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Geographic distribution of the Cross Seamount beaked whale based on acoustic detections

Jennifer L. K. McCullough[1] | E. Elizabeth Henderson[2] | Jennifer S. Trickey[3] | Jay Barlow[4] | Simone Baumann-Pickering[3] | Roanne Manzano-Roth[2] | Gabriela Alongi[5] | Stephen Martin[5] | Selene Fregosi[6,7] | David K. Mellinger[6,8] | Holger Klinck[8,9] | Angela R. Szesciorka[7] | Erin M. Oleson[1]

[1]National Oceanic and Atmospheric Administration (NOAA) Fisheries, Pacific Island Fisheries Science Center, Honolulu, Hawaii

[2]Naval Information Warfare Center, San Diego, California

[3]Scripps Institution of Oceanography, University of California, La Jolla, California

[4]NOAA Fisheries, Southwest Fisheries Science Center, La Jolla, California (Retired)

[5]National Marine Mammal Foundation, San Diego, California

[6]Cooperative Institute for Marine Ecosystems and Resources Studies, NOAA Pacific Marine Environmental Laboratory and Oregon State University, Newport, Oregon

[7]Ocean Associates, Inc., Under Contract to NOAA Fisheries, Pacific Island Fisheries Science Center, Honolulu, Hawaii

[8]Marine Mammal Institute, Department of Fisheries, Wildlife, and Conservation Sciences, Oregon State University, Newport, Oregon

[9]K. Lisa Yang Center for Conservation Bioacoustics, Cornell Lab of Ornithology, Cornell University, Ithaca, New York

Correspondence
Jennifer L. K. McCullough, NOAA Fisheries, 1845 Wasp Boulevard, Bldg. 176, Honolulu, HI 96818.
Email: jennifer.mccullough@noaa.gov

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Abstract

Beaked whales produce frequency-modulated echolocation pulses that appear to be species-specific, allowing passive acoustic monitoring to play a role in understanding spatio-temporal patterns. The Cross Seamount beaked whale is known only from its unique echolocation signal (BWC) with no confirmed species identification. This beaked whale spans the Pacific Ocean from the Mariana Archipelago to Baja California, Mexico, south to the equator, but only as far north as latitude 29°N. Within these warm waters, 92% of BWC detections occurred at night, 6% during crepuscular periods, and only 2% during daylight hours. Detections of

BWC signals on drifting recorders with a vertical hydrophone array at 150 m depth demonstrated that foraging often occurred shallow in the water column (<150 m). No other species of beaked whale to date has been documented foraging in waters this shallow. Given their nocturnal, shallow foraging dives, this species appears to prefer prey that may be available in the water column only during those hours. The foraging behavior of Cross Seamount beaked whales appears to be unique among all beaked whales, and these findings contribute additional ecological and acoustic information which can help guide future efforts to identify this cryptic whale.

KEYWORDS
BWC, cetaceans, Cross Seamount beaked whale, distribution, echolocation, passive acoustic monitoring

1 | INTRODUCTION

Beaked whales represent a unique group of deep-diving odontocete cetaceans, encompassing three subfamilies (*Berardiinae*, *Hyperoodontinae*, *and Ziphiinae*) and 24 species that occur globally in Antarctic, temperate, and tropical waters. These whales produce echolocation signals in the form of a frequency-modulated (FM) pulse that is distinct for each species. However, the echolocation signals of some species also include shorter clicks that are not frequency-modulated (Baumann-Pickering et al., 2013). Of the 24 currently described species, 12 have been linked to unique upswept FM pulse types, each with a specific distribution of duration, interpulse interval (IPI), and peak frequency. Species-specific FM pulse characteristics are largely conserved, even between ocean basins (Baumann-Pickering et al., 2013; Cholewiak et al., 2013; Dawson et al., 1998; Gillespie et al., 2009a; Johnson et al., 2004). For example, Cuvier's beaked whales (*Ziphius cavirostris*) recorded in the Pacific and Atlantic Oceans have similar FM pulse characteristics, with a peak frequency around 40 kHz, ancillary spectral peaks around 17 and 23 kHz, and an IPI of 0.4–0.5 s (Baumann-Pickering et al., 2014; Johnson et al., 2004). Echolocation signal characteristics remain unknown for several beaked whale species that have not been simultaneously visually sighted and acoustically recorded. Conversely, there are several FM pulse types that have been recorded acoustically and not yet linked to a specific species. Baumann-Pickering et al. (2014) hypothesized some of the possible connections between recorded FM pulse types and species based on known distributions for both (MacLeod et al., 2006). Recent work has directly linked some of the unknown FM pulse types with known species. For example, Ballance et al. (in press) conclusively linked the BW37V FM pulse type (first described by Griffiths et al., 2019) to Hubbs' beaked whale (*Mesoplodon carlhubbsi*) when an acoustic recording was made in conjunction with a visual sighting and biopsy sample.

A unique FM pulse type was first recorded near Cross Seamount in the Pacific Ocean south of Hawaii, with a linear frequency upsweep from 35 to 100 kHz, duration of 932 μs, and mean IPI of 0.14 s (McDonald et al. 2009). This FM pulse type, called the BWC signal (Baumann-Pickering et al., 2013), has been recorded in a number of tropical locations throughout the central and western Pacific Ocean (Baumann-Pickering et al., 2014) and elsewhere in Hawaii (Manzano-Roth et al., 2023), the Mariana Archipelago (McCullough et al., 2021b), and off Baja California, Mexico (Simonis et al., 2018), but has never been definitively linked to a known species. Its acoustic features are distinctive from other beaked whale signals due to the pulse's longer duration, shorter IPI, and extremely wide bandwidth. Baumann-Pickering et al. (2014) hypothesized this FM pulse type might be produced by ginkgo-toothed beaked whales (*Mesoplodon ginkgodens*) based on that species' tropical Pacific distribution. However, unlike all other beaked whale FM pulses, the BWC signal has largely been recorded only at night (Baumann-Pickering et al., 2014; Manzano-Roth et al., 2023), making a definitive link to a species difficult.

This study analyzes data collected on multiple platforms across the Pacific Ocean from 2004 to 2022 to examine the spatio-temporal patterns in acoustic detections of the BWC signal (herein termed the BWC-FM pulse). These detections are also examined to explore the depth distribution of echolocation FM pulses along with looking for other vocalization types such as the short, echolocation clicks that are not frequency-modulated produced by some other beaked whales (Baumann-Pickering et al., 2013), as well as foraging buzzes (Johnson et al., 2006, 2008). This represents the first comprehensive, ocean basin-wide analysis of this FM pulse type, providing critical information on its distribution and insight into this beaked whale's unique ecological niche.

2 | METHODS

2.1 | Data collection and analysis by recording platform

Acoustic data were collected on multiple platforms by various programs/institutions (Table 1, Figure 1). Moving platforms consisted of ship-based towed hydrophone arrays (TOWED ARRAY), Drifting Acoustic Spar Buoy Recorders (DASBR), Seagliders (GLIDER), and rowboat towed hydrophone (ROWER). Stationary platforms included High-frequency Acoustic Recording Packages (HARP) and the hydrophone array at the Pacific Missile Range Facility (RANGE). All recordings were digital with 16-bit resolution and a sampling rate of at least 192 kHz with the exception of the RANGE (96 kHz). Due to the differences in the initial processing approach across instrument types, the total number of BWC detections are not directly comparable across platforms. However, this does not prevent evaluation of the spatio-temporal occurrence of BWC detections from multiple platforms over a large area of the North Pacific Ocean.

Across all platforms, BWC signals were assigned to a period of the day (daytime, nighttime, dawn, dusk) at the location of the recording based on their start time using the *maptools* package (v 1.1–4; Bivand & Lewin-Koh, 2022) in software R (R Core Team, 2021). "Dawn" and "dusk" were defined based on the angle of the sun relative to horizon. Following the definition of nautical twilight, a value of 12° was used, with dawn occurring when the sun was 12° below until 12° above the horizon, and dusk occurring when the sun was 12° above until 12° below the horizon. "Daytime" and "nighttime" were periods of daylight between dawn and dusk, and periods between dusk and dawn, respectively.

TABLE 1 Summary of acoustic data collection platforms used to assess presence of the Cross Seamount beaked whale via the BWC-FM pulse. Deployment is defined as single entry/exit of the acoustic sensor package from the water with the exception of the RANGE where it represents the start and stop of recording a single bottom-mounted hydrophone. ROWER distance represents the summed distance between deployments along its trackline.

Platform	Years of coverage	Deployments	Recording effort (days)	Distance traveled (km)	Type of recording effort
TOWED ARRAY	2017	171	110	~24,000	Continuous: sunrise to sunset
DASBR	2016–2020	93	6,108	18,710	Duty-cycle: over 24 hr
GLIDER	2014–2015	4	85	2,711	Duty-Cycle: over 24 hr
ROWER	2021–2022	17	7	14,250	Continuous: opportunistic
HARP	2004–2022	333	43,289	Stationary	Continuous/Duty-cycle: over 24 hr
RANGE	2007–2021	535	133	Stationary	Continuous: Monthly over 24 hr

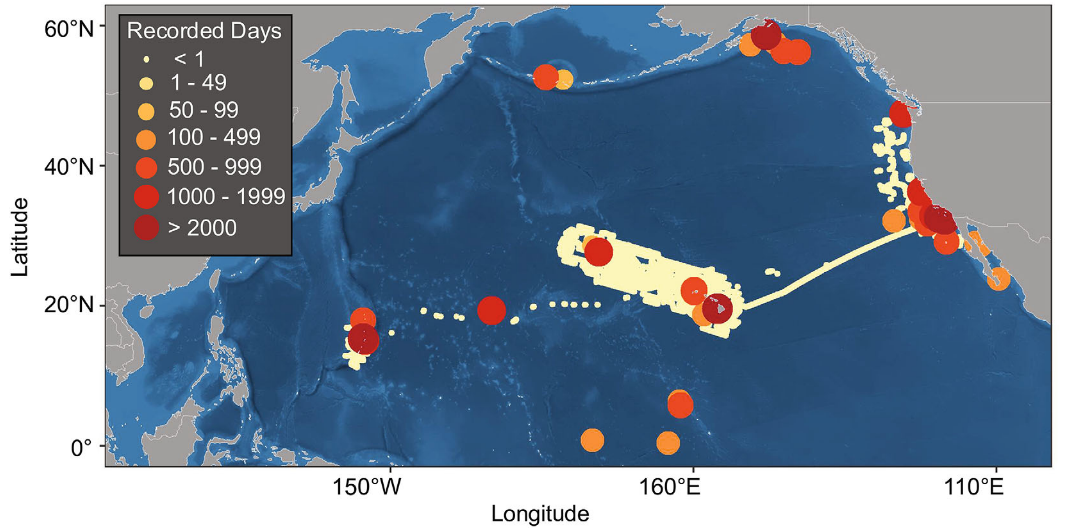

FIGURE 1 Bathymetric map of the North Pacific Ocean with marked locations of acoustic recording efforts used to assess presence of the Cross Seamount beaked whale via the BWC-FM pulse. Circle size and color indicate the number of recorded days at that location. All moving platform data (DASBR, GLIDER, ROWER, TOWED ARRAY) fall into the <1 day of recording effort category. ETOPO1 bathymetry downloaded using R package *marmap* (Pante & Simon-Bouhet, 2013).

