.5 kHz, a center frequency of 55.7 kHz, and a −10 dB of 37 kHz. Pulse duration was about 228 μs, with a FM rate of 155 kHz/ms and an IPI of 222 ms ($n = 639$). The BW53 had a median peak frequency of 53.1 kHz, a center frequency of 52.3 kHz, and a −10 dB of 33 kHz. Pulse duration was about 128 μs, with a FM rate of 252 kHz/ms and an IPI of 240 ms ($n = 1320$).

The Kruskal-Wallis test rejected the null hypothesis that each time-frequency parameter of BW39 and BW53 came from the same distribution at a 5% significance level (Table 1; $p < 0.001$).

4. Discussion

The BW39 and BW53 clicks recorded in the Cook Strait region are two new BW echolocation signals not previously reported. Both signals present the characteristic FM upsweep of BWs echolocation clicks, but are distinct in terms of time-frequency parameters.

Stranding records provide a resource to understand which BW species occur around New Zealand. Stranded BW species include: pygmy (*M. peruvianus*), Blainville's (*M. densirostris*), ginkgo-toothed (*M. ginkgodens*), Gray's (*M. grayi*), strap-toothed (*M. layardii*), Andrew's (*M. bowdoini*), Hector's (*M. hectori*), Shepherd's (*Tasmacetus sheperdii*), Cuvier's, True's (*M. mirus*), spade-toothed (*M. traversii*), Arnoux's BWs (*Berardius arnuxii*), and the southern bottlenose whale (*Hyperoodon planiformis*) (Baker and Van Helden, 1999; Constantine *et al.*, 2014; Dalebout *et al.*, 1998; Thompson *et al.*, 2012). The three most represented Ziphiid species in the stranding records are Gray's, strap-toothed, and Cuvier's BW, in that order (Thompson *et al.*, 2013). Among all stranded species, the echolocation clicks of only Arnoux's, Cuvier's, and Blainville's BWs have been described. Cuvier's and Blainville's BWs have a peak frequency close to BW39 (Madsen *et al.*, 2005; Zimmer *et al.*, 2005), but their center frequencies are much lower, with longer IPIs, durations, and narrower bandwidths. Rogers and Brown (1999) published a recording of Arnoux's BWs showing echolocation signals around 16 kHz. However, their recording system had a limited

Table 1. Time-frequency measurements. The values reported in the table are the medians. The values in parentheses are the 10th and 90th percentile values, respectively.

	BW39	BW53
Number of signals	266	813
Peak frequency (kHz)	39.5 (36.9, 42.8)	53.1 (49.5, 60.5)
Center frequency (kHz)	55.7 (46.8, 64.3)	52.3 (46.7,57.8)
−10 dB bandwidth (kHz)	37 (27, 47)	33 (27,38)
−3 dB bandwidth (kHz)	11(6, 16)	15 (9, 22)
Duration (μs)	228 (212, 268)	128 (104,184)
Q−3 dB	5 (3,8)	3 (2,5)
FM rate (kHz/ms)	155 (95,218)	252 (209.5, 303)
IPI (s)	0.22 (0.17, 0.34)	0.24 (0.22, 0.26)

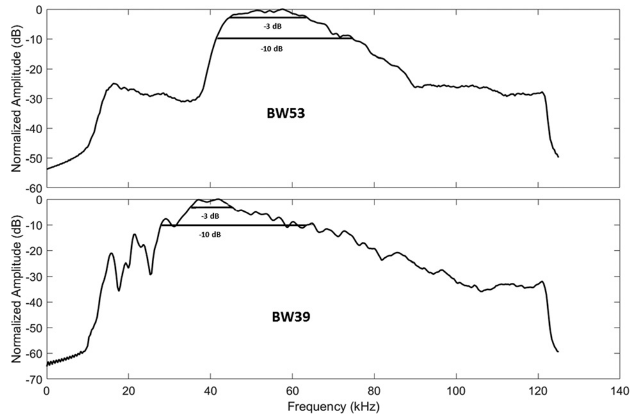

Fig. 3. Average spectra of the BW53 signal (top panel) and the BW39 signal (bottom panel).

recording bandwidth, resulting in a description of echolocation clicks that is likely incomplete.

Baumann-Pickering *et al.* (2013c) described several BW echolocation signals recorded in the North Pacific and in the Gulf of Mexico. Among the signals described, one is similar to BW53—the Stejneger's BW. However, the Stejneger's BW signals described have a shorter IPI, narrower bandwidth, and longer duration than BW53. In addition, there are no documented records of the occurrence of this species in the Cook Strait region.