2.1.1 | TOWED ARRAY

The Pacific Islands and Southwest Fisheries Science Centers conducted the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS) in summer–fall 2017 (Yano et al., 2018). During this ship-based survey, an experienced visual observer team worked jointly with an acoustics team to record all encounters with cetaceans along the survey track. The acoustics team used a towed hydrophone array deployed 300 m behind the ship to acoustically localize cetaceans. Towed arrays used HTI-96-MIN hydrophones (High Tech Inc. Long Beach, MS) and custom-built preamplifiers with combined average measured sensitivity of −144 dB ± 5 dB re: 1 V/μPa from 2 kHz to 100 kHz and approximately linear roll-off to −156 dB ± 2 dB re 1 V/ μPa at 150 kHz. The hydrophones had a high-pass filter at 1.6 kHz to reduce low-frequency flow noise and ship noise, reducing sensitivity by 10 dB at 1 kHz. Six hydrophones were sampled at 500 kHz, recorded with a SailDAQ soundcard (SA Instrumentation Limited), and recordings were processed using PAMGuard (Gillespie et al., 2009b).

During the HICEAS effort, a visual observation of an unidentified beaked whale at the surface coincided with acoustic detections of BWC signals on the towed array. These detections included both the FM pulses previously characterized to the Cross Seamount beaked whale (BWC-FM; McDonald et al., 2009) plus an additional, shorter duration echolocation signal type (herein termed BWC-EC), as had previously been documented, but not characterized, by Baumann-Pickering et al. (2013). The towed array data with BWC signals were processed using the click detector module (IIR Butterworth 2 kHz high pass filter) within PAMGuard and custom specifications based on peak frequency (Keating & Barlow, 2013), then manually verified for species identification. Horizontal conical bearing angle to BWC signals were calculated with two hydrophones spaced 1 m apart using time-difference-of-arrival methods (Gillespie et al., 2009b). Echolocation signals within this detection were binned into the two signal types (BWC-FM & BWC-EC). The PAMGuard binary data from the acoustic detections were processed using the open-source *PAMpal* package within R software (R Core Team, 2021; Sakai, 2020) to provide visualization of the bearing angles of individual signals for each of the two types of echolocation signals.

2.1.2 | DASBR

Since 2016, National Oceanic and Atmospheric Administration (NOAA) shipboard cetacean survey efforts in the Pacific Ocean have included the deployment of drifting recorders referred to as DASBRs. DASBRs have been deployed in waters along the U.S. West Coast, Baja California, Mexico, the main Hawaiian Islands, and throughout the Mariana Archipelago (Keating et al., 2018; McCullough et al., 2021a,b; Simonis et al., 2020; Yano et al., 2018, 2020). These acoustic drifters were composed of a surface float with GPS geolocator attached to 100–150 m of vertical line supporting two hydrophones (HTI-92-WB or HTI-96-Min) spaced 10 m apart at depth and weighted below the hydrophones to maintain the vertical orientation. A SoundTrap ST4300HF recording unit (OceanInstruments, Auckland, New Zealand) with a frequency response range of 20 Hz–150 kHz ±3 dB recorded time-synchronized acoustic data at 288–576 kHz sampling rates and duty cycles of either 2 out of 5 min or 2 out of 10 min. The combined frequency response of the HTI-92-WB hydrophone and the SoundTrap was flat between 20 Hz and 75 kHz ± 5 dB with a 10 dB roll-off between 75 and 115 kHz.

Similar to the towed array data analysis, echolocation signals from beaked whales were identified within the acoustic data using the click detector module (IIR Butterworth 2 kHz high pass filter) within PAMGuard and applying custom specifications based on peak frequency, then manually verified for species identification. Spectral and temporal characteristics of the echolocation signals were employed to manually classify the signals as individual beaked whale species (Baumann-Pickering et al., 2013, 2014; Keating et al., 2016). Due to the vertical array configuration of the DASBR, the association between BWC-FM and BWC-EC signals could be further evaluated. Once all 2-min recording files containing the BWC-FM pulse were identified, we evaluated whether concurrent signals within the wav file could be classified as BWC-EC based on bearing angle and timing relative to the BWC-FM signals. The vertical bearing angle to all BWC signals was then calculated using the two hydrophones following the methods of the PAMGuard click detector module (Gillespie et al., 2009b). Like the towed array data, PAMGuard binary data from DASBR detections were processed by the R package *PAMpal* package to provide bearing angles and plots representing these two types of echolocation signals. Given the nominal hydrophone depth of 150 m, bearing angles $<90^\circ$ corresponded to sound sources shallower than 150 m, and bearing angles $>90^\circ$ to sound sources deeper than 150 m.

2.1.3 | GLIDER

Four passive acoustic underwater gliders (Seagliders, Applied Physics Laboratory, University of Washington, Seattle, WA) were deployed in the vicinity of the Mariana Archipelago and Hawaii in 2014 and 2015, as part of a U.S. Navy marine mammal monitoring effort (Klinck et al., 2015a,b, 2016; Nieukirk et al., 2016). The gliders move through the water column in a sawtooth pattern, repeatedly diving to 1,000 m and back to the surface over 4–6 hr. They travel horizontally following a preplanned trackline of given waypoints. Horizontal speed is approximately 25 cm/s.

Acoustic recordings were made using a custom built Seaglider-integrated passive acoustic system. Acoustic signals were received via a single omnidirectional hydrophone (HTI-99-HF, sensitivity −164 dB re 1 V/µPa, High Tech Inc., Long Beach, MS), amplified by 36 dB, and recorded at a 194 kHz sample rate, effectively monitoring a frequency range of 15 Hz–97 kHz. Recordings were nearly continuous with two sources of short duration gaps: during intermittent brief periods when the glider was operating its noisy internal buoyancy pump and when the recording system was turned off at glider depths above 25 m to exclude periods of high noise levels near the sea surface.

Beaked whale signals were identified using manual analysis. Full-bandwidth sound files were used to create long-term spectral averages (LTSAs; 5 s temporal resolution, 100 Hz frequency resolution) using the MATLAB-based (MathWorks, Natick, MA) program *Triton* (v1.93; https://github.com/MarineBioAcousticsRC/Triton). LTSAs were visually and aurally inspected by an experienced analyst for any possible odontocete signals using 15–min windows. Signals that were potentially beaked whales were identified following Baumann-Pickering et al. (2013)—if they exhibited an FM pulse, long click duration (>400 μs), and long interpulse-interval (>130 ms), they were marked as possible beaked whales and investigated further. BWC-FM pulses specifically were identified by peak and center frequencies near 47 kHz, a large −10 dB bandwidth, and click durations over 500 μs (Baumann-Pickering et al., 2013). The location of the glider during a detection was approximated as the midpoint between the two GPS surface locations at the start and end of the dive during which the detection occurred.

2.1.4 | ROWER

A solo, self-powered rowboat traveled from Crescent City, California, to Legazpi, Philippines, from June 2021 to March 2022 (Erden Eruç, Explorers Club Flag Expedition, https://www.explorers.org/about/in-the-field/). While crossing the Pacific Ocean, a SoundTrap ST300HF with a frequency response range of 20 Hz–150 kHz ± 3 dB was deployed at various locations and towed behind the rowboat inside a streamlined flooded housing (Barlow, 2021; Barlow & Eruç, 2023). The towline initially consisted of a 10 m vertical line, a 2.7 kg spherical lead weight, and a 25 m horizontal towline 3 mm braided in diameter and was connected to the stern of the vessel. However, this configuration greatly affected the direction of travel when navigating in swell. To reduce drag, the 10 m down-line was shortened to 5 m. Acoustic recordings were sampled continuously at 288 kHz when the recorder was deployed.

Acoustic data were processed with PAMGuard and the same detection parameters as the DASBR analysis effort. Because there was only a single hydrophone, an amplitude-time window was used in PAMGuard Viewer instead of a bearing-time window. Analysts manually identified potential beaked whale signals and confirmed them by comparison with echolocation signals collected on DASBR SoundTraps.

2.1.5 | HARP

Passive acoustic recordings were collected by High-frequency Acoustic Recording Packages (HARPs; Wiggins & Hildebrand, 2007) at several sites in the North Pacific Ocean. HARPs are bottom-mounted, autonomous instruments that can continuously record from 10 Hz to 100 or 160 kHz over extended periods of up to 1 year. HARPs were configured in a variety of small to large moorings or seafloor package configurations. At most sites, where depths ranged from 250 to 1,400 m, the hydrophone was located within 30 m of the seafloor. At six deeper sites with seafloor depths ranging between 3,600 and 4,400 m, the hydrophone was suspended in the water column between 800 and 1,200 m depth. The hydrophone sensors were connected to custom-built preamplifier boards with bandpass filters. Each hydrophone's electronic circuit board was calibrated in the laboratory to provide a quantitative measurement of the received sound field. Representative data loggers and hydrophones were also calibrated at the U.S. Navy's Transducer Evaluation Center in San Diego, California, to provide the full-system frequency response of the instrument. HARPs recorded at a sampling rate of either 200 or 320 kHz. Different recording duty cycle schedules were used to maximize recording duration, depending on data storage and battery capacity; each deployment had either a single consistent duty cycle or recorded continuously. Within duty-cycled deployments, data were recorded for 5 min, followed by an "off" period ranging from 7 to 45 min.

A multistep process was used to detect and classify beaked whale signals; an automated click detection was followed by manual review and classification of the detected signals to the species level. Signal processing was performed by the MATLAB-based custom software program *Triton* and other MATLAB custom routines. A Teager-Kaiser energy detector (Roch et al., 2011; Soldevilla et al., 2008) in *Triton* was applied to all recorded data, and spectral and temporal signal parameters were computed for all detected signals. A decision regarding presence or absence of beaked whale signals within 75-s segments (the raw file length) was based on a heuristically optimized expert system (Baumann-Pickering et al., 2013, 2016). Only segments with more than seven individual signals were used in further analyses. All signals with a peak and center frequency below 32 and 25 kHz, respectively, a duration of <355 μs, and a sweep rate of <23 kHz/ms were ignored as they did not resemble beaked whale FM pulses. If more than 13% of all initially detected signals remained after applying these criteria, the segment was identified as containing beaked whale FM pulses. This threshold was chosen to obtain the best balance between missed and false detections. A third classification step, based on computer-assisted manual decisions by a trained analyst, labeled the automatically detected segments to beaked whale species or signal type (e.g., BWC-FM) and rejected false detections (Baumann-Pickering et al., 2013). The rate of missed segments was tested during detector development and was not verified for this analysis effort. It ranges between approximately 5% and 10%, depending on site conditions, mostly missing low amplitude and short duration acoustic detections.

2.1.6 | RANGE

Data from the Pacific Missile Range Facility (PMRF) utilized for this study were recorded using a subset of 13–62 PMRF hydrophones (depending on the year) from January 2007 through August 2021, typically comprising at least two continuous recordings per month, roughly 96 hr per monthly recording. Variability over the years in the number of hydrophones used to detect beaked whale signals occurred due to changes in available hydrophones with different recording bandwidths. From 2007 through 2010, 13 of the 31 recorded hydrophones had sufficient bandwidth (up to a Nyquist frequency of 48 kHz) to detect BWC-FM pulses; after an update at the range in late 2010, all 31 recorded hydrophones had sufficient bandwidth for detecting BWC-FM pulses. The number of recorded hydrophones suitable for BWC-FM pulse analysis again increased in August 2012 to 62. Starting in 2011, additional recordings were made before, during, and after Navy training events which occur biannually in February and August (Martin et al., 2015). Only the data before and after Navy training events, not during them, were included in this analysis to avoid data with potential changes in beaked whale behavior due to Navy activities.

The PMRF hydrophones used in this study are located near the seafloor in water depths between 625 and 4,825 m and are sampled at 96 kHz. Although the hydrophones' sampling frequency is below the full extent of the BWC-FM pulse and cuts off the upper frequency content, the hydrophones still record most of the lower frequency content, which can be used for detection and classification. The beaked whale pulse detector used in this analysis has been described in detail elsewhere (Henderson et al., 2016; Manzano-Roth et al., 2016, 2023) and will be briefly summarized here. The BWC-FM pulse detector utilizes a first stage energy band detector in a custom C++ program that applies a 16 k-point fast Fourier transform (FFT) with 1 k-point advances, then performs signal-to-noise ratio (SNR) tests for in-band energy (16–44 kHz) >1.5 dB and out-band energy (5–16 kHz) <1.15 dB. The second stage of processing utilizes a 64-point FFT with single point advancement for detecting FM sweeps. Pulse magnitude, signal-to-noise ratio (SNR), and duration were derived from the processed data. Detected BWC-FM pulses at PMRF were automatically sorted into a foraging dive or group vocal period (GVP) based on consecutive pulse detections on the same hydrophone or nearest hydrophones within 6 km. This distance was based on the probability of detection for a beaked whale FM pulse estimated by Ward et al. (2008) and Zimmer et al. (2008). If FM pulses were detected on multiple hydrophones within 6 km of each other, the hydrophone with the most detections was assigned as the "primary" hydrophone. If a hydrophone detected BWC-FM pulses at the same time but was farther than 6 km away from the primary hydrophone, a new GVP was formed on another primary hydrophone, and it was assumed that there were multiple GVPs occurring simultaneously. In addition, if a GVP was longer than 1 hr (based on the average length of deep dives conducted by Baird, 2019; Quick et al., 2020; Schorr et al., 2014), the acoustic data on hydrophones where the dive was recorded were manually inspected to determine whether the dive could be spatially separated into multiple Cross Seamount beaked whale GVPs. BWC-FM pulses on the primary hydrophone were used to estimate interpulse intervals (IPIs).

3 | RESULTS

3.1 | Spatio-temporal distribution

Acoustic detections of the Cross Seamount beaked whale (BWC-FM pulse) occurred on all six recording platforms (DASBR, GLIDER, HARP, RANGE, ROWER, TOWED ARRAY) throughout the Pacific Ocean (Figure 2). These detections ranged west to east from the Mariana Archipelago to Baja California, Mexico, south to the equator and as far north as latitude 29°N. Analyses of recordings collected along the U.S. West Coast and offshore of Alaska did not reveal any BWC-FM pulses in those regions (Figures 1 and 2).

Across all recording platforms, 92% of the BWC-FM pulses were detected at night, 3% at dawn, 3% at dusk, and 2% during daylight (Figure 3). In addition, when divided into three regions (Western, Central, and Eastern) across the Pacific Ocean there were no differences in the time of day of detections. The HARP and RANGE data sets showed slight peaks in acoustic detections after sunset and from midnight to four in the morning. These two data sets also provide the best assessment of seasonal presence of the BWC signal type given their year-round recording efforts and showed no seasonal variability in BWC signal detection rates throughout the year.

3.2 | Echolocation signals

During HICEAS 2017, there were two acoustic detections of BWC-FM pulses on the towed array on back-to-back evenings. The second detection happened at dusk on September 2; an unidentified beaked whale was seen near Cross Seamount by an experienced observer after visual effort had stopped for the day. There had been no other cetaceans sighted or acoustically detected for the five hours prior to the start of the detection. The acoustic detection lasted for roughly 35 min with a minimum of five subgroups passing the towed array (Figure 4a). A subgroup is defined as a series of echolocation signal trains starting forward of the ship and crossing the beam. Both types of echolocation signals (BWC-FM & BWC-EC) were detected on the towed array (Figure 4b). The BWC-FM pulse type was detected for each subgroup as they passed the ship (0°–180°), and the shorter duration echolocation signal, BWC-EC, was sporadically detected at the same bearing angles as the echolocation trains of BWC-FM pulse.

After BWC-EC signals were identified in the towed array data, they were then identifiable on the DASBR recordings, and the acoustic characteristics of this signal type were summarized from the DASBR events (Table 2 and Figure 5). Similar to other odontocete echolocation clicks, BWC-EC clicks can be produced as part of click trains, burst pulses, and terminal buzzes, and were identified in all three call types in the DASBR data. Available calibration information for combined hydrophone and recording units from DASBRs made their acoustic characteristics more comparable to other data sets than the towed array data.

Based on the characteristics of the two types of echolocation signals detected on the towed array, echolocation signals recorded on the DASBRs were also categorized as either BWC-FM or BWC-EC (Figure 6). BWC-EC signals were not present during all 2-min WAV files that contained BWC-FM pulses, but when detected in the form of a buzz, the length of the buzz could be highly variable (Figure 6a). In some instances, there were other odontocete signals simultaneously present in the DASBR data, and in such cases the BWC-EC signal type was not assessed given the potential to confuse it with other delphinid signal types.

3.3 | Depth distribution

Across all DASBR records, all BWC-FM (n = 23,972) and BWC-EC (n = 1,498) signals were compiled to examine their vertical conical bearing angle (Figure 7a). BWC-FM pulses occurred predominantly between 80° and 110° (Figure 7a). For BWC-FM and BWC-EC signals, 46% and 96%, respectively, were detected at ≤90° and were

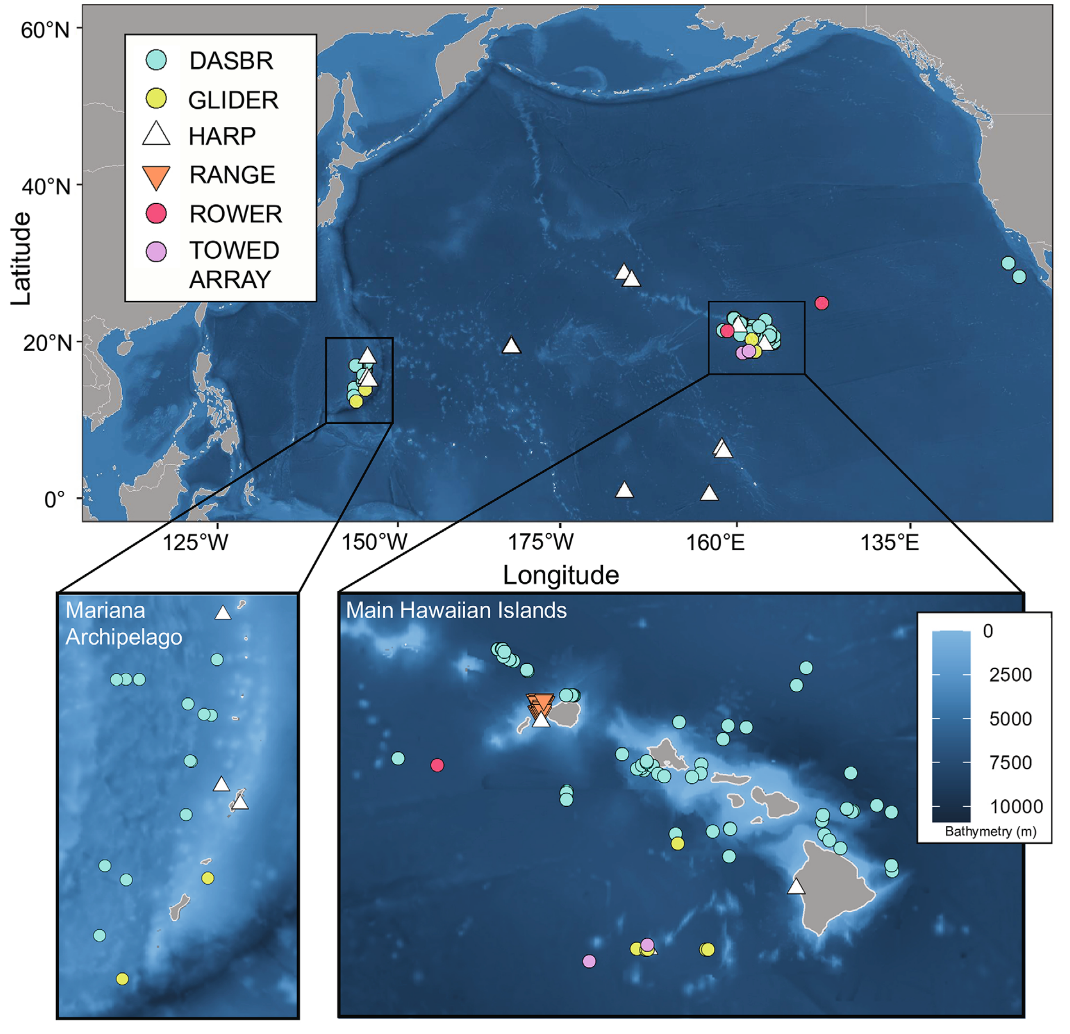

FIGURE 2 Map of the North Pacific Ocean with color-coded locations of acoustic detections of the Cross Seamount beaked whale (BWC-FM pulse) on various recording platforms (circle = moving platform, triangle = stationary platform). Insets show zoomed-in sections of the Mariana Archipelago and the main Hawaiian Islands. ETOPO1 bathymetry downloaded using R package *marmap* (Pante & Simon-Bouhet, 2013).

therefore produced at depths ≤150 m. Only BWC-EC signals occurred at angles <40°, suggesting that this signal occurs at shallower depths than typical BWC-FM pulses.