The echolocation signals of two unknown BWs were recorded near the South-Scotia Ridge in Antarctica (Trickey *et al.*, 2015). The authors report a signal labeled BW37, which they suggest may be produced by Gray's BW. Although the peak frequencies of BW37 and our BW39 are similar, all other time-frequency measurements are different, which may be the result of different recording devices. The click descriptions by Trickey *et al.* (2015) are based on towed-array data, while the data analyzed in this study were recorded near the bottom. The recording depth affects the most typically reported metrics of click spectral parameters, including peak frequency (Baumann-Pickering *et al.*, 2013b). Other contributing factors could include the low sample size used to characterize the BW37 clicks in Trickey *et al.* (2015). Six clicks may not be enough data to capture all the variability of clicks produced by a BW species. Finally, although evidence suggests range-wide, stable click characteristics in well-known species such as Cuvier's BW (Baumann-Pickering *et al.*, 2014), one cannot rule out the possibility that the differences between our measurements and those from Trickey *et al.* (2015) result from geographic variations. The potential assignment of our BW39 signal to Gray's BW therefore remains unresolved. But the prevalence of this species in the stranding record (Thompson *et al.*, 2013) along with several confirmed sightings east and north of New Zealand (Dalebout *et al.*, 2004) warrants further investigation.

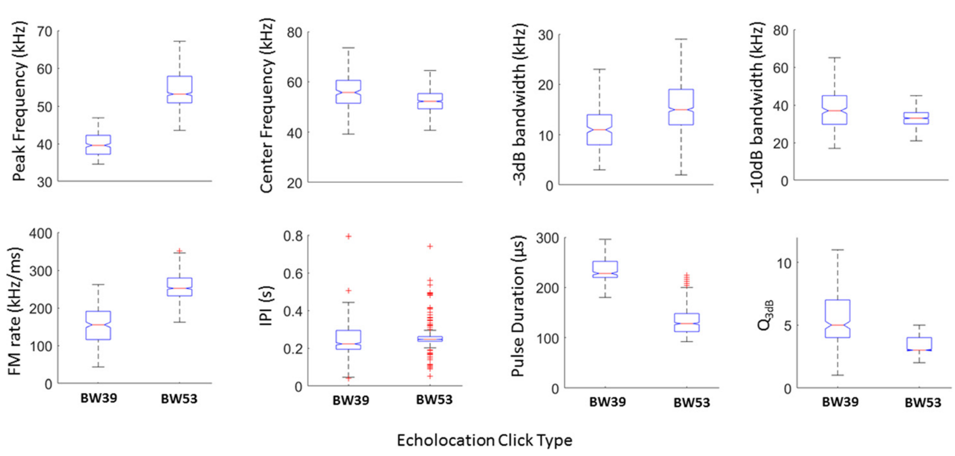

Fig. 4. (Color online) Boxplots showing the distribution of the different time-frequency parameters measured for each click type. All parameters were statistically different between click types (Kruskal-Wallis; $p < 0.05$). Only measurements from the validated signals were used in this analysis.

Another unidentified BW signal, labelled BW58, is described in a report from the International Whaling Commission (Baumann-Pickering *et al.*, 2015). Although a detailed description of the signal was not provided, this signal seems to be different from our BW53. The spectra of the two signals are quite different, and BW58 presents a peak at 25 kHz that does not appear in the BW53 signal reported in this paper.

Among the BWs occurring in New Zealand waters, the species whose echolocation clicks have not been yet described include: southern bottlenose whale, Shepherd's BW, strap-toothed BW, Hector's BW, Andrew's BW, True's BW, ginkgo-toothed BW, pygmy BW, Gray's BW, and spade-toothed BW (Baker and Van Helden, 1999; Brabyn, 1991; Constantine *et al.*, 2014; Thompson *et al.*, 2012). Considering the stranding record data, Gray's and strap-toothed BWs are possible sources of these signals. However, since direct observation of animals was not possible at the time of the recordings, uncertainties remain on the BW species producing the BW39 and BW53 signals. Simultaneous visual and acoustic observations of BWs in New Zealand are required to confidently identify which BW species produce the BW53 and BW39 signals in the Cook Strait region.

5. Conclusions

BWs have species-specific echolocation signals but the signals from all species have not been recorded and characterized. Understanding the characteristics of these signals is necessary to correctly identify species based on their echolocation signals and enables future monitoring of BWs using passive acoustic techniques. We identified two new types of echolocation signals from BWs in the Cook Strait region that are different from signals previously described in the literature. A dedicated study combining visual and acoustics surveys would be needed in the future to identify these two species of BWs in the Cook Strait region.

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