An example encounter illustrates the depth relationship between BWC-FM pulses and BWC-EC signals (Figure 7). A vertical time-bearing display (Figure 7b) shows at least four detected subgroups of Cross Seamount beaked whales, with three producing BWC-EC signals at variable bearing angles. Furthermore, these data suggest a progression from BWC-FM pulses to BWC-EC signals, with one subgroup producing BWC-FM pulses from 80° to 144° followed by BWC-EC signals, potentially representing a terminal foraging buzz (Figure 7b). Another subgroup produced a BWC-FM pulse train starting at 150° and approached the surface where it then alternated BWC-EC signals as both click trains and burst pulses with trains of BWC-FM pulses, suggesting multiple functions for the BWC-EC signals (Figures 6c and 7b).

Combining all recording platforms, BWC-FM pulses were detected in waters with bathymetry ranging from 104 to 5,674 m. Seventy-five percent of those detections were in waters with bottom depths deeper than 651 m.

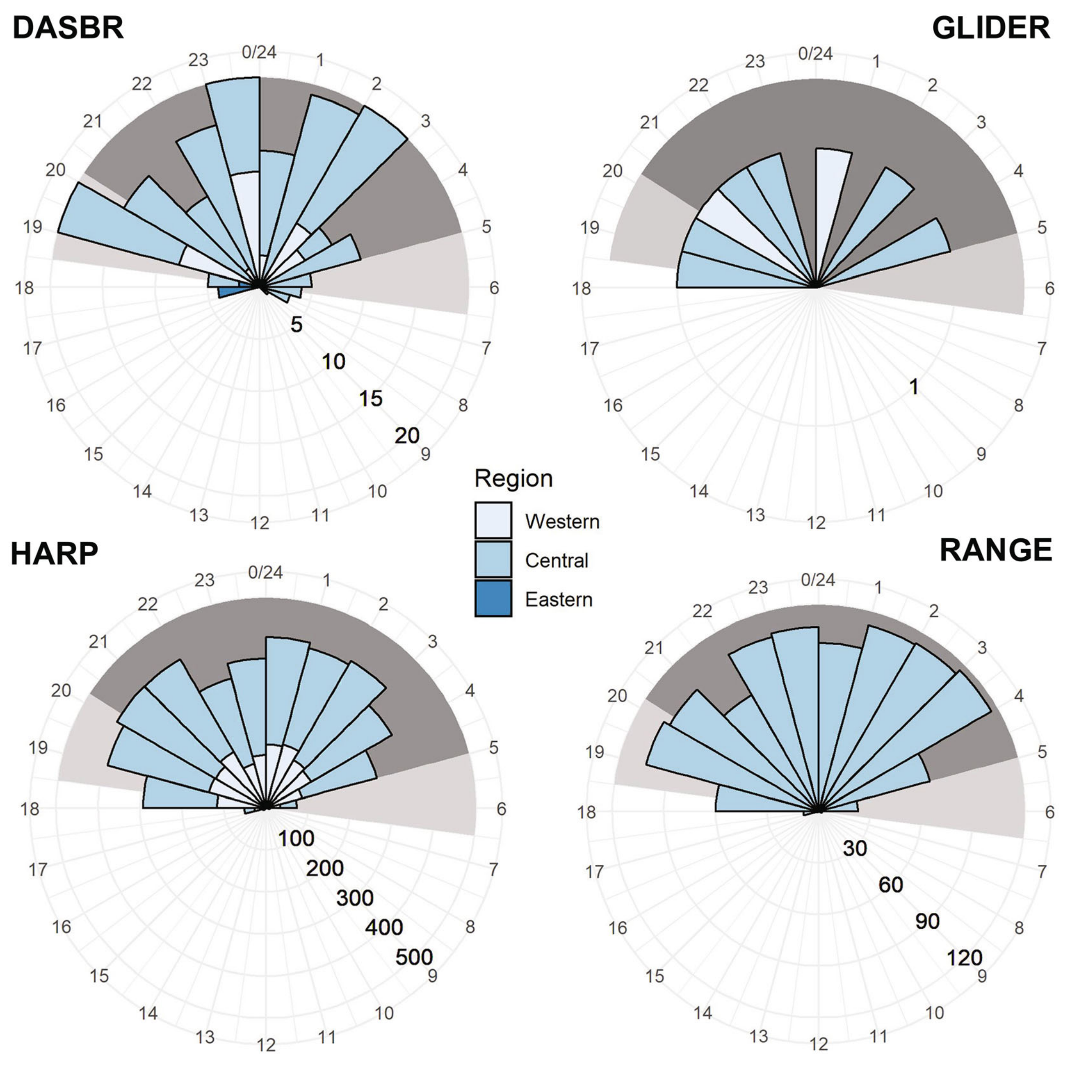

FIGURE 3 Polar histograms separated by recording platform displaying counts of acoustic detections of Cross Seamount beaked whale (BWC-FM pulse) per hour of the day (local time) and colored by region of the North Pacific Ocean (Western = <155°W; Central = 155°W to 135°E; Eastern = <135°E). Dark gray shading indicates nighttime hours and light gray shading represents dawn/dusk. TOWED ARRAY and ROWER data were not plotted due to limited available data. (Plotted using R package *ggplot2*; Wickham, 2016).

However, when considering effort there were considerably more detections at shallower depths with 39% of detections in <1,000 m with only 1.5% of effort. In its entirety, the recording effort covered bathymetry extending up to 10,000 m with 80% of the effort occurring between 1,449 and 5,489 m.

4 | DISCUSSION

4.1 | Spatio-temporal distribution

Acoustic detections of BWC signals were present in the tropical zone and the lower latitudes of subtropical waters. They spanned the Pacific Ocean from the Mariana Archipelago to Baja California, Mexico, south to the equator, but only

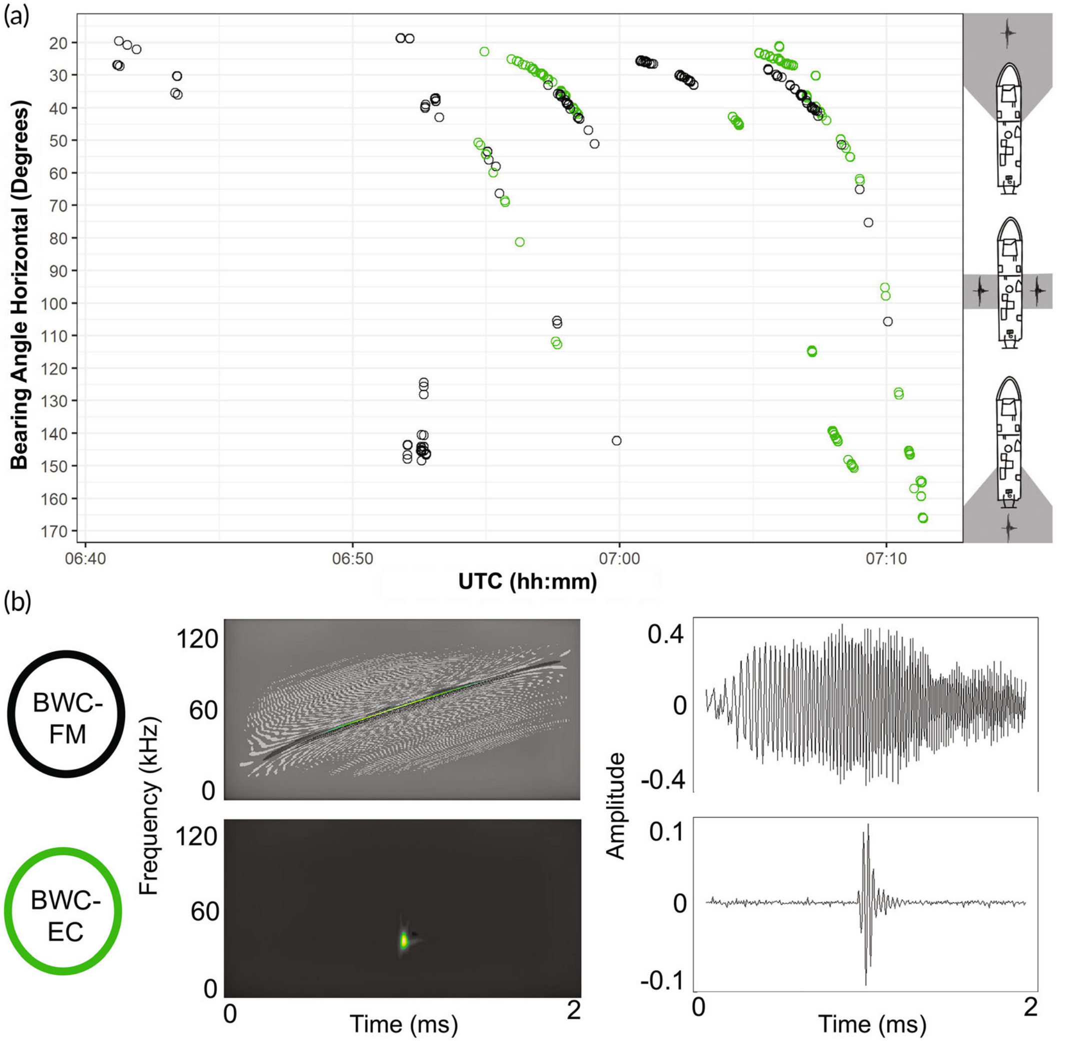

FIGURE 4 Echolocation signals from Cross Seamount beaked whale (BWC) detected on the TOWED ARRAY recording platform. (a) Horizontal time-bearing display of multiple subgroups passing the ship colored by signal type, with frequency-modulated pulses (BWC-FM) in black, and echolocation clicks (BWC-EC) in green. An infographic of where echolocation signals were measured via the towed array in relation to the ship is shown on the right.
(b) Example Wigner plots (left) and waveform plots (right) for the BWC-FM (top) and BWC-EC (bottom) signal types. (Plotted using R package *PAMpal*; Sakai, 2020).

TABLE 2 Acoustic characteristics of BWC signals from drifting recorders (DASBRs) given as median values with 10th and 90th percentiles in parentheses. To account for instances of multiple BWC-EC signals being detected in an analysis bin, we filtered out the top 50% of duration values from the data.

Signal type	BWC-FM (n = 23,972)	BWC-EC (n = 1,498)
Peak frequency (kHz)	42.40 (33.60, 50.40)	38.0 (29.60, 47.60)
Center frequency (kHz)	42.66 (33.43, 49.78)	38.17 (29.93, 47.11)
−10 dB bandwidth (kHz)	26.66 (10.24, 37.89)	22.29 (11.84, 39.42)
−10 dB lower end point (kHz)	29.22 (24.75, 38.60)	28.34 (21.99, 37.91)
Duration (μs)	424 (114, 844)	80 (42, 139)

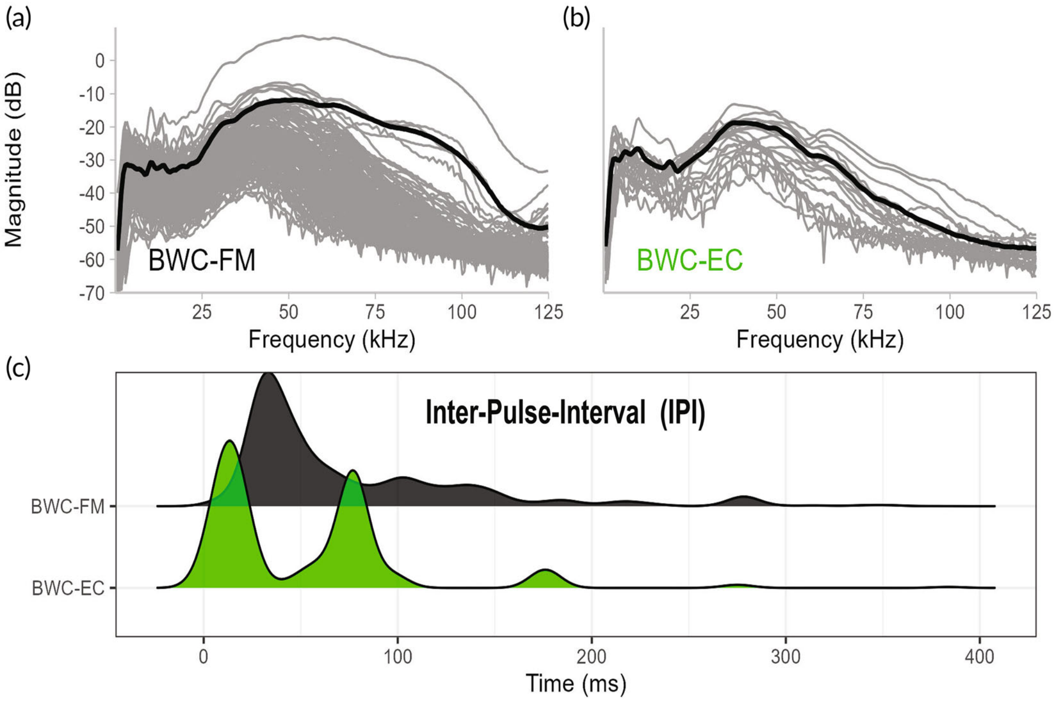

FIGURE 5 Spectral averages and interpulse-interval (IPI) plots of BWC signals from drifting recorders (DASBRs). (a) Spectral averages of individual event data (gray lines) for BWC-FM with the mean overlaid (thick black line). There were several exemplar on-axis, high signal-to-noise ratio BWC FM pulse events that have allowed the mean to be representative of the full signal. (b) Spectral averages of all BWC-EC pulse events (thick black line) and individual event data (gray lines), (c) Density plot of interpulse-intervals (IPIs) on a scale from 0 to 0.025 on the *y*-axis. (Plotted using R packages *PAMpal* and *ggplot2*; Sakai, 2020; Wickham, 2016).

as far north as 29°N. Interestingly, they were not detected along the U.S. West Coast nor offshore of Alaska despite the extraordinary amount of recording effort conducted in those regions. There was no seasonal shift in detections, leading us to believe the Cross Seamount beaked whale does not migrate but rather stays within a consistent temperature range, and if warmer waters move farther north or east from time to time, then their detection range stretches with that shift in temperature. This could explain why recording efforts detected them off Baja California, Mexico, only in 2018 when there were record-setting high sea surface temperatures that fall (Monroe, 2018). We had no acoustic monitoring south of the equator and cannot address the southern limit of the Cross Seamount beaked whale.

4.2 | Unique characteristics

The Cross Seamount beaked whale FM pulse has unique signal characteristics compared to other beaked whale pulses, with long signal duration, short IPI, and very broad bandwidth, making it easy to distinguish from FM pulses produced by other species. The BWC-FM pulse is much longer in duration than all other known beaked whale FM echolocation pulses, except for a signal type recorded in the Gulf of Mexico termed “BWG” (Baumann-Pickering et al., 2013) that is similar in bandwidth and duration to the BWC-FM pulse. The BWC's longer signal duration results in a frequency range spanning a minimum of 60 kHz, compared to other species that typically produce FM upsweeps with bandwidths of only 10–25 kHz (Barlow et al., 2021a; Baumann-Pickering et al., 2013, 2014; DeAngelis et al., 2018).

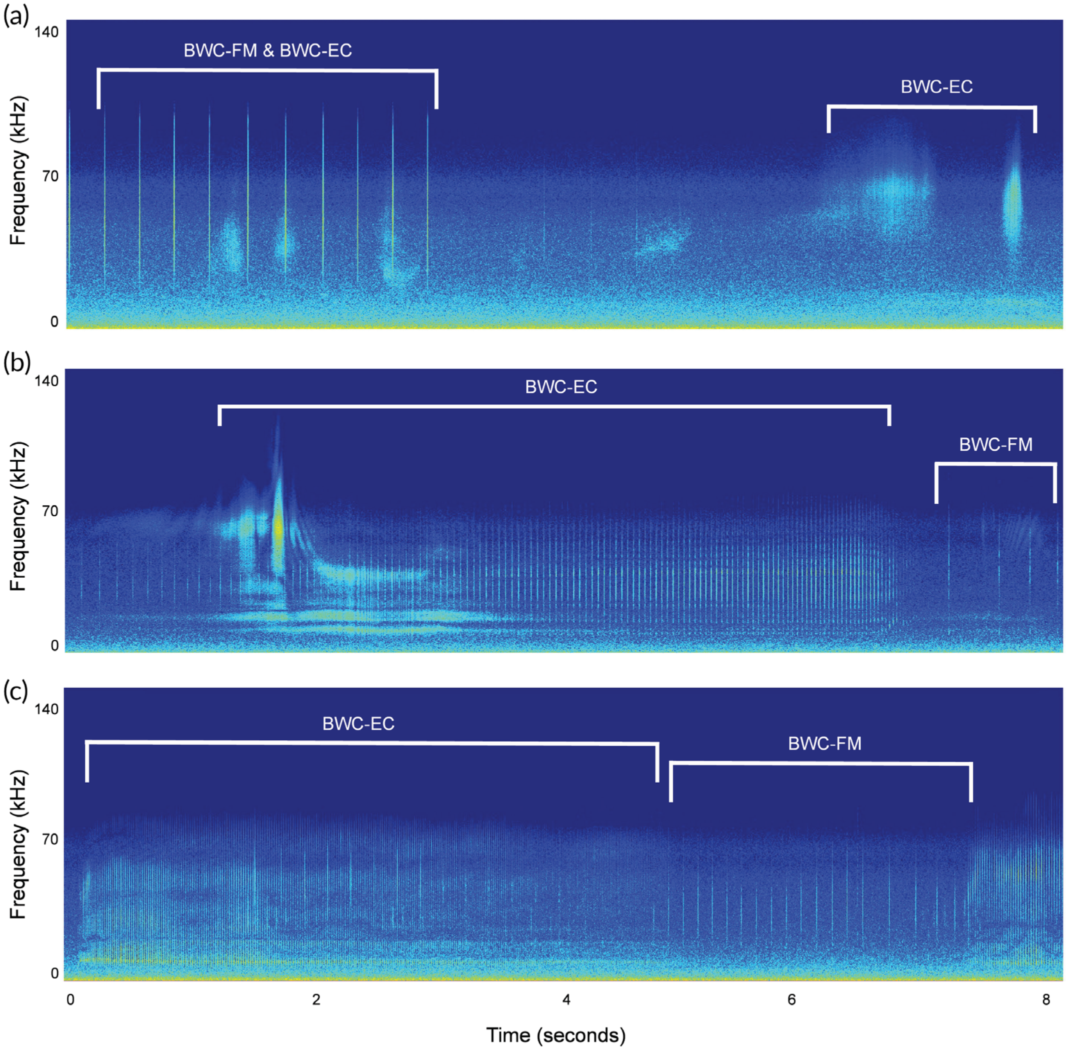

FIGURE 6 Spectrograms of echolocation signals detected on Drifting Acoustic Spar Buoy Recorders (DASBRs) highlighting the time periods of the Cross Seamount beaked whale frequency-modulated pulses (BWC-FM) and echolocation clicks (BWC-EC).

The BWC-FM pulse differs not only in its acoustic properties, but also in the behavioral context of its use. Very few species of beaked whales have been documented producing an echolocation click type like those produced by dolphins (Baumann-Pickering et al., 2013). When they are documented, it has been primarily in the form of a terminal foraging buzz (Jarvis et al. 2022; Johnson et al. 2006, 2008). Baird's (*Berardius bairdii*), Longman's (*Indopacetus pacificus*), and Northern bottlenose (*Hyperoodon ampullatus*) beaked whales are the main exceptions, with a multitude of signals produced (DeAngelis et al., 2023; Hooker & Whitehead, 2002; Rankin et al., 2011). These species produce signals at the surface and in social contexts but produce their FM pulses only at depths >450 m (DeAngelis et al., 2023). In contrast, the Cross Seamount beaked whale is shown to commonly produce BWC-FM pulses at depths less than 150 m. Foraging in waters this shallow is not known for any other species of beaked whale.

McDonald et al. (2009) noted the presence of buzzes on Cross Seamount HARP recordings but could not discern whether they were produced by the Cross Seamount beaked whale or another odontocete. The HARPs in this study

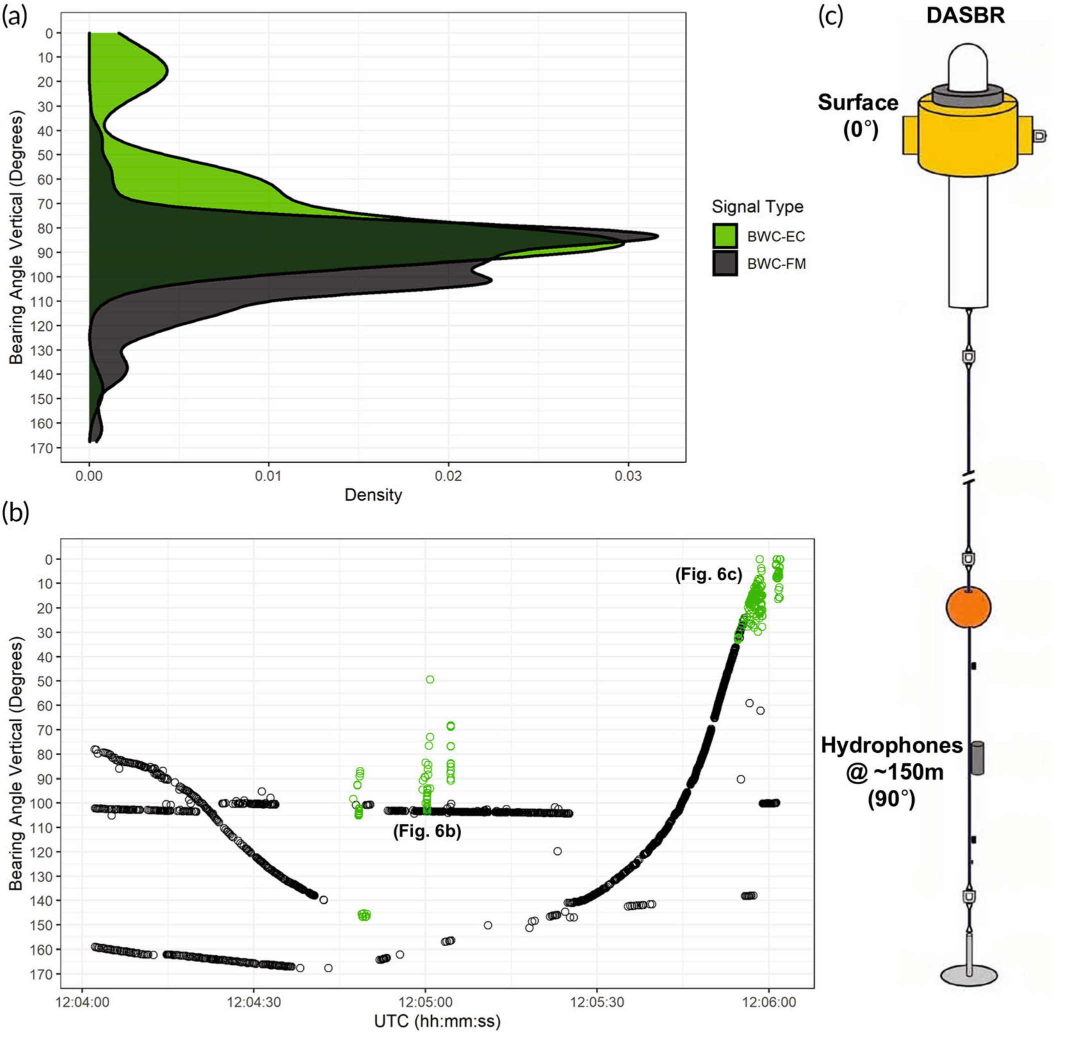

FIGURE 7 Echolocation signals of Cross Seamount beaked whales detected on a Drifting Acoustic Spar Buoy Recorder (DASBR) colored by signal type. (a) Density plot of detection angles in relation to the DASBR, where 0° represents straight upward, 90° is at the DASBR hydrophone depth (~150 m), and 180° is straight downward. (b) Vertical time-bearing display of multiple subgroups passing the DASBR; angles same as in (a). (c) Schematic of the DASBR. (Plotted using R-packages *PAMpal* and *ggplot2*; Sakai, 2020; Wickham, 2016).

contained only a single hydrophone, and thus we could not determine whether the same individual produced both types of BWC signals, especially in the presence of multiple species. The towed array data allowed us to associate buzzes produced during foraging (BWC-EC) with the BWC-FM pulse for the first time. Given this knowledge and the two hydrophones of the DASBRs enabling us to localize the depth of the vocalizing animals, we determined that BWC-EC signals are produced near the surface not just for foraging but, potentially in a social context as well. In addition, the strong bimodal peaks in the IPI for BWC-EC signals add to the possibility of varied usage of the signal (Figure 5). If these signals do serve as social communication, this may provide a way for researchers to identify BWC-EC signals within data sets recorded during daylight hours without the concurrent presence of the foraging FM pulses, and may thereby help us to visually link the BWC-FM pulse with a known species of beaked whale.

In addition to producing its foraging signals at shallow depths, the Cross Seamount beaked whale appears to be primarily a nocturnal hunter, which is unique among all other beaked whales that do not exhibit strong diel patterns in echolocation activity (Baird et al., 2008, 2019; Baumann-Pickering et al., 2014; Schorr et al., 2014). This nighttime foraging behavior, coupled with relatively shallow dive depths, may indicate that the beaked whale species producing BWC-FM pulses is foraging on diel, vertically migrating prey that come closer to the surface at night. All necropsied species of beaked whales were found to feed primarily on squid and mesopelagic fish (Adams et al., 2015; MacLeod et al. 2004; Santos et al., 2007). In the tropical Pacific Ocean, squid are known to conduct diel vertical migration include the Humboldt squid (*Dosidicus gigas*) and the purpleback flying squid (*Sthenoteuthis oualaniensis*; Gilly et al., 2006; Zuyev et al., 2002). However, most other studies of diel vertical migration in squid have been conducted in the western and eastern portions of the Pacific and largely in temperate waters, with little focus on the central tropical waters. Therefore, the potential prey species of Cross Seamount beaked whales and their associated diel vertical migration patterns remain unknown.

4.3 | Species assignment

In 2014, Baumann-Pickering et al. hypothesized that the BWC-FM pulse was associated with the ginkgo-toothed beaked whale. This was done partly because there is no acoustic signature match for ginkgo-toothed beaked whales, and also due to the spatial overlap between the distribution of BWC-FM pulse acoustic detections and the limited sighting and stranding records of this species throughout the Pacific Ocean, especially around Japan (Nishiwaki & Kamiya, 1958). Due to the strongly nocturnal occurrence of the BWC-FM pulse, it has also been theorized that this pulse type is produced by a beaked whale species with a known signal type as a secondary acoustic signature (Manzano-Roth et al., 2023). For several reasons, this theory seems unlikely. Blainville's and Cuvier's beaked whales are the only two species of beaked whales that have been acoustically detected over the entire geographic range of the BWC-FM pulse in the North Pacific Ocean (Keating et al., 2016, 2018; McCullough et al., 2021a,b; Simonis et al., 2020; Yano et al., 2018, 2020). Both species produce known FM pulse types with no diel patterning (Baumann-Pickering et al., 2014; Henderson et al. 2016; Manzano-Roth et al., 2023; McCullough et al., 2021a). Cuvier's beaked whales are commonly detected throughout the waters of the U.S. West Coast and no detections of the BWC-FM pulse have been found during concurrent survey efforts (Barlow et al., 2021b; Baumann-Pickering et al., 2014; Keating et al., 2018). Blainville's beaked whales appear to generally occur in the same tropical waters as the Cross Seamount beaked whale. In multiple instances in the DASBR data, BWC-FM pulses, and FM pulses of Blainville's beaked whales were detected at the same time but at distinct bearing angles with no overlap in the time-bearing tracks, suggesting the whales occurred at different depths. Similarly, in the RANGE data set, both BWC and Blainville's beaked whale echolocation signals were detected on the same hydrophones but never in a temporal pattern that would suggest they were produced by the same species.

The only species of beaked whale with a similar FM pulse type, termed BWG, has been detected in the Gulf of Mexico (Baumann-Pickering et al., 2013; Hildebrand et al., 2015) and in the western Atlantic Ocean along the southern portion of the United States, and similarly to the BWC-FM pulse, BWG signals have been detected only at night (S.B.-P. & J.S.T., unpublished data). BWC and BWG signals could thus represent the same species, or could be a result of two species converging on a similar echolocation signal type that helps them specialize on foraging at night, potentially in shallow waters. It is not yet known if the beaked whale producing BWG signals forages at similarly shallow depths. If BWC and BWG signals are made by the same species, that species is not likely to be the ginkgo-toothed beaked whale as it is not known to occur in neither the Gulf of Mexico nor the Atlantic Ocean.

The species identity of the Cross Seamount beaked whale is still very much a mystery, especially with BWC-FM pulses detected only under the cover of night. Through our extensive compilation of acoustic data, we now better understand the distribution and foraging behavior of this beaked whale. Passive acoustic monitoring has been key in unveiling the presence of considerable cetacean signaling without which we would have no understanding of species like the Cross Seamount beaked whale.

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AUTHOR CONTRIBUTIONS

Jennifer L. K. McCullough: Conceptualization; data curation; formal analysis; methodology; project administration; resources; writing – original draft; writing – review and editing. **E. Elizabeth Henderson:** Data curation; formal analysis; writing – original draft; writing – review and editing. **Jennifer Sandra Trickey:** Data curation; formal analysis; writing – original draft; writing – review and editing. **Jay Barlow:** Data curation; formal analysis; writing – review and editing. **Simone Baumann-Pickering:** Data curation; formal analysis; writing – review and editing. **Roanne Manzano-Roth:** Data curation; formal analysis; writing – review and editing. **Gabriela Alongi:** Data curation; formal analysis; writing – review and editing. **Steve Martin:** Data curation; formal analysis; writing – review and editing. **Selene Fregosi:** Data curation; formal analysis; writing – review and editing. **David K. Mellinger:** Data curation; formal analysis; writing – review and editing. **Holger Klinck:** Data curation; formal analysis; writing – review and editing. **Angela R. Szesciorka:** Formal analysis; writing – review and editing. **Erin Oleson:** Data curation; funding acquisition; writing – review and editing.

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ORCID

Jennifer L. K. McCullough https://orcid.org/0000-0003-4212-7846
E. Elizabeth Henderson https://orcid.org/0000-0002-3212-1080

Jennifer S. Trickey https://orcid.org/0000-0002-6080-8744
Jay Barlow https://orcid.org/0000-0001-7862-855X
Simone Baumann-Pickering https://orcid.org/0000-0002-3428-3577
Roanne Manzano-Roth https://orcid.org/0000-0002-2562-8158
Gabriela Alongi https://orcid.org/0009-0007-0078-4166
Stephen Martin https://orcid.org/0009-0004-6243-4813
Selene Fregosi https://orcid.org/0000-0002-2685-3736
David K. Mellinger https://orcid.org/0000-0002-5228-0513
Holger Klinck https://orcid.org/0000-0003-1078-7268
Angela R. Szesciorka https://orcid.org/0000-0002-0016-2144
Erin M. Oleson https://orcid.org/0000-0002-4889-6059

REFERENCES

Adams, J., Walker, W. A., Burton, E. J., & Harvey, J. T. (2015). Stomach contents of a Cuvier's beaked whale (*Ziphius cavirostris*) stranded in Monterey Bay, California. *Northwestern Naturalist*, *96*, 93–98. https://doi.org/10.1898/NWN14-10.1

Baird, R. W. (2019). Behavior and ecology of not-so-social odontocetes: Cuvier's and Blainville's beaked whales. In B. Würsig (Ed.), *Ethology and behavioral ecology of odontocetes, ethology and behavioral ecology of marine mammals* (pp. 305–329). Springer Nature. https://doi.org/10.1007/978-3-030-16663-2_14

Baird, R. W., Webster, D. L., Schorr, G. S., McSweeney, D. J., & Barlow, J. (2008). Diel variation in beaked whale diving behavior. *Marine Mammal Science*, *24*(3), 630–642. https://doi.org/10.1111/j.1748-7692.2008.00211.x

Ballance, L. T., Pitman, R. L., Barlow, J., Pusser, T., DeAngelis, A.I., Hayslip, C., Irvine, L., Irvine, L. Steel, D., Baker, S., Gillies, D., Trickey, J. S., & Baumann-Pickering, S. (in press). Acoustic and biological observations of a rare North Pacific beaked whale: *Mesoplodon carlhubbsi*. *Marine Mammal Science.*

Barlow, J. (2021). Design of a flooded housing for a towed autonomous hydrophone recording system. (NOAA Technical Report NMFS-SWFSC-647). U.S. Department of Commerce. https://doi.org/10.25923/rmzp-fh90

Barlow, J., Cheeseman, T., & Trickey, J. S. (2021a). Acoustic detections of beaked whales, narrow-band high-frequency pulses and other odontocete cetaceans in the Southern Ocean using an autonomous towed hydrophone recorder. *Deep Sea Research Part II: Topical Studies in Oceanography*, *193*, Article 104973. https://doi.org/10.1016/j.dsr2.2021.104973

Barlow, J., & Eruç, E. (2023). Acoustic detections of cetaceans from a towed recording system on a trans-Pacific rowing expedition. *Aquatic Mammals*, *49*(3), 236–240. https://doi.org/10.1578/AM.49.3.2023.236

Barlow, J., Moore, J. E., McCullough, J. L. K., & Griffiths, E. T. (2021b). Acoustic based estimates of Cuvier's beaked whale (*Ziphius cavirostris*) density and abundance along the U.S. West Coast from drifting hydrophone recorders. *Marine Mammal Science*, *38*(2), 517–538. https://doi.org/10.1111/mms.12872

Baumann-Pickering, S., McDonald, M. A., Simonis, A. E., Solsona-Berga, A., Merkens, K. P., Oleson, E. M., Roch, M. A., Wiggins, S. M., Rankin, S., Yack, T. M., & Hildebrand, J. A. (2013). Species-specific beaked whale echolocation signals. *Journal of the Acoustical Society of America*, *14*(3), 2293–2301. https://doi.org/10.1121/1.4817832

Baumann-Pickering, S., Roch, M. A., Brownell, R. L., Jr., Simonis, A. E., McDonald, M. A., Solsona-Berga, A., Oleson, E. M., Wiggins, S. M., & Hildebrand, J. A. (2014). Spatio-temporal patterns of beaked whale echolocation signals in the North Pacific. *PLoS ONE*, *9*(1), Article e86072. https://doi.org/10.1371/journal.pone.0086072

Baumann-Pickering, S., Trickey, J. S., Wiggins, S., & Oleson, E. M. (2016). Odontocete occurrence in relation to changes in oceanography at a remote equatorial Pacific seamount. *Marine Mammal Science*, *32*(3), 805–825. https://doi.org/10.1111/mms.12299

Bivand, R., & Lewin-Koh, N. (2022). *Tools for handling spatial object* [Computer software]. https://cran.r-project.org/web/packages/maptools/maptools.pdf

Cholewiak, D., Baumann-Pickering, S., & Van Parijs, S. (2013). Description of sounds associated with Sowerby's beaked whales (*Mesoplodon bidens*) in the western North Atlantic Ocean. *Journal of the Acoustical Society of America*, *134*(5), 3905–3912. https://doi.org/10.1121/1.4823843

Dawson, S., Barlow, J., & Ljungblad, D. K. (1998). Sounds recorded from Baird's beaked whale, *Berardius bairdii. Marine Mammal Science*, *14*(2), 335–344. https://doi.org/10.1111/j.1748-7692.1998.tb00724.x

DeAngelis, A. I., Barlow, J., Gillies, D., & Ballance, L. T. (2023). Echolocation depths and acoustic foraging behavior of Baird's beaked whales (*Berardius bairdii*) based on towed hydrophone recordings. *Marine Mammal Science*, *39*(1), 289–298. https://doi.org/10.1111/mms.12958

DeAngelis, A. I., Stanistreet, J. E., Baumann-Pickering, S., & Cholewiak, D. M. (2018). A description of echolocation clicks recorded in the presence of True's beaked whale (*Mesoplodon mirus*). *Journal of the Acoustical Society of America*, *144*(5), 2691–2700. https://doi.org/10.1121/1.5067379

Gillespie, D., Dunn, C., Gordon, J., Claridge, D., Embling, C., & Boyd, I. (2009a). Field recordings of Gervais' beaked whales *Mesoplodon europaeus* from the Bahamas. *Journal of the Acoustical Society of America*, *125*(5), 3428–3433. https://doi.org/10.1121/1.3110832

Gillespie, D., Mellinger, D.K., Gordon, J., McLaren, D., Redmond, P., McHugh, R., Trinder, P., Deng, X.-Y., & Thode, A. (2009b). PAMGUARD: Semiautomated, open source software for real time acoustic detection and localization of cetaceans. *Journal of the Acoustical Society of America*, *125*(4_Supplement), 2547–2547. https://doi.org/10.1121/1.4808713

Gilly, W. F., Markaida, U., Baxter, C. H., Block, B.A., Boustany, A., Zeidberg, L., Reisenbichler, K., Robison, B., Bazzino, G., & Salinas, C. (2006). Vertical and horizontal migrations by the jumbo squid *Dosidicus gigas* revealed by electronic tagging. *Marine Ecology Progress Series*, *324*, 1–17. https://doi.org/10.3354/meps324001

Griffiths, E. T., Keating, J. L., Barlow, J., & Moore, J. E. (2019). Description of a new beaked whale echolocation pulse type in the California Current. *Marine Mammal Science*, *35*(3), 1058–1069. https://doi.org/10.1111/mms.12560

Henderson, E. E., Martin, S. W., Manzano-Roth, R., & Matsuyama, B. M. (2016). Occurrence and habitat use of foraging Blainville's beaked whales (*Mesoplodon densirostris*) on a U.S. Navy Range in Hawaii. *Aquatic Mammals*, *42*(4), 549–562. https://doi.org/10.1578/am.42.4.2016.549

Hildebrand, J. A., Baumann-Pickering, S., Frasier, K. E., Trickey, J. S., Merkens, K. P., Wiggins, S. M., McDonald, M. A., Garrison, L. P., Harris, D., Marques, T. A., & Thomas, L. (2015). Passive acoustic monitoring of beaked whale densities in the Gulf of Mexico. *Scientific Reports*, *5*, Article 16343. https://doi.org/10.1038/srep16343

Hooker, S. K., & Whitehead, H. (2002). Click characteristics of northern bottlenose whales (*Hyperoodon ampullatus*). *Marine Mammal Science*, *18*(1), 69–80. https://doi.org/10.1111/j.1748-7692.2002.tb01019.x

Jarvis, S., Dimarzio, N., Watwood, S., Dolan, K. A., & Morrissey, R. (2022). Automated detection and classification of beaked whale buzzes on bottom-mounted hydrophones. *Frontiers in Marine Science*, *3*, 1–14. https://doi.org/10.3389/frsen.2022.941838

Johnson, M., Hickmott, L. S., Aguilar Soto, N., & Madsen, P. T. (2008). Echolocation behaviour adapted to prey in foraging Blainville's beaked whale (*Mesoplodon densirostris*). *Proceedings of the Royal Society B: Biological Sciences*, *275*(1631), 133–139. https://doi.org/10.1098/rspb.2007.1190

Johnson, M., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N., & Tyack, P. L. (2004). Beaked whales echolocate on prey. *Proceedings of the Royal Society B: Biological Sciences*, *271*(Suppl_6), S383–S386. https://doi.org/10.1098/rsbl.2004.0208

Johnson, M., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N., & Tyack, P. L. (2006). Foraging Blainville's beaked whales (*Mesoplodon densirostris*) produce distinct click types matched to different phases of echolocation. *Journal of Experimental Biology*, *209*(24), 5038–5050. https://doi.org/10.1242/jeb.02596

Keating, J. L., & Barlow, J. (2013). *Summary of PAMGuard beaked whale click detectors and classifiers used during the 2012 Southern California Behavioral Response Study* (NOAA Technical Report NMFS-SWFSC-517). U.S. Department of Commerce.

Keating, J. L., Barlow, J., Griffiths, E. T., & Moore, J. E. (2018). *Passive acoustics survey of cetacean abundance levels (PASCAL-2016) final report*. (OCS Study BOEM 2018-025). Bureau of Ocean Energy Management, U.S. Department of the Interior.

Keating, J. L., Barlow, J., & Rankin, S. (2016). Shifts in frequency-modulated pulses recorded during an encounter with Blainville's beaked whales (*Mesoplodon densirostris*). *Journal of the Acoustical Society of America*, *140*(2), EL166–EL171. https://doi.org/10.1121/1.4959598

Klinck, H., Nieukirk, S. L., Fregosi, S., Klinck, K., Mellinger, D. K., Lastuka, S., Shilling, G. B., & Luby, J. C. (2015a). *Cetacean studies on the Hawaii Range Complex in December 2014–January 2015: Passive acoustic monitoring of marine mammals using gliders* (Final report). Prepared for Commander, U.S. Pacific Fleet, Environmental Readiness Division, Pearl Harbor, HI. Submitted to Naval Facilities Engineering Command (NAVFAC) Pacific, Pearl Harbor, Hawaii under Contract No. N62470-10-D-3011, Task Order KB25, issued to HDR Inc., Honolulu, Hawaii.

Klinck, H., Nieukirk, S.L., Fregosi, S., Klinck, K., Mellinger, D. K., Lastuka, S., Shilling, G. B., & Luby, J. C. (2015b). *Cetacean studies on the Mariana Islands Range Complex in September–November 2014: Passive acoustic monitoring of marine mammals using gliders* (Final report). Prepared for Commander, U.S. Pacific Fleet, Environmental Readiness Division, Pearl Harbor, HI. Submitted to Naval Facilities Engineering Command (NAVFAC) Pacific, Pearl Harbor, Hawaii under Contract No. N62470-10-D-3011, Task Order KB25, issued to HDR Inc., Honolulu, Hawaii.

Klinck, H., Nieukirk, S. L., Fregosi, S., Klinck, K., Mellinger, D. K., Lastuka, S., Shilling, G. B., & Luby, J. C. (2016). *Cetacean studies on the Mariana Islands Range Complex in March–April 2015: Passive acoustic monitoring of marine mammals using gliders* (Final report). Prepared for Commander, U.S. Pacific Fleet, Environmental Readiness Division, Pearl Harbor, HI. Submitted to Naval Facilities Engineering Command (NAVFAC) Pacific, Pearl Harbor, Hawaii under Contract No. N62470-10-D-3011, Task Order KB23, issued to HDR Inc., Honolulu, Hawaii.

MacLeod, C. D., Pierce, G. J., & Santos Vazquez, M. B. (2004). Geographic and temporal variations in strandings of beaked whales (*Ziphiidae*) on the coasts of the UK and the Republic of Ireland 1800–2002. *Journal of Cetacean Research Management*, *6*(1), 79–86.

MacLeod, C. D., Santos, M. B., López, A., & Pierce, G. J. (2006). Relative prey size consumption in toothed whales: implications for prey selection and level of specialisation. *Marine Ecology Progress Series*, *326*, 295–307. https://doi.org/10.3354/meps326295

Manzano-Roth, R., Henderson, E. E., Alongi, G. C., Martin, C. R., Martin, S. W., & Matsuyama, B. M. (2023). Dive characteristics of Cross Seamount beaked whales from long-term passive acoustic monitoring at the Pacific Missile Range Facility, Kaua'i. *Marine Mammal Science*, *39*(1), 22–41. https://doi.org/10.1111/mms.12959

Manzano-Roth, R., Henderson, E. E., Martin, S. W., Martin, C., & Matsuyama, B. M. (2016). Impacts of U.S. Navy training events on Blainville's beaked whale (*Mesoplodon densirostris*) foraging dives in Hawaiian waters. *Aquatic Mammals*, *42*(4), 507–518. https://doi.org/10.1578/AM.42.4.2016.507

Martin, S. W., Martin, C. R., Matsuyama, B. M., & Henderson, E. E. (2015). Minke whales (*Balaenoptera acutorostrata*) respond to navy training. *Journal of the Acoustical Society of America*, *137*(5), 2533–2541. https://doi.org/10.1121/1.4919319

McCullough, J. L. K., Oleson, E. M., Barlow, J., Allen, A. N., & Merkens, K. P. (2021a). *An acoustic survey in the main Hawaiian Islands using drifting recorders*. (NOAA Administrative Report H-21-04). National Marine Fisheries Service. https://doi.org/10.25923/rzzz-0v38

McCullough, J. L. K., Wren, J. L. K., Oleson, E. M., Allen, A. N., Siders, Z. A., & Norris, E. S. (2021b). An acoustic survey of beaked whales and *Kogia* spp. in the Mariana Archipelago using drifting recorders. *Frontiers in Marine Science*, *8*, 1–8. https://doi.org/10.3389/fmars.2021.664292

McDonald, M. A., Hildebrand, J. A., Wiggins, S. M., Johnston, D. W., & Polovina, J. J. (2009). An acoustic survey of beaked whales at Cross Seamount near Hawaii. *Journal of the Acoustical Society of America*, *125*(2), 624–627. https://doi.org/10.1121/1.3050317

Monroe, R. (2018). *Highest-ever seawater temperature recorded at Scripps pier*. https://scripps.ucsd.edu/news/highest-ever-seawater-temperature-recorded-scripps-pier

Nieukirk, S. L., Fregosi, S., Mellinger, D. K., & Klinck, H. (2016). A complex baleen whale call recorded in the Mariana Trench Marine National Monument. *Journal of the Acoustical Society of America*, *140*(3), EL274–EL279. https://doi.org/10.1121/1.4962377

Nishiwaki, M., & Kamiya, T. (1958). A beaked whale *Mesoplodon* stranded at Oiso Beach, Japan. *Scientific Reports of the Whale Institute, Tokyo*, *13*, 53–83.

Pante, E., & Simon-Bouhet, B. (2013). marmap: A package for importing, plotting and analyzing bathymetric and topographic data in R. *PLoS ONE*, *8*(9), Article e73051. https://doi.org/10.1371/journal.pone.0073051

Quick, N. J., Cioffi, W. R., Shearer, J. M., Fahlman, A., & Read, A. J. (2020). Extreme diving in mammals: first estimates of behavioural aerobic dive limits in Cuvier's beaked whales. *Journal of Experimental Biology*, *223*(18), Article jeb222109. https://doi.org/10.1242/jeb.222109

R Core Team. (2021). *R: A language and environment for statistical computing* [Computer Software]. R Foundation for Statistical Computing.

Rankin, S., Baumann-Pickering, S., Yack, T., & Barlow, J. (2011). Description of sounds recorded from Longman's beaked whale, *Indopacetus pacificus*. *Journal of the Acoustical Society of America*, *130*(5), EL339–EL344. https://doi.org/10.1121/1.3646026

Roch, M. A., Klinck, H., Baumann-Pickering, S., Mellinger, D. K., Qui, S., Soldevilla, M. S., & Hildebrand, J. A. (2011). Classification of echolocation clicks from odontocetes in the Southern California Bight. *Journal of the Acoustical Society of America*, *129*(1), 467–475. https://doi.org/10.1121/1.3514383

Sakai, T. (2020). *PAMpal: Load and process passive acoustic data* (R package version 0.9.14) [Computer Software]. https://taikisan21.github.io/PAMpal/

Santos, M. B., Martin, V., Arbelo, M., Fernández, A., & Pierce, G. J. (2007). Insights into the diet of beaked whales from the atypical mass stranding in the Canary Islands in September 2002. *Journal of the Marine Biological Association of the United Kingdom*, *87*(1), 243–251. https://doi.org/10.1017/s0025315407054380

Schorr, G. S., Falcone, E. A., Moretti, D. J., & Andrews, R. D. (2014). First long-term behavioral records from Cuvier's beaked whales (*Ziphius cavirostris*) reveal record-breaking dives. *PLoS ONE*, *9*(3), Article e92633. https://doi.org/10.1371/journal.pone.0092633

Simonis, A. E., Trickey, J. S., Barlow, J., Rankin, S., Urbán R, J., Rojas-Bracho, L., & Moore, J. E. (2020). *Passive acoustic survey of deep-diving odontocetes in the California Current ecosystem 2018: Final report* (NOAA Technical Report NMFS-SWFSC-630). U.S. Department of Commerce.

Soldevilla, M. S., Henderson, E. E., Campbell, G. S., Wiggins, S. M., Hildebrand, J. A., & Roch, M. A. (2008). Classification of Risso's and Pacific white-sided dolphins using spectral properties of echolocation clicks. *Journal of the Acoustical Society of America*, *124*(1), 609–624. https://doi.org/10.1121/1.2932059

Ward, J., Morrissey, R., Moretti, D., DiMarzio, N., Jarvis, S., Johnson, M., Tyack, P., & White, C. (2008). Passive acoustic detection and localization of *Mesoplodon densirostris* (Blainville's beaked whale) vocalizations using distributed bottom-mounted hydrophones in conjunction with a Digital Tag (DTag) recording. *Canadian Acoustics*, *36*(1), 60–66.

Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. Springer-Verlag.

Wiggins, S. M., & Hildebrand, J. (2007). *High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring*. 2007 Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies (p. 551).

Yano, K. M., Oleson, E. M., Keating, J. L., Ballance, L. T., Hill, M. C., Bradford, A. L., Allen, A. N., Joyce, T. W., Moore, J. E., & Henry, A. (2018). *Cetacean and seabird data collected during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey (HICEAS), July–December* 2017. (NOAA Technical Report NMFS-PIFSC-72). U.S. Department of Commerce. https://doi.org/10.25923/7avn-gw82

Yano, K. M., Oleson, E. M., McCullough, J. L. K., Hill, M. C., & Henry, A. E. (2020). *Cetacean and seabird data collected during the Winter Hawaiian Islands Cetacean and Ecosystem Assessment Survey (Winter HICEAS), January–March 2020*. (NOAA Technical Report NMFS-PIFSC-111). U.S. Department of Commerce. https://doi.org/10.25923/ehfg-dp78

Zimmer, W. M., Harwood, J., Tyack, P. L., Johnson, M. P., & Madsen, P. T. (2008). Passive acoustic detection of deep-diving beaked whales. *Journal of the Acoustical Society of America*, *124*(5), 2823–2832. https://doi.org/10.1121/1.2988277

Zuyev, G., Nigmatullin, C., Chesalin, M., & Nesis, K. (2002). Main results of long-term worldwide studies on tropical nektonic oceanic squid genus *Sthenoteuthis*: an overview of the Soviet investigations. *Bulletin of Marine Science*, *71*(2), 1019–1060.

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